Université de Montréal

Mesure du développement de la capacité de discrimination auditive et visuelle chez des personnes malentendantes porteuses d'un implant cochléaire

par

Christine Turgeon

Département des Sciences Biomédicales
Faculté de Médecine

Thèse présentée à la Faculté de Médecine
en vue de l'obtention du grade de docteur
en sciences bio-médicales
option audiologie

Avril, 2011

Université de Montréal

Faculté des études supérieures et postdoctorales

Cette thèse intitulée :

Mesure du développement de la capacité de discrimination auditive et visuelle chez des personnes malentendantes porteuses d'un implant cochléaire

Présentée par :

Christine Turgeon

a été évaluée par un jury composé des personnes suivantes:

Sylvie Hébert, président-rapporteur

Franco Lepore, directeur de recherche

Dave Ellemberg, co-directeur

Tony Leroux, membre du jury

Karen Gordon, examinateur externe

Stéphane Molotchnikoff, représentant du doyen de la FES

Résumé

L'implant cochléaire devient une ressource importante pour contrer la surdité alors qu'il a été démontré qu'une privation auditive précoce ou tardive affecte le développement des systèmes auditif et visuel. Le but des études présentées dans cette thèse est d'évaluer l'impact développemental d'une privation auditive sur les systèmes auditif et visuel. En premier lieu, l'étude du développement chez une population entendante a montré que les systèmes auditif et visuel se développent à des rythmes distincts et qu'ils atteignent leur maturité respective à des âges différents. Ces conclusions suggèrent que les mécanismes qui sous-tendent ces deux systèmes sont différents et que leur développement respectif est indépendant. Aussi, tel qu'observé par une mesure comportementale et électrophysiologique, la discrimination fréquentielle auditive chez les personnes porteuses d'un implant cochléaire est altérée et corrélée aux performances de perception de la parole. Ces deux études suggèrent que suite à une privation auditive, le traitement auditif diffère d'une personne malentendante à une autre, et que ces différences touchent les processus de bas-niveaux, tel que suggéré par la disparité présente dans les performances de discrimination fréquentielle. La dernière étude observe qu'une privation auditive affecte aussi le développement de la modalité visuelle, tel qu'indiqué par une diminution des capacités de discrimination visuelle observée chez des malentendants. Cette indication appuie l'hypothèse qu'un développement normal de chacun des sens est requis pour un développement optimal des autres sens. Globalement, les résultats présentés dans cette thèse suggèrent que les systèmes auditif et visuel se développent de façon distincte, mais demeurent toutefois interreliés. En effet, une privation auditive affecte non seulement le développement des habiletés auditives, mais aussi celui des habiletés visuelles, suggérant une interdépendance entre les deux systèmes.

Mots-clés: implant cochléaire, développement, audition, vision, discrimination fréquentielle

Abstract

The cochlear implant is an important resource for deaf people, as it is known that an auditory deprivation alters the auditory and the visual systems. We aimed to study the impact of deafness on the development of the auditory and visual systems. First, the study of these systems in a hearing population has shown that both systems develop at different rates and reach adult-like levels at different ages. These conclusions suggest that the mechanisms underlying these treatments are different and that their developments are independent. Moreover, as shown with the behavioral and the electrophysiological study, auditory frequency discrimination in cochlear implant users is altered and correlated with the speech perception performance. These two studies suggest that following deafness, the auditory discrimination is different from one individual to another, and also that these differences affect lower processing, as shown by differences found in auditory discrimination. Finally, a hearing deprivation also modifies the visual system, as shown by a reduction in the visual frequency discrimination. This last study suggests that normal development in one modality is required for the efficient development of the other modalities. Globally, the results shown in this thesis suggest that the auditory and visual systems have a distinct development, but are however linked and suggest the interdependence of the two systems.

Keywords: cochlear implant, development, hearing, vision, frequency discrimination

Table des matières

Liste des tableaux

Chapitre II. Articles

Liste des figures

Chapitre I. Introduction

Chapitre II. Articles

Article 1

Article 2

Article 3

Article 4

Abréviations

En français:

Cpd: Cycle par degré

EEG: Électroencéphalographie

F: Fréquence

IRMf: Imagerie par résonnance magnétique fonctionnelle

ms: Millisecondes

P: Période

µV: Microvolts

En anglais:

AFC: Alternative forced-choice

CI: Cochlear implant

dB: Decibels

EEG: Electroencephalography

ERP: Evoked response potentials

JND: Just Noticeable Difference

F: Frequency

HL: Hearing level

Hz: Hertz

ICA: Independant component analysis

ISI: Interstimulus interval

ms: Millisecondes

MMN: Mismatch negativity

SPL: Sound pressure level

TDT: Tucker-Davis Technologies

μV: Microvolt

Blindness cuts us off from things, but
deafness cuts us off from people **-H. Keller**

Remerciements

Cette thèse n’aurait pas pu se concrétiser sans l’implication aidante de mes deux directeurs de recherche. Je tiens à exprimer ma reconnaissance à mon directeur de recherche Dave Ellemberg et à le remercier pour son implication, son soutien, sa disponibilité, son enthousiasme, sa patience. Il m’a offert les outils nécessaires à la réalisation de ce projet et grâce à lui, j’ai grandi en rigueur scientifique et en autonomie. Sa contribution importante me permet aujourd’hui de franchir cette étape. Ma reconnaissance va aussi à mon directeur de recherche, Franco Lepore. Son écoute, ses conseils, son expertise, sa confiance et ses encouragements ont été une importance source de motivation. Nos discussions m’ont fait réfléchir et nos rencontres ont marqué positivement ma vie.

Je tiens aussi à souligner l’implication de Phetsamone et à la remercier pour son important apport scientifique, pour son soutien et ses encouragements ainsi que pour le temps précieux qu’elle m’a consacré. Merci à Jean-Paul Guillemot et André Marcoux, deux professeurs qui ont influencé mon cheminement scolaire et professionnel et dont j’apprécie les conseils, autant sur le plan scientifique que personnel.

Merci à mes collègues, amis et amies du département, Mathilde, Annie, Élise, Marie-Claude, Julien et David, qui ont su agrémenter nos interactions de complicité, de gaietés au quotidien et d’entraide. Un merci spécial s’adresse à Mathilde et Annie qui m’ont accordé de précieux échanges en électrophysiologie et en statistique et à Élise pour ses corrections. Une pensée particulière s’adresse à François que je tiens à remercier pour nos discussions sur mes projets de recherche, pour ses conseils et son écoute. Il m'a inspiré le désir de continuer la chaîne de générosité dont il m'a rendue redevable. Merci à Réjane, pour son aide si précieuse à la clarification de mes pensées lors de l'écriture, pour nos discussions, pour ses encouragements.

Les membres de ma famille sont mes piliers et mes modèles. Sans le soutien, les encouragements et la présence de mes parents, je n'aurais assurément pas entrepris et accompli ce projet. Ils m'ont entouré d'un environnement facilitant la réussite de ces études. Merci de leur formidable générosité, de leur présence. Merci à ma mère, pour son amour, son écoute. Merci à mon père, pour son soutien, sa confiance en moi. Merci à mes deux frères, Nicolas et Jean-François pour leur support. Vous êtes une famille formidable.

Merci à Natja et Raphaëlle, qui m'ont soutenue quotidiennement dans les joies et les remises en question. Merci à Catherine et Joanie, pour leur support. C'est un immense privilège de les avoir dans ma vie. Un merci spécial s'adresse à Philippe, pour sa grande compréhension, sa présence et ses encouragements au cours de ces années. Son humour et sa façon de voir la vie m'ont aidée autant sur le plan professionnel que personnel.

Finalement, ma reconnaissance va aussi à toutes les personnes qui ont eu la gentillesse de participer à nos études. Sans leur présence et leur implication, ces projets n'auraient pu se réaliser. Un dernier merci aux membres du jury qui ont accepté de lire cette thèse et de me guider dans son amélioration.

Préambule

Notre cerveau développe la capacité de traiter de façon simultanée diverses informations provenant des différentes modalités sensorielles. Les neurosciences ont d'abord proposé que les aires sensorielles primaires, celles qui sont impliquées dans le traitement initial de l'information, soient respectivement spécialisées dans l'analyse d'un type spécifique d'information sensorielle et dites unisensorielles. Il était ainsi proposé que seules les aires associatives de haut niveau permettent l'intégration de l'information provenant de plusieurs sens. Ce modèle reposait majoritairement sur des études neuroanatomiques chez le chat et le singe, observant de rares, sinon absentes, interconnections entre les cortex somatosensoriel, auditif et visuel et qu'une lésion circonscrite engendrait un déficit unisensoriel (Kuypers, Szwarcbart, Mishkin, Rosvold, 1965; Massopust et al., 1965). Il a été par la suite généralement accepté qu'une majeure partie des structures corticales que l'on avait pensées unisensorielles étaient impliquées dans le traitement de plus d'un type d'informations sensorielles. Aujourd'hui, les évidences suggèrent que l'intégralité du cortex serait multisensorielle (Ghazanfar & Schroeder, C.E., 2006), et qu'il y aurait d'importants processus d'interactions entre les modalités. Notamment, il semble que les processus visuel et auditif auraient un développement hiérarchique similaire (Barlow & Mollon, 1982; Stein, 2001) et certains auteurs proposent la présence de traitements communs qui sous-tendraient le développement des systèmes auditif et visuel (Hockfield & Sur, 1990; Stein, 2001). Il apparaît donc probable que le développement d'une modalité sensorielle puisse en partie être en lien avec le développement d'une autre modalité.

Cette thèse vient contribuer à une meilleure compréhension du développement des habiletés auditives et visuelles et de leurs interactions en explorant la question: le développement d'une modalité sensorielle serait-il dépendant du développement de l'autre modalité? La partie prédominante de cette thèse repose sur l'étude de l'impact d'une privation auditive sur le développement fonctionnel de l'audition et sur le développement fonctionnel de la vision. Afin de cerner des réponses à ces questions, nos études ont observé une population de personnes ayant un développement auditif et visuel normal ainsi qu'une population de personnes sourdes porteuses d'un implant cochléaire. Avec ce dernier groupe, la restauration de l'audition au moyen de l'implant cochléaire permet d'étudier l'impact d'une privation auditive sur le système visuel, mais aussi l'impact de la restauration de l'audition sur le système auditif. Un développement normal des sens est-il nécessaire pour une calibration des autres modalités comme le proposent Withington-Wray et ces collègues (1994)? Le développement des habiletés auditive et visuelle sera-t-il influencé par la durée de la privation auditive ou par la durée de l'expérience avec l'implant? Globalement, cette thèse vise à mieux comprendre le développement auditif et visuel d'une part, en condition de développement normal et d'autre part, lors de privation auditive, permettant ainsi une meilleure compréhension de la réorganisation corticale.

Afin d'aborder ces questions, le développement des systèmes auditif et visuel normaux, incluant une description de la discrimination fréquentielle auditive et visuelle, est d'abord abordé dans le Chapitre I. Aussi, l'impact d'une privation auditive sur le développement des diverses capacités auditives et visuelles chez des individus malentendants avec et sans implant cochléaire y est décrit ainsi que les potentiels évoqués auditifs, incluant la négativité de discordance. Le Chapitre II est composé des quatre études incluses dans cette thèse. Finalement, la portée et les conclusions de ces études sont discutées dans les Chapitres III et IV.

Chapitre I. Introduction

Les développements auditif et visuel normaux

Les études développementales portant sur les premiers mois de la vie démontrent que les sens de l'audition et de la vision y sont bien fonctionnels, bien que non matures. En effet, ce fonctionnement permettra de capter l'information nécessaire au développement de la maturité.

L'acquisition des capacités sensorielles in utero a été pendant longtemps un sujet fort controversé. Aujourd'hui, il est admis que l'ouïe est généralement le sens le plus aiguisé du fœtus. Plusieurs études ont noté, vers la fin de la grossesse, des réponses fœtales suite à diverses stimulations acoustiques (Grimwade, Walker, Bartlett, Gordon & Wood, 1971; Lecanet, Granier-Deferre, Cohen, Le Houezec & Busnel, 1986; Ruben, 1995; Trudinger & Boylan,1980) et certaines études avancent que l'audition fœtale débuterait entre la vingtième et la vingt-huitième semaine de gestation (Aslin, Pisoni & Juczyk, 1983; Chelli & Chanoufi, 2008; Shahidullah & Hepper, 1993). D'un point de vue anatomique, le pavillon et l'oreille externe sont ségrégés vers la dixième semaine de gestation, mais ils ne prennent leur place définitive sur les côtés de la tête que vers la seizième semaine. La maturation et l'agrandissement de l'oreille externe et moyenne se poursuivent en même temps que l'enfant grandit, affectant la sensibilité auditive à différentes fréquences (Schneider, Trehub, Morrongiello & Thorpe, 1986). En ce qui concerne l'oreille moyenne, elle semble se différencier plus tôt, soit vers la cinquième et sixième semaine de gestation et vers la septième et huitième semaine, les osselets commenceraient à croître (Lecanuet, & Schaal, 1996). Pour sa part, la cochlée semble être fonctionnelle après 18-20 semaines de gestation et le développement de l'oreille interne se terminerait dans le huitième mois (Lecanuet, & Schaal, 1996). Vers la vingt-deuxième semaine, bien que présentant d'importantes variabilités interindividuelles, l'émergence du nerf auditif permet de projeter l'information au cortex auditif (Arabin, 2002). Les différentes structures composant la voie auditive primaire, telles que le noyau cochléaire, le complexe olivaire supérieur, le colliculus inférieur et le thalamus, sont majoritairement ségrégées à la naissance, mais vont tout de même se modifier avec l'expérience. Le développement du système auditif central continue jusqu'à la fin de l'enfance et même l'adolescence (Hnath-Chisolm, Laipply & Boothroyd, 1998).

Parallèlement, il est aussi largement admis que les nouveau-nés ne voient pas aussi bien que les adultes. Chez le singe et chez l'humain, tous les neurones de la voie visuelle seraient générés avant la naissance, bien qu'ils démontrent alors une immaturité en termes d'interconnections, de fonctions et même de positions. Les études suggèrent que la fovéa n’est pas différenciée dans la rétine durant les premiers mois de la vie. Les axones des cellules ganglionnaires de la rétine vont converger, puis former le nerf optique dont la myélinisation s'achève à la fin de la deuxième année. Bien que certaines structures de la voie centrale, telles que le corps genouillé latéral, soit ségrégées à la naissance, ces structures vont tout de même se modifier avec l’expérience (Barlow & Mollon, 1982). En effet, la lamination du corps genouillé latéral est identifiable dès la vingt-quatrième semaine de gestation (Hitchcock & Hickey, 1980). Chez les très jeunes enfants, le système visuel démontre plusieurs immaturités, telles que l’immaturité des photorécepteurs sur le plan de leur morphologie ainsi que de leur distribution sur la rétine (Abramov et al., 1982; Brown & Lidsey, 2009; Hendrickson, 1993). Le développement du système visuel se poursuit jusqu’au début de l’âge adulte (Barlow & Mollon, 1982).

Le traitement sensoriel auditif et visuel

Les systèmes auditif et visuel permettent d’interagir avec l’environnement en traitant l’information de façon hiérarchique. Les signaux perçus de l’environnement doivent en premier lieu être détectés, ce qui représente le plus bas niveau du traitement sensoriel. Ensuite, le système doit différencier les signaux d’une même modalité. Cette discrimination est nécessaire afin de permettre l’identification des stimuli environnementaux, tels que la reconnaissance d’un mot ou d’un visage (Goldstein, 2002).

La capacité à détecter un stimulus établit les limites absolues de sensibilité des organes sensoriels. Selon le théorème de Fourrier, chaque signal complexe peut être décomposé en une sommation de composantes, de différentes amplitudes, fréquences et phases, et ce, en modalité auditive et visuelle (Barlow & Mollon, 1982). En modalité auditive, le seuil minimal de la capacité de détection correspond à la pression sonore minimale nécessaire à la détection d'un son pur d'une fréquence donnée. Cette valeur reflète le traitement auditif de bas niveau et le développement du système auditif, de l'oreille externe jusqu'au cortex auditif (Katz, 2002). Les études développementales auditives montrent que la maturité de cette capacité serait atteinte entre 5 et 12 ans (Elliot & Katz, 1980; Maxon & Hochberg, 1982; Schneider, 1986; Roche, Sivervogel, Himes & Johnson, 1978). En parallèle, la limite maximum de détection en vision correspond au pourcentage de contraste nécessaire afin de percevoir une différence entre les régions foncées et pâles pour une fréquence spatiale donnée. Cette habileté sensorielle reflète les traitements de bas niveau, de la rétine jusqu'à la voie géniculo-striée (Avisan et al., 2002). Comparativement au système auditif, cette habileté perceptive atteindrait la maturité entre 4 et 12 ans (Adams & Courage, 2002; Beazley, Illingworth, Jahn & Greer, 1980; Gwiazda et al., 1997; Peterzell et al., 1995, Richamn & Lyons, 1994; Ellemberg et al., 1999). Dans les deux modalités sensorielles, cette détection diffère selon la fréquence testée.

La capacité de discrimination: fondement essentiel à notre perception

La capacité de discrimination sensorielle est reliée à la qualité de la perception. En effet, elle permet d'apprécier les détails d'une image, la beauté d'une symphonie ou la complexité langagière. Le seuil de discrimination fréquentielle représente la plus petite différence perceptible par un individu entre deux stimuli d'une même catégorie pour une modalité sensorielle donnée.

Discrimination fréquentielle auditive

Un son pur est la représentation acoustique de la fréquence de vibration des molécules d'air qui varie de façon sinusoïdale dans le temps. Un son pur est perçu avec une tonalité particulière (aiguë vs grave) en fonction de la fréquence de sa vibration. La fréquence est représentée en Hertz (Hz) et correspond à la propagation de l'onde sonore. Elle est décrite comme le temps requis par une onde sinusoïdale pour compléter un cycle complet (période) ou encore par le nombre de cycles qu'une molécule effectue durant une période spécifique de temps (F=1/P) (Barlow & Mollon, 1982; Stach, 1998) (Figure 1).

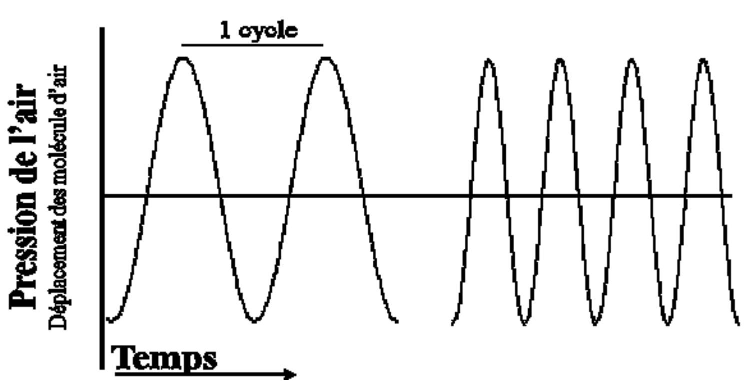


Figure 1. Schéma représentant, à gauche, un son de basse fréquence et, à droite, de plus haute fréquence. La ligne pointillée représente la durée d'un cycle.

La capacité à discriminer deux sons de fréquences rapprochées est essentielle pour une perception adéquate de la parole, particulièrement en présence de bruit compétitif, ainsi que pour la perception et l'appréciation de la musique (Gfeller, et al., 2007; Kraus, McGee, Carrell & Sharma, 1995; Kong, Cruz, Jones, & Zeng, 2004; Spahr & Dorman, 2004). En effet, une discrimination fréquentielle adéquate permet la distinction entre des voyelles ayant des formants fréquentiels comparables ainsi qu'entre des consonnes ayant une composition spectrale similaire. Une discrimination appropriée est nécessaire pour une compréhension et une production justes de la parole. Ainsi, de nombreuses observations ont révélé qu'une mauvaise performance sur le plan de la discrimination fréquentielle était liée à diverses dysfonctions, telles que des troubles de langage ou de la lecture, autant chez l'enfant que chez l'adulte (Amitay, Ahissar, Nelkin, 2002; Bishop & McArthur, 2005; Hill, Hogben & Bishop, 2005; McArthur & Bishop, 2004; Mengler, Hogben, Michue & Bishop, 2005). Les auteurs de ces études concluent que la discrimination fréquentielle fait partie des processus sensoriels de base, essentiels à un développement langagier normal.

In utero, il semble que le fœtus soit capable dès la trente-cinquième semaine de discriminer deux sons purs (Shahudullah & Hepper, 1994), mais les études en psychophysique ont montré que les seuils de discrimination fréquentielle des enfants d'âges préscolaires sont généralement moins performants que ceux des adultes. En effet, la littérature montre que la maturité de la discrimination fréquentielle auditive serait atteinte entre l'âge de 7 et de 12 ans (Halliday, Taylor, Edmondson-Jones, & Moore, 2008; Jensen & Donna, 1993; Maxon & Hochberg, 1982; Schneider et al., 1986; Thompson et al., 1999).

Discrimination fréquentielle visuelle

Dans l'étude de la vision et comparativement au modèle auditif, la modulation sinusoïdale de la luminance à travers l'espace représente le stimulus le plus simple. La luminance découle de la concentration des photons dans l'espace dispersés selon une courbe sinusoïdale. La fréquence spatiale d'une onde sinusoïdale est généralement donnée en cycles par degré et elle représente le nombre complet de cycles pour un degré d'angle visuel (Barlow & Mollon, 1982). Une fréquence spatiale apparaît comme la représentation de la luminance alternant entre le gris pâle et le gris foncé (Barlow & Mollon, 1982; Kandel, Schwartz, & Jessel, 2000) (Figure 2).

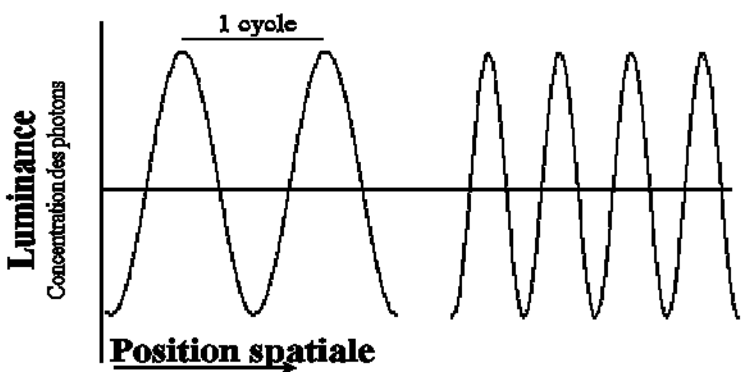


Figure 2. Schéma représentant, à gauche, un stimulus de basse fréquence et, à droite, un stimulus de plus haute fréquence. La ligne pointillée représente la durée d'un cycle.

Dans l'analyse d'une scène visuelle, la discrimination fréquentielle spatiale s'avère primordiale en ce qui concerne l'analyse des détails de l'environnement ou de l'image. Ainsi, cette habileté perceptive est capitale en ce qui a trait à la reconnaissance des visages ainsi qu'à la perception de l'expression faciale (Aquado, Serrano-Pedraza, Rodriguez & Roman, 2010; Kandel et al., 2000). En ce qui concerne le développement de cette habileté, l'unique étude ayant abordé son développement a indiqué qu'elle était supérieure chez des enfants de 10-11 ans comparativement à celle des enfants de 6-7 et de 8-9 ans (Moore, Ferguson, Halliday & Riley, 2008).

À ce jour, malgré l'abondance d'études, notre compréhension des systèmes auditif et visuel demeure incomplète et précaire. Notamment, la majorité des études développementales ont évalué isolément ces deux systèmes, sans aborder la comparaison de leur développement chez une même population. À notre connaissance, l'unique étude ayant mesuré le développement en parallèle des deux systèmes a rapporté que durant l'enfance, la sensibilité temporelle mature plus rapidement pour la modalité auditive que pour la modalité visuelle (Droit-Volet, Tourret, & Wearden, 2004). Vu la portée limitée de ces résultats et sachant que les diverses habiletés perceptives se développent à des rythmes différents (Ellemberg, Lewis, Liu, & Maurer, 1999; Ellemberg et al., 2003; Maxon & Hochberg, 1982; Thompson, Cranford, & Hoyer, 1999), on se gardera de généraliser ces résultats à tout le domaine perceptif auditif et visuel.

Impact d'une privation auditive sur le développement des capacités auditives et visuelles

Dans le milieu scientifique, il est généralement admis que les systèmes sensoriels ne sont pas composés de structures figées, mais qu'ils sont au contraire dotés d'une large capacité à se réorganiser. Ce phénomène, appelé la plasticité cérébrale, peut survenir dans diverses circonstances, telles qu'en situation d'apprentissage, lors d'une exposition répétée à un stimulus particulier ou suite à une suppression de l'information d'une modalité sensorielle particulière. Dans la présente thèse, l'étude des processus de bas niveau chez une population sourde aidera à mieux comprendre l'impact de la suppression de l'information auditive sur le développement sensoriel auditif et visuel.

Capacités auditives

Lors de privation sensorielle auditive, notamment lors de surdité profonde, le développement du système auditif est inévitablement perturbé dans toutes les étapes de traitement, de la détection à la reconnaissance. Les personnes malentendantes ont généralement recours aux appareils auditifs afin de leur permettre d'interagir avec le monde environnant et d'aider à la communication verbale. Chez certaines personnes ayant une surdité bilatérale sévère à profonde et pour lesquelles l'utilisation d'appareils auditifs ne permet pas une reconnaissance satisfaisante de la parole, l'implant cochléaire est proposé. Une surdité sévère à profonde fait référence à une détérioration des seuils auditifs de 70 à 100 dB sur tout le spectre fréquentiel audible, ce qui limite de façon très considérable la perception des signaux auditifs environnants. L'implant cochléaire permet maintenant à des milliers d'enfants et d'adultes d'avoir accès à l'information auditive. Le microphone du processeur de l'implant permet une capture des signaux sonores. Le processeur analyse et code ces stimuli auditifs qui sont ensuite, via l'antenne, transmis à travers la peau vers le récepteur interne. Ce dernier envoie des impulsions aux électrodes situées dans la cochlée, permettant une stimulation du nerf auditif.

Dès lors, et connaissant les capacités de réorganisation cérébrale, il s'avère indispensable d'évaluer le développement du système auditif suite à cette restauration de l'audition par l'implant cochléaire. Désireux de connaître le potentiel de cette technologie, différents chercheurs se sont penchés sur l'évaluation de diverses capacités auditives, à l'aide de mesures électrophysiologiques (Gordon, Tanaka, Wong & Papsin, 2008; Kelly, Purdy & Thorne, 2005; Sharma, Dorman & Kral, 2005) et comportementales (Lee, Hasselt, Chiu & Cheung, 2002; Grieco-Calub & Litovsky, 2010; Grose, Buss, 2007; Weig, Cao, Jin, Chen & Zeng, 2007). Cependant, c'est l'évaluation de la reconnaissance sous forme de divers tests évaluant la perception de la parole qui a reçu le plus d'attention (de Angelo, Bevilacqua & Moret, 2010; Bradley, Bird, Monteath & Wells, 2010; Holt & Svirsky, 2008; Oh et al., 2003; Osberger, Fisher & Kalberer, 2000a,b; Peterson, Pisoni & Miyamoto, 2010).

Sachant qu'un implant cochléaire induit généralement des seuils auditifs de moins de 40 dB HL de 250 à 4000Hz chez la majorité des individus (Champoux, Lepore, Gagné & Théoret, 2009; Singh, Liasis, Rajput, Towell & Luxon, 2004), on constate qu'il existe une importante différence entre les individus porteurs d'implant quant aux capacités de reconnaissance qui en résultent (Garnham, O'Driscoll, Ramsden & Saeed, 2002, Osberger et al., 2000a,b; Peterson et al., 2010, Shpak, Koren, Tzach, Most,& Luntz, 2009). Encore aujourd'hui, cette disparité est bien mal comprise et de nombreux audiologistes et neuro-audiologistes tentent de l'expliquer. S'intéressant à l'âge à l'implantation, à la durée de la surdité, à la cause de la surdité, à l'expérience avec l'implant, au type de programmation et de réadaptation, plusieurs études ont tenté d'identifier une cause déterminante de cette variabilité. En bout de ligne, tous ces facteurs semblent être des variables importantes à considérer (Bradley et al., 2010; Klop et al., 2008; Tajudeen, Waltzman, Jethanamest & Svirsky 2010).

Curieusement, on ne s'est pas encore penché sur les liens possibles entre les processus de base, tels que la capacité de discrimination fréquentielle auditive, et les performances de reconnaissance en termes de perception de la parole. Sachant qu'une discrimination fréquentielle adéquate est essentielle pour une perception appropriée de la parole, particulièrement en situation auditive difficile, il semble intéressant d'investiguer l'hypothèse d'un lien existant entre ces deux étapes de traitement.

Telle que décrite plus tôt, une discrimination fréquentielle adéquate est essentielle pour la qualité de la perception langagière. Conséquemment, il est logique de penser qu'une meilleure capacité en termes de traitement de base devrait s'avérer directement liée aux processus de plus haut niveau, tels que la perception de la parole. Une telle relation reste à être explorée chez une population malentendante porteuse d'un implant cochléaire. Sachant que la capacité de discrimination fréquentielle peut être améliorée suite à une période d'entraînement intensif (Amitay, Hawkey & Moore, 2005; Amitay, Irwin & Moore, 2006; Halliday, 2008; Moore & Amitay, 2007; Moore et al., 2008), la connaissance d'un lien entre cette habileté et la perception de la parole pourrait s'avérer fort prometteuse en réadaptation.

Capacités visuelles

Tel que mentionné plus tôt, on retrouve dans la littérature beaucoup de preuves selon lesquelles une privation sensorielle a un impact considérable sur les modalités sensorielles restantes suite à une réorganisation cérébrale. En effet, plusieurs études montrent qu'une privation sensorielle auditive ou visuelle peut induire une réorganisation qui peut être observée tant chez l'humain (Doucet, Bergeron, Lassonde, Ferron, & Lepore, 2006; Giraud, Price, Graham, Truy, & Frackowiak, 2001; Gougoux et al., 2004; Lee et al., 2001; Lee et al., 2003; Ponton & Eggermont, 2001; Rouger et al., 2007) que chez le modèle animal (Kral, Hartmann, Tillein, Heid, & Klinke, 2001, 2002, 2006; Rauschecker, 1995, 1996).

La majorité des études portant sur la réorganisation cérébrale chez la population sourde ont investigué l'impact de cette privation sur les habiletés visuelles de haut niveau, lesquelles semblent se modifier pour compenser le manque d'audition. Ces études indiquent que les individus ayant une importante surdité auraient des habiletés supérieures en ce qui à trait au traitement de l'information, notamment en termes de détection de mouvement ou de détection des changements lumineux, lorsque les stimuli sont présentés dans le champ visuel périphérique (Bosworth & Dobkins, 2002; Neville & Lawson, 1987; Loke & Song, 1991, Bavelier et al., 2000-2001). Pour une revue plus exhaustive des habiletés visuelles chez les personnes sourdes, voir Bavelier, Dye & Hauser, 2006; Dye & Bavelier, 2010. Ces études suggèrent une redistribution spatiale de l'attention visuelle en faveur de la périphérie, permettant ainsi aux personnes sourdes de gérer plus efficacement leur environnement sensoriel.

Des différences au niveau neuronal pourraient expliquer ces modifications de la perception visuelle. Par exemple, des études en électrophysiologie ont révélé que l'activité corticale mesurée dans les régions temporales et induite par une stimulation visuelle, telle qu'obtenue avec des potentiels évoqués visuels, était augmentée chez les individus sourds (Neville & Lawson, 1987; Neville, Schmidt & Kutras, 1983). Une étude en imagerie par résonnance magnétique fonctionnelle (IRMf) a aussi démontré, en cas de surdité, une augmentation du recrutement des aires temporales, comparativement à des personnes contrôles entendantes lors d'une tâche de recherche visuelle (Bavelier, 2001). Aussi, une activité neuronale a été rapportée dans les aires auditives primaires et associatives en réponse à une présentation de langage signé (Nishimura et al., 1999-2000). D'autres études ont rapporté la présence d'activité neuronale dans les aires normalement consacrées à l'audition lors de diverses tâches visuelles, signe de réorganisation cérébrale (Sadato et al, 2004; Finney, Fine & Dodkins, 2001; Finney, Clementz, Hickok & Dobkins, 2003). Selon les auteurs, cette réorganisation pourrait sous-tendre les diverses différences observées quant aux traitements visuels chez les individus malentendants.

Toutefois, le manque de stimulation auditive semble avoir un impact différent sur le développement d'habiletés visuelles de bas niveau. L'étude de la discrimination de la luminance (Bross, 1979), la résolution temporelle (Mills, 1985; Nava, Bottari, Zampini & Pavani, 2008) ou la résolution de contrastes (Finney & Dobkins, 2001) ne révèlent aucune différence entre les personnes sourdes et les personnes contrôles ayant une audition normale. D'autres études suggèrent qu'un manque de stimulation dans une modalité sensorielle particulière pourrait plutôt réduire certaines habiletés perceptives. Selon la théorie du déficit (Dye & Bavelier, 2010), le développement normal de chacun des sens est requis pour une efficace perception sensorielle globale. En effet, certaines études ont trouvé des déficits visuels chez les personnes sourdes. Par exemple, Heming & Brown (2005) ont noté une augmentation des seuils de discrimination temporelle visuelle chez une population sourde comparativement à des individus entendants. Dans le même sens, d'autres études rapportent aussi une résolution temporelle visuelle diminuée (Hanson, 1982; Withrow, 1968). D'autres processus de bas niveau, tels que la discrimination visuelle, n'ont pas été investigués chez une population malentendante et porteuse d'un implant cochléaire.

Finalement, certains chercheurs se sont penchés sur l'attention visuelle chez la population pédiatrique sourde et y ont observé un déficit quant à l'attention visuelle, tel que mesuré par un test d'attention visuelle soutenue (Horn, Davis, Pisoni & Miyamoto, 2005; Quittner, Smith, Osberger, Mitchell & Katz, 1994, Smith, Quittner, Osberger, Miyamoto, 1998).

