Université de Montréal

Réorganisation audiotactile suite à un entraînement multisensoriel ou à une privation auditive congénitale

Par

Andréanne Sharp

École d'orthophonie et d'audiologie, Faculté de médecine

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Cette thèse intitulée

Réorganisation audiotactile suite à un entraînement multisensoriel ou à une privation auditive congénitale

Présentée par

Andréanne Sharp

A été évaluée par un jury composé des personnes suivantes

Nathalie Gosselin
Président-rapporteur

François Champoux
Directeur de recherche

Adriana Lacerda
Membre du jury

Étienne deVillers-Sidani
Examinateur externe

Résumé

Des études suggèrent que certaines capacités sensorielles peuvent être augmentées chez l'humain, soit i) à la suite d'un entraînement ou ii) à la suite de privation sensorielle précoce. Des études suggèrent qu'une telle altération sensorielle peut être retrouvée chez les personnes ayant subi un entraînement musical. L'interaction entre ce qui est entendu et ressenti est spécialement importante lorsqu'un individu joue d'un instrument de musique. L'entraînement musical est reconnu comme étant une forme d'entraînement multisensoriel incluant des interactions entre des composantes auditives, visuelles et tactiles. Celui-ci peut mener à des réorganisations anatomiques et structurelles dans les régions corticales associées à ces modalités sensorielles. Plusieurs études comportementales ont révélé des habiletés de détection tactile améliorées chez les musiciens. Il est toujours incertain que ces améliorations puissent être retrouvées lors de processus plus complexes tels que la reconnaissance des émotions.

Une autre population d'étude pourrait aussi révéler une altération des capacités tactiles, soit les personnes sourdes de naissance. Des études en imagerie ont révélé que les stimuli vibrotactiles activaient les régions auditives chez les personnes sourdes, suggérant ainsi une importante réorganisation tactile chez ces individus. Pourtant, au niveau comportemental, les capacités de détection tactile semblent similaires aux contrôles. Récemment, il a été suggéré que des processus tactiles plus complexes pourraient permettre de révéler des différences comportementales entre les personnes sourdes et entendantes. Malheureusement, tout comme chez les musiciens, ces processus n'ont toujours pas été évalués à ce jour.

L'objectif principal de cette thèse est donc d'évaluer i) la perception unisensorielle tactile, auditive ainsi que multisensorielle chez les musiciens et ii) la perception unisensorielle tactile chez les sourds à l'aide de tâches non-musicales et musicales.

Chez les musiciens, les résultats de cette thèse suggèrent des capacités de discrimination fréquentielle auditive, tactile et audiotactile améliorées (étude 1) ainsi que des améliorations de la perception d'émotions musicales complexes auditive et tactile (étude 2). Ces études supportent l’hypothèse qu’une formation musicale à long terme : i) entraîne une amélioration des capacités unisensorielles auditives et tactiles, mais surtout que celle-ci s’étend à des processus tactiles complexes, ii) a un impact à tous les niveaux hiérarchiques du traitement sensoriel et cognitif.

Chez les individus sourds, les résultats ont révélé un plus haut taux d’erreurs lors de la tâche de détection d’ordre temporel tactile (étude 3). Ce résultat suggère que la cartographie spatiale du toucher est altérée chez les individus sourds. De plus, l’étude ayant mesuré la perception des émotions tactiles a révélé que ceux-ci sont capables d’identifier des émotions via la modalité tactile seule et ont même une capacité améliorée à identifier la joie (étude 4). Cette capacité accrue à percevoir la joie dans une mélodie via la modalité tactile illustre que des habiletés tactiles complexes peuvent être améliorées suite à une privation auditive de longue date. Ces deux études mises en commun illustrent que des capacités tactiles complexes non-musicales et musicales sont altérées chez l’individu sourd, ce qui supporte les études suggérant une réorganisation corticale des aires auditives et tactiles chez les individus sourds.

Mots-clés : entraînement musical, surdité, perception de la musique, perception auditive, perception tactile, intégration multisensorielle, plasticité cérébrale

Abstract

Studies suggest that some sensory abilities may be increased in humans, either i) following training or ii) following early sensory deprivation. Studies suggest that such sensory alteration can be found in people who have undergone musical training. The interaction between what is heard and felt is especially important when an individual is playing a musical instrument. Musical training is well-known as a form of multisensory training that includes interactions between auditory, visual and tactile modalities. This can lead to anatomical and structural reorganizations in the cortical regions associated with these sensory systems. Several behavioral studies have revealed improved tactile perception skills in musicians. It is still unclear whether these improvements can be found for more complex processes, such as recognition of emotions.

Similar alteration of tactile abilities may also be found in another population, namely early-deaf individuals. Imaging studies have shown that vibrotactile stimuli activate auditory regions following deafness, suggesting a significant tactile reorganization of their cortex. Yet, from a behavioral point of view, tactile perception in deaf seems similar to controls. Recently, it has been suggested that more complex tactile processes may reveal behavioral differences between deaf and normal-hearing individuals. Unfortunately, similarly to musicians, these processes have not been investigated to date.