Qu'advient-il lorsque des personnes sourdes ont la possibilité de recommencer à traiter de l'information auditive après une ou plusieurs années de surdité? Les conséquences sur le traitement visuel sont-elles comparables selon que la surdité est innée ou acquise? Parmi les rares études sur ce sujet quelques-unes ont abordé l'aspect de l'attention visuelle chez les enfants porteurs d'implant cochléaire. Les chercheurs y indiquent que le port de l'implant aide à la réorganisation de l'attention visuelle car, bien que diminuée chez une population pédiatrique sourde, cette habileté s'améliore avec l'usage de l'implant (Mitchell & Quittner, 1994; Smith et al., 1998; Quittner et al, 1994).

Potentiels évoqués de longue latence : la négativité de discordance

La discrimination auditive peut être mesurée de manière comportementale, à l'aide de test psychoacoustiques. Cependant, cette méthode s'avère difficile à utiliser chez une population pédiatrique ainsi que chez une population non-verbale. L'utilisation de potentiels évoqués auditifs permet aussi la mesure des habiletés auditives sans généralement nécessiter une participation active de la personne évaluée.

Potentiels évoqués auditifs

Les potentiels évoqués auditifs ont été largement utilisés dans la littérature afin de décrire et de mieux comprendre le développement neurophysiologique du système nerveux auditif périphérique et central. Ces mesures électrophysiologiques réfèrent à une série de changements électriques exprimés sous la forme d'une onde cérébrale (potentiel électrique) qui est générée en réponse à la présentation de stimuli acoustiques. Ces potentiels évoqués auditifs sont généralement classifiés selon leur site de génération ou selon leur latence relative à la présentation acoustique (Jacobson, 1994; Picton, 1990; McPherson, 1996; Wall, 1992). Le potentiel ayant la latence la plus courte est généré dans l'oreille interne et se nomme l'électrocochléographie. Quelques millisecondes plus tard, les potentiels sont générés par le nerf auditif et le tronc cérébral. L'activité induite par des structures de plus haut niveau est mesurée à l'aide des potentiels évoqués de moyennes et de longues latences (Jacobson, 1994; Picton, 1990; McPherson, 1996; Wall, 1992).

La négativité de discordance

Les mesures évoquées, telles que celles du tronc cérébral, sont très utilisées en contexte clinique en ce qui a trait à l'obtention de seuils de détection auditifs. Par contre, ces réponses évoquées sont moins utiles si l'on considère leur potentiel dans l'évaluation de la discrimination auditive. L'étude électrophysiologique proposée dans cette thèse porte sur une mesure de potentiels évoqués de longues latences. Les potentiels de longues latences sont caractérisés, principalement, par un pic initial positif (P1, latence: 60-80 msec), un premier pic négatif (N1, latence: 90-100 msec), un second pic positif (P2, latence: 100-160 msec) et un second pic négatif (N2, latence: 180-200 msec) (McPherson, 1996). Il est admis que les composantes P1 et N1 sont générées dans le gyrus temporel supérieur (Knight, Scabini, Woods & Clayworth, 1988), la composante P2 dans la fissure Sylvienne du cortex auditif primaire (Baumann, Rogers, Papanicolaou & Saydjari, 1990; Makela & Hari, 1990) et la composante N2 serait générée par le cortex supra temporel (Makela & Hari, 1990; Pantev, Hoke, Lehnertz & Lutkenhoner, 1988; Pelissone, Williamson & Kaufman, 1985).

Comme il peut être particulièrement ardu d'obtenir des mesures comportementales de discrimination auditive chez les individus nouvellement porteurs d'un implant cochléaire, particulièrement chez une population pédiatrique ou non-verbale, l'obtention du développement d'une mesure objective s'avère essentielle. En ce sens, les recherches dans le domaine des neurosciences ont été marquées par une utilisation accrue de la négativité de discordance (MMN). La MMN est une onde cérébrale obtenue à l'aide de potentiel évoqué de longue latence et elle marque une perception de changement entre deux stimuli. La MMN fut d'abord décrite par Näätänen et al. (1978) comme une mesure induite par la présentation d'un stimulus déviant inséré dans une suite de stimuli dits standards. Cette mesure est obtenue par la soustraction de l'onde engendrée par la réponse aux stimuli standards à celle de la réponse induite par la présentation des stimuli déviants. La MMN se présente comme une négativité présente dans l'aire fronto-centrale et survenant environ entre 100 et 250 ms après le stimulus, les différences de latence étant largement dues au type et à la durée des stimuli utilisés (pour une revue voir Näätänen, 1990) (Figure 3). Cette mesure reflète des processus pré-attentionnels de discrimination, du fait qu'elle est obtenue sans que les individus ne portent attention à la présentation acoustique en cours. Lorsque des stimuli verbaux sont utilisés, les chercheurs font référence à une mesure pré-attentive de la discrimination de la parole (pour une revue des potentiels évoqués de la parole, voir Martin, Tremblay & Korczak, 2008). Pour le moment, les diverses variables potentiellement utilisables, telles que le choix des stimuli, leur durée et la durée de l'expérimentation, varient considérablement d'une étude à l'autre, et le manque de convergence fait en sorte qu'il est encore difficile d'identifier une méthode fiable et rapide pour une utilisation clinique. Par ailleurs, la présence de l'implant cochléaire induit une composante électrique importante, ce qui augmente la présence d'artefact dans le tracé obtenu et ajoute à la difficulté de son utilisation clinique. Il s'avère nécessaire de pousser l'investigation de cette mesure afin d'avancer vers un paradigme optimal et de rendre ainsi son utilisation plus aisée en milieu clinique.

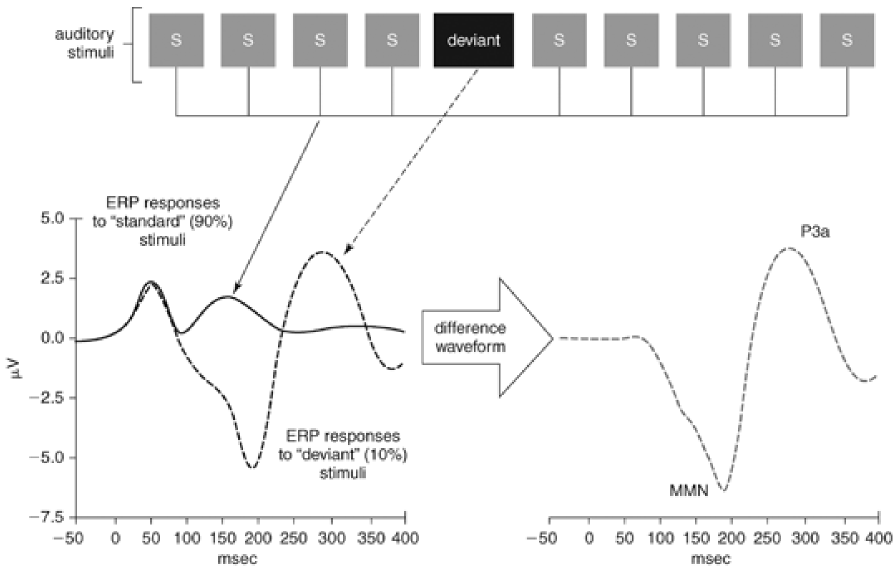


Figure 3. Schéma représentant un exemple de négativité de discordance. La ligne pleine représente l'onde cérébrale induite par la présentation d'un stimulus fréquent. La ligne pointillée de gauche représente l'onde cérébrale induite par la présentation d'un stimulus rare. La ligne pointillée de droite, représente la soustraction de l'onde induite par la présentation du stimulus fréquent à celle induite par la présentation d'un stimulus rare. Elle représente la négativité de discordance. Schéma tiré de Light et al., 2010.

Objectifs généraux de cette étude

À ce jour, les développements parallèles des processus sensoriels auditif et visuel de base sont peu connus. Nous apportons une contribution pour mieux comprendre ce développement. Notre première étude permettra de comparer les performances auditives et visuelles chez des enfants de différents âges ainsi que de connaître les performances attendues chez une population adulte mature ayant un développement auditif et visuel normal. Dans la littérature, les données disponibles suggèrent que les diverses habiletés auditives et visuelles se développent et atteignent maturité à des moments différents.

Pour les habiletés de bas-niveau évaluées dans cette thèse, nous posons l'hypothèse que les courbes développementales respectives des habiletés auditives et visuelles seront distinctes. Aussi, l'étude des processus sensoriels de discrimination auditive chez une population adulte sourde et porteuse d'un implant cochléaire sera effectuée en vue d'explorer d'une part, l'impact d'une privation auditive sur le développement de cette habileté et d'autre part, d'investiguer le possible lien entre cette mesure et les performances de reconnaissance de la parole. Tel que discuté, nous visons à évaluer le lien entre la méthode électrophysiologique de négativité de discordance et les capacités de reconnaissance de la parole chez une population de personnes malentendantes porteuses d'un implant cochléaire. Cette étude, avec la précédente, apportera une meilleure connaissance de l'impact d'une privation auditive sur les habiletés de discrimination auditive. Considérant les études antérieures chez la population porteuse d'un implant cochléaire, nous croyons d'une part, que plus courte aura été la privation auditive, meilleures seront les habiletés de discrimination auditive, tant au niveau comportemental qu'électrophysiologique. Aussi, connaissant le lien existant entre les habiletés de discrimination auditive et la perception de la parole, nous croyons que meilleure sera la discrimination auditive, meilleure sera aussi la perception de la parole. Enfin, évaluer l'impact d'une privation auditive sur le développement du traitement de la discrimination visuelle apportera un nouvel indice en ce qui a trait aux capacités de réorganisation cérébrale en cas de privation auditive. Nous basant sur les études évaluant les habiletés visuelles de bas-niveau chez les personnes sourdes, nous formulons l’hypothèse que l’habileté de discrimination spatiale sera inférieure ou inchangée chez cette population.

Chapitre II. Articles

Article 1

Turgeon C, Lepore F & Ellemberg D. Comparison of auditory and visual detection and discrimination thresholds during development.

Comparison of auditory and visual detection and discrimination thresholds during development.

Turgeon C[1], Lepore F[1] & Ellemberg D[1,2]

[1]Centre de Recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Québec, Canada.

[2]Département de Kinésiologie, Université de Montréal, Montréal, Québec, Canada.

Correspondences should be addressed to:

Dave Ellemberg, Ph.D.
Département de kinésiologie
Université de Montréal
2100 Edouard-Montpetit
Montréal (Quebec) H3T 1C5
Tel: (514) 343-7458 Fax: (514) 343-2115

Abstract

The investigation of visual and auditory development has mainly been carried out in isolation, without directly comparing their rates of maturation. The results of one study that did compare the development of both modalities suggest that temporal processing develops more rapidly for the auditory compared to the visual modality (Droit-Volet, Tourret, & Wearden, 2004). The aim of the present study was to chart and compare the development of sensory responses to basic visual and auditory stimulation. Specifically, we measured contrast (visual condition) and pure-tone (auditory condition) detection and discrimination for physically similar stimuli. The visual stimuli consisted of luminance modulated sinusoidal gratings that had a spatial frequency of 1 and 5 cycles per degree. The auditory stimuli consisted of pure-tones that had a frequency of 500 and 4000Hz. A control condition was implemented to equate the suprathreshold amplitude of the auditory and visual stimuli for the frequency discrimination condition. Thresholds were measured psychophysically with a temporal 2 AFC procedure combined with an adaptative staircase. Participants were children 6, 8, and 10 years of age and young adults (N= 16 per group). Statistical analyses using a general linear model showed that detection thresholds in the auditory modality are mature by 6 and 8 years of age for the lower and higher frequencies, respectively. In contrast, detection thresholds in the visual modality are still immature at 10 years of age for the lower frequency and become mature at 8 years of age for the higher frequency. A different pattern of results was found for frequency discrimination. In the auditory modality, it is still immature at 10 years of age for the lower frequency and becomes mature at 8 years of age for higher frequency, whilst in the visual modality it is

mature by 10 years of age for both frequencies. Together, these results suggest that sensitivity in the auditory modality matures more rapidly during early childhood and achieves adult levels earlier than sensitivity in the visual modality whilst the results for discrimination suggest the opposite trend.

Introduction

Charting and comparing the relative rates of visual and auditory development is of particular interest as this could lead to a better understanding of multisensory development. Real world perception is driven by the integration of information coming from each sensory modality and accumulating evidence suggests that multisensory integration is present at all levels of cortical processing (Ghazanfar & Schroeder, 2006). Second, it has been suggested that auditory and visual perception have similar processing hierarchies and that common underlying mechanisms determine their development (Barlow & Mollon, 1982; Hockfield & Sur, 1990; Stein, 2001). Finally, there is evidence that the normal development of each sensory modality depends on the normal development of other modalities. For example, animal studies indicate that normal visual development is critical for the development of the auditory spatial map (Withington-Wray, Binns, Ingham & Thornton, 1994a; 1994b) and auditory coding (Champoux, Bacon, Lepore & Guillemot, 2008). Further, human studies indicate that normal auditory development is critical for the development of visual discrimination (Turgeon, Lepore & Ellemberg, 2010) and the control of eye movements (Turgeon, Johnson, Pannasch & Ellemberg, 2009). These data support the *theory of deficit,* which suggests that the lack of sensory input in one modality during development can lead to perceptual deficits in other modalities (Dye & Bavelier, 2010).

Several studies measured the development of different aspects of auditory and visual perception, from simple detection to more complex perceptual functions (Ellemberg, Lewis, Liu, & Maurer, 1999; Ellemberg et al., 2003; Maxon & Hochberg, 1982; Thompson, Cranford, & Hoyer, 1999). However, the majority of these studies investigated each modality in isolation without comparing their rate of maturation. Their overall results suggest that auditory and visual perception develop at different rates and become mature at different ages (Gwiazda, Bauer, Thorn, & Held, 1997; Halliday, Taylor, Edmondson-Jones, & Moore, 2008; Maxon & Hochberg, 1982; Peterzell, Werner, & Kaplan, 1995). However, we are unable to directly compare these results as different stimuli and experimental protocols were used across studies.

To our knowledge only one study compared the development of both modalities. Droit-Volet et al. (2004) examined visual and auditory temporal perception in children and adults. Participants were required to compare the duration of the presentation of two stimuli, a simple 500Hz pure-tone stimulus presented near threshold and a more complex visual stimulus consisting of a blue circle. Their results suggest that the perception of duration develops more rapidly in the auditory than in the visual modality. Specifically, 5 year-olds were more efficient at identifying the duration of the auditory stimulus than they were at identifying the duration of the visual stimulus. Maturity was reached at 8 years of age for both modalities. However, it is difficult to draw conclusions from these findings given that the characteristics of the auditory and visual stimuli were quite different and likely implicated different perceptual mechanisms (viz., the auditory stimulus was simple in nature and evaluated low-levels of processing whilst the visual stimulus was more complex in nature and evaluated higher-levels of processing).

One way to study the relative development of auditory and visual perception is to compare the most similar and basic aspects of processing for each modality, namely, detection and discrimination. In both cases, this involves the use of the simplest forms of stimuli which are processed at the earliest and most comparable levels of these sensory systems.

Detection

The most basic aspect of sensory processing for both the auditory and visual modalities is the ability to detect a signal. Pure-tones of varying frequencies are typically used to measure auditory detection thresholds. These thresholds represent the lowest intensity at which the participant is able to respond and it reflects the lowest level of auditory processing, from the external ear canal to the primary auditory cortex (Katz, 2002). It is well known that the development of pure-tone sensitivity varies according to frequency, with middle and higher frequencies maturing more rapidly than lower frequencies (Maxon & Hochberg, 1982; Trehub, Schneider, Morrongiello & Thorpe, 1988; Schneider, Trehub, Morrongiello & Thorpe, 1986). Improvements are evident from infancy through the preschool years and then well into the school age years.

Visual detection seems to follow a similar developmental course to that reported for auditory detection. Luminance modulated sinusoidal gratings varying in spatial frequency are most often used to measure visual detection thresholds. These thresholds provide a measure of the spatial contrast sensitivity (minimum difference in luminance required to obtain a response) and they reflect the activity of the lowest level visual processing, from the retina to the primary visual cortex (Avidan et al., 2002). The development of spatial contrast sensitivity also varies with frequency. Sensitivity to higher spatial frequencies develops very rapidly during infancy and seems to be more mature than sensitivity to lower spatial frequencies by 3 to 4 years of age. Contrast sensitivity is then characterized by an expansion of sensitivity at lower frequencies (Adams & Courage, 2002; Beazley, Illingworth, Jahn & Greer, 1980; but see also Bradley & Freeman (1982) and Ellemberg et al., (1999) who found that contrast sensitivity develops proportionately across all spatial frequencies). Some studies suggest that visual contrast sensitivity becomes adult-like by 7–9 years of age whilst others suggest that maturity is only reached by mid-adolescence (Beazley et al., 1980; Ellemberg, et al., 1999; Gwiazda et al., 1997; Hainline & Abramov, 1997; Peterzell et al., 1995; Richman & Lyons, 1994).

Frequency discrimination

Frequency discrimination in the auditory system reflects the ability to differentiate two pure-tones based on differences in their frequency. This fundamental ability is critical for speech (Kraus, McGee, Carrell, & Sharma, 1995; Spahr & Dorman, 2004) and music perception (Kong, Cruz, Jones, & Zeng, 2004). Psychophysical studies found that frequency discrimination thresholds are poorer for young children compared to adults. Moore and colleagues (2008) report that the minimum change necessary to detect a difference in frequency from a baseline pure-tone of 1000Hz gradually decreases with age from about 10% in 6-7 year-olds, 8% in 8-9 year-olds, 6% in 10-11 year-olds, and 2-3 % in adults. The majority of studies suggest that maturity is reached between 7 to 12 years of age (Halliday et al., 2008; Jensen & Neff, 1993; Maxon & Hochberg, 1982; Thompson et al., 1999).

In comparison, frequency discrimination in the visual system is generally probed with sinusoidal gratings. Spatial frequency discrimination is also a fundamental building block of visual perception. It is essential for the analysis of fine details in a visual scene and it is critical for face recognition (Aquado, Serrano-Pedraza, Rodriguez & Roman, 2010; Kandel et al., 2000). To our knowledge, only one study measured thresholds for discriminating spatial frequency during development. The minimum change necessary to detect a difference in the spatial frequency of a baseline grating of 0.5 cycle per degree gradually decreased with age from about 20% in 6-7 year-olds to 10% in 8-9 year-olds, and 8% in 10-11 year-olds (Moore, Ferguson, Halliday & Riley, 2008). Adults can discriminate two different spatial frequencies if they differ by about 2-11%, depending on the particular characteristics of the gratings (Burbek & Regan, 1983; Hirsh & Hylton, 1982; Lin & Wilson, 1996; Mayer & Kim, 1986).

The purpose of this study was to chart and compare the development of comparably low-level auditory and visual sensory processes. This was done by measuring detection and discrimination in both modalities using physically comparable stimuli (i.e., sinusoidal modulation of air pressure for the auditory stimuli and sinusoidal modulation of luminance for the visual stimuli) and psychophysical procedures (a two-alternative forced-choice staircase method). Given that the available data suggest that the two modalities develop at different rates, we hypothesized that the low-level auditory and visual sensory processes follow distinct developmental courses.

Methods

Participants

Participants were divided into 5 groups according to age: 6 year-olds +/- 6 months (N=16), 8 year-olds +/- 6 months (N=16), 10 years-old +/- 6 months (N=16) and adults (N=16). Participants were native French speakers who had no prior experience with psychophysical testing. To be included in the study, participants were required to pass an audiometric screening test (pure-tone thresholds ≤ 25 dB HL bilaterally, at 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz). Middle-ear function was obtained with a Grason-Stadler GSI 38 tympanometer (Milford, MA, USA) and all subjects had normal mobility of the eardrum and normal middle ear function. Vision was measured with the Snellen eye chart at a distance of 10 feet (model R.J.'s). The set criterion was 10/10 for each eye either for normal or corrected to normal vision. None of the participants had learning disabilities, neurological problems or other known medical conditions. Three children (two 6 year-olds and one 10 year-old) were excluded from the study. Both 6 year-olds did not understand the task and the 10 year-old was far-sighted. All participants were consenting volunteers. Children were recruited via summer camps and adults were recruited via the university population. Informed consent was obtained for all adults and from the parents of the children.

Stimuli and apparatus

Auditory

All stimuli had a duration of 1000ms. We used sound pressure modulated sine waves (pure-tones) of 500 or 4000Hz, with a 50ms cosine rise-fall time. The stimuli were digitally generated using SykofizX software (version 2.0) and a 24-bit processor (TDT, RX6) from Tucker-Davis Technologies (TDT, Gainesville, FL, USA). The signal waveforms were generated at a sampling rate of 48,828Hz. Stimuli were presented in free field via a TDT magnetic speaker (model FF1) at a distance of 1 meter at ear level in front of the participant. Participant responses were recorded via a response box (TDT, model RBOX-RX6). The sound pressure level was calibrated using a Brüel and Kjaer sound level meter (model 2239) and a prepolarized condenser microphone (model 4188, Naerum, Danemark).

Vision

The stimuli were luminance modulated Gabors (i.e., a sine wave grating multiplied by a Gaussian) with a spatial frequency of 1 or 5 cycles per degree and a 50ms cosine rise-fall time. The stimuli had a width and height of 4 degrees when viewed from a distance of 60cm. They were generated by Psychinematik software (version 1.0.0) and a Mactintosh 0S X (version 10.5.5) computer. The stimuli were displayed using a linearized lookup table (generated by calibrating with a Colour Vision Spyder 2 Pro) and were presented on a 19-inch View Sonic G90*f*B CRT driven by an NVIDIA Quadro FX3500 Graphics card with 10-bit greyscale resolution. Maximum luminance was 100 cd/m^2, frame refresh rate was 85Hz, and the resolution was 1024 × 768 pixels.

Procedure

All tests were carried out in a standardized audiometric sound-attenuated chamber. The session consisted of an audiometric and a visual screening followed by the four experimental conditions. For each modality, detection and frequency discrimination thresholds were each assessed at a high and low frequency (500 and 400Hz for the auditory stimuli and 1 and 5 cycles per degree for the visual stimuli). Therefore, eight thresholds were obtained and testing was counterbalanced in the following manner: half of the participants in each age group completed auditory thresholds first; of those, half completed detection first and the other half completed frequency discrimination first. The same procedure was applied for the participants who completed the visual thresholds first. Moreover, half of the participants in each age group completed low frequency thresholds first. This was done to control for any effects of fatigue and/or practice. Each experimental condition was preceded by a familiarisation protocol during which the task was explained and the stimuli were presented. Specifically, before completing an entire staircase procedure, each participant had to successfully answer to the first three trials of a similar staircase. The same procedure was used for each participant and they were tested during a single session that lasted about one hour.

Auditory-Detection threshold

Detection thresholds were determined using an adaptive two-alternative forced choice (2AFC) staircase procedure. The classical two-alternative forced choice (2AFC) paradigm has been successfully used in acoustic psychophysical experiments with children and has the advantage of minimizing subject bias and criterion (Elliott, Hammer, Scholl & Wasowicz, 1989; Crandford, Thompson, Hoyer & Faires, 1997; Thompson et al., 1999; Kopelovich, Eisen & Franck, 2010). Each trial consisted of one pure-tone that was randomly presented at the same time as one of two lights, that were positioned side by side on the response box and that were flashed consecutively. The onset of each light was separated by a 500ms interval. The participant had to indicate, by a keypress, during which of the two light presentations the sound occurred. The first pure-tone was always presented at 50 dB SPL. Step size changed by 10 dB SPL until the first reversal and then by 2 dB SPL for the subsequent reversals. An experiment session ended once six reversals were recorded. No feedback was provided. However, the subsequent trail was only initiated once the participant's response was entered. Thresholds were calculated according to Levitt's (1971) transformed staircase using a 2-down, 1-up decision rule (Levitt, 1971) (Kopelovich et al., 2010; Thompson et al., 1999; Wier, Jesteadt, & Green, 1977). This procedure estimates a threshold of 70.7%.

Auditory-Frequency discrimination

Frequency discrimination was also determined using the same two-alternative forced choice (2AFC) staircase procedure. Each trial consisted of two pure-tones and the same two lights flashed on the response box separated by a 500ms interval. The stimuli were presented at a comfortable level of 50 dB SPL (see section on the *Intensity control condition* for the experimental rational behind this choice). Randomly, one tone corresponded to the reference frequency and the other to the probe frequency. The first presentation of the probe frequency was always set at 100Hz above the reference frequency. Step size was subsequently adjusted according to Levitt's (1971) staircase procedure. Step size changed by 50% until the first reversal and then by 25% for subsequent reversals. An experiment session ended once six response reversals were recorded for each reference frequency. No feedback was provided. The subsequent trail was only initiated once the participant's response was entered.

Visual-Detection threshold

Contrast sensitivity was determined using the same adaptive two-alternative forced choice (2AFC) staircase procedure. The first stimulus presentation was always at 10% contrast and the step size was subsequently adjusted according to Levitt's (1971) procedure. Step size changed by 50% until the first reversal and then by 25% for subsequent reversals. An experimental session ended once six response reversals were recorded for each frequency. No feedback was provided. The subsequent trail was only initiated once the participant's response was entered.

Visual-Frequency discrimination

Frequency discrimination was also determined using an adaptative two-alternative forced choice (2AFC) procedure. Each trial consisted of reference and a probe Gabor, each presented randomly one after the other and separated by a 500ms interval. The stimuli were presented at a contrast of 50% (see section on the *Intensity control condition* for the experimental rational behind this choice). The first presentation of a probe frequency was 4 cycles per degree above the reference frequency. Step size was subsequently adjusted according to Levitt's (1971). Step size changed by 50% until the first reversal and then by 25%. An experiment session ended once six response reversals were recorded for a specific frequency. No feedback was provided and the subsequent trail was initiated once the participant's response was entered.

Intensity control condition

The intensity of a stimulus, whether it is the SPL of a pure-tone or the contrast of a grating, can affect frequency discrimination when the stimuli are presented near detection threshold (Greenlee, 1992). However, several studies suggest that when they are presented well above threshold, relatively large differences in SPL and contrast have little to no impact on discrimination (Greenlee, 1992; Wier et al., 1977). As series of pilot studies were conducted to confirm this and determine suprathreshold levels of SPL and contrast that produce maximum performance (i.e., the lowest discrimination thresholds for both the auditory and visual stimuli). We tested a second group of 8 year-old children (N=14) using the same two-alternative forced choice (2AFC) staircase procedure and stimuli as describe above. Discrimination thresholds were obtained for three suprathreshold SPL's for the pure-tones at 500 and 4000Hz (40 dB SPL, 50 dB SPL, and 60 dB SLP) and three suprathreshold contrasts for the Gabors at 1 and 5 cycles per degree (25 %, 50 % and 75% of contrast). The thresholds were counterbalanced for modality and intensity was randomized. Four separate one-way ANOVAs conducted for each modality and each frequency with intensity as repeated measure did not reveal any significant difference in discrimination as a function of intensity: auditory low frequency, $F_{(2, 42)}= 0.405$, $p= 0.669$; auditory high frequency, $F_{(2, 42)}= 0.229$, $p= 0.796$; vision low frequency, $F_{(2, 42)}= 0.143$, $p= 0.867$; and vision high frequency, $F_{(2, 42)}= 0.390$, $p= 0.680$. These findings suggest that discrimination reached asymptote by 40 dB SPL for each auditory condition and by 25% contrast for each visual condition. Therefore, for the main experiment we chose an intensity of 50 dB SPL for the pure-tone and 50% contrast for the Gabors. Both values were within the range of best performance for the children and this ensures that subjects would not have performed better if had we chosen different values.

Statistical Analysis

Because detection thresholds are expressed on different scales for each modality (ie., dB SPL in the auditory modality and in % of contrast in the visual modality) the analyses were conducted separately for each modality. The detection data were analysed with two 2-way analysis of variance (ANOVA). Each ANOVA had one between-subjects factors of age with four levels (6, 8, 10 year-olds and adults) and a within-subjects factor of frequency (low and high). For post-hoc analyses on main effects the confidence intervals were adjusted for multiple comparisons with an LSD correction and for post-hoc analyses on the interaction the confidence intervals were adjusted with a Dunnett correction.

To compare frequency discrimination thresholds between modalities, we transformed thresholds into a value of Just Noticeable Difference (JND) (%): ΔF-F(reference)*100. This value represents percent change in frequency required to detect a difference in frequency between two pure-tones or between two Gabors. Because discrimination data for the two modalities were on the same scale, they were analysed with a 3-way ANOVA. The ANOVA had one between-subjects factors of age with four levels (6, 8, 10 year-olds and adults), a within-subjects factor of modality (auditory and visual), and a within-subjects factor of frequency (low and high). The significant 3-way interaction was further analysed with separate 2-way ANOVAs for each modality, in which each ANOVA had a between-subjects factors of age and a within-subjects factor of frequency. Analyses of simple effects were used to analyse all significant 2-way interactions. The interactions and within-subject effects are reported according to Greenhouse-Geisser's correction. For post-hoc analyses on the interactions, the confidence intervals were adjusted with a Dunnett correction. Statistical analyses were performed with SPSS 16.0.

Results

Detection

Figure 1a and 1b present the detection thresholds for the auditory and visual modalities respectively. The 2-way ANOVA for auditory detection revealed no interaction, but a significant main effect of frequency $F_{(1,60)}= 169.33$, $p < 0.01$ and of age $F_{(1,60)}= 3.32$, $p < 0.01$. Post-hoc analyses showed that detection thresholds in the auditory modality are adult-like by 6 years of age for the lower frequency (6 year-olds are not statistically different then adults, p=0.896) and are adult-like by 8 years of age for the higher frequency (6 year-olds are statistically different than adults, p=0.004; 8 year-olds are not statistically different than adults, p=0.095).

The 2-way ANOVA on visual detection showed a significant interaction between age and frequency $F_{(1,60)}$= 6.33, p < 0.01, a significant main effect of frequency $F_{(1,60)}$= 72.80, p < 0.01, and age $F_{(1,60)}$= 27.3, p < 0.01. Post-hoc statistical analyses on the interaction indicate that detection threshold is still immature at 10 years of age for the lower frequency (10 year-olds are statistically different then adults, p<0.001), but is adult-like at 8 years of age for the higher frequency (6 year-olds are statistically different than adults, p<0.001; 8 year-olds are not statistically different than adults, p=0.685).

Frequency discrimination

Figure 2 presents the results for frequency discrimination for both modalities. The 3-way ANOVA showed an interaction amongst age, modality, and frequency, $F_{(1,60)}$= 12.16, p < 0.01. The other significant effects were interactions between age and modality, $F_{(1,60)}$= 7.88, p < 0.01, age and frequency, $F_{(1,60)}$= 38.81, p < 0.01, and frequency and modality, $F_{(1,60)}$= 50.16, p < 0.01. A main effect of age, $F_{(1,60)}$= 61.12, p < 0.01, a main effect of modality, $F_{(1,60)}$= 37.94, p < 0.01, and a main effect of frequency, $F_{(1,60)}$= 313.04, p < 0.01 were also found.

To evaluate the 3-way interaction, we conducted two 2-way ANOVAs to compare age to frequency for each modality. The 2-way ANOVA for the auditory modality revealed a significant interaction between age and frequency, $F_{(1,60)}$= 8.51, p < 0.01, a main effect of age, $F_{(1,60)}$= 15.31, p < 0.01, and a main effect of frequency, $F_{(1,60)}$= 70.63, p < 0.01. Post-hoc analyses on the interaction indicated that discrimination threshold is still immature at 10 years of age for the lower frequency (10 year-olds are statistically different then adults, *p*=0.04) and become mature at 8 years of age for the higher frequency (6 year-old are statistically different than adults, $p < 0.001$; 8 year-olds are not statistically different than adults, $p=0.685$).

The 2-way ANOVA for vision revealed a significant interaction, $F_{(1,60)} = 36.43$, $p < 0.01$, and a main effect of age, $F_{(1,60)} = 51.53$, $p < 0.01$, but no main effect of frequency, $p > 0.01$. Post-hoc analyses on the interaction showed that discrimination is mature by 10 years of age for the lower (8 year-olds are statistically different than adults, $p < 0.001$; 10 year-olds are not statistically different than adults, $p=1.000$) and the higher frequency (8 year-olds are statistically different than adults, $p=0.04$; 10 year-olds are not statistically different than adults, $p=1.000$).

Discussion

The auditory and visual systems continuously interact to process and integrate sensory information. The goal of this study was to verify any relationship between their respective rates of development. To do so, we charted and compared the development of low-level auditory and visual processes. Our results show that thresholds improve with age for both auditory and visual detection and discrimination. Specifically, the detection of a pure-tone in the auditory modality matures more rapidly during early childhood and achieves adult-levels earlier than the detection of a luminance modulated grating in the visual modality. On the other hand, adult-like frequency discrimination is achieved earlier in the visual modality than in the auditory modality. Although similar low-level processes were assessed in the auditory and visual modalities, there does not appear to be any common pattern of development between the two modalities.

Non-visual or auditory factors such as differences in attention or criterion could have contributed to differences in performance between the adults and children, but are unlikely to account for the overall pattern of results. All tasks measured thresholds, yet the children's performance was more immature for some conditions than others. For example, 6 year-olds are about three times worse than adults for visual discrimination for the lower frequency, whilst they are less than two times worse than adults for the higher frequency. In comparison, whilst 6 year-olds are adult-like for auditory detection for the lower frequency, they are about two times worse than adults for the higher frequency.

Poor optics also likely did not contribute to reductions in visual performance. Participants were screened for refractive errors. Moreover, by 6 years of age (the youngest age tested), children typically no longer have the refractive and accommodative errors that are common during infancy (Hainline, Riddell, Grose-Fifer &Abramov, 1992; Howland, 1993). For the auditory modality, all of the structures necessary for inner ear function are present and adult-like in structure and size by the end of five months of gestation (Bellis, 2003). Moreover, the size of the external ear canal has little impact on auditory perception for the age groups tested given that generally by 5 years of age, its maturation no longer affects detection (Bagatto, Scollie, Seewald, Moodie & Hoover, 2002; Keefe, Bulen, Campbell, & Burns, 1994). In fact, based on measures of the resonant frequency of the ear canal, the greatest changes in ear canal length and volume occur before 5 years old (Bernstein & Kruger, 1986).

Detection

The results from the present study show that auditory detection is mature by 6 and 8 years of age for the lower (500Hz) and the higher (4000Hz) frequencies, respectively. In the visual modality, detection is still immature at 10 years of age for the lower frequency (1 cycle per degree) and is mature at 8 years of age for the higher frequency (5 cycles per degree). At least three patterns appear from these findings. First, for the lower frequency, maturity is reached earlier in the auditory compared to the visual modality, where the auditory modality is mature at 6 years whilst still not mature at 10 years of age for the visual modality. Second, for the higher frequency, the pattern of maturation is the same for both modalities, where both are mature at 8 years of age. Finally, for the auditory modality, it is for the lower frequency that maturity is reached earlier whilst in the visual modality it is for the higher frequency that maturity is reached earlier. Overall, these results suggest that for detection, maturity is reached earlier in auditory compare to the visual modality. Moreover, our findings suggest that the mechanisms underlying detection are different for both modalities and that they develop at different rates.

Our findings put forward a pattern of improvement of auditory detection with age, as suggested by the results of previous studies (Elliot & Katz, 1980; Maxon & Hochberg, 1982; Schneider et al., 1986; Trehub et al., 1988). Our results also suggest that maturity is reach at 6 and 8 years of age for the lower and to the higher frequency, respectively. This finding goes against those from other studies that indicate either a comparable development across frequencies or that maturity is reached earlier for higher frequencies (Elliot & Katz (1980; Maxon & Hochberg, 1982; Roche et al., 1978; Schneider et al., 1986). However, the detection of the lower frequency for the 6 year-old group (M= -0.5 dB SPL) is quite similar to that of the 8 year-old group (M= -1.0 dB SPL) even thought they are still different than that of the adult group (M= -2.0 dB SPL). It is possible that with a smaller variability within the 6 and the 8 year-olds results, we would have found that maturity is also reached only at 8 years of age for the lower frequency, given maturity reach for both frequencies at 8 years of age and then, results consistent with the literature.

In the visual modality, the pattern of improving visual detection with age is also in agreement with the results of previous studies that report that adult-like sensitivity is achieved between 7 and 12 years of age (Adams & Courage, 2002; Benedek et al., 2003; Bradley & Freeman, 1982; Ellemberg et al., 1999; Gwiazda et al., 1997). Our results also show that maturity is reached earlier for the higher compared to the lower frequency, which is consistent with most of the literature (Adams & Courage, 2002; Beazley et al., 1980), although some studies suggested that contrast sensitivity develops proportionately across spatial frequencies (Ellemberg et al, 1999; Bradley & Freeman, 1982).

Frequency discrimination

Frequency discrimination in the auditory modality is still immature at 10 years of age for the lower frequency, whilst it is mature at 8 years of age for the higher frequency. In the visual domain, frequency discrimination is mature at 10 years of age for the lower and higher frequencies. Therefore, a different pattern of results is found for discrimination compared to detection. First, for the lower frequency, maturity is reached later in the auditory modality compare to the visual modality, where the auditory modality is not yet mature at 10 years of age and it is mature at 10 year of age for the visual modality. Second, for the higher frequency, maturity is reached earlier in the auditory compare to the visual modality, where the auditory modality is mature at 8 years whilst it is mature at 10 years of age for the visual modality. Finally, for both modalities, immaturities are much greater for the lower frequency for the 6 year-olds compare to the higher frequency. For example, for the auditory modality, 6 year-olds are about four times worse than adults for the lower frequency but are about three times worse than adults for the higher frequency. For the visual modality, 6 year-olds were about three times worse than adults for the lower frequency but were less than two times worse than adults for the higher frequency. Overall, these results suggest that adult-like discrimination is reached earlier in visual modality compared to the auditory modality and, at least for the age range tested, lower frequencies mature more slowly than the higher frequencies.

In the auditory modality, these results are consistent with findings suggesting that adult-like discrimination is reached between 6 and 12 years of age (Halliday et al., 2008; Jensen & Neff, 1993; Maxon & Hochberg, 1982; Moore and al., 2008; Plack, Oxenham, Fay & Popper, 2005; Thompson et al., 1999). However, most of these studies only tested one frequency, which does not allow for a developmental comparison across frequencies (Halliday et al., 2008; Jensen & Neff, 1993; Moore and al., 2008; Thompson et al., 1999). To our knowledge, one study measured frequency discrimination for several frequencies and found that maturity is reached at 12 years of age for every frequency (500, 1000, 2000 and 4000Hz) (Maxon and Hochberg, 1982).

In the visual domain, frequency discrimination is mature at 10 years of age for the lower and higher frequencies. These results are in agreement with the literature showing that spatial frequency discrimination in 10-11 year-old children is better that in 6-7 year-olds (Moore et al., 2008).

Frequency discrimination in adults is quite similar for both modalities and both frequencies tested, ranging between 2 and 5%. Indeed, for adults, frequency discrimination in the auditory modality is known to be around 2% (Moore et al., 2008), and frequency discrimination in the visual modality ranges from 2-11% (Hirsh & Hylton, 1982; Mayer & Kim, 1986).

The goal of the study was to compare the developmental of detection and frequency discrimination for each modality. In the auditory modality, frequency discrimination matures more slowly than detection. Detection and frequency discrimination are mature at 8 years of age for the higher frequency, whilst for the lower frequency detection is mature at 6 years of age or before, and discrimination is still not mature at 10 years of age. This is not surprising given that frequency discrimination is believed to be a more complex treatment and hierarchically more advanced. The pattern of results is different and somewhat unexpected for the visual modality. For the higher frequency, detection matures earlier than frequency discrimination, becoming adult-like at 8 and 10 years of age, respectively. However, for the lower frequency it is discrimination that matures earlier, at

10 years of age, whist detection is still not mature at 10 years of age. It is possible that a more pronounced difficulty to process stimuli when they are presented near threshold could lead to the later maturation of detection.

Limits of the study

The goal of the study was to verify if the auditory and visual systems followed a similar rate of maturation by comparing the development of detection and frequency discrimination in both modalities. To do so, we used stimuli and a paradigm that were similar. Specifically, in both modalities we used two basic sensory treatments: detection and frequency discrimination. First, it is generally accepted that detection is the most basic treatment in each sensory modality. It is also generally hypothesized that the subsequent processing step is discrimination. However, we cannot know if those two processes imply similar neurophysiological mechanisms and if we are measuring a comparable treatment in both modalities. It is possible that frequency discrimination involve different levels and complexities neural processing in these two modalities. Secondly, we used the simplest form of stimuli (i.e., pure-tones in the auditory modality and patterns consisting of the sinusoidal modulation of luminance in the visual modality). For each modality, these stimuli represent the more basic sensory stimulation. However, here again, we cannot be sure that the neural excitation is really similar in both modality. Moreover, a series of pilot studies were conducted to ensure that the intensity of the suprathreshold pure-tones and sinusoidal gratings used in the discrimination tasks were equivalent. Although it is impossible to confirm that an equal quantity of energy was presented to both the auditory and the visual systems, we nevertheless used supratreshold levels that lead to asymptote discrimination in both modalities. Thirdly, the literature shows that the development of detection and frequency discrimination may vary according to frequency to frequency. For example, the development of auditory detection is quite different for much higher frequencies (e.g., 10 000, 20 000Hz) compared to lower frequencies, with a faster rate of maturity and an earlier decline (Schneider, 1986). Knowing that, testing for a more complete range of frequencies, including lower and higher frequencies than the ones used in this study, would have provided a more complete profile for each modality. Finally, we find that some of the thresholds measured are not yet adult-like in the oldest age group that we tested, such as the frequency discrimination in the auditory modality and the visual detection. Consequently, we cannot fully ascertain which of the two modalities tested attains adult-like levels first. It is possible that some of the conclusions regarding the end-point could change if older age groups were tested.

Conclusion

Perception depends on the interaction and integration of auditory and visual information; both modalities work together and their neuronal processes present a similar hierarchic structure (Barlow & Mollon, 1982; Hockfield & Sur, 1990; Stein, 2001). Nevertheless, the results from the present study show that their developments are independent and that both modalities reach adulthood at a different age.

Acknowledgements

This work was supported by grants from CIHR and NSERC to DE and to FL. This research was also supported by an Infrastructure grant from CFI to DE. We want to thanks every participant.

References

Adams, J.R. & Courage, M.L. (2002). Using a single test to measure human contrast sensitivity from early childhood to maturity. *Vision Research*, 42, 1205-1210.

Adams, R.J., Mercer, M.E., Courage, M.L. & van Hof-van Duin, J. (1992). A new technique to measure contrast sensitivity in human infants. *Optometry & Vision Sciences*, 69, 440-446.

Aguado, L., Serrano-Pedraza, I., Rodriguez, S. & Roman, F.J. (2010). Effects of spatial frequency content on classification of face gender and expression. *The Spanish journal of psychology*, 13, 525-537**.**

Ahissar, M., Lubin, Y., Putter-Katz, H. & Banai, K. (2006). Dyslexia and the failure to form a perceptual anchor, *Nature Neurosciences*, 9, 1558-1564.

Avidan, G., Harel, M., Hendler, T., Ben-Bashat, D., Zohary, E. & Malach, R. (2002). Contrast sensitivity in human visual areas and its relationship to object recognition. *Journal of Neurophysiology*, 87, 3102-3116.

Bagatto, M.P., Scollie, S.D., Seewald, R.C., Moodie, K.S. & Hoover, B.M. (2002). Real-ear-to-coupler differences predictions as a function of age for two coupling procedures. *The Journal of American Academy of Audiology*, 13, 407-415.

Barlow, H.B. & Mollon, J.D. (1982). *The sense*. Cambridge University Press. New York, USA.

Beaudot, W.H.A. (2009). Psykinematic: A new psychophysical tool for investigatisng visual impairment due to neural dysfunctions. *Vision*, 21, 19-32.

Beazley, J.D., Illingworth, D.J., Jahn, A. & Greer, D.V. (1980). Contrast sensitivity in children and adults. *British Journal of Ophthalmology*, 64, 863-866.

Benedek, G., Benedek, K., Kéri, S. & Janáky, M. (2003) The scotopic low-frequency spatial contrast sensitivity develops in children between the ages of 5 and 14 years *Neuroscience letters*, 345, 161-164.

Bellis, T.J. (2003). *Assessment and management of central auditory processing disorders in the educational setting: from science to practice*. Singular, New York.

Bernstein, R.S. & Kruger, B. (1986). The external ear sound pressure level transformation in infants. *The Journal of the Acoustical Society of America,* 79, S33.

Bradley, A. & Freeman, R.D. (1982). Contrast sensitivity in children. *Vision Research*, 22, 953-959.

Brown, A. & Lindsey, D. (2009). Contrast insensitivity: the critical immaturity in infant visual performance. *Optometry and vision science*, 86, 572-576.

Burbeck, C.A. & regan, D. (1983). Independence of orientation and size in spatial discriminations. *The Journal of the Acoustical Society of America*, 73, 1691-1694,

Cranford, J.L., Thompson, N., Hoyer, N. & Faires, W. (1997). Brief tone discrimination by children with histories of early otitis media. *Journal of the American Academy of Audiology*, 8, 137-141.

Droit-Volet, S., Tourret, S. & Wearden, J. (2004). Perception of the duration of auditory and visual stimuli in children and adults. *The Quartely Journal of Experimentation Psychology Section A*, 57, 797-818.

Ellemberg, D., Lewis, T.L., Liu, C. & Maurer, D. (1999). Development of spatial and temporal vision during childhood. *Vision Research*, 39, 2325-2333.

Ellemberg, D., Lewis, T.L., Meghji, K.S., Maurer, D., Guillemot, J.P., & Lepore, F. (2003). Comparison of sensitivity to first- and second-order local motion in 5-year-olds and adults. *Spatial vision*, 16, 419-428.

Elliott, L.L., Hammer, M.A., Scholl, M.E. & Wasowicz, J.M. (1989). Age difference in discrimination of simulated single-formant frequency transitions. *Perception and Psychophysics*, 46, 181-186.

Elliott, L.L. & Katz, D.R. (1980). Children's pure-tone detection. *The Journal of the Acoustical Society of America*, 67, 343-344.

Ghazanfar, A.A. & Schroeder, C.E. (2006). Is neocortex essentially multisensory? *Trends in Cognitive Sciences*, 10, 278-285.

Greenlee, N.W. (1992). Spatial frequency discrimination of band-limited periodic targets: effects of stimulus contrast, bandwidth and retinal eccentricity. Vision Research, 32, 275-283.

Gwiazda, J., Bauer, J., Thorn, F. & Held, R. (1997). Development of spatial contrast sensitivity from infancy to adulthood: psychophysical data. *Optometry and vision sciences*, 74, 785-789.

Hainline, L. & Abramov, I. (1997). Development of spatial contrast sensitivity from infancy to adulthood: psychophysical data. *Optometry and vision science,* 74, 790–799.

Hainline, L., Riddell, P., Grose-Fifer, J. & Abramov, I. (1992). Developement of accommodation and convergence in infancy. *Behavioral Brain Research*, 49, 33-50.

Halliday, L.F. & Bishop, D.V.M. (2006). Auditory frequency discrimination in children with dyslexia. *Journal of Research and Reading*, 29, 213-228.

Halliday, L.F., Taylor, J.L., Edmondson-Jones, A.M. & Moore, D.R. (2008). Frequency discrimination learning in children. *The Journal of the Acoustical Society of America*, 123, 4393-4402.

Hepper, P.G. & Shahidullah, B.S. (1994). Development of fetal hearing. *Archives of Disease in Childhood,* 71, 81-87.

Hill, P.R., Hogben, J.H. & Bishop, D.V.M. (2005). Auditory frequency discrimination in children with specific language impairement: A longitudinal study. *Journal of Speech, Language, and Hearing Research*, 48, 2964-2968.

Hirsch, J. & Hylton, R. (1982). Limits of spatial-frequency discrimination as evidence of neural interpolation. *Journal of the Optical Society of America*, 72, 1367-1374.

Hockfield, S. & Sur, M. (1990). Monoclonal CAT 301 identifies Y cells in cat LGN. *The Journal of Clinical Neurology*, 300, 320–330.

Howland, H.C. (1993). Early refractive development. In K. Simons. Early Visual Developement: normal and abnormal. Commision on Behavioral and Social Sciences and Education. National Research Council, Oxford: Oxford University Press.

Jensen, J.K. & Neff, D.L. (1993). Development of basic auditory discrimination in preschool children. *Psychological Sciences*, 4, 104-107.

Kandel, E.R., Schwartz, J.H. & Jessel, T.M. (Eds.). (2000). Principles of neural science (4e ed.).

Katz, J. (2002). Handbook of Clinical Audiology (5e ed). Lippincott William & Wilkins, Baltimore, Maryland.

Keefe, D.H., Bulen, J.C., Campbell, S.L. & Burns, E.M. (1994). Pressure transfer function and absorption cross section from the diffuse field to the human infant ear canal. *The Journal of the Acoustical Society of America,* 95, 355-371.

Kong, Y-Y., Cruz, R., Jones, J.A., & Zeng, F-G. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear and Hearing*, 25, 173-185.

Kopelovich, J.C., Eisen, M.D. & Franck, K.H. (2010) Frequency and electrode discrimination in children with cochlear implants. *Hearing Research*, 268, 105-113

Kraus, N., McGee, T., Carrell, T. D. & Sharma, A. (1995). Neurophysiologic bases of speech discrimination. *Ear and hearing*, 16, 19-37.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America*, 49. Suppl 2,467.

Lin, L.M. & Wilson, H.R. (1996). Fourier and non-Fourier pattern discrimination compared. *Vision Research*, 36, 1907-1918.

Maxon, A.B. & Hochberg, I. (1982). Development of psychoacoustic behavior: sensitivity and discrimination. *Ear and Hearing*, 3, 301-308.

Mayer, M.J. & Kim, B.Y. (1986). Smooth frequency discrimination functions for foveal, high-contrast, mid spatial frequencies. *Journal of the Optical Society of America*, 3, 1957-1969.

Mengler, E.D., Hogben, J.H., Michie, P. & Bishop, D. (2005). Poor frequency discrimination is related to oral language disorder in children: A psychoacoustic study. *Dyslexia*, 11, 155-173.

Moore, D.R., Ferguson, M.A., Halliday, L.F. & Riley, A. (2008). Frequency discrimination in children: Perception, learning and attention. *Hearing Research*, 238(1-2), 147-154.

Olsho, L.W., Koch, E.G., Carter, E.A., Halpin, C.F. & Spetner, N.B. (1988). Pure-tone sensitivity of human infants. *The Journal of the Acoustical Society of America*, 84, 1316-1324.

Peterzell, D., Werner, J. & Kaplan, P. (1995). Individual differences in contrast sensitivity functions: longitudinal study of 4-, 6- and 8-month-old human infants. *Vision Research*, 35, 961-979.

Plack, C.J., Oxenham, A.J., Fay, R.R. & Popper, A.N. (2005). Pitch. Neural coding and perception. Spinger Handbook of Auditory Research. New York, USA.

Richman, J.E. & Lyons, S. (1994). A forced choice procedure for evaluation of contrast sensitivity function in preschool children. *Journal of the American Optometric Association*, 65, 859-864.

Roche, A.F., Sivervogel, R.M., Himes, J.H. & Johnson, D.L. (1978). Longitudinal study of hearing in children: baseline data concerning auditory thresholds, noise exposure, and biological factors. *The Journal of the Acoustical Society of America*, 64, 1593-1601.

Schneider, B.A., Trehub, S.E., Morrongiello, B.A. & Thorpe, L.A. (1986). Auditory sensitivity in preschool children. *The Journal of the Acoustical Society of America*, 79, 447-452.

Shahidullah, S. & Hepper, P.G. (1994). Frequency discrimination by the fetus. *Early Human Development*, 36, 13-26.

Spahr, A.J. & Dorman, M.F. (2004). Performance of subjects fit with the Advanced Bionics CII and Nucleus 3G cochlear implant devices. *Archives of otolaryngology--head & neck surgery*, 130, 624-628.

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia*, 7, 12-36.

Teas, D.C., Klein, A.J. & Kramer, S.J. (1982). Cochlear responses to acoustic transient. An interpretation of whole nerve action potentials. *The Journal of the Acoustical Society of America*, 34, 1438-1489.

Thompson, N.C., Cranford, J.L. & Hoyer, E. (1999). Brief-tone frequency discrimination by children. *Journal of Speech, Language, and Hearing Research*, 42, 1061-1068.

Trehub, S.E., Schneider, B.A., Morrongiello, B.A. & Thorpe, L.A. (1988). Auditory sensitivity in school-age children. *Journal of Experimental Child Psychologia,* 46, 273-285.

Turgeon, C., Johnson, A., Pannasch, S. & Ellemberg, D. (2009). Auditory deprivation during infancy results in oculomotor deficits. *Journal of Vision*, 9, 8. Abstract 425. ISSN:1534-7362.

Turgeon, C., Lepore, F. & Ellemberg, D. (2010). Auditory and Visual frequency discrimination in cochlear implant users. [CAA Résumé] In: Association Canadienne d'Audiologie, Montréal, Canada.

Wier, C.C., Jesteadt, W. & Green, D.M. (1977). Frequency discrimination as a function of frequency and sensation level. *The Journal of the Acoustical Society of America*, 61, 178-184.

Wunderlich, J.L. & Cone-Wesson, B.K. (2006). Maturation of CAEP in infants and children: A review. *Hearing Research*, 212, 212-223.

Legends

Figure 1: Auditory detection thresholds for lower and higher frequency by age group (**A**). Visual detection thresholds for lower and higher frequency by age group (**B**). The * show results that are statistically different from adult values. Errors bars are standard errors.

Figure 2: Auditory and visual frequency discrimination for lower and higher frequency by age group. The * show results that are statistically different from adult values. Errors bars are standard errors.

Figure 1.

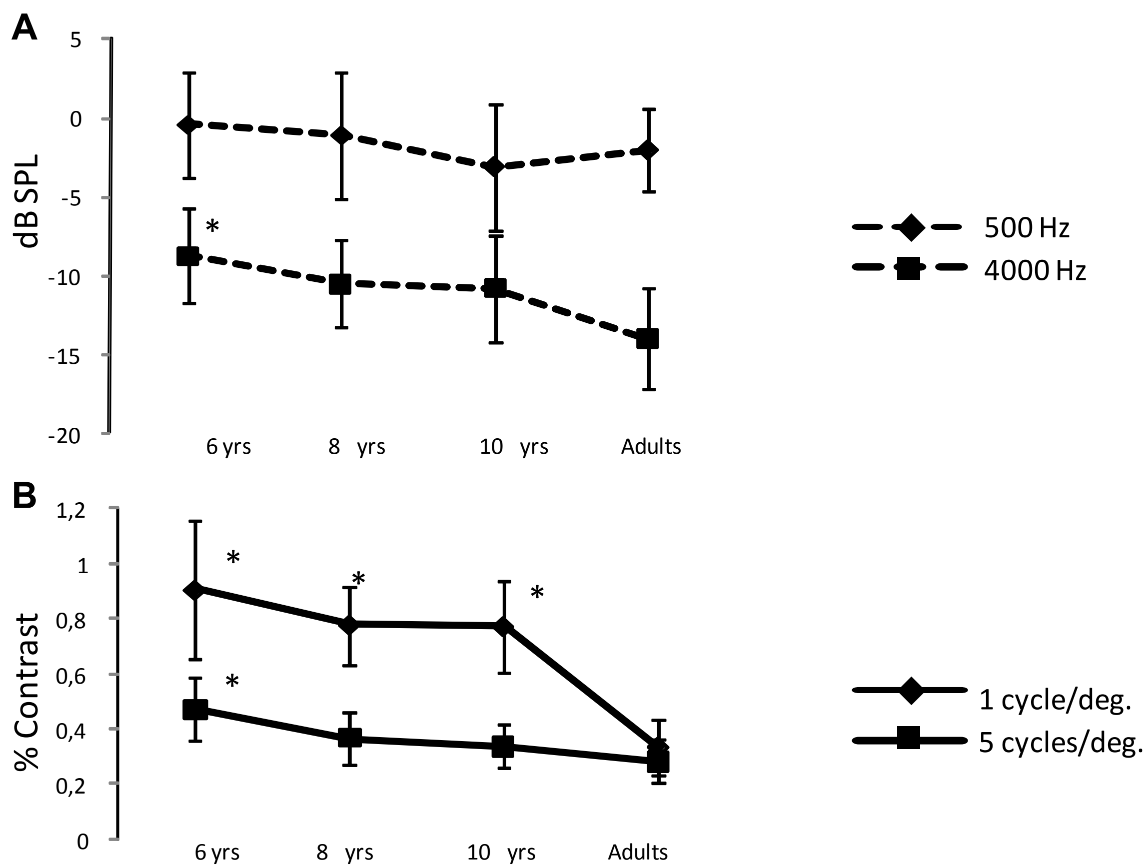
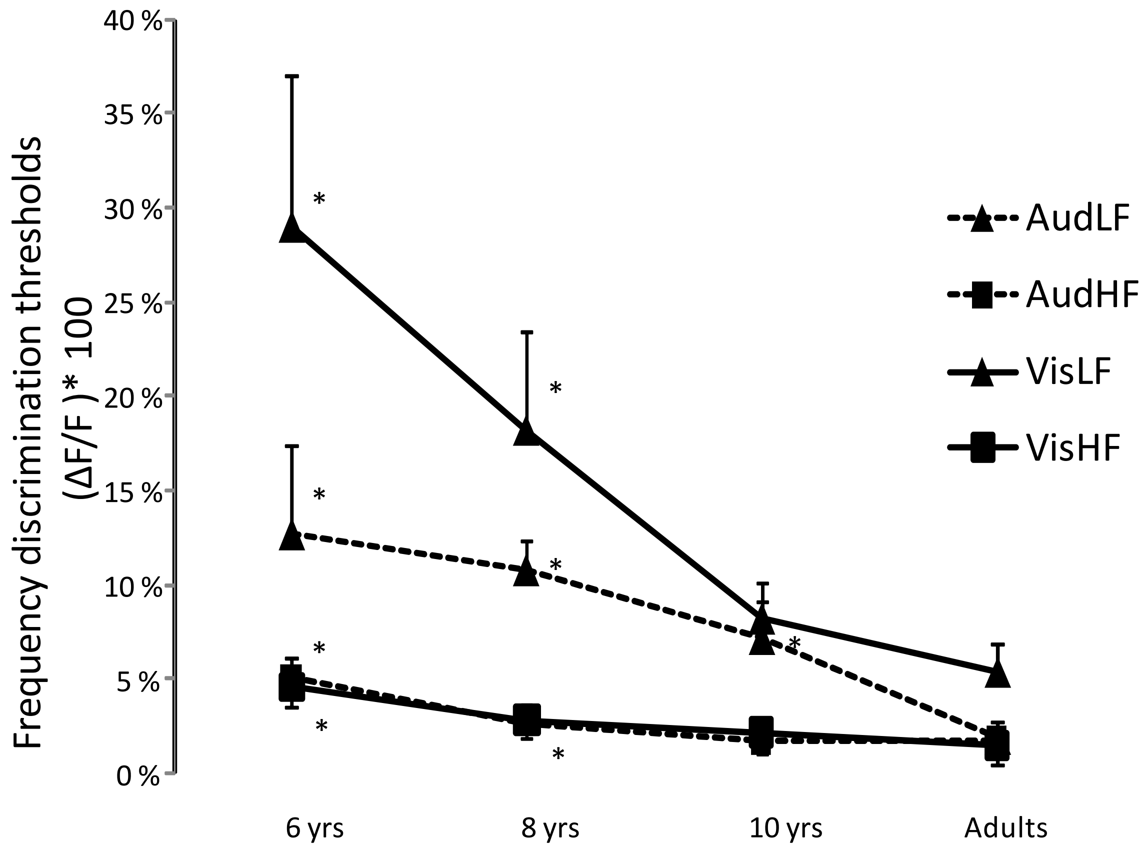

A
5
0
-5
-10
-15
-20
dB SPL
*
6 yrs
8 yrs
10 yrs
Adults
500 Hz
4000 Hz
B
1,2
1
0,8
0,6
0,4
0,2
0
% Contrast
*
*
*
*
6 yrs
8 yrs
10 yrs
Adults
1 cycle/deg.
5 cycles/deg.

Figure 2.


40 %
35 %
30 %
25 %
20 %
15 %
10 %
5 %
0 %
Frequency discrimination thresholds
(ΔF/F)* 100
6 yrs
8 yrs
10 yrs
Adults
AudLF
AudHF
VisLF
VisHF

Article 2

Turgeon C, Champoux F, Lepore F & Ellemberg D. Auditory frequency discrimination thresholds predict the proficiency of cochlear implants.

Auditory frequency discrimination thresholds predict the proficiency of cochlear implants.

Turgeon C[1], Champoux F[1,2], Lepore F[1] & Ellemberg D[1,3]

[1]Centre de Recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Québec, Canada.
[2]Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain/Institut Raymond-Dewar, Université de Montréal, École d'orthophonie et d'audiologie, Montréal, Québec, Canada.
[3]Département de Kinésiologie, Université de Montréal, Montréal, Québec, Canada.

Correspondence should be addressed to:

Dave Ellemberg, Ph.D.
Département de kinésiologie
Université de Montréal
2100 Edouard-Montpetit
Montreal (Quebec) H3T 1C5
Tel: (514) 343-7458 Fax: (514) 343-2115

Abstract

The aim of this study was to investigate the relationship between auditory frequency discrimination and speech recognition in cochlear implant users. Auditory frequency discrimination was assessed in groups of participants with normal hearing and with a cochlear implant. Detection thresholds are equivalent between all cochlear implant users but worst than the normal hearing participant. Non-proficient cochlear implant users have poorer auditory frequency discrimination compared to normal hearing participants and proficient cochlear implant users. No significant difference was found between the proficient cochlear implant and the normal hearing group. The present findings suggest an association between auditory frequency discrimination and speech recognition proficiency in cochlear implant users. The repercussions of these findings for auditory rehabilitation and new avenues for research are discussed.

Introduction

The option of cochlear implantation for individuals with profound bilateral sensory hearing loss has been available for almost three decades. This device can partially restores hearing in the profoundly deaf by converting auditory signals into electrical impulses, which bypasses the missing or damaged hair cells in the cochlea by directly stimulating the neurons of the auditory nerve. The primary goal of the cochlear implant is to allow speech recognition in every day listening situations. Although this is achieved for many cochlear implant users, there is important variability in auditory performance among individuals.

Three basic abilities are used to determine auditory proficiency in cochlear implant users: detection, discrimination, and recognition. In the evaluation of the proficiency of a cochlear implant, detection is without a doubt the most important. Without minimal detection of auditory input, it is impossible to process more complex auditory signals. The thresholds for the detection of pure-tones in individuals with a cochlear implant are generally below 40 dB HL for frequencies that range from 250 to 4000Hz (e.g. Singh et al., 2004; Champoux, Lepore, Gagné & Théoret, 2009; Tremblay, Champoux, Lepore & Théorêt, 2010). Generally, most implants lead to a similar level of auditory detection, which is usually reached as soon as the implant is turned on (Giraud et al., 2001).

Studies that investigated auditory frequency discrimination are far less common. Predictably, discrimination is reduced in cochlear implant users compare to normally hearing individuals. For example, in children of 14-17 years of age, the mean frequency discrimination obtained at 1000Hz was 5.5 and 11% for the hearing group and the cochlear implant group, respectively (Kopelovich, Eisen & Franck, 2010). It is believed that this leads to hearing difficulties in the presence of background noise (Spahr & Dorman, 2004) and that it affects the recognition and appreciation of music (Gfeller et al., 2007; Kong, Cruz, Jones, & Zeng, 2004). Frequency discrimination in cochlear implant users was mostly investigated in relation with the technical aspects of the implant itself, such as *i*) the type of electrical stimulation, *ii*) the depth of the insertion of the electrodes, *iii*) the numbers of electrodes and, *iv*) the type of implant. It appears that these factors do not have a significant impact on discrimination thresholds. For example, a more perimodiolar electrode position as well as the type of implant (either Clarion CII, Clarion HiRes90K or Nucleus 24) does not seem to influence frequency discrimination (Fitzgerald et al., 2007; Kopelovich, et al., 2010). Moreover, the duration with the implant, the gender, and the speech coding strategies are all others factors that have a negligible effect on frequency discrimination performance (Barry, Blamey & Martin, 2002; Fitzgerald & Wright 2005; Hsu, Horng, & Fu, 2000; McDermott & McKay, 1994; Qi et al., 2011).

To our knowledge the relationship between auditory frequency discrimination and speech recognition has never been investigated. This is surprising given that frequency discrimination is fundamental for auditory scene analysis. It is essential for speech perception, especially in demanding listening conditions such as speech perception in background noise, and for the identification and the localization of auditory signals (see Bregman, Liao & Levitan, 1990). Thus, it is important to investigate the possible relation between this low-level treatment and speech recognition as an improvement in frequency discrimination might naturally improve the capability of higher-order functions (e.g., Bregman, et al., 1990; Moore, Ferguson, Halliday & Riley, 2008).

Speech recognition in cochlear implant users has received more attention. In speech recognition tasks, cochlear implant users show a large variability in performance, ranging from not being able to repeat any of the words heard to obtaining a perfect score (e.g., Peterson, Pisoni & Miyamoto, 2010; Dorman, 1993; Arisi et al., 2010). The reasons for this variability are still poorly understood. Considering the role of frequency discrimination in normal speech recognition, the goal of this study was to verify the relationship between auditory frequency discrimination and speech recognition in cochlear implant users. A group of normal hearing and a group of cochlear implant users performed a psychoacoustic detection thresholds task with pure-tones of 250, 500, 1000, 2000 and 4000Hz, a frequency discrimination threshold task with pure-tones of 500Hz (lower frequency) and 4000Hz (higher frequency), and a speech recognition test.

Materials and Methods

Participants

Sixteen adults with normal hearing (mean age = 26 years) and 20 adults with profound deafness and a cochlear implant (mean age = 36 years) participated in the study. To be included in the study, normal hearing participants were required to pass an audiometric test. They were assessed independently with intra-auricular earphone for each ear. All participants had detection thresholds below 25 dB HL at every frequency, which corresponds to normal hearing and to what was expected. Middle-ear function was obtained with a Grason-Stadler GSI 38 tympanometer (Milford, MA, USA) and all subjects had normal mobility of the eardrum and normal middle ear function. The second group was composed of cochlear implant users (n = 20) who had a minimum of one year of experience with their implant. All cochlear implant users suffered from severe-profound bilateral hearing loss before their surgery. The majority of them reported progressive hearing loss during their life, until implantation. Nine were congenitally deaf (i.e., early onset deafness) and 11 were between 2 and 20 years age (mean age = 9 years) at the time of deafness (i.e., late onset deafness). All participants used oral language as a primary mode of communication. The clinical profile of each cochlear implant user is presented in Table 1. As indicated in the table, all but two participants in each group used hearing aids before implantation. None of the participants had learning disabilities or other known medical conditions. The subjects all had normal or corrected-to-normal vision as determined with the Snellen eye chart (model R.J.'s) at a distance of 10 feet. All participants were unaware of the nature of the experiment and they gave written informed consent in accordance with the University of Montreal Ethics Board. Recruitment was made possible with the participation of the Centre de Recherche Interdisciplinaire en Réadaptation du Montréal Métropolitain/Institut Raymond-Dewar (IRD) and the Centre de Réadaptation en Déficience Physique Le Bouclier.

Stimuli, design, and procedure

Speech recognition- Speech recognition was evaluated with a list of 50 phonetically balanced French words. This speech assessment was an open-set test in which monosyllable words were presented without any visual cues at a comfortable level of 70 dB SPL. The stimuli were calibrated using a Brüel and Kjaer sound level meter (type 2239) and a prepolarized condenser microphone (type 4188) (Naerum, Danemark) at an ear level position. Participants had to verbally repeat what they heard. The dependent variable was the percentage of words correctly repeated. Performance on this task determined the proficiency of the cochlear implant. According to the accepted clinical standards, individuals with a speech score > 65% were considered as good performers, whilst those with a speech score < 65% were considered poor performers (Zhang et al., 2010).

Detection- Pure-tone detection thresholds were assessed using an adaptative method at 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz. They were assessed independently for each ear for the normal hearing individuals and in free field at a distance of 1 meter for the participants with a cochlear implant. Prior to the testing, each participant with a cochlear implant was asked to adjust their implant processors at their usual setting.

Frequency discrimination- All stimuli had duration of 1000ms. We used sound pressure modulated sine waves (pure-tones) of 500 or 4000Hz, with a 50ms cosine rise-fall time. The stimuli were digitally generated using SykofizX software (version 2.0) and a 24-bit processor (TDT, RX6) from Tucker-Davis Technologies (TDT, Gainesville, FL, USA).