The main objective of this thesis is therefore to evaluate via non-musical and musical tasks i) tactile, auditory and multisensory perception of music among musicians and ii) tactile perception of music among deaf individuals.

For musicians, results of this thesis suggest enhanced auditory, tactile and audio-tactile frequency discrimination capabilities (Study 1). Also, results suggest an increase perception of emotions in music, which suggests improvements for complex auditory and tactile abilities (Study 2). These studies support the hypothesis that long-term musical training: i) leads to improved auditory and tactile perception, but especially that it extends to complex tactile processes, ii) has an impact at all hierarchical levels of sensory and cognitive processing For deaf individuals, results revealed a higher error rate during the tactile temporal order detection task (Study 3). This result suggests that spatial mapping of touch is impaired in deaf individuals. In addition, the study measuring tactile perception of emotion in music revealed that they are able to identify emotions via tactile modality solely. Also, improvements were found for the identification of happy emotion via tactile modality solely (Study 4). This increased ability to perceive happiness in a melody via the tactile modality illustrates that complex tactile skills can be improved following longstanding hearing deprivation. These two studies together suggest that complex non-musical and musical tactile abilities are altered in the deaf individual, which supports studies suggesting a cortical reorganization of auditory and tactile areas following long-term auditory deprivation.

Keywords : musical training, deafness, perception of music, auditory perception, tactile perception, multisensory integration, brain plasticity

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ANOVA : Analysis of variance

CI : Cochlear Implant

ERAN : Early right anterior negativity

MANOVA : Multivariate analysis of variance

MMN : Mismatch-negativity

NH : Normal-Hearing

PCD : proportion correct difference

SOA : Stimulus onset asynchrony

TOJ : Temporal order judgment

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Chapitre 1 - Introduction

1.1 - Mise en contexte

La musique fait partie de la nature humaine. À travers l'histoire et dans chaque culture, les gens ont joué et apprécié la musique (Koelsch, 2011). L'équipe de Conard, Malina et Münzel (2009) a découvert sur des sites archéologiques des flûtes datant de plus de 35 000 ans indiquant la présence d'une tradition musicale bien établie à l'époque où les humains modernes colonisaient l'Europe. La musique occidentale telle que nous la connaissons repose sur des principes et règles dont l'histoire remonte à l'Antiquité grecque. Pythagore fût le premier à enregistrer les rapports vibratoires qui ont établi la série de notes encore utilisées dans la musique actuelle (Crocker, 1963). À travers le temps, plusieurs philosophes et scientifiques ont tenté de décrire la perception musicale. D'un côté, les artistes tentent de réinventer les règles propres à l'écriture de la musique tandis que le domaine de la psychologie tente plutôt d'en comprendre les traits du point de vue de l'auditeur (Deutsch, 2013).

1.2 - Perception auditive de base

Pour produire un son, la mécanique de l'instrument de musique va créer une perturbation de l'air environnant. La variation de pression qui en résulte se propage sous forme d'une onde. Les caractéristiques physiques du son correspondent à la fréquence, l'amplitude et le spectre de puissance (Tan, Pfordresher et Harré, 2017). En résumé, cette onde se propage jusque dans le conduit auditif externe et entraîne mécaniquement un mouvement du tympan. Celui-ci transmet cette énergie mécanique aux osselets. L'étrier pousse la fenêtre ovale de la cochlée, organe qui transforme l'énergie mécanique en énergie électrique. Le signal électrique passe alors par le nerf auditif jusqu'aux relais auditifs centraux qui mènent au cortex auditif. C'est à cette étape que le traitement de l'information sensorielle se fait. La résultante de ce traitement complexe est la perception d'un son (Tan, Pfordresher et Harré, 2017). Les dimensions physiques du son se transforment donc pour devenir la hauteur (correspondant à la fréquence), l'intensité (correspondant à l'amplitude) et le timbre (correspondant au spectre de puissance). Les dimensions temporelles (durée, temps d'attaque, temps de relâche, organisation temporelle des sons, etc.) ont aussi une influence sur la perception globale de l'objet auditif. Un des grands objectifs des neurosciences cognitives auditives est de comprendre ce phénomène.

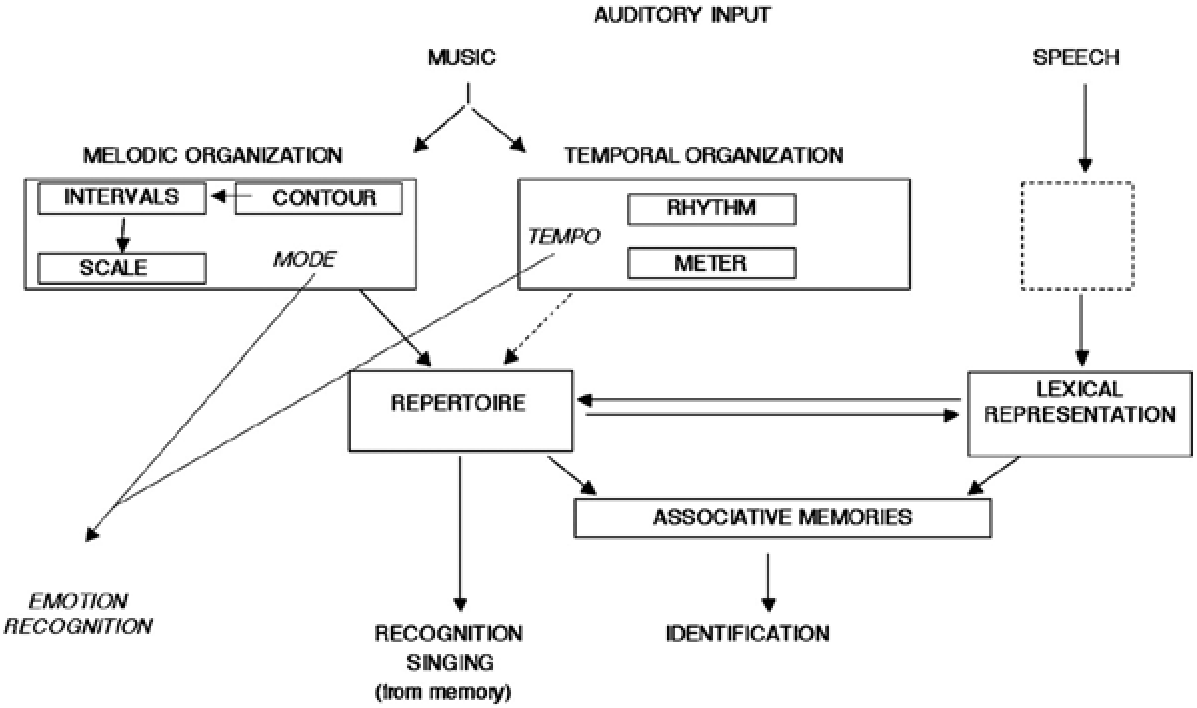
1.3 - Perception de la musique

Pour pouvoir apprécier la musique, une analyse complexe de l'extrait musical doit être faite par périphérique et central. Toutes les dimensions physiques et perceptuelles des sons décrites précédemment sont nécessaires à la perception musicale, car elles permettent d'accéder à des traitements plus complexes tels que la perception de la mélodie, du rythme, etc. Ce n'est que suite à cette analyse qu'il est possible de percevoir des émotions dans la musique et de donner un sens à ce qui est entendu (Peretz et Coltheart, 2003).

1.3.1 - Modèle de Peretz, Champod et Hyde (2003)

Plusieurs modèles ont tenté de rassembler tous ces éléments pour expliquer l'organisation de la perception musicale. L'un des modèles proposés est celui de Peretz, Champod et Hyde (2003). Celui-ci suggère qu'il existe un module spécifique dans le cerveau pour le traitement de la musique. En résumé, Peretz, Champod et Hyde (2003) (voir Figure 1.1) suggèrent qu'un stimulus musical doit être analysé dans sa dimension mélodique (variations séquentielles de la hauteur) et temporelle (variations séquentielles de la durée) avant même d'être reconnu (mémoire), susciter des émotions ou être associé à des souvenirs (dimension cognitive). Ce modèle fait une séparation entre langage et musique. Deux réseaux distincts feraient le traitement des paroles d'une chanson versus la trame instrumentale. Cette séparation devient claire dans le cas d'individus amusiques. Ces individus présentent des dommages cérébraux causant des difficultés dans la perception musicale sans affecter la compréhension et l'expression du langage (Peretz, 2009). De plus, Peretz, Champod et Hyde (2003) suggèrent que la musique instrumentale est analysée par deux systèmes parallèles représentant le quoi (mélodie) et le quand (temporel). Les chercheurs expliquent que ce modèle en deux voies est aussi vérifiable grâce aux patients présentant des lésions cérébrales, considérant qu'il est possible d'avoir une perte sélective du « quoi » (mélodie) ou du «quand» (temporel) seulement. Les étapes décrites précédemment sont nécessaires pour accéder au répertoire qui contient toutes les représentations spécifiques des phrases musicales emmagasinées auxquelles un individu a été exposé au cours de sa vie. Ce répertoire a aussi comme rôle de créer une empreinte lors de l'exposition à de nouveaux stimuli. L'étape suivante est l'accès à la mémoire sémantique (représentation lexicale liée aux paroles sur la chanson ou permettant d'en dire le titre = identification) et associative (souvenir d'un événement lié à cette chanson, émotion, etc.). La cascade d'événements permettant l'analyse des objets auditifs musicaux résulte aussi en la perception d'émotions dans la musique.