The signal waveforms were generated at a sampling rate of 48, 828Hz. The stimuli were presented in free field via a TDT magnetic speaker (model FF1) at a distance of 1 meter at ear level in front of the participant. The participants' responses were recorded via a response box (TDT, model RBOX-RX6). The sound pressure level was calibrated using a Brüel and Kjaer sound level meter (model 2239) and a prepolarized condenser microphone (model 4188, Naerum, Danemark).

Frequency discrimination thresholds were determined using an adaptative two-alternative forced choice (2AFC) staircase procedure. Each trial consisted of two pure-tones and two lights flashed that were positioned side by side on the response box and that were flashed consecutively. The onset of each light was separated by a 500ms interval. The stimuli were presented at a comfortable level of 70 dB SPL. Randomly, one tone corresponded to the reference frequency and the other to the probe frequency. The first presentation of the probe frequency was always set at 100Hz above the reference frequency. Step size was subsequently adjusted according to Levitt's (1971) staircase procedure. Step size changed by 50% until the first reversal and then by 25% for subsequent reversals. The subsequent trail was only initiated once the participant's response was entered (mean number of trials = 25, SD = 6). An experiment session ended once six response reversals were recorded for each reference frequency. No feedback was provided. Each experimental condition was preceded by a familiarisation protocol during which the task was explained and the stimuli were presented. All experiments took place in an audiometric sound room. The entire procedure lasted about 30 minutes.

Results

Speech recognition- Each of the normal hearing participants correctly repeated all of the words. For the group of participants with a cochlear group, the score varied from 0 to 92% (Mean= 54%). Based on the 65% cut-off for this task, 10 individuals were considered as good performers and 10 were considered as poorer performers.

Detection- The normal hearing participants had detection thresholds below 25 dB HL at 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz, which corresponds to what is expected. The group of participants with a cochlear implant presented detection thresholds that were generally below 40 dB HL for all frequencies tested. Mean detection thresholds for the cochlear implant group and the normal hearing participants are presented in Figure 1. For the normal hearing participant, the results from the right ear are presented in the Figure 1 and used in the analyses. A 3 (controls, proficient cochlear implant users, and non-proficient cochlear implant users) X 5 (250, 500, 1000, 2000 and 4000Hz) ANOVA showed a significant interaction $F_{(1,33)}= 2.28$, $p= 0.038$, a main effect of group $F_{(1,33)}= 97.66$, $p < 0.01$, and no main effect of frequency $F_{(1,33)}= 2.44$, $p = 0.065$. Post-hoc analyses indicated that both the proficient ($p< 0.001$) and non-proficient users ($p< 0.001$) had significantly higher thresholds than the normal hearing participants. However, no significant difference was revealed between the proficient and the non-proficient cochlear implant users ($p= 0.716$).

Frequency discrimination- Frequency discrimination thresholds for the normal hearing and for cochlear implant users are showed in Figure 2. A 3 (controls, proficient cochlear implant users, and non-proficient cochlear implant users) X 2 (500Hz and 4000Hz) ANOVA showed a main effect of group $F_{(1,33)}$= 26.48, $p < 0.01$, but no interaction $F_{(1,33)}$= 0.31, $p = 0.736$ and no main effect of frequency $F_{(1,33)}$= 1.06, $p = 0.311$. Post-hoc analyses on the main effect of group indicated that frequency discrimination is not different between the normal hearing group and the proficient cochlear implant users ($p > 0.05$). A significant difference was revealed between the normal hearing group ($p < 0.001$) and the non-proficient cochlear implant users ($p < 0.001$).

We also decided to measure if there were any correlation between the auditory performance and different variables, which may explain the results. To do so, we conducted different correlations. No significant correlations were found between the frequency discrimination and *i)* the age at testing ($p > 0.6$), *ii)* the experience with the implant ($p > 0.1$), *iii)* the duration of deafness ($p > 0.2$), *iv)* the aided thresholds with the cochlear implant ($p > 0.2$), and *v)* the number of actives electrodes ($p > 0.3$).

Discussion

The purpose of this study was to investigate the relationship between auditory frequency discrimination and speech recognition in cochlear implant users. Our results indicate that cochlear implant users with poorer speech recognition also have poorer auditory frequency discrimination compared to normal hearing participants or to cochlear implant users with better speech recognition. However, no such relationship was found between detection thresholds and speech recognition. These results suggest that there is a specific relationship between the proficiency of a cochlear implant for recognizing speech and frequency discrimination. This finding could potentially have some important repercussions for the rehabilitation of deaf individuals who have a cochlear implant.

No correlations were observed between the frequency discrimination and the age at testing, the duration of deafness, the experience with the implant, and the age at hearing loss. This agrees with the literature suggesting that participant characteristics and technical aspects of the cochlear implant have a limited impact on the auditory frequency discrimination (Fitzgerald et al., 2007; Kopelovich, et al., 2010; Barry, Blamey & Martin, 2002; Fitzgerald & Wright 2005; Hsu, Horng, & Fu, 2000; McDermott & McKay, 1994; Qi et al., 2011). However, others studies have suggested that some technical aspects such as channel interaction in the cochlear device may have an impact on pitch discrimination between electrodes (McKay, O'Brien & James, 1999; Pfingst, Holloway, Zwolan, & Collins, 1999). Also, it has been show that perimodiolar position of the electrodes can improved electrode pitch discrimination ability (Hughes & Abbas, 2006). In the current study, it is possible that cochlear implant devices had an impact on frequency discrimination results, but because most of our participants received similar cochlear implant devices, it probably doesn't explain the entire variation in the result. Frequency discrimination most likely reflects the response characteristic of central auditory processes, which appear to be much more variable from one cochlear implant user. Moreover, a substantial number of individuals factors, such as the etiology of deafness, the duration of deafness, the residual hearing, the length of hearing aids could probably explain, at least in part, the post-implantation outcome. In the current study, we did not obtain significant correlation between clinical factors and auditory performance, but they could have been revealed with a larger cochlear implant population tested.

Detection thresholds are within or close to normal limits promptly after cochlear implantation (e.g. Giraud et al., 2001). In this study, there is no relationship between detection thresholds and the speech recognition, as detection thresholds are equivalent for the proficient and the non-proficient cochlear implant users. Even if detection thresholds are similar among cochlear implant users, speech recognition performance is more variable, as some individuals achieve normal results whilst others have quite poor results (e.g. Champoux et al., 2009; Tremblay et al., 2010). The findings presented here suggest that frequency discrimination is a better predictor of higher auditory performance, as speech recognition, than is detection. These results suggest that frequency discrimination evaluation should be included, as is detection and speech recognition, in the regular cochlear implant assessment.

Accumulating evidence suggests that frequency discrimination can be improved through training in normally hearing adults and children (e.g. Amitay, Hawkey & Moore, 2005; Delhommeau, Michey & Jouvent, 2005; Demany & Semal, 2002; Grimault et al., 2003; Halliday, Taylor, Edmondson-Jones& Moore, 2008; Irvine, Martin, Klimkeit & Smith, 2000; Wright and Sabin, 2007). For example, in adults, thresholds at 3000Hz improved by a factor of 2.4 after ten training sessions of about 1 hour (Demany & Semal, 2002). Fewer studies explored the possibility of improving discrimination in a clinical population or verified the transfer to other auditory functions such as speech recognition (MacArthur, Ellis, Atkinson & Coltheart, 2008; Schäffler, Sonntag, Hartnegg & Fischer, 2004). Schäffler et al (2004) did report that frequency discrimination can be improved in individuals with dyslexia and that this amelioration is accompanied by an improvement in language-related phonological skills and spelling. Currently, most of the auditory rehabilitation in cochlear implant users is geared towards speech detection and recognition, with somewhat equivocal results (Graham et al., 2009). Therefore, training frequency discrimination might represent a promising avenue for the rehabilitation of some cochlear implant users for which the technological devices are not as successful as expected.

Acknowledgements

This work was supported by grants from CIHR and NSERC to DE and to FL. This research was also supported by an Infrastructure grant from CFI to DE. We want to thanks every participant.

References

Amitay, S., Hawkey, D.J.C. & Moore, D.R. (2005). Auditory frequency discrimination learning is affected by stimulis variability. *Perception & Psychophysics*, 67, 691-698.

Arisi, E., Forti, S., Pagani, D., Todini, L., Torretta, S., Ambrosetti, U. & Pignataro, L. (2010). Cochlear implantation in adolescents with prelinguistic deafness. *Otolaryngolohy, Head and Neck Surgery*, 142, 804-808.

Barry, J.G., Blamey, P.J. & Martin, L.F. (2002). A multidimensional scaling analysis of tone discrimination ability in Cantonese-speaking children using a cochlear implant. *Clinical Linguistics and Phonetics*, 16, 101-113.

Bishop, D.V. & McArthur, G.M. (2005). Individual differences in auditory processing in specific language impairment: a follow-up study using event-related potentials and behavioural thresholds. *Cortex*, 41, 327-341.

Bregman, A.S., Liao, C. & Levitan, R. (1990). Auditory grouping based on fundamental frequency and formant peak frequency. *Canadian Journal of Psychology*, 44, 400-413.

Champoux, F., Lepore, F., Gagné, J.-P. & Théoret, H. (2009). Visual stimuli can impair auditory processing in cochlear implant users. *Neuropsychologia*, 47, 17-22.

Delhommeau, K., Micheyl, C. & Jouvent, R. (2005). Generalization of frequency discrimination learning across frequencies and ears: implication for underlying neural mechanism in humans. *Journal of the Association for Research in Otolaryngology*, 6, 171-179.

Demany, L. & Semal, C. (2002). Learning to perceive pitch differences. *The Journal of the Acoustical Society of America*, 111, 1377-1388.

Dorman, M.F., Smith, L. & Parkin, J.L. (1993). Loudness balance between acoustic and electric stimulation by a patient with a multichannel cochlear implant. *Ear and Hearing*, 14, 290-292.

Fitzgerald, M.B., Shapiro, W.H., McDonald, P.D., Neuburger, H.S., Ashburn-Reed, S., Immerman, S., et al. (2007). The effect of perimodiolar placement on speech perception and frequency discrimination by cochlear implant users. *Acta oto-laryngologica,* 127, 378-383.

Fitzgerald, M.B. & Wright, B.A. (2005). A perceptual learning investigation of the pitch elicited by amplitude-modulated noise. *The Journal of the Acoustical Society of America*, 118, 3794-3803.

Gfeller, K., Turner, C., Oleson, J., Zhang, X., Gantz, B., Froman, R., et al. (2007). Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear and hearing, 28*(3), 412-423.

Graham, J., Vickers, D., Eyles, J., Brinton, J., Al Malky, G., et al. (2009). Bilateral sequential cochlear implantation in the congenitally deaf child: Evidence to support the concept of a 'Critical Age' after which the second ear is less likely to provide an adequate level of speech perception on its own. *Cochlear Implants International*, 10, 119-141.

Giraud, A.L., Price, C.J., Graham, J.M., Truy, E. & Frackowiak, R.S. (2001). Cross-modal plasticity underpins language recovery after cochlear implantation. *Neuron*, 30, 657-663.

Grimault, N., Micheyl, C., Carlyon, R.P., Bacon, S.P. & Collet, L. (2003). Learning in discrimination of frequency or modulation rate: generalization to fundamental frequency discrimination. *Hearing Research*, 184, 41-50.

Halliday, L.F., Taylor, J.L., Edmondson-Jones, A.M. & Moore, D.R. (2008). Frequency discrimination learning in children. *The Journal of the Acoustical Society of America*, 123, 4393-4402.

Hill, P.R., Hogben, J.H. & Bishop, D.M. (2005). Auditory frequency discrimination in children with specific language impairment: a longitudinal study. *The Journal of Speech, Language, and Hearing Research*, 48, 1136-1146.

Hughes, M.L. & Abbas, P.J. (2006). Electrophysiologic channel interaction, electrode pitch ranking, and behavioral threshold in straight versus perimodiolar cochlear implant electrode arrays. *J Acoust Soc Am.,119,* 1538-1547.

Hsu, C.J., Horng, M.J. & Fu, Q.J. (2000). Effects of the number of active electrodes on tone and speech perception by Nucleus 22 cochlear implant users with SPEAK strategy. *Advances in Otorhinolaryngology*, 57, 257-259.

Irvine, D.R., Martin, R.L., Klimkeit, E. & Smith, R. (2000). Specificity of perceptual learning in a frequency discrimination task. *The Journal of the Acoustical Society of America,* 108, 2964-2968.

Kong, Y-Y., Cruz, R., Jones, J.A. & Zeng, F.-G. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear and Hearing*, 25, 173-185.

Kopolovich, J.C., Eisen, M.D. & Franck, K.H. (2010). Frequency and electrode discrimination in children with cochlear implants. *Hearing Research*, 268, 105-113.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America*, 49, 467.

McArthur, G.M. & Bishop, D.V. (2004). Frequency discrimination deficits in people with specific language impairment: reliability, validity, and linguistic correlates. *Speech, Language and Hearing Research*, 47, 527-541.

McKay, C.M., O'Brien, A. & James, C.J. (1999). Effect of current level on electrode discrimination in electrical stimulation. *Hearing Research*, 136, 159–164.

McDermott, H.J. & McKay, C.M. (1994). Pitch ranking with nonsimultaneous dual-electrode electrical stimulation of the cochlea. *The Journal of the Acoustical Society of America,* 96, 155-162.

Moore, D.R., Ferguson, M.A., Halliday, L.F. & Riley, A. (2008). Frequency discrimination in children: perception, learning and attention. *Hearing Research*, 238, 147-154.

Peterson, N.R., Pisoni, D.B. & Miyamoto, R.T. (2010). Cochlear implants and spoken language processing abilities: Review and assessment of the literature. *Restorative Neurology and Neurosciences*, 28, 237-250.

Pfingst, B.E., Holloway, L.A., Zwolan, T.A. & Collins, L.M. (1999). Effects of stimulus level on electrode-place discrimination in human subjects with cochlear implants. *Hearing Research*, 134, 105–115.

Qi, B. et al. (2011). The contribution of apical stimulation to Mandarin speech perception in users of the MED-EL COMBI 40+ cochlear implant. *Actac Oto-Laryngologica*, 131, 52-58.

Schäffler, T., Sonntag, J., Hartnegg, K. & Fischer, B. (2004). The effect of practice on low-level auditory discrimination, phonological skills, and spelling in dyslexia. *Dyslexia*, 10, 119-130.

Singh, S., Liasis, A., Rajput, K., Towell, A. & Luxon, L. (2004). Event-related potentials in pediatric cochlear implant patients. *Ear and Hearing*, 25, 598-610.Spahr, A.J. & Dorman, M.F. (2004). Performance of subjects fit with the Advanced Bionics CII and Nucleus 3G cochlear implant devices. *Archives of Otolaryngology, Head & Neck Surgery*, 130, 624-628.

Tallal, P. (2004). Improving language and literacy is a matter of time. *Nature Reviews Neurosciences*, 5, 721-728.

Tremblay, C., Champoux, F., Lepore, F. & Théoret, H. (2010). Audivisual fusion and cochlear implant proficiency. *Restorative Neurology and Neuroscience*, 28, 283-291.

Walker, M.M., Shinn, J.B., Cranford, J.L., Given, G.D. & Holbert, D. (2002). Auditory temporal processing performance of young adults with reading disorders. *Journal of Speech, Language, and Hearing Research*, 45, 598-605.

Wright, B.A. & Sabin, A.T. (2007). Perceptual learning: how much daily training is enough? *Experimental Brain Research*, 180, 727-736.

Zhang, F., Hammer, T., Banks, H.-L., Benson, C., Xiang, J. & Fu, Q.-J. (2010). Mismatch negativity and adaptation measures of the late auditory evoked potential in cochlear implant users. *Hearing Research*, doi: 10.1016/j.heares.2010.11.007.

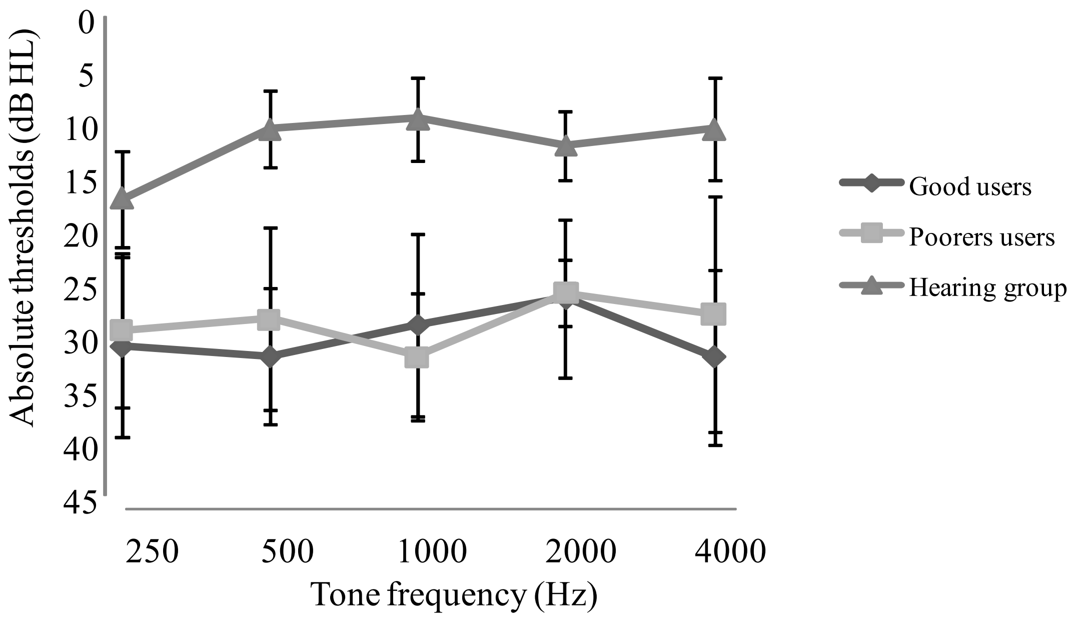
Legends

Figure 1: Pure-tone detection thresholds and standard deviation for the proficient cochlear implant users, the non-proficient cochlear implant users and the hearing group.

Figure 2: Frequency discrimination thresholds and standard deviation for the proficient cochlear implant users, the non-proficient cochlear implant users and the hearing group.

Table 1: Clinical profile of cochlear implant users

Figure 1.



Absolute thresholds (dB HL)
0
5
10
15
20
25
30
35
40
45
250
500
1000
2000
4000
Tone frequency (Hz)
Good users
Poorers users
Hearing group

Figure 2.

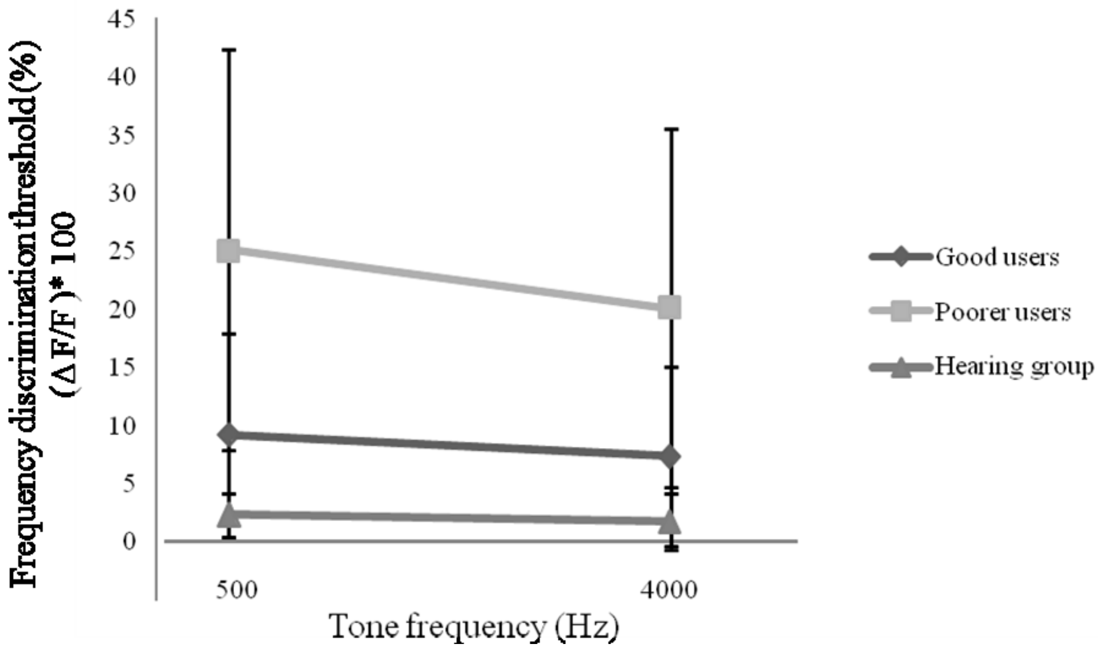

Frequency discrimination threshold (%) (ΔF/F) * 100
45
40
35
30
25
20
15
10
5
0
500
4000
Tone frequency (Hz)
Good users
Poorer users
Hearing group

Table 1.

Subject	Age (years)	Number of years wearing CI	Etiology of deafness	Speech recognition (%)	Age at deafness (years)	Age at implantation (years)	Side of the Implant	Age at amplification with hearing aids (years)‡	Pre-implant hearing thresolds (MPT_R/L)*	Aided thresholds with implant (MPT)**	Number of actives electrodes	Type of cochlear implant
S1	20	2	Congential	82	Birth	18	G	1	>110/>110	37	22	Cochlear-Freedom Nucleus
S2	22	6	Congential	8	Birth	6	G	3	>120/97	40	15	Neurolec- Saphyr CX
S3	35	5	Congenital	37	Birth	30	G	0,8	107/>120	33	16	Advances Bionic-Clarion
S4	45	4	Congential	6	Birth	41	G	3	95/103	35	19	Cochlear-Freedom Nucleus
S5	46	5	Congenital	74	Birth	41	G	5	95/93	27	14	Advances Bionic-Clarion
S6	22	6	Congenital	92	Birth	16	G	3	>117/93	15	22	Cochlear-ESPrit Nucleus
S7	44	1	Congenital	0	Birth	44	G	1	117/>117	33	20	Cochlear-Freedom Nucleus
S8	30	2	Congenital	64	Birth	28	G	Ø	93/>100	32	15	Advances Bionic-Clarion
S9	27	2	Congenital	76	Birth	25	G	4	>107/>107	22	22	Cochlear-Freedom Nucleus
S10	22	12	Unknown	0	8	10	D	8	>120/>120	27	6	Cochlear-Freedom Nucleus
S11	30	22	Meningitis	8	3	8	D	Ø	>120/>120	40	9	Cochlear-Freedom Nucleus
S12	34	7	Unknown	82	11	27	G	12	108/108	32	15	Advances Bionic-Clarion
S13	55	3	Ototoxicity	74	7	52	G	7	68/97	23	22	Cochlear-Freedom Nucleus
S14	23	*2*	Meningitis	74	2	22	G	2	110/91	23	22	Cochlear-Freedom Nucleus
S15	51	1	Mumps	36	8	50	G	8	110/110	23	13	Advances Bionic-Clarion
S16	48	2	Congential	72	6	46	G	20	118/107	18	16	Advances Bionic-Clarion
S17	38	2	Congential	86	2	36	D	29	103/106	27	16	Advances Bionic-Clarion
S18	51	6	Congential	64	20	44	G	40	>117/68	25	15	Advances Bionic-Clarion
S19	42	4	Unknown	52	5	38	D	30	88/88	22	22	Cochlear-Freedom Nucleus
S20	39	2	Congential	92	Birth (L) 25 (R)	37	37	25	101/>120	38	22	Cochlear-Freedom Nucleus

‡The age at hearing aid amplification indicates age when the individual first received a hearing aid. They were used mostly binaurally.

* MPT = Mean of pure-tone (500, 1000, 2000 Hz).

**MPT = Mean of pure-tone (500, 1000, 2000 Hz) ; > no measurable response at the limit of the audiometer.

The duration of deafness can be obtained by substracting the onset of deafness of the age at implantion.

Article 3

Turgeon, C., Lepore, F. & Ellemberg, D. The relationship between the MMN and speech perception in adult cochlear implant users.

The relationship between the MMN and speech perception in adult cochlear implant users.

Turgeon C[1], Lepore F[1] & Ellemberg D[1,2]

[1]Centre de Recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Québec, Canada.
[2]Département de Kinésiologie, Université de Montréal, Montréal, Québec, Canada.

Correspondence should be addressed to:
Dave Ellemberg, Ph.D.
Département de kinésiologie
Université de Montréal
2100 Edouard-Montpetit
Montreal (Quebec) H3T 1C5
Tel: (514) 343-7458 Fax: (514) 343-2115

Abstract

Cochlear implants are now accessible to a younger population. The development of electrophysiological measures is important because it can be used to evaluate the benefits of the cochlear implant in infants, young children, and non-verbal adults that cannot cooperate for behavioural speech discrimination testing. The mismatch negativity (MMN) is a preattentive measure known to represent auditory discrimination ability. The MMN is evoked by deviant stimuli and it is characterized by an increased negativity in the waveform. No study has yet investigated the characteristics of the MMN on a large population of deaf participants implanted at adult age. We aim to develop an efficient MMN paradigm, which will reveal electrophysiological differences between good and poorer performers on a speech recognition task. We also aim to investigate the relationship between MMN measures and speech performance. Twenty adults with a cochlear implant and 11 normal hearing subjects participated in the study: based on a speech perception test, 10 cochlear implant users were considered as good performers and 10 were considered as poor performers. We measured the MMN with /da/ as the standard stimulus and /ba/ and, /ga/ as the deviants. Separate analyses were conducted on the amplitude and latency. An MMN was evoked to both deviant stimuli in all normal hearing participants as well as in all good performers. For the poorer cochlear implant subjects there was a trend toward either a greatly reduce amplitude and a longer latency than the better performers. A bivariate correlation analyse showed a significant correlation between the speech perception score

and the amplitude of the MMN. The pattern of results suggests that the MMN can be used as a tool to investigate outcome in a population of adults with a cochlear implant.

Introduction

Individuals with a severe-profound bilateral hearing loss, who cannot benefit from conventional hearing aids, have now the option to receive a cochlear implant. This technological device bypasses the outer and the middle ear and directly stimulates the fibres of the auditory nerve, restoring some degree of auditory perception. The primary goal of a cochlear implant (CI) is to permit speech perception in the everyday listening environment, but its success in terms of speech perception varies greatly among users. For many of them, speech perception far exceeds the expectation of early investigations and generally, CI yield to an important improvement (Holt & Svirsky, 2008; Oh et al., 2003; Peterson, Pisoni & Miyamoto, 2010). With modern multi-electrode CI, speech performance scores can increase up to 70-80% for sentence recognition in a quiet environment but can also remain really problematic for other CI users (Osberger, Fisher & Kalberer, 2000; Garnham, O'Driscoll, Ramsden & Saeed, 2002).

Auditory evoked potentials are used to measure the integrity of the implant as well as for the settings of the device parameters (Oviatt & Kileney, 1991). However, in the field of audiology, behavioural methods are the primary tools used to investigate auditory performance. For younger children, infants and non-verbal adults that cannot cooperate for behavioural speech discrimination testing, the use and the development of electrophysiological measures are especially important. It can be used to evaluate the improvement in auditory performance of these populations.

Auditory evoked potentials have been used to investigate the auditory system integrity and the speech capacities in paediatric and adult populations of CI users with considerable success (Dinces, Chobot-Rhodd & Sussman, 2009; Gordon, Tanaka, Papsin, 2005; Groenen, Snik & van den Broek, 1996; Kelly, Purdy & thorne, 2005; Kileny, Boerst & Zwolan, 1997; Krauss et al., 1993; Roman et al., 2004; Singh et al., 2004; Wable, van den Abbeele, gallégo & Frachet, 2000). The ability to discriminate small acoustic differences is important for music and speech perception and most studies with cortical auditory evoked responses investigated the mismatch negativity component (MMN) to evaluate discrimination ability. The MMN was first described by Näätänen et al. (1978) as an objective tool that provides a measure of automatic stimuli discrimination. It is elicited following occasional deviant stimuli embedded in a sequence of standard stimuli. In adults with normal hearing the MMN is typically characterized by a negativity which is maximal over the frontocentral electrodes and that occurs approximately 100 to 250ms after the onset of the deviant stimulus (for a review see Näätänen et al., 1990). The MMN can be obtained when a patient does not pay attention to the auditory stimuli, so it is thought to index preattentive discrimination. Therefore, when speech stimuli are used, the MMN is thought to index preattentive speech discrimination (for a review of speech evoked potentials, see Martin, Tremblay & Korczak, 2008). However, the clinical applications of the MMN for audiologists working with the CI population are still limited. A number of studies on CI users employed the MMN to investigate auditory performances, results are promising but the methods and the conclusions are quite different.

The first study using the MMN for the evaluation of CI users was conducted by Kraus et al. (1993). The MMN was obtained with speech stimuli, /da/ and /ta/, in ten adults with normal hearing and in nine adults with CI, all but one considered to be good users. Their performance with the implant was based upon their subjective reports of satisfaction, their everyday communication competence and their ability to understand monosyllabic words. They found that the MMN waveforms in good CI users were strikingly similar to those recorded with the adults that have normal hearing. The single poor implant user in the study did not have a MMN waveforms. A similar MMN study with seven adult CI users was conducted by Groenen et al. (1996) who used the speech stimuli (/ba/, /da/) and categorized the CI participants on the basis of their performance in monosyllables, spondee and short vowel identification tests. These results yielded the same conclusions as Kraus and her team, a MMN for good performers was visualized (3 CI) but not for poorer performers (4 CI). Several other studies have also been conducted on adult CI users with an MMN paradigm, the MMN was obtained with different types of stimuli, duration and pitch differences, in both electrical stimulation and in free field (Kelly et al., 2005; Ponton & Don, 1995; Roman et al., 2004; Wable et al., 2000). They all found that a MMN could be observed for good performers and some studies also reported a correlation between speech score and MMN measures (Kelly et al., 2005; Roman et al., 2004). All these results, even if based on limited numbers of CI users, suggest that the outcomes of electrophysiological measurements seem to be related to the proficiency of the CI.

To date MMN studies in CI subjects have large variations in terms of the numbers of participants, the stimuli, and the paradigms used as well as the presence or not of control participants. The present study was undertaken to investigate the MMN characteristics with a two-deviant oddball paradigm, using three different speech stimuli on a group of adult CI users and normal hearing participants. We aim to develop an efficient MMN paradigm, which will separate the good from the poorer performers. We also aim to investigate the relationship between the MMN characteristics (amplitude and latency) and speech performance.

Methods

Participants

One group of normal hearing individuals and one group of CI users participated in the study. None of them had learning disabilities, neurological problems or other known medical conditions. The hearing group was composed of 11 adults (mean age= 36 years, SD= 14, min=24, max=58). All had normal peripheral hearing and no known otologic problems. They all had thresholds better than 25 dB HL from 250 to 4000Hz, which corresponds to normal hearing and to what was expected. Middle-ear function was obtained with a Grason-Stadler GSI 38 tympanometer (Milford, MA, USA) and all subjects had normal mobility of the eardrum and normal middle ear function. The study group consisted of 20 experienced adults CI users (mean age= 45 years, SD= 14, min= 20, max= 63). Almost all participants had their surgery in adulthood (mean age of surgery= 40 years, SD= 14) and they all had an experience of at least one year with their implant. Prior to surgery, all CI participants had a bilateral severe-profound sensorineural hearing loss and after their implantation, all CI patients had pure-tone thresholds to tones stimuli between 15-45 dB HL from 250 to 4000Hz. The majority of them reported progressive hearing loss during their life, until implantation. Table 1 provides additional subject information. All participants gave written informed consent, in accordance with the Université de Montréal Board of Ethics. Recruitement was made possible with the participation of the Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain/Institut Raymond-Dewar (IRD) and the Centre de réadaptation en déficience physique Le Bouclier.

Psychoacoustic measures

Psychoacoustic tests were run, in addition to the evoked response potentials (ERP) recording, in a sound attenuated room. All acoustic signals were delivered through a loudspeaker, placed 1meter in front of the participant ear level for both pure-tone detection and speech recognition test.

Detection- Pure-tone detection thresholds were assessed using an adaptative method at 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz. They were assessed independently for each ear under intra-auricular earphones for the normal hearing individuals and in free field for the participants with a cochlear implant. Prior to the testing, each participant with a cochlear implant was asked to adjust their implant processors at their usual setting.

Speech recognition- Speech recognition was evaluated with a list of 50 phonetically balanced French words. This speech assessment was an open-set test in which monosyllable words were presented without any visual cues at a comfortable level of 70 dB SPL. The stimuli were calibrated using a Brüel and Kjaer sound level meter (type 2239) and a prepolarized condenser microphone (type 4188) (Naerum, Danemark) at an ear level position. Participants had to verbally repeat what they heard. The dependent variable was the percentage of words correctly repeated. Each phoneme included in a word had to be properly repeated. The performance on this task determined the proficiency of the cochlear implant. According to the accepted clinical standards, individuals with a speech score > 65% were considered as good performers, whilst those with a speech score < 65% were considered poor performers (Zhang et al., 2010). Each of the normal hearing participants correctly repeated all of the words.

Electrophysiological recording

Stimuli

Speech stimuli were used to evaluate a preattentive speech discrimination (Martin et al., 2008). All MMN stimuli, /da/, /ba/ and /ga/, were elicited with a male voice from a computer-generated speech stimuli. These phonemes were created with the MBROLA speech synthesizer program (version 3.0) and they were analyzed with the PRAAT analyzer software (Boersma & Weenink, 2010). All stimuli were 225ms in duration. The fundamental frequency was 100Hz for all stimuli. The first formant (F1) of the standard stimuli /da/ was 553Hz, the second (F2) was 1708Hz, the third (F3) was 3221Hz, and the fourth (F4) was 3923Hz. The first formant of the deviant /ga/ was 538Hz, the F2 was 1787Hz, the F3 was 3144Hz, and the F4 was 3968Hz. The first formant of the deviant /ba/ was 741Hz, the F2 was 1918Hz, the F3 was 3217Hz, and the F4 was 4095Hz. Figure 1 shows the frequency spectrum of the stimuli and the y-axes represents the sound pressure level (dB SPL). As the three stimuli used /d/, /b/ and /g/ are voiced consonants, the most important spectral difference between them is on the attack of the consonant, which is mostly in low frequencies.