Figure 1.1 - Modèle de la perception musicale tiré de Peretz, Champod et Hyde (2003).



1.3.2 - Perception des émotions dans la musique

Dubé et Le Bel (2003) rapportent que la musique se retrouve au 8è rang des sources de plaisir les plus typiques. Cette étude suggère donc que la musique est une source de plaisir importante et difficilement égalée. Il n'est donc pas surprenant qu'au cours des dernières décennies, l'étude des émotions musicales est devenue un domaine de recherche de plus en plus populaire. Il est bien connu que la capacité à identifier une émotion dans la musique commence tôt dans la vie. Les jeunes enfants fondent leur jugement sur des indices psychoacoustiques de base tels que le tempo, la sonie et la hauteur (Adachi, Trehub et Abe, 2004). À 3 ans, les enfants sont sensibles aux connotations positives et négatives de la musique, mais leur analyse n'est pas encore suffisamment nuancée pour distinguer des émotions plus spécifiques (Kastner et Crowder, 1990). Ce n'est que vers l'âge de 5 ans que les enfants commencent à discriminer la joie et la tristesse (Terwogt et van Grinsven, 1991). Vers l'âge de 11 ans, les enfants sont capables d'identifier les émotions comme un adulte (Hunter, Schellenberg et Stalinski, 2011). Par la suite, la perception des émotions musicales est, bien sûr, modulée par l'âge et l'expérience individuelle de chacun. L'expérience émotionnelle est largement dépendante des caractéristiques structurelles décrites au tout début du modèle de Peretz, Champod et Hyde (2003), c'est-à-dire le mode et le tempo (voir Figure 1.1). Gosselin, Paquette et Peretz (2015) ajoute plus spécifiquement que l'expérience émotionnelle dépend de la hauteur, du rythme et de la dynamique de l'extrait musical. L'étude des phénomènes de base tels que la discrimination fréquentielle est donc essentielle et préalable à la compréhension des processus musicaux complexes comme la perception des émotions.

1.3.3 - Modèle neuroanatomique de la perception musicale

Zatorre, Chen et Penhune (2007) expliquent que les recherches à ce jour sur l'anatomie du cortex auditif permettent d'avoir une idée de l'organisation hiérarchique de la perception musicale dans le cerveau. Tout d'abord, plusieurs voies distinctes émergent du cortex auditif primaire dont les projections s'étendent à différentes structures. Une des voies est une projection provenant du cortex auditif primaire et serait positionnée de façon ventrale dans le néocortex temporal. Zatorre, Chen et Penhune (2007) suggèrent aussi qu'une possible seconde voie est positionnée antérieurement le long du gyrus temporal supérieur. Finalement, une autre voie suit un chemin dorsal-postérieur pour atteindre des cibles dans le cortex pariétal. Les propriétés de ces voies sont encore source d'investigation. Il est tout de même possible de mettre en lien le modèle de Peretz, Champod et Hyde (2003) de perception de la musique et les activations des structures anatomiques au niveau du cerveau mesurées par des techniques de neuroimagerie. Toutes ces recherches combinées permettent de poser des hypothèses sur l'implication des différentes voies impliquées dans la perception musicale.

Par exemple, il est bien connu que la perception d'émotions dans la musique active le système limbique (système impliqué dans la production des émotions). Une étude de Blood et Zatorre (2001) a mesuré des changements dans le rythme cardiaque, la respiration ainsi que dans l’activité électrique des nerfs et des muscles lors de l’écoute d’un stimulus musical très plaisant, provoquant des frissons chez les participants. Les résultats suggèrent aussi des augmentations et diminutions du flux sanguin dans plusieurs aires cérébrales tels le striatum ventral (qui contient les noyaux accumbens), le mésencéphal dorsal, l’insula et le cortex orbitofrontal. Ces structures sont aussi activées lors d’autres activités considérées plaisantes, comme la consommation de chocolat (Small, Zatorre, Dagher, Evans et Jones-Gotman, 2001). Ceci suggère donc que la simple écoute de musique est suffisante pour activer des circuits neuronaux impliqués dans les mécanismes du plaisir chez l’humain en général. De plus, Goldstein (1980) suggère que les frissons sont reliés à l’action de l’endorphine, hormone du plaisir. Finalement, l'étude de Salimpoor, Benovoy, Larcher, Dagher et Zatorre (2011) suggère que le striatum ventral (noyau accumbens) relâcherait plus de dopamine lors de l'écoute de musique plaisante, mais aussi lors de son anticipation (noyau caudé). Le tout témoigne que le cerveau est programmé pour que l’écoute musicale soit une activité plaisante chez l’humain.

1.3.4 - Perception de la musique : un processus multimodal

La musique demeure à ce jour un concept difficile à définir (McDermott, 2004). Historiquement, elle a été décrite comme des sons organisés (Goldman et Craft, 1961) et plus tard, comme un arrangement ordonné de sons et de silences (Cook et Clifton 1983). Le problème de ces définitions est qu’elles se concentrent uniquement sur l’aspect sonore de la musique (Good, Reed et Russo, 2014). Pourtant, la musique est un outil permettant d’étudier de nombreux aspects des neurosciences allant des apprentissages moteurs jusqu’aux émotions (Zatorre, 2005). Il ne faut donc pas négliger les éléments multimodaux tels que les mouvements du corps, les mouvements faciaux et les éléments vibrotactiles associés directement aux activités musicales, car ce sont principalement ces éléments qui rendent la musique accessible aux personnes malentendantes (Good, Reed et Russo, 2014).

Un son est en fait une vibration (Morse, 1948). Un son de forte intensité a donc la capacité de faire vibrer des objets tels que le plancher, les murs et les meubles (Good, Reed et Russo, 2014). Les récepteurs vibrotactiles de la peau sont biomécaniquement similaires aux cellules ciliées de la cochlée (Good, Reed et Russo, 2014). La principale différence entre le son et la vibration est que le spectre fréquentiel traité par la peau diffère en fonction des types de récepteurs tactiles et est plus limité (1 kHz à 1000 kHz) que celui des cellules ciliées de la cochlée (Rovan et Hayward, 2000). Les seuils de discrimination fréquentielle sont beaucoup plus élevés pour les présentations vibrotactiles que pour les présentations auditives (Verrillo, 1992). Cependant, la majorité de ces résultats sont basés sur des recherches impliquant des participants entendants (Good, Reed et Russo, 2014). Tel que décrit par Purves et al. (2011), plusieurs types de récepteurs dans la peau et le tissu sous-cutané agissent comme transducteurs pour l'information tactile et la nature biophysique de ces récepteurs varie avec leur emplacement. La peau glabre des lèvres, des paumes et des doigts contient la plus haute densité de récepteurs sensibles au toucher. La peau glabre contient cinq types principaux de récepteurs : ceux-ci incluent les terminaisons nerveuses libres, les corpuscules de Meissner, les disques de Merkel, les corpuscules de Pacini et les corpuscules de Ruffini. Les corpuscules de Pacini ne déchargent qu’une seule fois lorsqu’ils sont stimulés, ce qui les rend insensibles à pression constante. Cette propriété les rend les mieux adaptés pour la détection de l'accélération et des vibrations.

La littérature sur la perception de la musique par des sources de stimulation vibrotactile est un domaine en effervescence. Il est connu que le tempo est un élément musical facilement accessible par les vibrations chez les personnes entendantes, mais que la perception du timbre est, quant à elle, plus limitée (Good, Reed et Russo, 2014). Plusieurs études supportent l’idée que les éléments non auditifs, telle la vibration, peuvent améliorer la perception de la musique (Brochard, Touzalin, Després et Dufour, 2008; Wollman, Fritz et Poitevineau, 2014).

1.4 - Effet d’un entraînement multisensoriel sur la perception musicale

Il est bien établi que l’entraînement musical peut entraîner des changements cérébraux fonctionnels et structurels. Les études d’imagerie ont dévoilé que plusieurs zones cérébrales dont le planum temporal, le corps calleux antérieur, l’aire motrice principale de la main et le cervelet, diffèrent par leur structure et leur taille entre les musiciens et les non-musiciens (Münte, Altenmüller et Jäncke, 2002). Ces changements anatomiques donnent lieu à des améliorations comportementales. Entre autres, les musiciens présentent de meilleures performances dans des tâches impliquant le traitement auditif de la musique. Par exemple, des performances améliorées ont été mesurées pour la discrimination du timbre, de la hauteur, du rythme, etc. (pour une revue, voir Kraus et Chandrasekaran, 2010). Des processus auditifs de base sont aussi améliorés chez les musiciens. Par exemple, l'étude de Spiegel et Watson (1984) suggère que les musiciens ont un seuil inférieur dans une tâche de discrimination fréquentielle auditive. De plus, cet effet semble être corrélé avec le nombre d'années d'expertise musicale (Kishon-Rabin, Amir, Vexler et Zaltz 2001).

Des processus de plus haut niveau ont aussi été étudiés chez les musiciens. Tel que décrit précédemment, l'identification des émotions dans la musique est basée sur l'analyse faite par le cerveau des indices psychoacoustiques et des caractéristiques musicales. La possibilité que l'entraînement musical puisse améliorer la perception des émotions dans la musique a donc longtemps été présumée. En effet, il apparaît que les musiciens sont plus précis que les non-musiciens dans l'identification des émotions dans la musique (Vieillard et al., 2008). Le déclin dû à l'âge dans l'identification de l'émotion dans la musique est également moins marqué chez les musiciens (Castro et Lima, 2014).