The stimuli were presented using a two-deviant oddball paradigm where /da/ was the standard (probability of occurrence= 80%) and /ba/ and /ga/ were the deviants (probability of occurrence= 10% each). The spectral difference between the standard and the deviant was smaller in one of the two conditions (/da/ and /ba/). These three stimuli were chosen to induce two different conditions, in order to evaluate if one was more useful at dividing the good and the poorer CI users. The interstimulus interval was 1000ms (ISI). Stimuli were presented in pseudorandom sequence with at least three standard stimuli presented before the presentation of the deviant stimuli. The recording session contained six blocks with 330 standard and 30 deviant stimuli. All together, 1980 standards and 180 of each deviant (/ba/ and /ga/) were presented. Prior to the testing, each CI participant was asked to adjust their implant processors at their usual setting so they could hear the stimuli at a comfortable loudness level. Subjectively from the participant, all stimuli were heard with the same loudness.

Evoked potential recordings

Electroencephalography (EEG) was measured using the Geodesic Sensor Net ™ (GSN) (Electrical Geodesic System Inc., Eugene, OR) consisting of 128 electrodes. Before the installation of the electrode cap, the electrodes were soaked in a saline solution and Nuprep gel (Nuprep, Weaver & Co., Aurora, CO, USA) was applied on the scalp of the subjects with an alcohol pad (PDI) to reduce skin impedance. Participants removed their CI during the installation of the electrode cap to avoid any device damage. During the installation and the recording, participants were asked to watch a silent movie with subtitles. Electrode impedance was kept below 50 kΩ before baseline recording, which is the standard for high input impedance amplifiers (Tucker, 1993). One additional impedance measurement was performed in the middle of the task to be sure impedance remained below 50 kΩ. The EEG signal was amplified with the Net Amps 200 amplifier (EGI, Eugene, OR, USA) and a band-pass filter was set at 0.1-100Hz. The signal was digitalized at 250Hz and the data were recorded with Net Station software (EGI, Eugene, OR, USA). A G4 Macintosh computer controlled data acquisition. The electrodes were referenced to the Cz and a ground was installed anterior to Pz. Vertical eye movements were monitored with electrodes placed above and below each eye and horizontal eye movements were monitored with electrodes placed beside both eyes. During evoked-potential recording session, the participants were instructed to ignore the auditory stimuli. Between each bloc, a short pause of about two minutes was provided.

Data Analysis

A problematic factor well known with the EEG signals measured with a CI population is the artifacts induced by the implant device. These artifacts are perfectly time-locked to the acoustic stimulus and can lead to larger amplitude than the one induced by the stimuli (Gilley et al., 2006; Debener, Hine, Bleeck & Eyles, 2008). To avoid an over-estimation of the cortical responses evoked by the acoustic stimuli, it is imperative to detect these artifacts and remove them. Several techniques are proposed and the Independent Component Analysis (ICA) has been suggested as one of the most effective technique to remove EEG artifacts (Gilley et al., 2006). In fact, when used with a large number of recording electrodes, ICA greatly minimized the implant artifacts (Gilley et al., 2006). The ICA decomposition of the EEG signal provides spatially fixed and temporally independent components (Debener, Makeig, Delorme & Engel, 2005). We used the ICA analyse for both groups to remove artifacts in the EEG signal induced from the CI device and from the eye movements. This statistic method is well described in Gilley et al. (2006).

All analyses were performed with Brain Vision Analyzer version 1.05 (Brain Products GmbH, Munich, Germany). First high and low pass filters were set at 0.1 and 30Hz (24 dB/octave). Data were re-referenced to the mastoid controlateral to the implanted ear for CI users and to the right mastoid for the normal hearing participants. ICA, as implemented in Brain Vision Analyzer version 1.05, was then applied to all raw data, for both normal hearing and CI users. Following that, component coming from the CI device and/or the eye movements were removed from the raw data. Component activations were treated as CI artifacts if they met the following criteria, as described in Gilley el al (2006): 1) the onset/offset of activity occurred at the onset/offset of the auditory stimulus; 2) the duration of the activity was constant throughout the duration of the auditory stimulus; and 3) scalp projections of the activity revealed a centroid on the side of the implant device. The EEG was segmented in 2340 epochs with each epoch beginning 200ms before stimulus onset and ending 1000ms after stimulus onset. A semi-automatic artifact rejection was then inspected to mark EEG activity exceeding ±100 μV. A local DC trend correction and a baseline correction within the pre-stimulus interval were applied to the segments. A grand average for all stimuli was computed for each participant. Thus the individual grand average consisted of a total of 1980 responses to the standard /Da/, and 180 responses to each deviant /ba/ and /Ga/. The MMN was calculated by subtracting the individual grand average response of the standard stimulus from the response of the deviant stimulus.

The electrodes AFz, Fz, and FCz were used to investigate the MMN, as this measure has been found to be topographically distributed in the frontocentral regions (Duncan et al., 2009; Ilvonen et al., 2004; Näätänen et al., 2004; van Zuijen et al., 2005; Ylinen et al. 2006). For each electrode, the MMN amplitude was detected semi-automatically as the most negative deflection occurring just before the P2 component induce by the presentation of the deviant stimuli in a specific time window, and the latency was defined at this specific maximal negative deflection. The temporal window in which the MMN took place varied across groups with and without CI. Therefore, the latencies and the amplitudes of the most negative peaks were measured in a quite different temporal window between groups as follows: Control group (130-230ms), Good performers (215-295ms) and Poorer performers (215-350ms). Moreover, the principal components evoked by the auditory stimulation had a longer tendency in the poorer performer group. Consequently, we had to consider a longer temporal window to include all the MMN in this group.

Statistical Analysis

Separate analyses were conducted on the mean amplitude and the latency using a mixed model ANOVA 3X2X3, on the factor group (normal hearing, good performers, and poorer performers, on the factor condition (MMNGA, MMNBA), and on the factor electrodes (AFz, Fz, and FCz) with repeated measures on the last two factors. This was done to determine if there were any differences in amplitude and latency according to group, condition, and electrode location. Within subjects effects are reported according to Greenhouse-Geisser's correction. For post-hoc analyses, confidence intervals were adjusted for multiple comparisons with LSD corrections. To evaluate the presence of any relationship between the speech recognition and the MMN amplitude and latency, a bivariate correlation was conducted. Statistical analyses were performed with SPSS 16.0.

Results

Artifact minimization using independant component analysis (ICA)

Scalp distribution maps revealed that artifacts evoked by the CI were centered on the hemisphere of the CI device for each CI user. ICA was performed on raw data for both groups of CI participants and normal hearing participants. For the CI group, artifacts came mostly from the CI device as well as from the eye movements. There was considerable variability across subjects for the scalp distribution of the component of the CI artifact, but it was centered generally near the implant. Figure 2 shows an example of a waveform from the electrode Fz of one cochlear implant user before and after the application of the ICA filtering. For all participants eye movement artifacts were centered around and between the eyes.

Mismatch Negativity

A clear MMN was evoked to both deviant stimuli in all normal hearing participants as well as in all good performers. In contrast, for the poorer CI subjects there was a trend toward either a greatly reduced amplitude and a longer latency compared to the better performers (see Figures 3 and 4).

MMN Amplitude

The ANOVA on amplitude did not show any significant interaction; however, there was a main effect of group $F_{(1,28)}= 4.49$, $p < 0.05$, and a main effect of condition $F_{(1,28)}= 14.34$, $p <$

0.01. There was no effect on electrodes $F_{(1,28)}= 1.49$, $p = 0.242$, indicating that the amplitudes were about the same for each of the three electrodes. A post-hoc analysis on the main effect of group indicated that the mean amplitude of all three electrodes and for both conditions was the same between the hearing group and the good performer CI users ($p= 0.220$), and between the good and the poor CI performers ($p= 0.101$). There was a significant difference between the hearing group and the poorer performers ($p= 0.006$). A pairwise comparison on the main effect of condition indicated that the mean amplitude of all three electrodes for the condition MMNGA (M= -1.31µV, SD= 0.95) was greater that the mean amplitude of the MMNBA (M= -.086 µV, SD= 0.85); $t (30) = 3.89$, $p < .05$.

MMN Latency

The analyses did not show any significant interaction; however, there was a main effect of group $F_{(1,28)}= 86.68$, $p < 0.01$. There was no main effect of condition $F_{(1,28)}= 3.36$, $p= 0.077$ and no main effect of electrodes $F_{(1,28)}= 2.051$, $p=0.148$, indicating that latency was about the same for each condition and for each of the three electrodes. A post-hoc analysis on the main effect of group indicated that the mean latency of all three electrodes and for both conditions was different between the hearing group and the good performer CI users ($p< 0.001$), and between the hearing group and the poor CI performers ($p<0.001$). There was no significant difference between the good and the poorer CI performers ($p=0.524$).

Correlation analyses

The outcome of the bivariate correlation analysis revealed no significant relationship between the latency and the speech score but we found a significant correlation between the speech score and, the amplitude at the electrodes FCz (r= -0.473, *p*=0.035) and Fz (r= -0.451, *p*=0.046) in the condition with the deviant /ga/. We also decided to measure if there were any correlation between the electrophysiological data and different variables, which may explain the results The relationship between the MMN amplitude and latency and, *i)* the age at implant ($p > 0.2$), *ii)* the experience with the implant ($p > 0.1$), *iii)* the duration of deafness ($p > 0.2$),), *iv)* the aided thresholds with the cochlear implant ($p > 0.2$), and *v)* the number of actives electrodes ($p > 0.2$) revealed no signification relationship.

Discussion

The aim of this study was to investigate the presence of the MMN in a group of adults with CI and a group of normal hearing participants, using two different deviant speech stimuli. We also aimed to study the possible relationship between MMN characteristics and the speech recognition. The two-deviant oddball paradigm was successful in demonstrating electrophysiological differences between the normal hearing participants and the better and the poorer CI groups. The electrophysiological task (MMN) was completed by all participants and the speech recognition test was completed by the CI participants. The results indicated that all normal hearing participants as well as all good performers had a MMN induced by both deviant stimuli. There was also a trend for the cochlear implant subjects with poorer results on the speech recognition test to have reduced amplitude and a longer latency than the better performers. Several studies using either tonal or speech stimuli also found this tendency (Groenen et al., 1996; Kraus, 1993; Sing, 2004).

Independant component analysis (ICA)

In all CI users' data, at least two independents components attributed to the CI were identified. Following the extraction of these components, the auditory evoked potentials responses contained normal amplitude and latencies for the CI population. However, the correct identification of the artifact components may be complicated, as some activation was not always around the implant but sometime also in a more frontal area. As discussed earlier, extraction of a component was based on its location on the scalp, its duration and the moment it appears in the EEG data. We assume that the origin of the artifact in the recording comes from the implanted electrode array. Consequently, the projection may vary with the number of active electrodes, the orientation of the electrodes in the cochlea, and the type of electrodes as suggested by Gilley and al. (2006). As a result, the CI artifacts were in some way different in intensity and location among participants.

Electrophysiological measures

Amplitude

Our findings suggest that the amplitude of the MMN may be used as an indicator of CI speech recognition performance. In fact, our results indicate that regardless the condition (MMNGA, MMNBA) and the electrodes (AFz, Fz and FCz), the amplitude of the MMN was larger for the control group and the good users than for the poorer users. However, our analyses did not reveal a difference between the good and the poor CI users. The MMN was analysed based on three electrodes, which are believed to provide a reliable MMN. Our findings did not expose any difference between the amplitude of the MMN from each of the three electrodes used, signifying that all of them can represent a good choice to get the MMN measures. Finally, we also obtained a main effect of condition, with larger amplitude for the MMN achieved with the deviant /ga/ than the condition with the deviant /BA/. This result is not surprising, given that the spectral differences are more pronounced between the sounds /d/ and /g/ than between the sounds /d/ and /b/; the /g/ has a more pronounced energy in the low frequencies (see Figure 1). The expected effect of reduced MMN amplitude with more difficult discrimination task occurred for all groups (Näätänen, 1990).

Latency

Our findings suggest that the latency of the MMN can also be use as an indicator of CI speech recognition performance. In fact, our results indicate that regardless the condition (MMNGA, MMNBA) and the electrodes (AFz, Fz and FCz), the latency of the MMN was shorter for the control group then the good CI users and the poorer CI users. The analyses did not reveal differences between the good and the poor CI users. Our findings did not expose any difference between the latency of the MMN from each of the three electrodes used and between different conditions.

In the present findings, the amplitude measures suggest a difference between the normal hearing and the poor performer CI users. However, the good performers can achieve quite normal MMN amplitude, as no significant difference was obtained between them and the normal hearing group for both conditions. Similar results have been proposed by other studies (Groenen et al., 1996; Roman et al., 2005) showing no difference in the MMN amplitude between a normal hearing group and a group of good CI users. However, the latency, even for the good performers, was still longer than the hearing group, results that are also supported by other studies (Kelly et al., 2005; Roman et al., 2005). Roman et al., (2005) found that for an easy condition (1000 Hz and 2000Hz), the MMN latency was similar to that of the control hearing group. However, when the condition became more difficult, with a lower difference between the standard and the deviant (1000Hz and 1500Hz), they observed a significant difference between the CI users and the hearing group. It is possible that in our study, both conditions were too difficult to induce a normal latency. It needs to be noted that the amplitude and the latency measures failed to make a significant difference between the good and the poorer performers, even if a tendency of larger amplitude and shorter latency is found in the better CI group compare to the poorer CI group.

Speech recognition

We also tried to predict speech recognition performance according to the MMN characteristics (latency and amplitude). Our finding revealed a correlation between the speech recognition score and the amplitude of the MMN, for the condition with the GA deviant. This correlation was present for the electrodes FCz (r= -.473, *p*= 0.035) and Fz (r= -.451, = 0.046). According to these results, the MMN evoked by the standard /da/ and the deviant /ga/ seems to be a better indicator of the CI outcome, than MMN evoked by the standard /da/ and the deviant /ba/, as the last condition did not revealed any correlation (all *P*> 0.15) with the speech recognition performance. Such relationship between the speech recognition score and the MMN characteristics, have been revealed by other studies, showing a correlation between latency of the MMN and the speech score (Roman et al., 2005) and a relation between the amplitude and latency and speech score in the study of Kileny et al. (1997).

Conclusion

These findings suggest that the MMN component can be use to assess the auditory system integrity and the speech recognition in a population of CI users. Indeed, we report a relationship between the MMN characteristics and the speech recognition performance which is likely to be very beneficial for more structured evaluation and rehabilitation programs in a CI population, especially with population that cannot be tested with regular speech recognition task, as infants and others non-verbal population.

Acknowledgements

This work was supported by grants from CIHR and NSERC to DE and to FL. This research was also supported by an Infrastructure grant from CFI to DE. We want to thanks every participant.

References

Boersma, P. & Weenink, D. (2010). http://www.fon.hum.uva.nl/praat/.

Debener, S., Hine, J., Bleeck, S. & Eyles, J. (2008). Source localization of auditory evoked potentials after cochlear implantation. *Psychophysiology*, 45, 20-24.

Debener, S., Makeig, S., Delorme, A. & Engel, A.K. (2005).What is novel in the novelty oddball paradigm? Functional significance of the novelty P3 event-related potential as revealed by independent component analysis. *Cognitive Brain Research,* 22, 309-321.

Dinces, E., Chobot-Rhodd, J. & Sussman, E. (2009). Behavioral and electrophysiological measures of auditory change detection in children following late cochlear implantation: A preliminary study. *International Journal of Pediatric Otorhinolaryngology,* 73, 843-851.

Garnham, C., O'Driscoll, M., Ramsden, R. & Saeed, S. (2002). Speech understanding in noise with a Med-El COMBI 40+ cochlear implant using reduced channels sets. *Ear and Hearing,* 23, 540-552.

Gilley, P.M., Sharma, A., Dorman, M., Finley, C.C., Panch, A.S. & Martin, K. (2006). Minimization of cochlear implant stimuls artefact in cortical auditory evoked potentials. *Clinical Neurophysiology*, 117, 1772-1782.

Gordon, K.A., Tanaka, S. & Papsin, B.C. (2005). Atypical cortical responses underlie poor speech perception in children using cochlear implants. *Neuroreport*, 19, 2041-2045.

Groenen, P., Snik, A. & van den Broek, P. (1996). On the clinical relevance of mismatch negativity: Results from subjects with normal hearing and cochlear implant users. *Audiology and Neurotology*, 1, 112-124.

Holt, R.F. & Svirsky, M.S. (2008). An exploratory look at pediatric cochlear implantation: is earlier always best? *Ear and Hearing*, 29, 492-511.

Ilvonen, T., Kujala, T., Kozou, H., Kiesilainen, A., Salonen, O., Alku, P. & Näätänen, R. (2004). The processing of speech and non-speech sounds in aphasic patients as reflected by the mismatch negativity (MMN). *Neurosciences Letters*, 366, 235–240.

Kelly, A.S., Purdy, S.C. & Thorne, P.R. (2005). Electrophysiological and speech perception measures of auditory processing in experienced adult cochlear implant users. *Clinical Neurophysiology,* 116, 1235-1246.

Kileny, P.R., Boerst, A. & Zwolan, T. (1997). Cognitive evoked potentials to speech and tonal stimuli in children with implants. *Otolaryngology, Head and Neck Surgery*, 1117, 161-169.

Kraus, N., Micco, A.G., Koch, D.B., McGee, T., CArrell, T., Sharma, A., Wiet, R.J. & Weingarten, C.Z. (1993). The mismatch negativity cortical evoked potential elicited by speech in cochlear-implant users. *Hearing Research*, 65, 118-124.

Martin, B.A., Tremblay, K.L. & Korczak, P. (2008). Speech evoked potentials: From the laboratory to the clinic. *Ear and Hearing*, 29, 285-313.

Näätänen, R., Gaillard, A.W. & Mantysalo, S. (1987). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychology (Amst)*, 42, 313-329.

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral Brain Sciences*, 13, 201-288.

Näätänen, R., Syssoeva, O. & Takegata, R. (2004). Automatic time perception in the human brain for intervals ranging from milliseconds to seconds. *Psychophysiology*, 41, 660–663.

Oh, S.H., Kim, C.S., Kang, E.J., Lee D.S., Lee H.J., Chang, S.O. et al. (2003). Speech perception after cochlear implantation over 4-year time period. *Acta Otolaryngology*, 123, 148-153.

Osberger, M.J., Fisher, L. & Kalberer, A. (2000). Speech perception results in adults implanted with the CLARION Multi-Strategy cochlear implants. *Advances in Otorhinolaryngology,* 57, 421-424.

Oviatt, D. & Kileny, P. (1991) Auditory event-related potentials elicited from cochlear implant recipients and hearing subjects. *American Journal of Audiology*, 1, 48-55.

Peterson, N.R., Pisoni, D.B. & Miyamoto, R.T. (2010). Cochlear implant and spoken language processing abilities: Review and assessment of the literature. *Restorative Neurology and Neurosciences,* 28, 237-250.

Ponton, C.W. & Don, M. (1995). The mismatch negativity in cochlear implant users. *Ear and Hearing*, 16, 131-146.

Roman, S., Canévet, G., Marquis, P., Triglia, J-M. & Liégeois-Chauvel, C. (2004). Relationship between auditory perception skills and mismatch negativity recorded in free field in cochlear-implant users. *Hearing Research*, 201, 10-20.

Singh, S., Liasis, A., Rajput, K., Towell, A. & Luxon, L. (2004). Event-related potentials in pediatric cochlear implant patients. *Ear and Hearing*, 25, 598-610.

Tucker, D.M. (1993). Spatial sampling of head electrical fields: the geodesic sensor net. *Electroencephalography and Clinical Neurophysiology,* 87, 154-163.

van Zuijen, T.L., Sussman, E., Winkler, I., Näätänen, R. & Tervaniemi, M. (2005). Auditory organization of sound sequences by a temporal or numerical regularity – a mismatch negativity study comparing musicians and nonmusicians. *Brain Research. Cognitive Brain Research*, 23, 270–276.

Ylinen, S., Shestakova, A., Huotilainen, M., Alku, P. &, Näätänen, R. (2006). Mismatch negativity (MMN) elicited by changes in phoneme length: a crosslinguistic study. *Brain Research*, 1072, 175–185.

Zhang, F., Hammer, T., Banks, H.-L., Benson, C., Xiang, J. & Fu, Q.-J. (2010). Mismatch negativity and adaptation measures of the late auditory evoked potential in cochlear implant users. *Hearing Research*, doi: 10.1016/j.heares.2010.11.007.

Legends

Figure 1: Frequency spectrum of the stimuli. The y-axes represent the sound pressure level (dB SPL).

Figure 2: An example of a waveform from the electrode Fz of one cochlear implant user before and after the application of the ICA filtering.

Figure 3: Average of the waveforms recorded from electrodes AFz, Fz and, FCz for each condition (MMN with deviant /ga/ and with deviant /Ba/) and for each group (A. One poor performer, B. One good performer, C. One from the hearing group). The long dashed line represents 0 ms following the stimulation. The short lines represent the MMN. The black waveforms represent the average of the MMN, the red waveforms represent the average of the standard and the blue waveforms represent the average of the deviant. Negative polarities are down and positive polarities are up. Latency must be considered with an adjustment of -68 msec coming from a computer lag.

Figure 4: Mean latency (A) and (B) amplitude obtained from electrodes AFz, Fz and, FCz for each condition (MMN with deviant /ga/ and with deviant /Ba/) and for each group. The error bars show one standard deviation of the mean.

Table 1: Clinical profile of cochlear implant users

Figure 1.

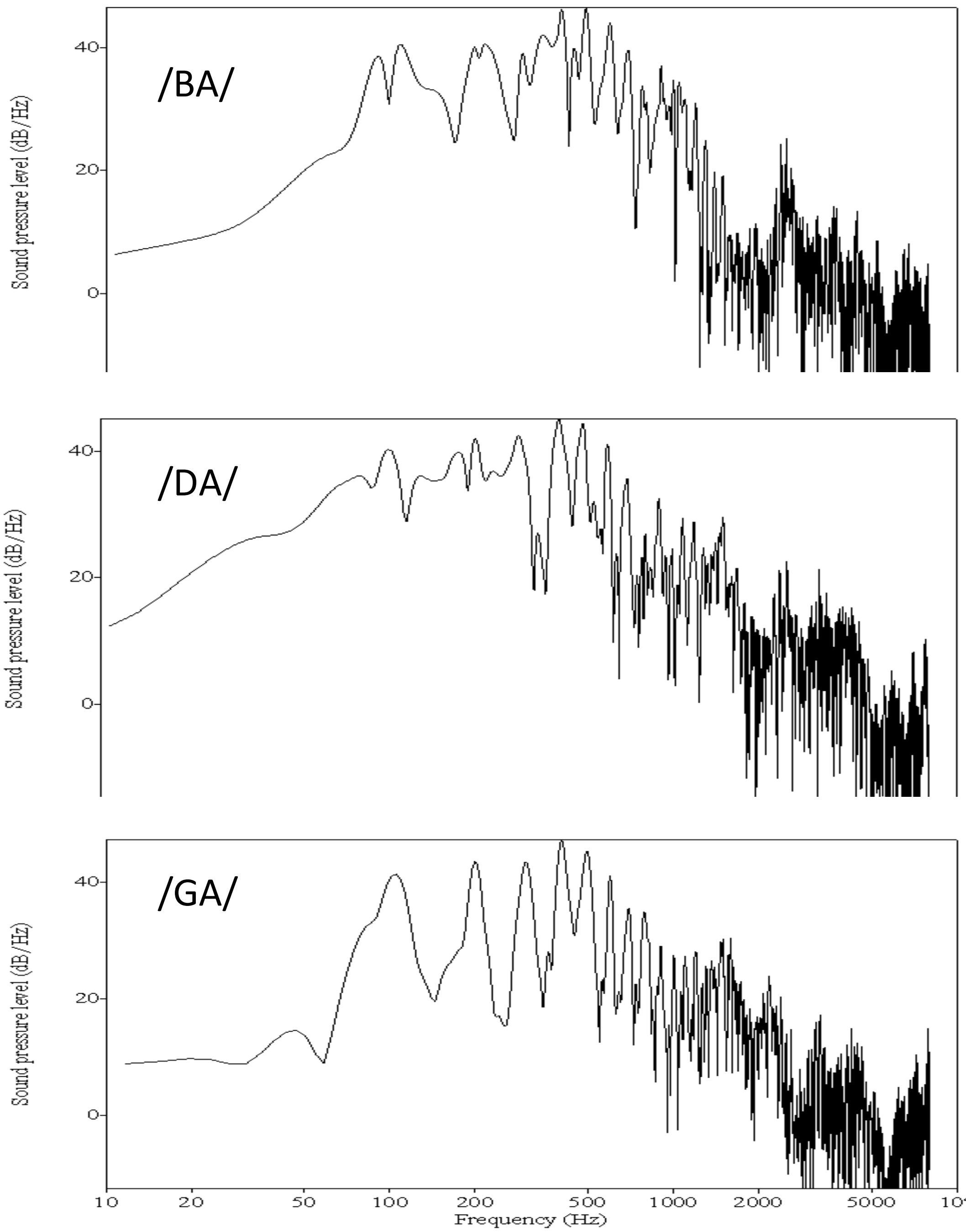
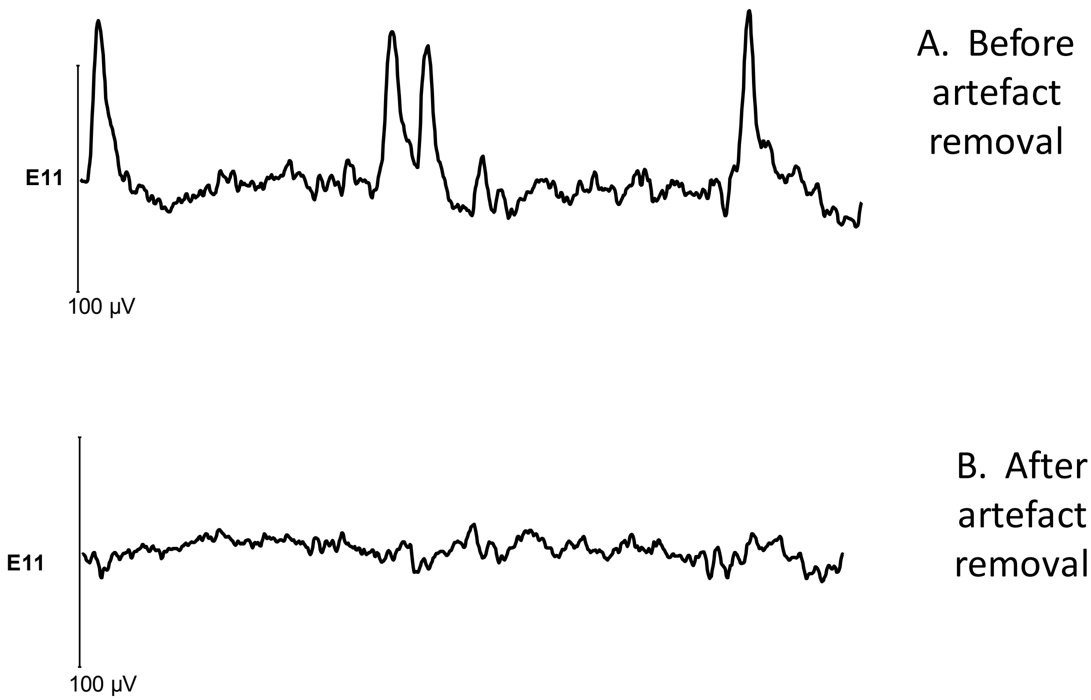

/BA/
/DA/
/GA/
Sound pressure level (dB/Hz)
Sound pressure level (dB/Hz)
Sound pressure level (dB/Hz)
40
20
0
Frequency (Hz)
10
20
50
100
200
500
1000
2000
5000
10^4

Figure 2.



E11
100 µV
A. Before artefact removal
E11
100 µV
B. After artefact removal

Figure 3.

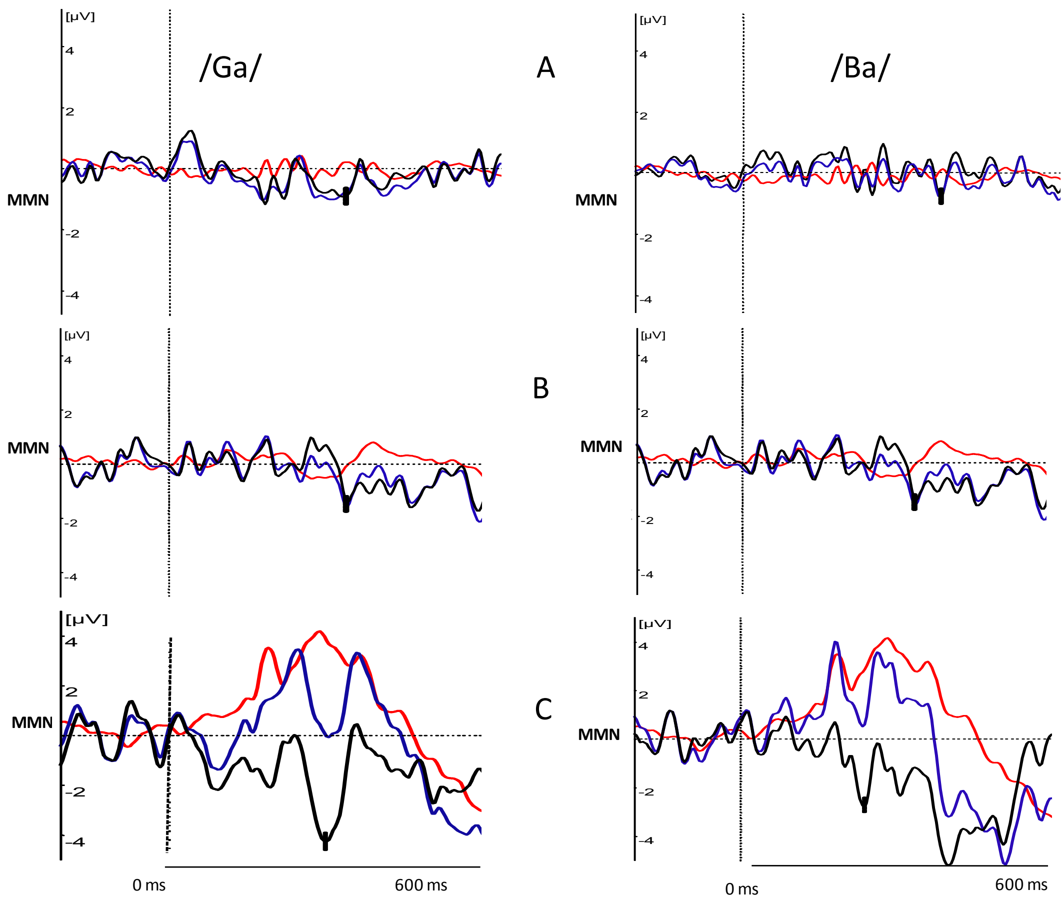


Figure 4.

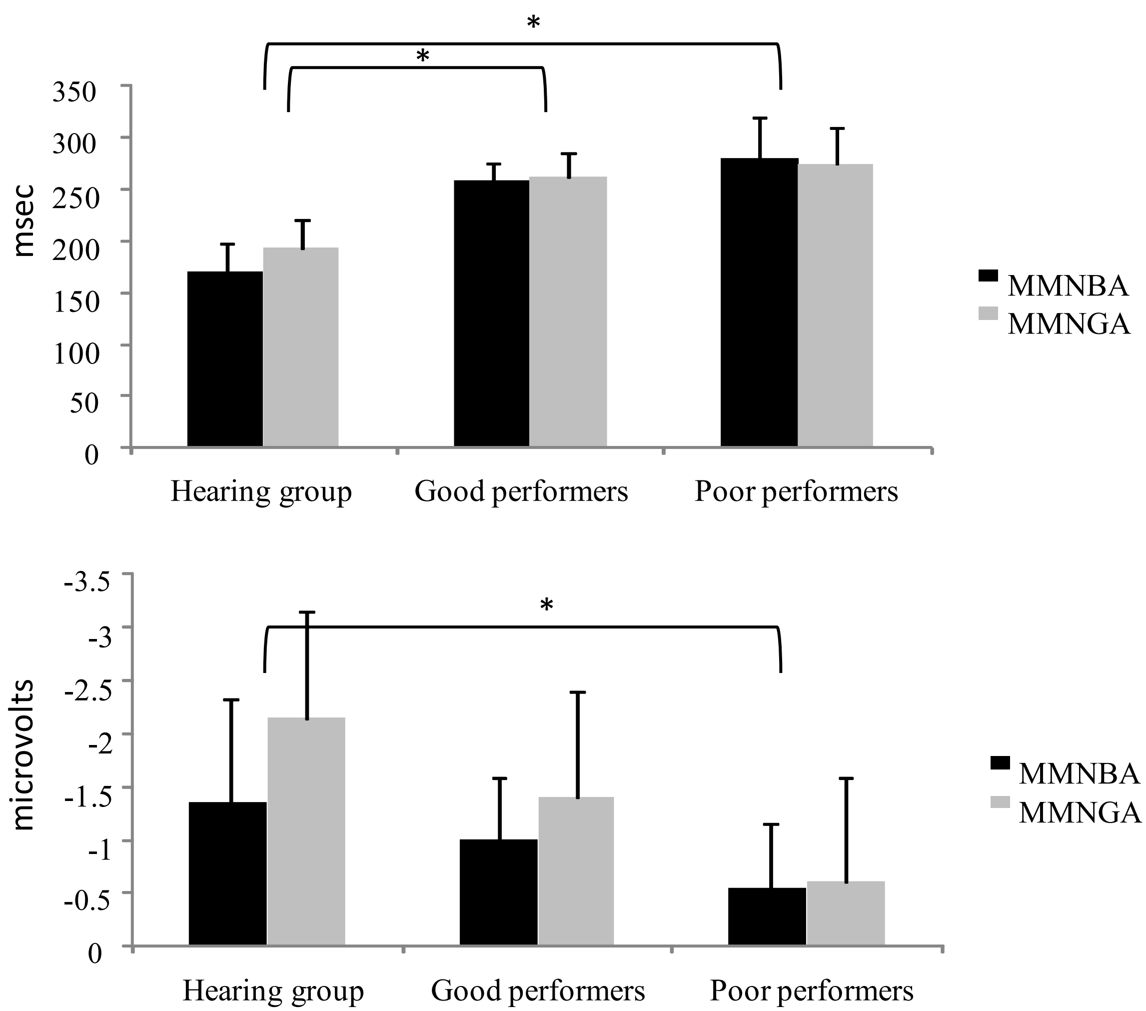

*
*
350
300
250
200
150
100
50
0
msec
Hearing group
Good performers
Poor performers
MMNBA
MMNGA
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
microvolts
*
Hearing group
Good performers
Poor performers
MMNBA
MMNGA

Table 1.