1.4.1 - Réorganisation tactile chez les musiciens et changements comportementaux associés

Un grand nombre d'études a aussi révélé qu'un entraînement multisensoriel favorise la plasticité cérébrale et génère une réorganisation dans les régions liées au traitement audiotactile (e.g. Baumann et al. 2007; Herholz et Zatorre, 2012 ; Schulz, Ross et Pantev, 2003; Zimmerman et Lahav, 2012). En lien avec ces modifications corticales, des modulations des systèmes sensoriels chez les musiciens ont également été suggérées par des résultats dans des tâches comportementales. Par exemple, il a été démontré que les musiciens réagissent plus rapidement que les non-musiciens aux stimuli visuels (Anatürk et Jentzsch, 2015; Chang et al., 2014), tactiles (Landry et Champoux, 2017) et auditifs (Landry et Champoux, 2017; Strait, Kraus, Parbery-Clark et Ashley, 2010). L'étude de Kuchenbuch, Paraskevopoulos, Herholz et Pantev (2014) suggère que les musiciens ont de meilleures habiletés à détecter des stimuli auditifs et tactiles incongruents dans une tâche inspirée de la production musicale. De plus, une étude de notre laboratoire a utilisé une « Race Model Inequality analysis » (Raab, 1962) dans une tâche de détection auditive et tactile. Les résultats suggèrent un gain plus important lors de l'ajout d'informations tactiles aux stimulations auditives chez les musiciens versus les non-musiciens (Landry et Champoux, 2017).

De plus, une étude récente suggère que l'amélioration de la discrimination fréquentielle, telle que mesurée précédemment par Spiegel et Watson (1984), pourrait également s'étendre au traitement multisensoriel. Young, Murphy et Weeter (2017) ont utilisé une tâche simple à choix forcé comportant deux alternatives. Le participant devait décider si deux stimuli étaient identiques ou différents lorsqu'il entendait ou entendait et ressentait ces stimuli (avec l'ajout d'un gant vibrotactile). Trois types d'ondes (sinusoïdale, en dents de scie et carrée) ont été présentés afin d'évaluer les capacités musicales et non musicales de discrimination fréquentielle. Les résultats de l'étude suggèrent que l'ajout d'une stimulation tactile améliore considérablement la discrimination fréquentielle chez les musiciens par rapport aux non-musiciens, et ce tant pour les sons purs (onde sinusoïdale) que pour les formes d'ondes plus complexes (ondes en dents de scie et carrées). Les résultats sont importants, car ils suggèrent que les musiciens pourraient utiliser la modalité tactile pour percevoir la musique, ce qui peut avoir des implications pour la pratique musicale. Cependant, il n'est pas encore clair si l'amélioration des capacités de discrimination fréquentielle observée chez les musiciens résulte d'une meilleure capacité à intégrer des informations multisensorielles ou de l'addition de meilleures capacités de discrimination unisensorielle. De plus, la capacité des musiciens à mieux identifier les émotions dans la musique via différentes modalités sensorielles reste également à déterminer.

Mieux comprendre les bienfaits d'un entraînement multisensoriel sur la perception auditive et tactile est une avenue qui pourrait permettre d'améliorer les techniques de réadaptation pour aider des populations présentant une écoute de la musique déficiente en raison de leur handicap.

1.5 - Effet de la surdité sur la perception de la musique

Pour les gens ayant une audition normale, la perception de sons complexes tels que la musique fait partie du quotidien (e.g. Iakovides et al., 2004). La musique est partout autour de nous : à la radio, dans le métro, au centre d'achat ou encore dans nos technologies portables, permettant à chacun d'être entouré de mélodies tout au long de la journée. Une croyance populaire est que les individus sourds ne peuvent pas apprécier la musique. Pourtant, les statistiques illustrent que cela semble être une fausse idée commune. La majorité des individus sourds rapportent participer à des activités musicales (Good, Reed et Russo, 2014). La plupart des études s'étant intéressées à cette population ont mis l'accent sur la perception de la musique avec leur reste auditif ou avec l'aide de technologies (tels les appareils auditifs ou l'implant cochléaire). Une des plaintes principales des porteurs d'appareils auditifs est que la musique semble déformée (Feldmann et Kumpf, 1988; Chasin et Russo, 2004). La reconnaissance des mélodies et la compréhension des paroles de chansons sont aussi des difficultés rapportées par les porteurs (Feldmann et Kumpf, 1988). De plus, les études s'intéressant plutôt à l'implant cochléaire suggèrent que les porteurs ont une pauvre perception des mélodies, de la hauteur, de l'harmonicité, et du timbre (Gfeller, Witt, Stordahl, Mehr et Woodworth, 2000; Limb, 2006; Limb et Roy, 2014; McDermott, 2004; Sharp, Delcenserie et Champoux, 2018). Seuls le tempo et les rythmes de base semblent bien reconnus par les porteurs d'implant cochléaire (Cooper, Tobey et Loizou, 2008; Gfeller, Witt, Stordahl, Mehr et Woodworth, 2000; Gfeller, et al., 2007; Kong, Cruz, Jones, et Zeng, 2004; Limb, 2006; Sharp, Delcenserie et Champoux, 2018). Il est important de comprendre que ce n'est pas seulement la technologie qui entraîne ces limites à la perception adéquate de la musique, mais aussi les altérations biologiques accompagnant la surdité (pour une revue de la littérature, voir Limb et Roy, 2014).

Jusqu'à présent, peu d'études se sont intéressées à l'utilisation d'autres sens pour percevoir la musique (par exemple, la perception tactile). Pourtant, plusieurs musiciens sourds profonds confirment que l'audition n'est pas un prérequis pour participer à des activités musicales. L'exemple du célèbre compositeur Ludwig Van Beethoven, ayant écrit plusieurs pièces musicales à la suite de l'acquisition de sa surdité, reste à ce jour un cas discuté dans la littérature (par ex. Stevens, Jacobson et Crofts, 2013) et plus récemment, la célèbre percussionniste malentendante Evelyn Glennie décrit qu'elle ressent la plupart des stimuli musicaux à travers ses membres, c'est-à-dire par les jambes, les pieds, les bras, les poignets, la poitrine et la gorge (Good, Reed et Russo, 2014).

1.6 - Réorganisation tactile chez les personnes sourdes et changements comportementaux associés

Plusieurs études ont révélé que la privation d’une modalité sensorielle peut altérer le développement des autres modalités (Bavelier et Neville, 2002). La plasticité cérébrale à la suite de la désafférentation peut mener à des changements comportementaux adaptatifs ou maladaptatifs (Merabet et Pascual-Leone, 2010). Les études en imagerie réalisées à ce jour suggèrent que la stimulation tactile provoque des activations dans le cortex auditif secondaire des personnes sourdes (e.g. Auer, Bernstein, Sungkarat et Singh, 2007; Levänen, Jousmäki et Hari, 1998; Schürmann, Caetano, Hlushchuk, Jousmäki et Hari, 2006). Lorsque la vibration est présentée aux paumes et aux doigts, l'activation du cortex auditif secondaire est plus grande et plus étendue chez les participants sourds que chez les participants entendants.

1.6.1 - Détection

Tout d’abord, peu d’études ont été capables de révéler des améliorations comportementales en lien avec cette réorganisation intermodale dans des tâches de détection tactile. Les études portant sur la sensibilité cutanée chez les enfants sourds ont révélé une amélioration de la sensibilité en comparaison avec les contrôles (Chakravarty, 1968; Schiff et Dytell, 1972). Levänen et Hamdorf (2001) suggèrent des résultats similaires chez les adultes sourds. Plusieurs études ne suggèrent aucune différence entre les sourds et les contrôles dans des tâches de détection tactile de base (Donahue et Letowski, 1995; Moallem, Reed et Braida, 2010; Conway et al., 2011). Les études sur les temps de réaction tactiles sont contradictoires. Nava et al. (2014) suggèrent des temps de réaction tactiles plus rapides chez les sourds de naissance utilisateurs d’implant cochléaire. Au contraire, d’autres études suggèrent que les individus sourds de naissance ainsi que les individus sourds plus tardivement, mais porteurs d’implant cochléaire, auraient des performances similaires aux contrôles (Donahue et Letowski, 1995; Heimler et Pavani, 2014; Moallem, Reed et Braida, 2010).

Une étude récente de Noël et Wallace (2016) a utilisé la tâche bien connue des bras croisés pour mesurer la détection tactile. Cette tâche consiste à indiquer à quelle main une stimulation tactile est induite en premier dans deux conditions (bras croisés et décroisés). Chez l’individu normal, une diminution de la performance est observée lors de la position bras croisés en raison d'un conflit entre les cadres de référence permettant la perception de l'espace (Cadieux, Barnett-Cowan et Shore, 2010). Les résultats de Noël et Wallace (2016) suggèrent une augmentation significative du taux d'erreurs dans la tâche suite à une privation auditive et audio-visuelle temporaire chez un des individus normo-entendants. Les résultats pour la privation visuelle temporaire n'entraînent pas ces changements. Il semblerait donc que l'audition joue un rôle crucial, mais sous-étudié dans la détection tactile permettant la compréhension de l'espace et la perception du corps, considérant qu'aucune étude à ce jour n'a été faite chez l'individu sourd de naissance.