CI	Age at testing (years)	Age at implant (years)	Age at onset of deafness (years)	Etiology of deafness	Implant ear	Open-set speech perception score (%)	Age at amplification with hearing aids‡	Pre-implant hearing thresolds (MPT_R/L)*	Aided thresholds with implant (MPT)**	Number of active electrodes	Type of cochlear implant
1	20	18	Birth	Congential	G	94	1	>110/>110	37	22	Cochlear-Freedom Nucleus
2	46	41	Birth	Congential	G	60	5	95/93	27	14	Advances Bionic-Clarion
3	63	52	16	Unknown	G	70	27	>100/>102	27	16	Advances Bionic-Clarion
4	49	47	10	Unknown	D	38	39	63/63	27	19	Cochlear-Freedom Nucleus
5	58	52	5	Mumps	D	0	17	>110/>110	35	20	Cochlear-Freedom Nucleus
6	67	63	20	Unknown	G	10	20	>110/103	27	22	Cochlear-Freedom Nucleus
7	22	10	8	Unknown	D	0	8	>120/>120	27	6	Neurolec- Saphyr CX
8	61	55	6	Hereditary	G	70	49	>105/>105	27	16	Advances Bionic-Clarion
9	68	60	Birth	Unknown	G	58	15	>120/>120	30	8	Advances Bionic-Clarion
10	48	46	10	Hereditary	G	72	20	118/107	18	16	Advances Bionic-Clarion
11	38	36	2	Hereditary	D	86	29	103/106	27	16	Advances Bionic-Clarion
12	45	41	Birth	Congential	G	8	3	95/103	35	19	Cochlear-Freedom Nucleus
13	34	27	11	Unknown	G	92	12	108/103	32	15	Advances Bionic-Clarion
14	30	28	Birth	Congential	G	66	Ø	93/>100	32	15	Advances Bionic-Clarion
15	35	30	Birth	Congential	G	30	0,8	107/>120	33	16	Advances Bionic-Clarion
16	55	52	7	Ototoxicity	G	88	7	38/97	23	22	Cochlear-Freedom Nucleus
17	27	25	Birth	Congential	G	76	4	107/107	22	22	Cochlear Freedom Nucleus
18	51	44	30	Hereditary	G	64	40	117/68	25	15	Advances Bionic-Clarion
19	42	38	31	Unknown	D	52	30	88/88	22	22	Cochlear Freedom Nucleus
20	39	37	Birth	Congential	D	92	25	101/>120	38	22	Cochlear Freedom Nucleus

‡The age at hearing aid amplification indicates age when the individual first received a hearing aid. They were used mostly binaurally.

* MPT = Mean of pure-tone (500, 1000, 2000 Hz).

**MPT = Mean of pure-tone (500, 1000, 2000 Hz) ; > no measurable response at the limit of the audiometer.

The duration of deafness can be obtained by substracting the onset of deafness of the age at implantion.

Article 4

Turgeon C, Champoux F, Lepore F & Ellemberg D. Reduced visual discrimination in cochlear implant users.

Reduced visual discrimination in cochlear implant users.

Turgeon C[1], Champoux F[1,2], Lepore F[1] & Ellemberg D[1,3]

[1]Centre de Recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Québec, Canada.

[2]Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain/Institut Raymond-Dewar, Université de Montréal, École d'orthophonie et d'audiologie, Montréal, Québec, Canada.

[3]Département de Kinésiologie, Université de Montréal, Montréal, Québec, Canada.

Correspondences should be addressed to:

Dave Ellemberg, Ph.D.
Département de kinésiologie
Université de Montréal
2100 Edouard-Montpetit
Montréal (Quebec) H3T 1C5
Tel: (514) 343-7458 Fax: (514) 343-2115

Abstract

The aim of the study was to investigate the visual frequency discrimination in cochlear implant users. Sinusoidal gratings containing high and low spatial frequencies were presented to a group of normal hearing participants and to a group of deaf participants with cochlear implants. Thresholds for both frequencies indicate that cochlear implant users have poorer spatial frequency discrimination compared to normal hearing participants. Our findings are consistent with the notion that auditory deprivation can alter visual processing.

Introduction

Sensory deprivation can induce extensive brain reorganization. For decades, researchers have shown that these changes, occurring after the deprivation of a sensory modality, can alter performance in the remaining modalities. For example, electrophysiological results show enhanced activation of anterior temporal areas in deaf compared to hearing subjects (Neville & Lawson, 1987; Neville, Schmidt & Kutras, 1983). Imaging data also demonstrate extensive reorganization in temporal cortical regions. Activation in auditory areas is found in congenitally deaf individuals in response to irrelevant visual stimuli such as moving dot patterns or moving sinusoidal gratings (Bavelier et al., 2001; Finney et al., 2001; 2003). Sign language and lip movement stimuli also seem to activate temporal regions in deaf subjects (Nishimura et al., 1999; 2000; MacSweeney et al., 2002; Sadato et al., 2004). Researchers suggest that such extensive brain reorganization might concomitantly lead to behavioural changes in numerous visual tasks. Deaf individuals can have enhanced capabilities for processing visual information in the peripheral visual field compared to the central visual field. They are also faster and more accurate at detecting the direction of moving peripheral visual stimuli (Bosworth & Dobkins, 2002; Neville & Lawson, 1987), they are better at detecting a luminance increment in the periphery (Loke & Song, 1991), and they have enhanced visual attention in periphery compared to hearing individuals (Bavelier et al., 2000; 2001; 2006). In opposition to such enhancements of performance following auditory deprivation, several researchers argue that deafness may lead to a reduction in some visual capabilities. Higher visual temporal thresholds (e.g.

Heming & Brown, 2005) and poorer visual resolution (e.g. Hanson, 1982; Withrow, 1968) are reported in deaf individuals. A theory known as the *theory of deficit* suggests that a lack of a particular sensory stimulation may lead to an abnormal perceptual development (Dye & Bavelier, 2010). This suggests that the auditory system plays a role in the development and maturation of several visual functions.

It is possible to restore hearing in deaf individuals through the surgical implantation of a cochlear implant. This raises the question about how the restoration of the deprived sensory modality affects visual performance. Indeed, if auditory deprivation leads to modifications of several visual processes, one may wonder if the restoration of the auditory modality would also restore visual performance. Few studies have investigated visual abilities in deaf individuals with a cochlear implant. Some findings indicate that children with cochlear implants perform more poorly on visual attention tasks than hearing children of the same age (Horn et al., 2005; Smith et al., 1998; Yucel & Derim, 2008). However, Horn and collegues (2005) suggested that visual attention might improve as auditory experience with the cochlear implant increases. On the other hand, using a change blindness paradigm, Bottari and his collaborators (2008) found that deaf individuals with a cochlear implant were less sensitive to visual changes compared to deaf participants who did not have a cochlear implant. Hence, the aim of the present study is to investigate visual spatial frequency discrimination in deaf individuals with a cochlear implant to assess whether performance is enhanced, unchanged or perturbed. Spatial frequency discrimination represents a critical basic treatment, which allows the analysis of fine details in a visual scene. Investigation of this ability has been chosen because, compare to higher visual ability, less is known on the impact of deafness on low-level visual ability treatment and development.

Materials and Methods

Participants

Sixteen adults with normal hearing (mean age = 26 years) and 20 adults with profound deafness and a cochlear implant (mean age = 36 years) participated in the study. To be included in the study, normal hearing participants were required to pass an audiometric test. Pure-tone detection thresholds were assessed using an adaptive method at 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz. They were assessed independently with intra-auricular earphone for each ear. All participants had detection thresholds below 25 dB HL at every frequency, which corresponds to normal hearing and to what was expected. Middle-ear function was obtained with a Grason-Stadler GSI 38 tympanometer (Milford, MA, USA) and all subjects had normal mobility of the eardrum and normal middle ear function. The second group was composed of cochlear implant users (n = 20) who had a minimum of one year of experience with their implant. All cochlear implant users suffered from severe-profound bilateral hearing loss before their surgery. The majority of them reported progressive hearing loss during their life, until implantation. Nine were congenitally deaf (i.e., early onset deafness) and 11 were between 2 and 20 years age (mean age = 9 years) at the time of deafness (i.e., late onset deafness). All participants used oral language as a primary mode of communication. Pure-tone detection thresholds with the cochlear implant were also assessed using an adaptive method at 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz in free field at a distance of 1 meter. This group presented detection thresholds that were generally above 40 dB HL for all frequencies tested ranged, corresponding to what is generally reported in the literature (Peterson et al., 2010). Speech recognition was evaluated with a list of 50 phonetically balanced French words. This speech assessment was an open-set test in which monosyllabic words were presented without any visual cues at a level of 70 dB HL. Participants had to verbally repeat what they heard. The dependent variable was the percentage of words correctly repeated. The clinical profile of each cochlear implant user is presented in Table 1. As indicated in the table, all but two participants in each group used hearing aids before implantation. None of the participants had learning disabilities or other known medical conditions. The subjects all had normal or corrected-to-normal vision as determined with the Snellen eye chart (model R.J.'s) at a distance of 10 feet. All participants were unaware of the nature of the experiment and they gave written informed consent in accordance with the University of Montreal Ethics Board. Recruitment was made possible with the participation of the Centre de Recherche Interdisciplinaire en Réadaptation du Montréal Métropolitain/Institut Raymond-Dewar (IRD) and the Centre de Réadaptation en Déficience Physique Le Bouclier.

Stimuli and procedure

The stimuli were luminance modulated Gabors (i.e., a sine wave grating multiplied by a Gaussian) with a spatial frequency of 1 or 5 cycles per degree and a 50ms cosine rise-fall time. The stimuli had a width and height of 4 degrees when viewed from a distance of 60cm. They were generated by Psychinematik software (version 1.0.0) and a Mactintosh 0S X (version 10.5.5) computer. The stimuli were displayed using a linearized lookup table (generated by calibrating with a Colour Vision Spyder 2 Pro) and were presented on a 19-inch View Sonic G90*f*B CRT. Maximum luminance was 100 cd/m^2, frame refresh rate was 85Hz, and the resolution was 1024 × 768 pixels.

Frequency discrimination thresholds for each visual condition (low and high frequencies) were determined using an adaptive two-alternative forced choice (2AFC) procedure. Each trial consisted of two luminance modulated sine wave Gabor gratings separated by a 500ms inter-stimulus interval, with one always corresponding to the reference frequency and the other being the probe frequency. The stimuli were presented at a suprathreshold contrast of 50%. All experiments took place in a dimly lit room where each participant was tested in a single session of about 40 minutes. Each experiment was preceded by a training phase to ensure that the participant understood the instructions. The participants were asked to report whether the two stimuli were identical or different. Participants reported their response by pressing on the appropriate key of a conventional keyboard disposed in front of them. The first presentation of a probe frequency was 4 cycles per degree above the spatial frequency of the reference grating. Step size was subsequently adjusted according to Levitt's (1971) transformed up-down staircase technique using a 2-down 1-up decision rule. 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 and subjects were not allowed to see a stimulus-pair twice. A subsequent pair would not be presented before user response had been 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. Each experimental condition was preceded by a familiarisation protocol during which the task was explained and the stimuli were presented.

Results

Spatial frequency discrimination thresholds for normally hearing and cochlear implant users are shown in Figure 1. A 2-way analysis of variance (ANOVA) with group (controls, cochlear implant users) and visual condition (1 cycle per degree, 5 cycles per degree) as a within-subjects factor was conducted. Within-subject effects are reported according to Greenhouse-Geisser's correction. The analyses show a significant interaction ($F(2,33) = 4.23$, $p = 0.023$), a main effect of frequency ($F(2,33) = 24.66$, $p = 0.001$), and a main effect of group ($F(2,33) = 21.62$, $p < 0.001$). Post-hoc analyses on the main effect of group, revealed significant differences between groups both for the lower ($t = 4.410$, $P = 0.001$) and the higher spatial frequency gratings ($t = 6.472$, $p = 0.001$).

We also decided to verify if the onset of deafness had an impact on the results. To do so, another 2-way analysis of variance (ANOVA) with group (congenitally deaf and late onset deafness) and visual condition (1 cycle per degree, 5 cycles per degree) as a within-subjects factor was conducted. The analyses did not show significant interaction ($P < 0.05$) and no effect of group but a main effect of frequency ($F = 22.36$, $p<0.001$) which was not analysed further.

We also decided to measure if there were any correlation between the visual performance and different variables, which may explain the results. To do so, we conducted different correlations. No significant correlations were found ($p>0.05$) between the visual performance and the *i*) age at testing, *ii*) duration of deafness, *iii*) age at the hearing loss, *iv*) the length of experience with the implant, *v*) the auditory thresholds with the cochlear implant ($p>0.05$), or *vi*) speech discrimination performance while using the implant.

Discussion

The purpose of the present study was to examine spatial frequency discrimination in cochlear implant users compared to normal hearing adults. Our results indicate that cochlear implant users have significantly higher visual frequency discrimination thresholds compared to normal hearing participants, especially for higher spatial frequencies. We conclude that auditory deprivation, coupled with experience using a cochlear implant, can lead to a substantive reduction in visual sensitivity, at least for low-level visual processing such as spatial frequency discrimination.

The vast majority of studies on the effects of deafness on visual processing suggest that deafness results in an enhancement in perceptual abilities when higher-level visuocognitive or peripheral tasks are performed (Bavelier et al., 2000; 2001; Bosworth & Dobkins, 2002; Loke & Song, 1991; Neville & Lawson, 1987). In opposition, other studies report perceptual deficits in deaf individuals compared to hearing controls for lower-level visual tasks (Hanson, 1982; Herming & Brown, 2005; Withrow, 1968). Our results support the notion that auditory deprivation alters low-level visual processes, given that visual discrimination is impaired in deaf participants with a cochlear implant.

A clear visual deficit was found in the cochlear implanted group, regardless of the characteristics of the hearing loss, such as age of onset, duration of deafness or length of implant use. It could be argued that cochlear implant users with the shortest period of sensory deprivation would have a better visual performance given that a brief period of auditory deprivation would lead to reduced cross-modal reorganization and thus, smaller behavioural changes (see Lee et al., 2001; 2007; Doucet et al., 2006; Champoux et al., 2009). The present findings, however, do not confirm this hypothesis. However, several factors could have led to these results. First, the clinical profiles were very similar among individuals. Globally, all subjects had an important period of complete or progressive hearing loss (mean in the early deafness group: 28.6 years; mean in the late onset deafness group: 22.5 years) before acquiring a cochlear implant. This extensive period of auditory deprivation might have a great influence on brain reorganization, explaining the poor visual performance in both early and late onset deaf participants.

It is also important to note that only one participant developed a profound hearing loss in adulthood; all other cochlear implant users were younger than 12 years of age at the time of the sensory loss. Given that the auditory system is not entirely mature at that age (see Bellis, 2003), it could be argued that more extensive reorganization might have occurred in our participants. The various factors triggering brain reorganization, including the age at the moment of the deafness and the duration of deafness need to be investigated further.

A visual deficit in the temporal domain could also explain, at least in part, the present results. Indeed, deaf individuals have significantly higher visual temporal thresholds compare to hearing controls (Heming & Brown, 2005; Hanson, 1982; Withrow, 1968). In the present study, the stimuli were presented relatively rapidly (500ms interstimulus gap). It could thus be argued that a longer gap could have lead to different results. Another explanation is that deficits in visual attention (Horn et al., 2005; Smith et al., 1998; Yucel & Derim, 2008) could be responsible for poorer visual discrimination.

The exact nature of the deficit in visual performance certainly needs to be clarified. Irrespective of the reasons, the current findings support the notion that the auditory modality is essential for the normal development of at least some of the mechanisms underlying visual processing.

Acknowledgements

This work was supported by grants from the CFI, CIHR and the NSERC to DE and grants from CIHR and NSERC to FL. We also wish to thank all of the participants for their time and their precious collaboration.

References

Bavelier, D., Tommann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G. & Neville, H. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neurosciences*, 1, 93.

Bavelier, D., Brozinsky, C., Tomman, A., Mitchell, T., Neville, H. & Liu, G. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *Journal of Neurosciences*, 21, 8931-8942.

Bavelier, D., Dye, M.W.G. & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitives Sciences,* 10, 512-518.

Bellis, T.J. (2003). Assessment and management of central auditory processing disorders in the educational setting: from science to practice. Singular, New York.

Bosworth, R.G. & Dobkins K.R. (2002). Visual field asymmetries for motion processing in deaf and hearing signers. *Brain and Cognition*, 49, 170-181.

Bottari, D., Nava, E., Ley, P. & Pavani, F. (2010). Enhances reactivity to visual stimuli in deafs individuals. *Restorative Neurology and Neuroscience*, 28, 167-179.

Buckley, K.A. & Tobey, E.A. (2011). Cross-Modal plasticity and speech perception in pre- and postlingually deaf cochlear implant users. *Ear and Hearing*, 32, 2-15.

Champoux, F., Lepore, F., Gagné, J.-P. & Théoret, H. (2009). Visual stimuli can impair auditory processing in cochlear implants users. *Neuropsychologia*, 47, 17-22.

Doucet, M.E., Bergeron, F., Lassonde, M., Ferron, P. & Lepore, F. (2006). Cross-modal reorganization and speech perception in cochlear implant users. *Brain*, 129, 3376-3383.

Dye, M. & Bavelier, D. (2010). Attentional enhancements and deficits in deaf populations: An integrative review. *Restorative Neurology and Neuroscience,* 28, 181–192.

Finney, E.M., Clementz, B.A., Hickok, G. & Dobkins, K.R. (2003). Visual stimuli activate auditory cortex in the deaf subjects: evidence from MEG. *Neuroreport*, 14, 1425-1427.

Finney, E.M., Fine, I. & Dodbkins, K.R. (2001). Visual stimuli activate auditory cortex in the deaf. *Nature Neurosciences*, 4, 1171-1173.

Hanson, V.L. (1982). Short-term recall by deaf signers of American Sign Language: Implication of encoding strategy for order recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 8, 572-583.

Heming, J.E. & Brown, L.N. (2005). Sensory temporal processing in adults with early hearing loss. *Brain and Cognition*, 59, 173-82.

Horn, D.L., Davis, R.A., Pisoni, D.B. & Miyamoto, R.T. (2005). Development of visual attention skills in prelingually deaf children who use cochlear implants. *Ear and Hearing, 26*, 389-408.

Lee, D. S., Lee, J. S., Oh, S. H., Kim, S. K., Kim, J. W., Chung, J. K., et al. (2001). Cross-modal plasticity and cochlear implants. *Nature*, 409, 149-150.

Lee, H. J., Giraud, A. L., Kang, E., Oh, S. H., Kang, H., Kim, C. S. & Lee, D. S. (2007). Cortical activity at rest predicts cochlear implantation outcome. *Cerebral Cortex*, 17, 909-917.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America*, 49. Suppl 2,467.

Loke, W.H. & Song, S. (1991). Central and peripheral visual processing in hearing and nonhearing individuals. *Bulletin of the Psychonomic Society*, 29, 437-440.

MacSweeney, M., Woll, B., Campbell, R., Calvert, G. A., McGuire, P. K., David, A. S., Simmons, A. & Brammer, M. J. (2002). Neural correlates of British sign language comprehension: spatial processing demands of topographic language. *Journal of Cognitive Neurosciences*, 14, 1064-1075.

Neville, H.J. & Lawsom, D. (1987). Attention to central and peripheral visual space in a movement detection task: an event-related potential and behavioural study. II. Congenitally deaf adults. *Brain Research*, 405, 284-294.

Neville, H. J., Schmidt, A & Kutras, M. (1983). Altered vision-evoked potentials in congenitally deaf adults. *Brain Research*, 266, 127-132.

Nishimura, H., Hashikawa, K., Doi, K., Iwaki, T., Watanabe, Y., Kusuoka, H., Nishimura, T. & Kubo, T. (1999). Sign language 'heard' in the auditory cortex. *Nature*, 397, 116.

Nishimura, H., Doi, K., Iwaki, T., Hashikawa, K., Nishimura, T. & Kubo, T. (2000). Sign language activated the auditory cortex of a congenitally deaf subject: revealed by positron emission tomography. *Advances in Oto-Rhino-Laryngol*ogy, 57, 60-62.

Sadato, N., Okada, T., Honda, M., Matsuki, K., Yoshida, M., et al. (2004) Cross-modal integration and plastic changes revealed by lip movement, random-dot motion and sign languages in the hearing and deaf. *Cerebral Cortex*, 15, 1113-1122.

Smith, L.B., Quittner, A.L., Osberger, M.J. & Miyamoto, R. (1998). Audition and visual attention: the developmental trajectory in deaf and hearing populations. *Developmental Psychology*, 34, 840-85.

Withrow, R. (1968). Immediate memory span of deaf and normally hearing children. *Exceptional Children,* 35, 33-41.

Yucel, E. & Derim, D. (2008). The effect of implantation age on visual attention skills. *International Journal of Pediatric Otorhinolaryngology*, 72, 869-877.

Legends

Figure 1: Spatial frequency discrimination thresholds and standard deviations for the control (white bar) and cochlear implant (black bar) group for the low (left panel) and the high (right panel) frequency discrimination conditions. An example of a low and a higher stimulus are presented above each panel.

Table 1: Clinical profile of cochlear implant users

Figure 1.

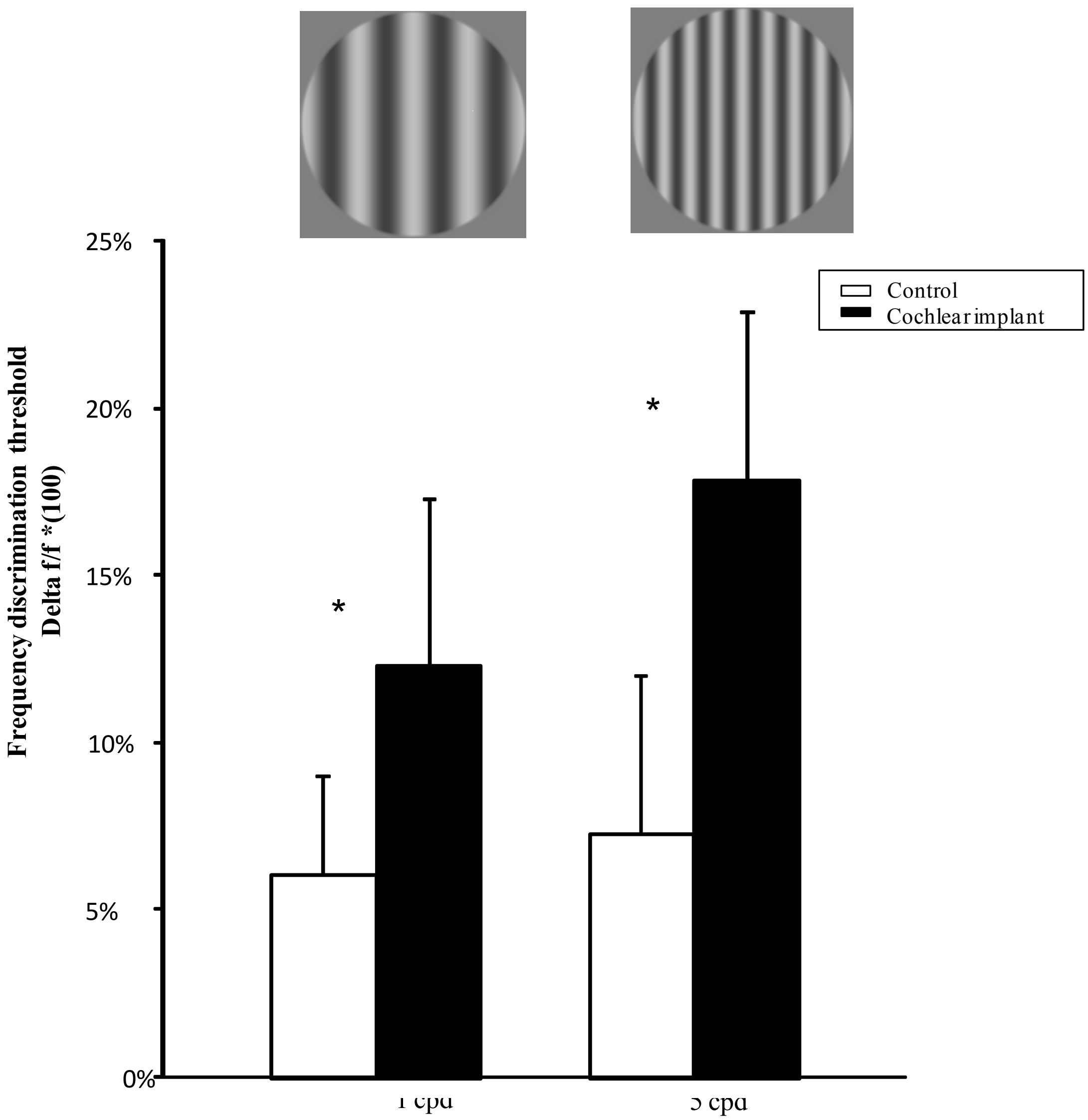

25%
20%
15%
10%
5%
0%
Frequency discrimination threshold
Delta f/f *(100)
Control
Cochlear implant
*
*
1 cpd
5 cpd

Table 1.

CI	Age at testing (years)	Age at implant (years)	Age at onset of deafness (years)	Etiology of deafness	Implant ear	Open-set speech perception score (%)	Age at amplification with hearing aids‡	Pre-implant hearing thresolds (MPT_R/L)*	Aided thresholds with implant (MPT)**	Type of cochlear implant
1	20	18	Birth	Congential	G	94	1	>110/>110	37	Cochlear-Freedom Nucleus
2	46	41	Birth	Congential	G	60	5	95/93	27	Advances Bionic-Clarion
3	63	52	16	Unknown	G	70	27	>100/>102	27	Advances Bionic-Clarion
4	49	47	10	Unknown	D	38	39	63/63	27	Cochlear-Freedom Nucleus
5	58	52	5	Mumps	D	0	17	>110/>110	35	Cochlear-Freedom Nucleus
6	67	63	20	Unknown	G	10	20	>110/103	27	Cochlear-Freedom Nucleus
7	22	10	8	Unknown	D	0	8	>120/>120	27	Neurolec- Saphyr CX
8	61	55	6	Hereditary	G	70	49	>105/>105	27	Advances Bionic-Clarion
9	68	60	Birth	Unknown	G	58	15	>120/>120	30	Advances Bionic-Clarion
10	48	46	10	Hereditary	G	72	20	118/107	18	Advances Bionic-Clarion
11	38	36	2	Hereditary	D	86	29	103/106	27	Advances Bionic-Clarion
12	45	41	Birth	Congential	G	8	3	95/103	35	Cochlear-Freedom Nucleus
13	34	27	11	Unknown	G	92	12	108/103	32	Advances Bionic-Clarion
14	30	28	Birth	Congential	G	66	Ø	93/>100	32	Advances Bionic-Clarion
15	35	30	Birth	Congential	G	30	0,8	107/>120	33	Advances Bionic-Clarion
16	55	52	7	Ototoxicity	G	88	7	38/97	23	Cochlear-Freedom Nucleus
17	27	25	Birth	Congential	G	76	4	107/107	22	Cochlear Freedom Nucleus
18	51	44	30	Hereditary	G	64	40	117/68	25	Advances Bionic-Clarion
19	42	38	31	Unknown	D	52	30	88/88	22	Cochlear Freedom Nucleus
20	39	37	Birth	Congential	D	92	25	101/>120	38	Cochlear Freedom Nucleus

‡The age at hearing aid amplification indicates age when the individual first received a hearing aid. They were used mostly binaurally.

* MPT = Mean of pure-tone (500, 1000, 2000 Hz).

**MPT = Mean of pure-tone (500, 1000, 2000 Hz) ; > no measurable response at the limit of the audiometer.

The duration of deafness can be obtained by substracting the onset of deafness of the age at implantion.

Chapitre III. Discussion

Cette thèse a comme premier objectif de mieux comprendre les processus sensoriels auditif et visuel de bas niveau afin d'explorer les possibles liens de leurs développements respectifs. Cette thèse vise aussi l'étude des processus de discrimination auditive chez une population sourde porteuse d'un implant cochléaire. Au moyen d'une tâche auditive comportementale et d'une mesure électrophysiologique, nous visons d'une part, à mieux comprendre l'impact de la privation auditive sur le développement de la discrimination auditive et, d'autre part, à investiguer le lien entre les résultats de discrimination et les performances langagières. Finalement, afin d'obtenir plus d'information sur les processus de réorganisation cérébrale lors de privation auditive, l'étude du développement de la discrimination visuelle a aussi été menée chez une population porteuses d'un implant cochléaire.

Les développements auditif et visuel normaux

L'évaluation des habiletés de détection et de discrimination fréquentielle auditive et visuelle chez une population d'enfants de six, huit et dix ans et chez une population adulte a révélé une augmentation générale de la sensibilité avec l'âge. Les résultats obtenus suggèrent que la détection mature plus rapidement et atteint la maturité plus tôt dans la modalité auditive, mais que les habiletés de discrimination fréquentielle sont matures plus tôt dans la modalité visuelle que dans la modalité auditive. Le but principal de cette première étude étant de comparer le développement en parallèle des habiletés de bas niveau en modalités auditive et visuelle, l'utilisation d'un paradigme méthodologique similaire s'avérait nécessaire. Ainsi, l'utilisation d'une mesure psychophysique utilisant une méthode adaptative, la méthode de Levitt (1971), et présentant toujours deux choix de réponses fermées a été utilisée pour chacune des quatre expérimentations, soit 1) la détection auditive, 2) la détection visuelle, 3) la discrimination fréquentielle auditive et 4) la discrimination fréquentielle visuelle. Par ailleurs, les stimuli ont été créés afin qu'ils soient le plus comparables possible. Des sons purs ainsi que des fréquences spatiales simples de type Gabor ont été utilisés pour toutes les expérimentations. La durée, le temps d'attaque et de relâche des stimuli étaient aussi similaires dans les deux modalités. Des stimuli de basses et de hautes fréquences ont été utilisés pour la mesure de la détection auditive (500 Hz et 4000 Hz) ainsi que pour la détection visuelle (1 cycle/degré et 5 cycles/degré). Les mêmes stimuli ont été utilisés pour les tâches de discrimination fréquentielle. Finalement, afin de rendre la comparaison entre la modalité auditive et visuelle la plus similaire possible, les stimuli auditifs ont été présentés via un haut-parleur situé devant le participant plutôt que sous écouteurs. La présentation visuelle effectuée sur écran engendre une stimulation binoculaire, et similairement en audition, une stimulation en champ libre permet une stimulation binaurale. Par ailleurs, en audition, ce type de présentation permet une stimulation binaurale plus écologique, en gardant l'effet d'amplification naturelle du pavillon et de la conque.

La détection auditive et visuelle

Les résultats de la première étude montrent que la détection auditive est mature à l'âge de six ans pour la plus basse (500Hz) et à huit ans pour la plus haute fréquence (4000Hz). Dans la modalité visuelle, la détection est encore immature à l'âge de dix ans pour la basse fréquence (1 cycle/degré) et est mature à huit ans pour la haute fréquence (5 cycles/degré). Différentes particularités ressortent de ces résultats. D'une part, pour les basses fréquences, la maturité est atteinte d'abord en audition, puis en vision. Pour les plus hautes fréquences, la maturité est atteinte à l'âge de huit ans pour les deux modalités. D'autre part, pour la modalité auditive, c'est d'abord la plus basse fréquence qui atteint maturité contrairement à la détection visuelle qui atteint d'abord la maturité en plus haute fréquence.

En modalité auditive, ces résultats concordent avec ceux d'autres études ayant montré une augmentation de la sensibilité avec l'âge. Par exemple, Schneider et al. (1986) soutiennent que cette habileté n'est pas encore mature à l'âge de 5 ans. Elliot & Katz (1980) ont montré que chez les adultes et des enfants de dix ans, les seuils sont diminués comparativement à une population d'enfants de six ans. Évaluant différents groupes d'âge, d'autres chercheurs sont aussi parvenus à des conclusions convergentes, dont Maxon et Hochberg (1982), qui ont montré une diminution des seuils avec l'âge chez des enfants de quatre à douze ans ainsi que chez des adultes. Roche et al. (1978) ont aussi noté une meilleure sensibilité chez un groupe d'adolescents de 12-17 ans comparativement à un groupe d'enfants de 6-11 ans.

Bien que les structures essentielles au fonctionnement de l'oreille interne soient comparables à l'adulte vers la fin du cinquième mois de gestation (Wedenberg, 1965), les études montrent que le développement de l'oreille externe se poursuit au-delà de la naissance et que ces changements structuraux ont un impact sur la maturation de la sensibilité auditive chez les enfants (Bernstein & Kruger, 1986; Feigin, Kopun, Stelmachowicz & Gorga, 1989, Keefe, Bulen, Campbell & Burns, 1994). Il n'y a cependant pas de consensus quant à la limite d'âge à partir duquel la maturation du canal auditif externe cesse d'influencer la détection. Certains auteurs proposent qu'après l'âge de 5 ans, l'impact développemental est négligeable sur la détection auditive (Bagatto, Scollie, Seewald, Moodie & Hoover, 2002; Keefe et al., 1994). D'autres suggèrent plutôt que la résonnance du conduit auditif externe pourrait continuer d'influencer la détection jusqu'à environ 8 ans et même au-delà (Feigin et al., 1989). L'agrandissement du canal auditif externe augmente la cavité de résonnance et engendre ainsi une meilleure sensibilité en basses fréquences (Schneider et al., 1985). Nos données suggèrent que la maturité est atteinte à 6 ans à 500 Hz, mais qu'elle ne l'est toujours pas à 4000 Hz. Ces résultats suggèrent que l'amélioration notée serait surtout induite par une amélioration des processus neuronaux plutôt que par l'agrandissement de la cavité du canal externe.

En comparaison, dans la modalité visuelle, les résultats de la détection visuelle ont montré que cette habileté est encore immature à dix ans en basse fréquence (1cycle/degré) et que la maturité est atteinte plus tôt en haute fréquence (5c ycles/degré), soit à l'âge de huit ans. Les résultats vont dans le même sens que ceux d'autres études développementales. Ellemberg et al. (1999) ont rapporté une sensibilité mature à sept ans, Bradley & Freeman (1982) ont révélé une augmentation de la sensibilité allant jusqu'à l'âge de huit ans, et

Gwiazda et al. (1997) ont plutôt suggéré que la maturité n'était pas encore atteinte à huit ans. Certaines autres études suggèrent aussi que la maturité serait atteinte plus tard, tel qu'Adams & Courage (2002) qui observent une sensibilité comparable aux adultes chez des enfants de neuf ans et Benedek, Keri & Janaky, (2003) qui ont obtenu des résultats indiquant la maturité chez des enfants de 11-12 ans.

La discrimination fréquentielle

En ce qui concerne les habiletés de discrimination fréquentielle, les résultats montrent une maturité atteinte un peu plus précocement en vision qu'en audition. Spécifiquement, pour la plus basse fréquence, la discrimination fréquentielle est encore immature à l'âge de dix ans dans la modalité auditive, et elle devient mature à l'âge de huit ans pour la plus haute fréquence. Dans la modalité visuelle, la maturité est atteinte en haute comme en basse fréquence à l'âge de dix ans. Différentes particularités ressortent de ces résultats. D'une part, pour les basses fréquences, la maturité est atteinte d'abord en vision, puis en audition; pour les plus hautes fréquences, la maturité est atteinte d'abord en audition, puis en vision. D'autre part, à l'âge de six ans, l'immaturité est beaucoup plus importante pour les basses fréquences comparativement aux hautes fréquences.

Dans le domaine auditif, nos résultats concordent avec ceux d'autres études qui ont montré que la discrimination fréquentielle atteint la maturité entre six et douze ans et qui suggèrent que pour un stimulus de référence de 1000Hz, une différence minimale d'environ

2% entre deux fréquences est nécessaire pour la perception d'une différence (Halliday et al., 2008; Jensen & Neff, 1993; Maxon & Hochberg, 1982; Plack, Oxenham, Fay & Popper, 2005; Thompson et al., 1999). Dans le domaine visuel, nos résultats concordent avec ceux de Moore et al. (2008) qui ont montré que chez un groupe d'enfants de 10-11 ans, la discrimination était meilleure que chez des groupes d'enfants de 6-7 et de 8-9 ans. De plus, les résultats chez l'adulte concordent avec ceux qui ont été obtenus par d'autres études, montrant qu'une différence entre deux fréquences spatiales de 2-11 % est nécessaire pour la perception d'une différence entre les stimuli, pour un stimulus de référence de 0,5 cycle/degré (Hirsh & Hylton, 1982; Mayer & Kim, 1986). Nos résultats, montrant une différence de 7% et 8% en basse et haute fréquence respectivement, concordent avec ceux des études précédentes.

Une comparaison entre les processus de détection et de discrimination fréquentielle montre qu'en modalité auditive, la discrimination fréquentielle mature plus lentement que la détection. Ces résultats ne sont pas surprenants, sachant que la discrimination fréquentielle est un processus plus complexe et hiérarchiquement plus avancé dans le système auditif, demandant ainsi plus de temps avant d'atteindre maturité. Dans le domaine visuel, un patron de réponse différent et quelque peu inattendu fut obtenu. Pour les plus hautes fréquences, les résultats suggèrent que la détection mature plus vite que la discrimination fréquentielle. Cependant pour les plus basses fréquences, les résultats suggèrent que la maturité pour la discrimination fréquentielle est atteinte à l'âge de dix ans, mais au même âge, la maturité n'est pas encore atteinte pour la détection. Une immaturité encore présente dans le traitement de stimuli présentés tout juste au-dessus du seuil pourrait expliquer ces résultats.

Malgré le fait que le traitement hiérarchique soit comparable entre les deux modalités sensorielles et qu'il ait été suggéré qu'elles semblent dépendre de mécanismes similaires (Barlow & Mollon, 1982; Stein, 2001), les rythmes développementaux des habiletés évaluées dans cette étude sont différents et propres à chaque système. Par ailleurs, ces habiletés atteignent la maturité à des âges différents. L'étude de Droit-Volet et al., (2004), ayant auparavant comparé le développement des habiletés temporelles auditive et visuelle, a aussi montré que le rythme développemental variait d'une modalité à une autre. A l'âge de cinq ans, dans l'identification de la durée des stimuli, les performances des enfants étaient meilleures en modalité auditive qu'en modalité visuelle. La maturité était atteinte à huit ans pour les deux modalités. Cette dernière étude appui aussi l'idée voulant que les rythmes de développement soient différents d'une modalité à une autre et d'une habileté particulière à une autre. Bien que la perception dépende de l'intégration et de l'interaction de l'information auditive et visuelle et que les deux systèmes présentent des processus hiérarchiques similaires (Barlow & Mollon, 1982; Hockfield & Sur, 1990; Stein, 2001), les diverses habiletés auditive et visuelle demeurent indépendantes quant à leur développement. Cela suggère que ces deux systèmes semblent reposer sur des mécanismes et sur des structures distincts, qui atteignent leurs maturités respectifs à des âges différents.

La discrimination auditive chez une population malentendante porteuse d'un implant cochléaire

Comme deuxième objectif, cette thèse visait l'étude des processus de discrimination chez une population porteuse d'un implant cochléaire. L'utilisation d'une tâche comportementale et électrophysiologique a été retenue afin d'obtenir une mesure de la discrimination auditive. La pertinence de l'électrophysiologie repose sur ces caractéristiques particulières, en ce sens qu'elle est obtenue de façon pré-attentionnelle et automatique, sans nécessiter l'implication active du participant, évitant ainsi le biais possible induit par un manque de concentration ou par la fatigue. En premier lieu, le but était de mesurer l'effet de la privation auditive sur le développement de la discrimination auditive et de voir des indications d'un lien existant entre la durée de la surdité et/ou la durée de l'expérience avec l'implant et les performances obtenues. En deuxième lieu, l'étude d'une possible relation entre les performances de discrimination et celles de la perception de la parole était visée. Une telle indication mettrait à jour un lien entre les processus de bas niveau, tels que la discrimination auditive, et les processus de reconnaissance de la parole. Cette relation pourrait être fort utile dans le domaine de l'évaluation auditive et en réadaptation.

Étude comportementale de la discrimination fréquentielle auditive chez une population avec implant cochléaire

La deuxième étude avait pour objectifs l'évaluation de l'impact d'une privation auditive sur le développement de la discrimination fréquentielle et l'évaluation du lien entre cette habileté et les performances de reconnaissance de la parole. Ce possible lien pourrait contribuer à expliquer la disparité des performances de reconnaissance de la parole chez la population porteuse d'un implant cochléaire.

Sur la base d'un test de perception de la parole, les participants ont été séparés en trois groupes : 1) les individus entendants, 2) les individus porteurs d'implant cochléaire et ayant obtenu de bons résultats au test de reconnaissance de la parole et 3) les individus porteurs d'implant cochléaire et ayant montré de moins bonnes performances langagières. Le test de reconnaissance de la parole utilisé évaluait la perception, à niveau confortable, de mots monosyllabiques dans le silence. Cette mesure permet une évaluation auditive sans implication syntaxique et sémantique (Shafiro, Gygi, Cheng, Vachhani & Mulvey, 2011). La mesure de performance langagière aurait pu être plus robuste si d'autres tests de perception de la parole avaient été ajoutés à cette unique mesure. En effet, un test de perception de phrases dans le silence et dans le bruit, tel que le HINT (version française) (Vaillancourt et al., 2005), aurait permis une mesure langagière d'un niveau linguistique plus élevé tout en évaluant aussi l'habileté d'écoute dans le bruit (Shafiro et al., 2011). Considérant que la majorité des participants porteurs d'un implant ont participé à trois études incluses dans cette thèse, l'évaluation de leurs performances langagières a généralement été faite à deux reprises, à environ 1 an d'intervalle; les deux études comportementales effectuées dans un premier temps et l'étude électrophysiologique effectuée dans un deuxième temps. L'ajout d'un deuxième test d'évaluation de la perception de la parole aurait rendu la mesure vraisemblablement plus stable. Cette variabilité pourrait contribuer à expliquer que deux participants font partie du groupe des porteurs d'implant performants dans une étude et des non-performants dans l'autre étude.

Le seuil de discrimination fréquentielle, lequel représente la différence minimale nécessaire entre deux stimuli pour les différencier, a été évalué en basse fréquence (500Hz) et en plus haute fréquence (4000Hz). Les résultats, pour le seuil en plus basse fréquence, ont montré une performance presque similaire entre les individus porteurs d'un implant cochléaire et présentant de bonnes performances langagières (8%) et les personnes entendantes (4%). Par contre, les individus porteurs d'un implant cochléaire et présentant de moins bonnes performances au test de reconnaissance de la parole présentaient un seuil de 25%. Comparativement, la performance en plus haute fréquence a montré une légère différence entre les individus porteurs d'un implant et présentant de bonnes performances au test de parole (7%) et les personnes entendantes (1%) et une différence plus marquée chez les individus porteurs d'un implant et présentant de moins bonnes performances au test de reconnaissance de la parole (20%). Toutefois, chez les individus entendants, tout comme chez la population ayant un implant cochléaire, les performances entre les conditions en basse et plus haute fréquences sont relativement semblables.

Il semble ainsi possible, via la restauration de l'audition par un implant cochléaire, d'atteindre des performances de discrimination fréquentielle relativement comparables à celles des personnes entendantes. Lors d'audition normale, la perception de la fréquence repose sur un codage tonotopique présent dans la cochlée et dans le système auditif central, ainsi que sur un codage temporel. Ce dernier représente la synchronisation de la décharge neurale avec la périodicité des ondes sinusoïdales des stimuli, codage présent seulement pour les plus basses fréquences (Barlow & Mollon, 1982). Ainsi, il semble que les électrodes de l'implant cochléaire permettent un codage qui est temporellement et tonotopiquement suffisamment précis pour engendrer une certaine perception de la fréquence, indispensable au processus de discrimination fréquentielle.

Dans cette étude, les participants porteurs d'un implant cochléaire présentaient tous une importante période de surdité et utilisaient leur implant cochléaire depuis au moins un an (M= 5 ans). Par ailleurs, leur détection auditive était semblable. Cependant, il demeure difficile d'expliquer l'importante disparité dans les résultats de discrimination fréquentielle, disparité présente aussi pour les performances de reconnaissance de la parole. Aucune corrélation ne fut observée ni entre les performances de discrimination fréquentielle et la durée de la privation auditive, ni entre ces performances et la durée de l'expérience avec l'implant. Considérant le nombre restreint de participants (20 participants porteurs d'implant cochléaire), il est difficile de conclure à l'inexistence de cette relation. En effet, bien que cette relation ne fut pas observée dans nos résultats, il semble vraisemblable qu'une durée plus courte de privation auditive puisse engendrer de meilleurs résultats au test de discrimination fréquentielle (Peterson et al., 2010). D'autres chercheurs avaient précédemment montré que le type de stimulation électrique, la profondeur d'insertion des électrodes, le nombre d'électrodes, le type de l'implant, le genre, la durée de l'expérience avec l'implant et la stratégie de programmation avaient aussi un impact négligeable sur la discrimination fréquentielle (Barry et al., 2002; Fitzgerald et al., 2005; Hsu, Horng, & Fu, 2000; Kopelovich, Eisen & Franck, 2010; Qi et al., 2011). Il semble que les caractéristiques techniques de l'implant influencent peu la discrimination fréquentielle. Il se pourrait donc que l'explication de la disparité dans les résultats puisse être liée aux processus de réorganisation cérébrale qui semblent être différents d'une personne à l'autre, conséquence d'une différente expérience auditive pré et post-implant (Collignon, Champoux, Voss & Lepore, 2011).

Plusieurs études ont montré que l'implant cochléaire procure généralement une détection et une audibilité des sons de l'environnement qui se compare à celles des personnes entendantes, ou qui s'en approche (e.g. Signh et al., 2004; Champoux et al., 2009; Tremblay et al., 2010). Cependant, une importante variabilité existe en termes de perception de la parole, telle que mesurée par divers test de parole (Champoux et al., 2009; Garnham et al., 2002, Osberger et al., 2000a,b; Peterson et al., 2010, Shpak et al., 2009). Comme le seuil d'audibilité demeure généralement le même chez les porteurs d'implant cochléaire, le traitement auditif, tel que la discrimination fréquentielle, semble être une variable possible pouvant expliquer la différence de performance observée en terme de perception de la parole. Afin de vérifier cette piste d'explication, cette étude visait l'évaluation des processus de discrimination fréquentielle, se situant entre la détection et la reconnaissance de la parole dans la hiérarchie du traitement auditif, et à voir si cette mesure de discrimination pouvait contribuer à expliquer la disparité d'une des performances de plus haut niveau, soit la reconnaissance de la parole.

Les individus porteurs d'un implant évalués dans cette recherche présentaient des seuils de détection légèrement supérieurs aux personnes entendantes mais les seuils étaient semblables entre les individus porteurs d'implant cochléaire ayant obtenu de bons résultats au test de reconnaissance de la parole et ceux ayant obtenu de moins bons résultats. Toutefois, les résultats portant sur la discrimination fréquentielle proposent un lien entre ce processus de bas niveau et la perception de la parole chez une population ayant un implant cochléaire. Les participants ayant une moins bonne performance en termes de reconnaissance de la parole avaient aussi une moins bonne performance de discrimination fréquentielle, et ce, pour les deux fréquences évaluées (500Hz et 4000Hz). Considérant qu'une bonne discrimination fréquentielle est essentielle pour une juste production et compréhension de voyelles et de consonnes, cette relation paraît cohérente. Ces résultats pourraient avoir une implication importante pour la réadaptation auditive proposée aux personnes porteuses d'un implant cochléaire.

Il a été montré qu'il est réaliste de penser qu'à la suite d'un entraînement auditif intensif, la discrimination fréquentielle puisse s'améliorer et ainsi permettre l'amélioration de la perception de la parole. En effet, il a été largement établi que chez une population entendante, les capacités auditives de bas niveau pouvaient être améliorées à l'aide d'entraînements auditifs. Par exemple, diverses études ont spécifiquement démontré qu'un apprentissage et une amélioration des habiletés de discrimination fréquentielle étaient possibles chez l'adulte (e.g. Amitay et al., 2005; Delhommeau, Micheyl & Jouvent, 2005; Demany and Semal, 2002; Grimault, Micheyl, Carlyon, Bacon & Collet ,2003; Irvine, Martin, Klimkeit & Smith, 2000; Wright and Sabin, 2007) et chez l'enfant (Halliday, Taylor, Edmondson-Jones & Moore, 2008; Moore, Ferguson, Halliday & Riley, 2007). Des entraînements intensifs induiraient des changements dans la carte sensorielle auditive du cortex auditif primaire et ces changements engendreraient les différences comportementales. Certains chercheurs proposent que les performances seraient dépendantes des stimuli utilisés (Demany & Semal, 2002). En effet, tel que démontré chez le singe, ces changements seraient tonotopiquement reliés aux stimuli utilisés lors de l'entraînement et seraient reliés à l'augmentation des habiletés comportementales (Recanzone, Schreiner & Merzenich, 1993). D'autres études ne soutiennent pas que cet entraînement soit exclusivement "fréquence-spécifique", ou encore n'excluent pas qu'une partie soit induite par une meilleure attention. Elles appuient néanmoins la présence d'une augmentation des performances suite à l'entraînement (Irvine et al., 2000).

Bien qu'il soit généralement admis que la discrimination fréquentielle puisse être améliorée suite à un entraînement, rares sont les études qui ont porté leur attention sur l'entraînement chez des populations cliniques. Les plus connues ont majoritairement étudié les individus ayant divers troubles langagiers et les auteurs suggèrent que la discrimination fréquentielle peut être améliorée et que cette amélioration peut se transférer aux habiletés langagières (McArthur, Ellis, Atkinson & Coltheart, 2008; Schäffler, Sonntag, Hartnegg & Fischer, 2004). Connaissant le potentiel d'apprentissage de cette habileté perceptive ainsi que son lien direct avec la reconnaissance de la parole, les résultats de cette deuxième étude proposent une voie nouvelle et innovatrice pour le domaine de la réadaptation chez des personnes ayant un implant cochléaire. Jusqu'à maintenant, les centres de réadaptation s'intéressent surtout à la mesure de la détection de sons purs ou à la reconnaissance de la parole. La relation entre les processus de bas niveau, tels que la discrimination fréquentielle et son implication dans la perception de la parole, devrait être particulièrement étudiée, surtout chez les individus pour qui les résultats n'atteignent pas les objectifs fixés. Des études portant sur cet entraînement devront le considérer chez diverses populations ainsi qu'avec différents processus auditifs permettant d'améliorer l'efficacité des méthodes de réadaptation.

Étude électrophysiologique de la discrimination auditive chez une population avec implant cochléaire

Cette troisième étude avait pour objectifs l'évaluation de l'impact d'une privation auditive sur la discrimination auditive et l'évaluation du lien entre ces mesures électrophysiologiques et les habiletés de reconnaissance de la parole. À l'aide de la négativité de discordance, cette étude a apporté une mesure pré-attentionnelle et automatique des processus de discrimination auditive. Un paradigme utilisant deux stimuli déviants et un stimulus standard a été utilisé. Des stimuli verbaux ont été utilisés afin de s'approcher le plus possible d'une mesure de discrimination de la parole (Martin, et al., 2008). Les résultats discutés découlent ainsi de deux mesures de négativité de discordance, induites par la présentation de deux stimuli déviants différents. Dans le cadre de cette étude, les participants porteurs d'un implant cochléaire ont également été séparés en deux groupes, le premier ayant une bonne reconnaissance de la parole et le deuxième ayant une moins bonne reconnaissance de la parole. Les participants entendants ainsi que les participants considérés comme performants avec leur implant cochléaire ont tous montré une négativité de discordance claire lors de la présentation des deux stimuli déviants (condition utilisant le stimulus déviant /ga/ et condition utilisant le stimulus déviant /ba/. Par ailleurs, une tendance a indiqué un lien entre la reconnaissance de la parole et les mesures de la négativité de discordance. Ainsi, les individus porteurs d'un implant ayant de meilleurs résultats langagiers présentaient une négativité de discordance ayant une latence diminuée et une amplitude plus grande que le groupe d'individus porteurs d'implant ayant de moins bons résultats au test de reconnaissance de la parole.

Tout comme pour l'étude précédente, aucune corrélation n'a pu être montrée entre les mesures électrophysiologiques, tel que démontré par la latence et l'amplitude de la négativité de discordance et la durée de la surdité/expérience avec l'implant cochléaire.

Encore une fois, considérant le nombre restreint de participants (20 participants porteur d'implant cochléaire), il est difficile de conclure à l'inexistence de cette relation. Par contre, les résultats ont montré que l'amplitude de la négativité de discordance engendrée par la présentation du stimulus déviant /ga/ était corrélée avec les performances de reconnaissance de la parole. Ces résultats sont en concordance avec d'autres études ayant aussi démontré la présence d'une relation entre la négativité de discordance et les performances de parole telles que mesurées par différents tests langagiers chez les porteurs d'implant cochléaire (Kelly et al., 2005; Kileney et al., 1997; Kraus et al., 1993; Groenen, 1996).

De façon générale, meilleures sont les performances de reconnaissance de la parole, meilleurs sont les résultats aux mesures électrophysiologiques, exprimées par une latence plus courte et par une plus grande amplitude de la négativité de discordance. Il est toutefois à noter qu'aucune différence significative n'a pu être trouvée entre les deux groupes de porteurs d'implant cochléaire. En termes d'amplitude et de latence, il est possible de différencier le groupe de porteurs d'implant ayant de moins bons résultats au test de reconnaissance de la parole du groupe entendant. Quant à eux, les porteurs d'implant ayant eu un meilleur résultat au test de reconnaissance de la parole, obtiennent des résultats semblables à ceux des entendants en termes d'amplitude, mais demeurent différents des entendants pour la latence. Ces résultats suggèrent qu'afin de rendre plus utile une mesure de négativité de discordance en milieu clinique, il serait souhaitable de valider d'abord des normes obtenues chez une population entendante, afin de pouvoir ultimement comparer les résultats d'une personne porteuse d'un implant cochléaire. Aussi, un paradigme utilisant une différence plus subtile entre les stimuli déviant et standard, pourrait peut-être engendrer une différence dans la négativité de discordance entre des porteurs d'implant performants et moins performants avec leur implant. Il est aussi à noter que chacune des trois électrodes utilisées dans cette étude (AFz, Fz, FCz) montrait une négativité de discordance relativement similaire en termes d'amplitude et de latence, ce qui propose que l'utilisation de n'importe laquelle de ces électrodes est acceptable pour une mesure de la négativité de discordance. Cependant, considérant la présence accrue d'artéfact chez cette population, l'utilisation de plusieurs électrodes lors de l'enregistrement électrophysiologique permet de soustraire plus facilement l'artéfact induit par l'implant et engendre ainsi des données moins bruitées, donc plus fiables. En ce qui concerne les deux conditions induites par l'utilisation de deux stimuli déviants, les résultats indiquent qu'une plus grande amplitude de la négativité de discordance est induite par le stimulus /ga/, mais que la latence n'est pas affectée par le type de stimuli. Concernant l'amplitude, cette distinction était probante, sachant que la différence spectrale entre le stimulus standard et déviant /ga/ est plus grande qu'entre le stimulus standard et déviant /ba/. La première condition est ainsi plus évidente à discriminer et engendre en conséquence une amplitude plus grande (Näätänen, 1990).

Une étude longitudinale chez des personnes porteuses d'un implant, débutant rapidement après la chirurgie et se poursuivant sur quelques années, serait nécessaire afin de mieux explorer le potentiel de cette mesure électrophysiologique dans l'investigation de la restauration auditive avec l'implant cochléaire. En tel cas, cette mesure serait utile en réadaptation, surtout lors de suivi auprès de très jeunes enfants et de personnes non-verbales chez qui l'utilisation de tests langagiers est restreinte. Poursuivre l'investigation de cette mesure, afin de diminuer la durée de passation en augmentant l'efficacité, participerait au défi important d'inclure une méthode électrophysiologique dans le domaine de la réadaptation auditive chez la population de personnes malentendantes. Considérant que l'implant cochléaire est fourni désormais à une population de plus en plus jeune, ces besoins deviennent criants au Québec.

Impact d'une privation auditive sur le développement des capacités visuelles comportementales

Notre quatrième étude visait à évaluer les processus de discrimination fréquentielle visuelle chez une population malentendante ayant un implant cochléaire. Nos résultats ont montré que les individus porteurs d'un implant cochléaire démontraient une discrimination fréquentielle spatiale moins bonne que les sujets entendants, et ce, pour les deux fréquences spatiales testées (1 et 5 cyl./deg.). Il semble donc que la surdité puisse mener à des changements dans les processus de traitement visuel et que ces changements puissent perdurer après l'implantation.

Les participants évalués dans cette étude étaient sourds de naissance (9) ou avaient une surdité acquise (11). Ils utilisaient tous le langage oral comme premier mode de communication. Bien qu'une moitié seulement des participants présentent une surdité congénitale, le profil clinique de tous les participants présentait certaines similitudes. En effet, la majorité avaient eu une surdité complète ou progressive de longue durée et avaient reçu leur implant à l'âge adulte. Cette importante période de privation auditive pourrait fortement avoir influencé la réorganisation cérébrale, expliquant ainsi les pauvres résultats visuels chez tous les participants, qu'ils soient sourds de naissance ou ayant eu une surdité acquise. De plus, la majorité des participants ont développé leur surdité en bas âge, soit à moins de 11 ans. Considérant que le système auditif n'est pas encore mature en bas âge (Bellis, 2003; Turgeon, Lepore & Ellemberg, 2010), il est probable que suite à leur privation auditive prolongée, une importante réorganisation cérébrale ait eu lieu chez nos participants. Il est probable que des résultats différents aient été obtenus si l'étude avait été menée chez une population ayant reçu son implant en très bas âge, laissant ainsi moins de temps à la réorganisation.

Aussi, une série de corrélations a été effectuée entre les performances auditives de perception de la parole et diverses caractéristiques cliniques des participants, mais aucune d'entres elles n'a pu révéler un lien significatif, incluant la durée de la privation ainsi que la durée de l'expérience avec l'implant. Cette absence de relation fut aussi observée dans les deux autres études discutées plus tôt et portant sur des porteurs d'implant cochléaires. Ici encore, il est vraisemblable de dire qu'un nombre plus grand de participants aurait permis d’évaluer avec plus de certitude la présence ou non d’une telle relation. La majorité des études suggèrent que la durée de la privation auditive pré-implant a un impact considérable sur le développement des habiletés auditives post-implant. Généralement, les individus ayant eu une certaine expérience auditive vont performer mieux suite à l’implantation (Border et al., 2007). Nos résultats n’ont pas montré de différence quant à la perception de la parole entre notre groupe de personnes sourdes de naissance et celui avec une surdité acquise. Ces résultats peuvent trouver une piste d’explication dans la longue période de privation pré-implant notée chez la majorité des individus. Cette période prolongée de privation auditive pourrait avoir annulé l’avantage qui aurait dû être présent chez le groupe d’individus avec une surdité tardive.

De la cohorte évaluée, deux participants se distinguaient par leur profil. En effet, deux participants ont eu une surdité durant l’enfance mais ont reçu leurs implants à un plus jeune âge que les autres participants, soit à 10 et 8 ans respectivement. La durée de leurs expériences avec l’implant était aussi nettement plus importante que celle des autres participants. Contrairement à ce à quoi on aurait pu s’attendre, leur test de perception de la parole montre une faible performance. Ces résultats peuvent toutefois s’expliquer par leur histoire auditive pré et post-implant respective. En effet, suite à une perte subite à l’âge de 8 ans, le premier participant a reçu son implant à l’âge de 10 ans, mais ne le porte qu’occasionnellement et utilise surtout la lecture labiale. Ainsi, il pourrait ne pas avoir développé de façon optimale ses habiletés auditives. En ce qui concerne le deuxième participant, suite à une surdité subite profonde, il n’a reçu aucune amplification auditive, pas même avec un appareil auditif, entre l'âge de 3 et de 8 ans. Cette privation totale peut être considérée pour expliquer l'importante difficulté de perception de la parole sans lecture labiale.

Ces deux participants ont aussi eu une période de privation auditive de moins longue durée. Sachant qu'une longue privation auditive entraîne une importante réorganisation cérébrale (Gilley et al., 2010; Buckley & Tobey, 2010; Peterson et al., 2010; Merabet & Pascual-Leone, 2009), on aurait pu s'attendre à des différences quant aux performances visuelles. Toutefois ces participants montrent une performance visuelle comparable aux autres personnes porteuses d'un implant. Il semble que malgré leur privation auditive moindre que les autres participants, celle-ci est suffisante pour avoir engendré une réorganisation cérébrale et avoir influencé le développement des habités visuelles.

Une quantité considérable d'études chez la population sourde se sont penchées sur l'impact d'une privation auditive sur le développement des habiletés visuelles lesquelles, tel que discuté dans l'introduction, semblent se modifier afin de compenser pour le manque de stimulation auditive. Ces études ont démontré que les personnes sourdes présentaient des performances supérieures dans le traitement de l'information présentée dans le champ périphérique, qu'ils étaient plus rapides et plus précis dans la détection de stimuli en mouvement, ainsi que dans la détection de changements lumineux en périphérie (Bosworth & Dobkins, 2002; Bottari, Nava, Ley & Pavani, 2010; Loke & Song, 1991; Neville & Lawson, 1987) et qu'ils montraient une plus grande attention en périphérie, comparativement aux personnes entendantes (Bavelier et al., 2000; 2001; 2006). Les résultats d'études portant sur les performances visuelles de bas niveau présentées dans le champ visuel central, sont plus rares et leurs résultats divergent, certains rapportant une diminution de ces habiletés et d'autres aucune différence comparativement à la population entendante (Bross, 1979; Finney & Dobkins, 2001; Hanson, 1982; Herming & Brown, 2005; Mills, 1985; Nava et al., 2008; Withrow, 1968). Les résultats obtenus dans notre étude supportent la théorie du déficit, telle que décrite dans l'introduction, en supposant qu'un développement normal de chacune des modalités est nécessaire pour un développement normal des autres modalités sensorielles. Suite à une privation auditive, certaines habiletés visuelles lorsqu'évaluées en champ périphérique semblent s'améliorer, conséquence probable d'une attention accrue portée en périphérie, mais peut-être qu'un développement normal de tous les sens est nécessaire pour une croissance et une calibration normale des processus de bas niveau, tels que la discrimination fréquentielle? Jusqu'à maintenant, beaucoup de connaissances ont été obtenues sur les habiletés visuelles telles qu'évaluées dans le champ visuel périphérique chez une population sourde; par contre, celles sur les habiletés de bas niveau, présentées dans le champ central sont plus rares et disparates.

Enfin, il est aussi possible que cette diminution de performances ne soit pas reliée à un désordre visuel, mais plutôt à un déficit plus global d'attention. Tel que le suggèrent certains auteurs, l'attention visuelle non-périphérique est diminuée chez les personnes sourdes, porteuses ou non d'un implant cochléaire (Horn et al., 2005; Smith et al., 1998;

Yucel & Derim, 2008). En effet, ces auteurs suggèrent un déficit tel que mesuré par un test d'attention visuelle soutenue. Cependant, les individus évalués dans ces études proviennent d'une population pédiatrique. La même évaluation chez une population adulte sourde, porteuse ou non d'un implant cochléaire, pourrait être intéressante. Par ailleurs, sachant que l'attention visuelle semble être améliorée en périphérie, il aurait été intéressant de connaître les performances pour la même tâche de discrimination visuelle, mais effectuée cette fois en périphérie.

La nature exacte de cette réduction de performance se doit d'être investiguée. Une étude portant sur une population plus nombreuse permettrait de voir, entre autres, les liens entre la durée de la surdité, l'âge au moment de la surdité, la durée de l'expérience avec l'implant et la performance visuelle. L'étude de la discrimination fréquentielle visuelle chez une population ayant reçu l'implant cochléaire en bas âge serait aussi particulièrement intéressante. Néanmoins, il demeure que ces résultats démontrent une performance moindre chez la population sourde évaluée, suggérant ainsi qu'un développement auditif normal est nécessaire pour le développement de cette habileté visuelle.

Les études incluses dans cette thèse portent sur un groupe relativement homogène d'individus porteurs d'un implant cochléaire. En effet, le groupe était majoritairement composé de participants ayant expérimenté une longue période de privation auditive avant de recevoir leur implant cochléaire, donc n'ayant eu aucune amplification ou des appareils auditifs pendant plusieurs années. En ce qui concerne les deux études en modalité auditive, une population plus hétérogène ainsi qu'un plus grand nombre de participants aurait peut-être pu révéler des liens entre les performances auditives et la durée de la surdité ainsi qu'entre ces performances et la durée de l'expérience avec l'implant. Aussi, il aurait été souhaitable de refaire une étude similaire chez une population pédiatrique dont les participants auraient reçu leurs implants respectifs à différents âges. Une telle étude permettrait de voir l'effet de la durée de la surdité chez une population de jeunes enfants chez qui le cerveau est en plein développement. Par ailleurs, une étude portant sur une population adulte ayant reçu l'implant rapidement après le diagnostic de surdité aurait amené une meilleure connaissance de l'effet de la durée d'une privation auditive sur le développement fonctionnel du système auditif. Quant à l'étude portant sur le développement de la modalité visuelle, tel que mentionné plus tôt, une population plus hétérogène ayant eu une privation auditive plus ou moins longue aurait permis d'évaluer les différences possibles dans la réorganisation cérébrale en investiguant la présence ou non de déficit visuel. Finalement, il aurait été intéressant de refaire cette étude, mais cette fois chez une population sourde, mais non porteuse d'un implant cochléaire. Idéalement, cette mesure aurait pu être prise chez un groupe de personnes sourdes, avant et après la chirurgie d'implantation cochléaire. L'apport de l'implant dans les processus de réorganisation cérébrale aurait pu être mieux connu. Une population de personnes sourdes de naissance et implantées rapidement après la naissance aurait aussi permis d'explorer l'impact sur les processus visuelles d'une courte privation auditive

À la lumière de ces quatre études, diverses conclusions sont apportées. En premier lieu, l'étude développementale chez une population entendante a montré que les systèmes auditif et visuel se développent à des rythmes distincts et qu'ils atteignent leur maturité respective à des âges différents. Ces résultats suggèrent que les mécanismes qui sous-tendent la détection et la discrimination fréquentielle dans ces deux systèmes sont différents et que leurs développements respectifs sont indépendants. Bien que ces résultats suggèrent que les systèmes auditif et visuel se développent de façon distincte, la quatrième étude de cette thèse démontre toutefois qu'ils demeurent interreliés. En effet, il semble qu'un développement normal de l'audition soit essentiel pour un développement optimal de la discrimination fréquentielle visuelle, tel que démontré par un déficit présent chez la population porteuse d'un implant cochléaire. Curieusement, il a déjà été démontré que chez une population de personnes aveugles, la discrimination fréquentielle auditive était supérieure à celle d'une population ayant une vision normale (Gougoux et al., 2004). Comment expliquer le fait qu'une privation visuelle précoce engendre une amélioration des processus de discrimination fréquentielle auditive, mais qu'au contraire, une privation auditive engendre plutôt une diminution de la discrimination visuelle? Visiblement, la réorganisation corticale lors de cécité semble refléter un processus de compensation et engendrer une amélioration des habiletés de bas niveau, ce qui semble être moins évident lors de privation auditive. Cette distinction démontre que bien que ces deux systèmes semblent interreliés et qu'ils démontrent certaines similitudes, des différences demeurent présentes entre ces deux systèmes.

Finalement, cette thèse a aussi soulevé, par les conclusions des deux études portant sur la discrimination auditive telle que mesurée de façon comportementale et par la négativité de discordance, l'importante relation présente entre les processus de discrimination auditive et de la reconnaissance de la parole. Ces données soulèvent deux points importants négligés en réadaptation. D'une part, les processus de bas niveau sont prédicteurs de la performance de reconnaissance de la parole. Ainsi il pourrait être possible d'améliorer les performances langagières par l'amélioration de la discrimination fréquentielle. D'autre part, il est possible de mesurer de manière pré-attentionnelle et automatique, les habiletés de discrimination auditive et conséquemment de la reconnaissance de la parole par l'entremise de la négativité de discordance.

Chapitre IV. Conclusion

Les études menées dans le cadre de cette thèse ont mené à quatre pistes principales. En premier lieu, cette thèse a permis de mieux comprendre les processus auditif et visuel de bas niveau en précisant le rythme développemental de la détection auditive et visuelle ainsi que celui des processus de discrimination auditive et visuelle. Ainsi, il a été montré que, malgré un traitement hiérarchique sensoriel similaire dans les deux modalités, leurs développements respectifs se montrent distincts et indépendants. Ces développements se révèlent cependant interreliés, tel que démontré par la dernière étude incluse dans cette thèse. Deuxièmement, nos études amènent une meilleure compréhension des processus de discrimination auditive chez une population avec implant cochléaire en démontrant que ce traitement est lié à la compréhension de la parole. Ainsi, ces résultats proposent une nouvelle piste en réadaptation cochléaire, comme quoi une amélioration des processus de bas niveau pourrait être liée à une amélioration de la perception de la parole. Troisièmement, un lien entre la mesure de négativité de discordance et les performances de reconnaissance de parole a été montré. Ainsi, les résultats de cette étude proposent un paradigme permettant une mesure électrophysiologique liée aux habiletés de reconnaissance de la parole qui pourrait s'avérer particulièrement utile dans l'évaluation post-implant d'une population non-verbale, telle que les très jeunes enfants. Finalement, l'étude portant sur la discrimination visuelle a révélé un déficit présent chez les individus ayant un implant cochléaire, ce qui a amené une nouvelle information quant aux processus de réorganisation et apporté un nouvel appui à la théorie du déficit.

Bibliographie

Abramov, I., Gordon, J., Hendrickson, A., Hainline, L., Dobson, V. & LaBossiere, E. (1982). The retina of the newborn human infant. *Science*, 217, 265-267.

Adams, J.R. & Courage, M.L. (2002). Using a single test to measure human contrast sensitivity from early childhood to maturity. *Vision Research*, 42, 1205-1210.

Aguado, L., Serrano-Pedraza, I., Rodriguez, S. & Roman, F.J. (2010). Effects of spatial frequency content on classification of face gender and expression. *The Spanish journal of psychology*, 13, 525-537.

Amitay, S., Ahissar, M. & Nelken, I. (2002). Auditory processing deficits in reading disabled adults. *The Journal of the Association for Research in Otolaryngology*, 3, 302-320.

Amitay, S., Hawkey, D.J.C. & Moore, D.R. (2005). Auditory frequency discrimination learning is affected by stimulis variability. *Perception & Psychophysics*, 67, 691-698.

Amitey, S., Irwin, A. & Moore, D.R. (2006). Discrimination learning induced by training with identical stimuli. *Nature Neurosciences*, 9, 1446-1448.

De Angelo, T.C., Bevialacqua, M.C. & Moret, A.L. (2010). Speech perception in pre-lingual deaf users of cochlear implant. *Pro Fono*, 22, 275-279.

Arabin, B. (2002). Opinion, music during pregnancy. *Ultrasound Obstetrics & Gynecology*, 20, 425-430.

Aslin, R.N., Pisoni, D.B. & Juczyk, P.W. (1983). Auditory developement and speech perpcetion in infancy. In. Musard. T.H. (Ed.). Handbook of Child Psychology, 4th edn., Vol II. Infant Developement and Psychology. John Wiley & Sun. New York, 2, 573-687.

Bagatto, M.P., Scollie, S.D., Seewald, R.C., Moodie, K.S. & Hoover, B.M. (2002). Real-ear-to-coupler differences predictions as a function of age for two coupling procedures. *The Journal of American Academy of Audiology*, 13, 407-415.

Barlow, H.B. & Mollon, J.D. (1982). *The sense*. Cambridge University Press. New York, USA.

Barry, J.G., Blamey, P.J. & Martin, L.F. (2002). A multidimensional scaling analysis of tone discrimination ability in Cantonese-speaking children using a cochlear implant. *Clinical Linguistics and Phonetics*, 16, 101-113.

Baumann, S.B., Rogers, R.L., Papanicolaou, A.C. & Saydjari, C.L. (1990). Intersession replicability of dipole parameters from three components of the auditory evoked magnetic field. *Brain Topography*, 3, 311-319.

Bavelier, D., Tommann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G. & Neville, H. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neurosciences*, 1, 93.

Bavelier, D., Brozinsky, C., Tomman, A., Mitchell, T., Neville, H. & Liu, G. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *Journal of Neurosciences*, 21, 8931-8942.

Bavelier, D., Dye, M.W.G. & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitives Sciences,* 10, 512-518.

Beazley, J.D., Illingworth, D.J., Jahn, A. & Greer, D.V. (1980). Contrast sensitivity in children and adults. *British Journal of Ophthalmology*, 64, 863-866.

Bellis, T.J. (2003). Assessment and management of central auditory processing disorders in the educational setting: from science to practice. Singular, New York.

Benedek, G., Benedek, K., Kéri, S. & Janáky, M. (2003). The scotopic low-frequency spatial contrast sensitivity develops in children between the ages of 5 and 14 years. *Neuroscience letters*, 345, 161-164.

Bishop, D.V. & McArthur, G.M. (2005). Individual differences in auditory processing in specific language impairment: a follow-up study using event-related potentials and behavioural thresholds. *Cortex*, 41, 327-341.

Border, D., Shipp, D. B., Ostroff, J. M., Ng, A. H., Stewart, S., Chen, J. M. & Nedzelski J. M. (2007). A comparison of postcochlear implantation speech scores in an adult population. *Laryngoscope*, 117, 1408-1411.

Bosworth, R.G. & Dobkins, K.R. (2002). Visual field asymmetries for motion processing in deaf and hearing signers. *Brain and Cognition*, 49, 170-81.

Bottari, D., Nava, E., Ley, P. & Pavani, F. (2010). Enhances reactivity to visual stimuli in deafs individuals. *Restorative Neurology and Neuroscience*, 28, 167-179.

Bradley, J., Bird, P., Monteath, P. & Wells, J.E. (2010). Improved speech discrimination after cochlear implantation in the Southern Cochlear Implant Adult Programme. *The New Zealand Medical Journal*, 123, 34-44.

Bradley, A. & Freeman, R.D. (1982). Contrast sensitivity in children. *Vision Research*, 22, 953-959.

Bross, M. (1979). Residual sensory capacities of the deaf: a signal detection analysis of a visual discrimination task. *Perceptual and Motor Skills*, 48,187-194.

Brown, A.M. & Lindsey, D.T. (2009). Contrast insensitivity: the critical immaturity in infant visual performance. *Optometry and Vision Science*, 86, 572-576.

Buckley, K.A. & Tobey, E.A. (2011). Cross-Modal plasticity and speech perception in pre- and postlingually deaf cochlear implant users. Ear and Hearing, 32, 2-15.

Chelli, D. & Chanoufi, B. (2008). Audition fœtale. Mythe ou réalité? *Journal de Gynécologie Obstétrique et Biologie de la Reproduction*, 37, 554-558.

Champoux, F., Bacon, B.A., Lepore, F. & Guillemot, J.P. (2008). Effetcs of early binocular enucleation on auditory and somatosensory coding in the superior colliculus of the rat. *Brain research*, 29, 84-95.

Champoux, F., Lepore, F., Gagné, J.-P. & Théoret, H. (2009). Visual stimuli can impair auditory processing in cochlear implants users. *Neuropsychologia*, 47, 17-22.

Collignon, O., Champoux, F., Voss, P. & Lepore, F. (2011). Sensory rehabilitation in the plastic brain. *Progressive Brain Research*, 191, 211-231.

Delhommeau, K., Micheyl, C. & Jouvent, R. (2005). Generalization of frequency discrimination learning across frequencies and ears: implication for underlying neural mechanism in humans. *Journal of the Association for Research in Otolaryngology*, 6, 171-179.

Demany, L. & Semal, C. (2002). Learning to perceive pitch differences. *The Journal of the Acoustical Society of America*, 111, 1377-1388.

Dillon, H. (2001). *Hearing Aids*. Sydney: Boomerang Press.

Doucet, M.E., Bergeron, F., Lassonde, M., Ferron, P. & Lepore, F. (2006). Cross-modal reorganization and speech perception in cochlear implant users. *Brain*, 129, 3376-3383.

Droit-Volet, S., Tourret, S. & Wearden, J. (2004). Perception of the duration of auditory and visual stimuli inchildren and adults. *The Quartely Journal of Experimentation Psychology Section A,* 57, 797-818.

Dye, M. & Bavelier, D. (2010). Attentional enhancements and deficits in deaf populations: An integrative review. *Restorative Neurology and Neuroscience,* 28, 181–192.

Dye, M.W.G., Hauser, P.C. & Bavelier, D. (2009). Is visual attention in deaf individuals enhanced or deficient? The case of the Useful Field of View. *PloS ONE, 4*, e5640.

Elliott, L.L. & Katz, D.R. (1980). Children's pure-tone detection. *The Journal of the Acoustical Society of America*, 67, 343-344.

Finney, E.M., Clementz, B.A., Hickok, G. & Dobkins, K.R. (2003). Visual stimuli activate auditory cortex in the deaf subjects: evidence from MEG. *Neuroreport*, 14, 1425-1427.

Finney, E.M. & Dobkins, K.R. (2001). Visual contrast sensitivity in deaf versus hearing populations: exploring the perceptual consequences of auditory deprivation and experience with a visual language. *Brain Research. Cognitive Brain Research*, 11, 171-183.

Finney, E.M., Fine, I. & Dodbkins, K.R. (2001). Visual stimuli activate auditory cortex in the deaf. *Nature Neurosciences*, 4, 1171-1173.

Fitzgerald, M.B., Shapiro, W.H., McDonald, P.D., Neuburger, H.S., Ashburn-Reed, S., Immerman, S., et al. (2007). The effect of perimodiolar placement on speech perception and frequency discrimination by cochlear implant users. *Acta oto-laryngologica,* 127, 378-383.

Fitzgerald, M.B. & Wright, B.A. (2005). A perceptual learning investigation of the pitch elicited by amplitude-modulated noise. *The Journal of the Acoustical Society of America*, 118, 3794-3803.

Garnham, C., O'Driscoll, M., Ramsden, R. & Saeed, S. (2002). Speech understanding in noise with a Med-El COMBI 40+ cochlear implant using reduced channels sets. *Ear and Hearing,* 23, 540-552.

Gates, G.A. & Miyamoto, R.T. (2003). Cochlear implants. *The New England Journal of Medicine*, 349, 421-423.

Gfeller, K., Turner, C., Oleson, J., Zhang, X., Gantz, B., Froman, R., et al. (2007). Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear and hearing, 28*(3), 412-423.

Ghazanfar, A.A. & Schroeder, C.E. (2006). Is neocortex essentially multisensory? Trends in Cognitive Sciences, 10, 278-285.

Gilley, P.M., Sharma, A., Mitchell, T.V. & Dorman, M.F. (2010). The influence of a sensitive period for auditory-visual integration in children with cochlear implants. *Restorative Neurology and Neurosciences*, 28, 207-218.

Giraud, A.L., Price, C.J., Graham, J.M., Truy, E. & Frackowiak, R.S. (2001). Cross-modal plasticity underpins language recovery after cochlear implantation. *Neuron*, 30, 657-663.

Goldstein, E.B. (Ed.). (2002). Sensation and perception (6e édition ed.). Pittsburgh: Thomson Learning.

Gordon, K.A., Tanaka, S., Wong, D.D.E. & Papson, B.C. (2008). Characterizing responses from auditory cortex in young people with severe years of cochlear implant experience. *Clinical Neurophysiology*, 119, 2347-2362.

Gougoux, F., Lepore, F., Lassonde, M., Voss, P., Zatorre, R.J. & Belin, P. (2004). Neuropsychology : pitch discrimination in the early blind. *Nature*, 430, 309.

Grieco-Calub, T.M. & Litovsky, R.Y. (2010). Sound localization skills in children who use bilateral cochlear implants and in children with normal acoustic hearing. *Ear and Hearing*, 31, 645-656.

Grimault, N., Micheyl, C., Carlyon, R.P., Bacon, S.P. & Collet, L. (2003). Learning in discrimination of frequency or modulation rate: generalization to fundamental frequency discrimination. *Hearing Research*, 184, 41-50.

Grimwade, J.C., Walker, D.W., Bartlett, M., Gordon, S. & Wood, C. (1971). Human fetal heart rate change and movement in response to sound and vibration. *The American Journal of Obstetrics and Gynecology*, 109, 86-90.

Groenen, P., Snik, A. & van den Broek, P. (1996). On the clinical relevance of mismatch negativity: Results from subjects with normal hearing and cochlear implant users. *Audiology Neurootolology*, 1, 112-124.

Grose, J.H. & Buss, E. (2007). Within-and across-channel gap detection in cochlear implants listeners. *The Journal of the Acoustical Society of America*, 122, 3651-3658.

Gwiazda, J., Bauer, J., Thorn, F. & Held, R. (1997). Development of spatial contrast sensitivity from infancy to adulthood: psychophysical data. *Optometry and vision science,* 74, 785-789.

Hainline, L., Riddell, P., Grose-Fifer, J. & Abramov, I. (1992). Developement of accommodation and convergence in infancy. *Behavioral Brain Research*, 49, 33-50.

Hall III, J.W. (1992). *Handbook of auditory evoked potentials*. Boston: Allyn and Bacon.

Halliday, L.F., Taylor, J.L., Edmondson-Jones, A.M. & Moore, D.R. (2008). Frequency discrimination learning in children. *The Journal of the Acoustical Society of America*, 123, 4393-4402.

Hanson, V.L. (1982). Short-term recall by deaf signers of American Sign Language: Implication of encoding strategy for order recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 8, 572-583.

Hawkey, D.J., AMitay, S. & Moore, D.R. (2004). Early and rapid perceptual learning, *Nature Neurosciences*, 7, 1055-1056.

Heming, J.E. & Brown, L.N. (2005). Sensory temporal processing in adults with early hearing loss. *Brain and Cognition*, 59, 173-82.

Hendrickson, A.E. (1993). Morphological development of the primate retina. In: Simons K, ed. Early Visual Development: Normal and Abnormal. New York: Oxford University Press, 287-295.

Hill, P.R., Hogben, J.H. & Bishop, D.M. (2005). Auditory frequency discrimination in children with specific language impairment: a longitudinal study. *The Journal of Speech, Language, and Hearing Research*, 48, 1136-1146.

Hirsch, J. & Hylton, R. (1982). Limits of spatial-frequency discrimination as evidence of neural interpolation. *Journal of the Optical Society of America*, 72, 1367-1374.

Hitchcock, P.F. & Hickey, T.L. (1980). Prenatal development of the human lateral geniculate nucleus. *The Journal of Comparative Neurology*, 194, 395-411.

Hockfield, S. & Sur, M. (1990). Monoclonal CAT 301 identifies Y cells in cat LGN. *The Journal of Clinical Neurology*, 300, 320–330.

Holt, R.F. & Svirsky, M.A. (2008). An exploratory look at pediatric cochlear implantation: is earliest always best? *Ear and Hearing*, 29, 492-511.

Horn, D.L., Davis, R.A., Pisoni, D.B. & Miyamoto, R.T. (2005). Development of visual attention skills in prelingually deaf children who use cochlear implants. *Ear and Hearing, 26*, 389-408.

Howland, H.C. (1993). Early refractive development. In K. Simons. Early Visual Developement: normal and abnormal. Commision on Behavioral and Social Sciences and Education. National Research Council, Oxford: Oxford University Press.

Hnath-Chisolm, T.E., Laipply, E., Boothroyd, A. (1998). Age-related changes on a children's test of sensory-level speech perception capacity. *Journal of Speech, Language and Hearing Research*, 41, 94-106.

Hsu, C.J., Horng, M.J. & Fu, Q.J. (2000). Effects of the number of active electrodes on tone and speech perception by Nucleus 22 cochlear implant users with SPEAK strategy. Advances in Otorhinolaryngology, 57, 257-259.

Huttenlocher, P.R. & Dabholkar, A.S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *The Journal of Comparative Neurology*, 387, 167-178.

Irvine, D.R., Martin, R.L., Klimkeit, E. & Smith, R. (2000). Specificity or perceptual learning in a frequency discrimination task. *The Journal of the Acoustical Society of America*, 108, 2964-2968.

Jacobson, J.T. (1994). *Principles & applications in auditory evoked potentials*. Virginia: Allyn and Bacon.

Jensen, J.K. & Neff, D.L. (1993). Development of basic auditory discrimination in preschool children. *Psychological Sciences*, 4, 104-107.

Kandel, E.R., Schwartz, J.H. & Jessel, T.M. (Eds.). (2000). *Principles of neural science* (4e ed.). The McGraw-Hill Companies, Health Professions Division, USA.

Katz, J. (2002). *Handbook of Clinical Audiology* (5e ed). Lippincott William & Wilkins, Baltimore, Maryland.

Keefe, D.H., Bulen, J.C., Campbell, S.L. & Burns, E.M. (1994). Pressure transfer function and absorption cross section from the diffuse field to the human infant ear canal. *The Journal of the Acoustical Society of America,* 95, 355-371.

Kelly, A.S., Purdy, S.C. & Thorne, P.R. (2005). Electrophysiological and speech perception measures of auditory processing in experienced adult cochlear implant users. *Clinical Neurophysiology,* 116, 1235-1246.

Kileny, P.R., Boerst, A. & Zwolan, T. (1997). Cognitive evoked potentials to speech and tonal stimuli in children with implants. *Otolaryngology, Head and Neck Surgery*, 1117, 161-169.

Klop, W.M., Boermans, P.P., Ferrier, M.B., van der Hout, W.B., Stiggelbout, A.M. & Frijns, J.H. (2008). Clinical relevance of quality of life outcome in cochlear implantation in postlingually deafened adults. *Otology and Neuro-otology*, 29, 615-621.

Knight, R.T., Scabini, D., Woods, D.L. & Clayworth, C. (1988). The effects of lesions of superior temporal gyrus and inferior parietal lobe on temporal and vertex components of the human AEP. *Electroencephalography & Clinical Neurophysiology*, 70, 499-509.

Kong, Y-Y., Cruz, R., Jones, J.A. & Zeng, F-G. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear and Hearing*, 25, 173-185.

Kopolovich, J.C., Eisen, M.D. & Franck, K.H. (2010). Frequency and electrode discrimination in children with cochlear implants. *Hearing Research*, 268, 105-113.

Kral, A., Hartmann, R., Tillein, J., Heid, S. & Klinke, R. (2001). Delayed maturation and sensitive periods in the auditory cortex. *Audiology & neuro-otology*, 6, 346-362.

Kral, A., Hartmann, R., Tillein, J., Heid, S. & Klinke, R. (2002). Hearing after congenital deafness: central auditory plasticity and sensory deprivation. *Cerebral Cortex*, 12, 797-807.

Kral, A., Tillein, J., Heid, S., Klinke, R. & Hartmann, R. (2006). Cochlear implants: cortical plasticity in congenital deprivation. *Progress in Brain Research*, 157, 283-313.

Kraus, N., McGee, T., Carrell, T.D. & Sharma, A. (1993). Neurophysiologic bases of speech discrimination. *Ear and Hearing*, 16, 19-37.

Kuypers, H.G., Szwarcbart, M.K., Mishkin, M. & Rosvold, H.E. (1965). Occipitotemporal corticocortical connections in the rhesus monkey. *Experimental Neurology*, 11, 245-262.

Lecanuet, J.P., Granier-Deferre, C., Cohen, H., Le Houezec, R. & Busnel, M.C. (1986). Fetal responses to acoustic stimulation depend on heart rate variability pattern, stimulus intensity and repetition. *Early Human Development*, 13, 269-283.

Lecanuet, J.P. & Schaal, B. (1996). Fetal sensory competencies. *European Journal of Obstetrics & Gynecology and Reproductive Biology*, 68, 1-23.

Lee, D. S., Lee, J. S., Oh, S. H., Kim, S. K., Kim, J. W., Chung, J. K., et al. (2001). Cross-modal plasticity and cochlear implants. *Nature*, 409, 149-150.

Lee, J.S., Lee, D.S., Oh, S.H., Kim, C.S., Kim, J.W., et al. (2003). PET evidence of neuroplasticity in adult auditory cortex of postlingual deafness. *The Journal of Nuclear Medicine*, 44, 1435-1439.

Lee, K.Y.S., van Hasselt, C.A., Chiu, S.N. & Cheung, D.M.C. (2002). Cantonese tone perception ability of cochlear implant children in comparison with normal-hearing children. *The International Journal of Pediatric Oto-Rhino-Laryngology*, 63, 137-147.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America*, 49. Suppl 2,467.

Light, G.A., Williams, L.E., Minow, F., Sprock, J., Rissling, A., Sharp, R., Swerdlow, N.R. & Braff, D.L. (2010). Electroencephalography (EEG) and event-related potentials (ERPs) with human participants. Current protocols in neuroscience, Chapter 6: Unit 6.25.1-24.

Loke, W.H. & Song, S. (1991). Central and peripheral visual processing in hearing and nonhearing individuals. *Bulletin of the Psychonomic Society*, 29, 437-440.

Luck, S.J. (2005). An Introduction to the Event-Related Potential Technique. The MIT Press, Cambridge, Massachusetts.

Makela, J.P. & Hari, R. (1990). Long-latency auditory evoked magnetic fields. *Advances in Neurology*, 54, 177-191.

Martin, B.A., Tremblay, K.L. & Korczak, P. (2008). Speech evoked potentials: From the laboratory to the clinic. *Ear and Hearing*, 29, 285-313.

Massopust, L.C., Barnes, H.W. & Verdura, J.(1965). Auditory frequency discrimination in cortically ablated monkeys. *Journal of Auditory Research*, 5, 85–93.

Maxon, A.B. & Hochberg, I. (1982). Development of psychoacoustic behavior: sensitivity and discrimination. *Ear and Hearing*, 3, 301-308.

Mayer, M.J. & Kim, B.Y. (1986). Smooth frequency discrimination functions for foveal, high-contrast, mid spatial frequencies. *Journal of the Optical Society of America*, 3, 1957-1969.

McArthur, G.M. & Bishop, D.V. (2004). Frequency discrimination deficits in people with specific language impairment: reliability, validity, and linguistic correlates. *Journal of Speech, Language, and Hearing Research*, 47, 527-541.

McArthur, G.M., Ellis, D., Atkinson, C.M. & Coltheart, M. (2008). Auditory processing deficits in children with reading and language impairments: can they (and should they) be treated? *Cognition*, 107, 946-977

McPherson, D.L. (1996). *Late potentials of the auditory system*. Evoked potential series. Provo: Singular Publishing Group Inc.

Mengler, E.D., Hogben, J.H., Michie, P. & Bishop, D. (2005). Poor frequency discrimination is related to oral language disorder in children: A psychoacoustic study. *Dyslexia*, 11, 155-173.

Mills, C. (1985). Perception of visual temporal patterns by deaf and hearing adults. *Bulletin of the Psychonomic Society,* 23, 483–486.

Mitchell, T.V. & Quittner, A.L. (1996). Multimethod study of attention and behaviour problems in hearing impaired children. *Journal of Clinical Child Psychology*, 25, 83-96.

Moore, D.R. & Amitay, S. (2007). Auditory training: Rules and applications. *Seminars in Hearing*, 28, 99-110.

Moore, D.R., Ferguson, M.A., Halliday, L.F. & Riley, A. (2008). Frequency discrimination in children: perception, learning and attention. *Hearing Research*, 238, 147-154.

Nava, E., Bottari, D., Zampini, M. & Pavani, F. (2008). Visual temporal order judgement in profoundly deaf individuals. *Experimental Brain Research,* 190, 179-188.

Näätänen, R., Gaillard, A.W. & Mantysalo, S. (1987). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42, 313-329.

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavior Brain Sciences*, 13, 201-288.

Näätänen, R., Jacobsen, T. & Winkler, I. (2005). Memory-based or afferent processes in mismatch negativity (MMN): a review of the evidence. *Psychophysiology*, 42, 25-32.

Neville, H.J. & Lawsom, D. (1987). Attention to central and peripheral visual space in a movement detection task: an event-related potential and behavioural study. II. Congenitally deaf adults. *Brain Research*, 405, 284-294.

Neville, H.J., Schmidt, A & Kutras, M. (1983). Altered vision-evoked potentials in congenitally deaf adults. *Brain Research*, 266, 127-132.

Nishimura H., Hashikawa, K., Doi, K., Iwaki, T., Watanabe, Y., et al. (1999). Sign language 'heard' in the auditory cortex. *Nature*, 397, 116.

Nishimura H., Doi, K., Iwaki, T., Hashikawa, K., Nishimura, T. & Kubo, T. (2000). Sign language activated the auditory cortex of a congenitally deaf subject: revealed by positron emission tomography. *Advances in Oto-Rhino-Laryngol*ogy, 57, 60-62.

Oh, S.H., Kim, C.S., Kang, E.J., Lee, D.S., Lee, H.J., et al. (2003). Speech perception after cochlear implantation over a 4-year time period. *Acta Oto-Laryngologica*, 123, 148-153.

Olsho, L.W., Koch, E.G., Carter, E.A., Halpin, C.F. & Spetner, N.B. (1988). Pure-tone sensitivity of human infants. *The Journal of the Acoustical Society of America*, 84, 1316-1324.

Osberger, M.J., Fisher, L. & Kalberer, A. (2000a). Speech perception in children implanted with the CLARION Multi-Strategy cochlear implant. *Advances in Oto-Rhino-Laryngology*, 57, 417-420.

Osberger, M.J., Fisher, L. & Kalberer, A. (2000b). Speech perception in adults implanted with the CLARION Multi-Strategy cochlear implant. *Advances in Oto-Rhino-Laryngology*, 57, 421-424.

Pantev, C., Hoke, M., Lehnertz, K. & Lutkenhoner, B. (1988). Neuromagnetic evidence of an amplitude organization of the human auditory cortex. *Electroencephalography & Clinical neurophysiology*, 69, 160-170.

Pelizzone, M., Williamson, S.J. & Kaufman, L. (1985). *Evidence for multiple areas in the human auditory cortex*. New York: Pergamon Press.

Peterson, N.R., Pisoni, D.B. & Miyamoto, R.T. (2010). Cochlear implants and spoken language processing abilities: Review and assessment of the literature. *Restorative Neurology and Neurosciences*, 28, 237-250.

Peterzell, D., Werner, J. & Kaplan, P. (1995). Individual differences in contrast sensitivity functions: longitudinal study of 4-, 6- and 8-month-old human infants. *Vision Research*, 35, 961-979.

Picton, T.W. (1990). Auditory evoked potentials. In: Daly DD, Pedley TA, eds. Current Practice of Clinical Electroencephalography. 2nd ed. New Yorks: Raven Press; 625-678.

Plack, C.J., Oxenham, A.J., Fay, R.R. & Popper, A.N. (2005). Pitch. Neural coding and perception. Spinger Handbook of Auditory Research. New York, USA.

Ponton, C.W. & Eggermont, J. (2001). Of kittens and kids: altered cortical maturation following profound deafness and cochlear implant use. *Audiology & Neuro-otology*, 6, 363-380.

Proksch, J. & Bavelier, D. (2002). Changes in the spatial distribution of visual attention after early deafness. *Journal of Cognitive Neuroscience, 14*,687-701.

Qi, B., Liu, B., Krenmayr, A., Liu, S., Zhang, N., et al. (2011). The contribution of apical stimulation to Mandarin speech perception in users of the MED-EL COMBI 40+ cochlear implant. *Actac Oto-Laryngologica*, 131, 52-58.

Quittner, A.L., Smith, L.B., Osberger, M.J., Mitchell, T. & Katz, D. (1994). The impact of audition on the development of visual attention. *Psychological Science, 5*, 347-353.

Rauschecker, J.P. (1995). Compensatory plasticity and sensory substitution in the cerebral cortex. *Trends in Neurosciences*, 18, 36-43.

Rauschecker, J.P. (1996). Substitution of visual by auditory inputs in the cat's anterior ectosylvian cortex. *Progress in Brain Research*, 112, 313-323.

Recanzone, G.H., Schreiner, C.E. & Merzenich, M.M. (1993). Plasticity in the frequency representation of primary auditory cortex following discrimination training in adult owl monkeys. *Journal of Neurosciences*, 13, 87-103.

Richman, J.E. & Lyons, S. (1994). A forced choice procedure for evaluation of contrast sensitivity function in preschool children. The *Journal of the American Optometric Association*, 65, 859-864.

Roche, A.F., Sivervogel, R.M., Himes, J.H. & Johnson, D.L. (1978). Longitudinal study of hearing in children: baseline data concerning auditory thresholds, noise exposure, and biological factors. *The Journal of the Acoustical Society of America*, 64, 1593-1601.

Rouger, J., Lagleyre, S., Fraysse, B., Deneve, S., Deguine, O. & Barone, P. (2007). Evidence that cochlear-implanted deaf patients are better multisensory integrators. *Proceedings of the National Academy of Sciences of the United States of America*, 104, 7295-7300.

Royal, D.W., Krueger, J., Fister, M.C. & Wallace, M.T. (2010). Adult plasticity of spatiotemporal receptive fields of multisensory superior colliculus neurons following early visual deprivation. *Restorative Neurology and Neurosciences*, 28, 259-270.

Ruben, R.J. (1995). The ontogeny of human hearing. *International Journal of Pediatric Otorhinolaryngology*, 32, S199-S204.

Sadato, N., Okada, T., Honda, M., Matsuki, K., Yoshida, M., et al. (2004). Cross-modal integration and plastic changes revealed by lip movement, random-dot motion and sign languages in the hearing and deaf. *Cerebral Cortex*, 15, 1113-1122.

Schäffler, T., Sonntag, J., Hartnegg, K., and Fischer, B. (2004). The effect of practice on low-level auditory discrimination, phonological skills, and spelling in dyslexia, *Dyslexia*, 10, 119-130.

Schneider, B.A., Trehub, S.E., Morrongiello, B.A. & Thorpe, L.A. (1986). Auditory sensitivity in preschool children. *The Journal of the Acoustical Society of America*, 79, 447-452.

Sharma, A., Dorman, M.F. & Kral, A. (2005). The influence of a sensitive period on central auditory development in children with unilateral and bilateral cochlear implants. *Hearing Research*, 203, 134-143.

Singh, S., Liasis, A., Rajput, K., Towell, A. & Luxon, L. (2004). Event-related potentials in pediatric cochlear implant patients. *Ear and Hearing*, 25, 598-610.

Shafiro, V., Gygi, B., Cheng, M.Y., Vachhani, J. & Mulvey, M. (2011). Perception of environmental sounds by experiences cochlear implant patients. *Ear and Hearing*, 32, 511-523.

Shahidullah, S. & Hepper, P.G. (1993). The development origins of fetal responsiveness to an acoustic stimulus. *The Journal of Reproductive and Infant Psychology*, 11, 135-142.

Shpak, T., Koren, L., Tzach, N., Most, T. & Luntz, M. (2009). Perception of speech by prelingual pre-adolescent and adolescent cochlear implant users. *The International Journal of Audiology*, 48, 775-783.

Spahr, A.J. & Dorman, M.F. (2004). Performance of subjects fit with the Advanced Bionics CII and Nucleus 3G cochlear implant devices. *Archives of Otolaryngology, Head & Neck Surgery*, 130, 624-628.

Smith, L.B., Quittner, A.L., Osberger, M.J. & Miyamoto, R. (1998). Audition and visual attention: the developmental trajectory in deaf and hearing populations. *Developmental Psychology*, 34, 840-85.

Stach, B.D. (1998). The Nature of hearing. Clinical audiology: an Introducion. Unpublished manuscript, San Diego.

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia*, 7, 12-36.

Tajudeen, B.A., Waltzman, S.B., Jethanamest, D. & Svirsky, M.A. (2010). Speech perception in congenitally deaf children receiving cochlear implants in the first year of life. *Otology and Neuro-otology*, 31, 1254-1260.

Tremblay, C., Champoux, F., Lepore, F. & Théoret, H. (2010). Audivisual fusion and cochlear implant proficiency. *Restorative Neurology and Neuroscience*, 28, 283-291.

Trudinger, B.J. & Boylan, P. (1980). Antepartum fetal heart rate monitoring: value of sound stimulation. *Obstetrics & Gynecology*, 55, 265-268.

Turgeon, C., Lepore, F. & Ellemberg, D. (2010). Comparison of auditory and visual detection and discrimination thresholds during development. [AAA Résumé] In: Audiology Now, San Diego, États-Unis.

Vaillancourt, V., Laroche, C., Mayer, C., Basque, C., Nali, M., Eriks-Brophy, A., Soli, S.D. & Giguere, C. (2005). Adaptation of the HINT (hearing in noise test) for adult Canadian Francophone populations. *International Journal of Audiology*, 44, 358-369.

Wei, C., Cao, K., Jin, X., Chen, X. & Zeng, F.G. (2007). Psychophysical performance and Mandarin tone recognition in noise by cochlear implant users. *Ear and Hearing*, 28, 62S-65S.

Wedenberg, E. (1965). Prenatal test of hearing. *Acta Otolaryngology*, 206, 27-32.

Withrow, R. (1968). Immediate memory span of deaf and normally hearing children. *Exceptional Children,* 35, 33-41.

Withington-Wray, D.J., Binns, K.E., Ingham, N.J. & Thornton, S.K. (1994a). The effect of monocular enucleation on the representation of auditory space in the superior colliculus of the guinea-pig. *Brain Research*, 636, 348–352.

Withington-Wray, D.J., Binns, K.E., Ingham, N.J. & Thornton, S.K. (1994b). Plasticity in the superior collicular space map of adult guinea-pigs. *Experimental Physiology*, 79 (3), 319-325.

Wright, B.A. & Sabin, A.T. (2007). Perceptual learning: how much daily training is enough? *Experimental Brain Research*, 180, 727-736.

Kong, Y.Y., Cruz, R., Jones, J.A. & Zeng, F.G. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear and Hearing*, 25, 173-185.