Au niveau musical, l'étude de Hopkins, Maté-Cid, Fulford, Seiffert et Ginsborg (2016), avait pour but de déterminer les seuils d'intensité tactile nécessaire pour détecter différentes notes de musique et suggère que les sourds sont similaires aux contrôles dans cette tâche. Deux études récentes suggèrent que les personnes sourdes peuvent suivre le rythme transmis par les vibrations (Phillips-Silver et al., 2015; Tranchant et al., 2017) ainsi que les personnes entendantes. Globalement, ces études suggèrent que les aspects fondamentaux de la musique peuvent être perçus par une perception tactile par les individus sourds, mais ne soulèvent pas de différences avec les individus contrôles.

1.6.2 - Discrimination

Les capacités de discrimination tactile ont aussi été investiguées chez l'individu sourd. Levänen, Jousmäki et Hari (1998) suggèrent que les individus sourds sont similaires aux contrôles pour discriminer des changements fréquentiels supra-seuils de stimuli vibrotactiles. Plus récemment, Landry, Guillemot et Champoux (2013) et Landry, Guillemot et Champoux (2014) suggèrent aussi des résultats similaires aux contrôles chez les porteurs d'implant cochléaire lors de tâches de discrimination fréquentielle tactile. Finalement, les études concernant la discrimination temporelle tactile sont plutôt contradictoires, alors que les résultats de Moallem, Reed et Braida (2010) ne révèlent pas de différence entre les sourds et les contrôles, Papagno, Cecchetto, Pisoni et Bolognini (2016) suggèrent une moins bonne performance chez les individus présentant une privation auditive de longue date. Par contre, la deuxième tâche de l'étude Papagno, Cecchetto, Pisoni et Bolognini (2016), mesurant la discrimination spatiale tactile, ne révèle aucune différence entre les sourds et les normo-entendants.

La discrimination tactile a aussi été investiguée à l'aide de tâches musicales. L'étude de Rosenstein (1957) suggère que la discrimination de patrons rythmiques via la modalité tactile est similaire chez l'individu sourd et normo-entendant. L'équipe de Russo, Ammirante et Fels (2012) a montré, par une étude exploratoire, que les personnes sourdes sont capables, au même titre que les individus contrôles, de distinguer efficacement le timbre musical par le biais d'une chaise transmettant uniquement la musique de façon tactile. Les études sur la discrimination tactile à ce jour ne révèlent donc pas de différence claire entre les individus sourds de naissance et les normo-entendants.

1.6.3 - Identification

Considérant que les processus de plus bas niveau (détection, discrimination) ne semblent pas être altérés par la surdité de longue date, il est possible de faire l'hypothèse que la plasticité cérébrale observée chez l'individu sourd entraîne des changements pour les tâches plus complexes. L'étude de Schiff et Dytell (1971) s'intéresse à l'identification tactile de lettres chez les enfants sourds et normo-entendants. Les résultats ne suggèrent pas de différence significative entre les groupes. Les processus tactiles plus complexes n'ont pas reçu plus d'attention à ce jour. Pourtant comme il est bien connu que les individus sourds apprécient la musique même s'ils ont de faibles capacités auditives pour la percevoir, il est possible de faire l'hypothèse que les personnes sourdes utilisent des signaux tactiles pour comprendre la musique. Les études à ce jour concernant la détection et la discrimination de stimuli auditifs chez l'individu sourd ne révèlent aucune différence significative. L'investigation à l'aide de tâches plus complexes d'identification de stimuli auditifs est donc nécessaire pour comprendre la réorganisation corticale tactile chez l'individu sourd.

Chapitre 2 - Objectifs et hypothèses de cette thèse

L'objectif principal de cette thèse est d'évaluer la perception musicale unisensorielle tactile, auditive ainsi que multisensorielle chez les musiciens et unisensorielle tactile chez les sourds à l'aide de tâches non-musicales et musicales.

Pour ce faire, quatre expériences ont été réalisées.

Étude 1

La première expérience (Chapitre 3) avait comme objectif d'évaluer la discrimination fréquentielle auditive, tactile et audiotactile chez les musiciens. En s'appuyant sur les données de neuroimagerie suggérant une réorganisation dans les régions liées au traitement audiotactile (e.g. Baumann et al. 2007; Schulz, Ross et Pantev, 2003; Zimmerman et Lahav, 2012) ainsi qu'en se basant sur les résultats comportementaux mesurés par Young, Murphy et Weeter (2017) pour des stimulations auditives et audiotactiles, nous avions prévu que les seuils de discrimination fréquentielle pour les stimulations auditives, tactiles, et audiotactiles seraient significativement plus petit chez les musiciens que chez les non-musiciens. Nous avions prévu un gain de performance plus grand chez les musiciens lors de l'ajout de la modalité tactile à la condition auditive.

Étude 2

La deuxième expérience (Chapitre 4) avait comme but d'évaluer la perception des émotions musicales par des stimulations auditives, tactiles, et audiotactiles chez les musiciens. En se basant sur les résultats comportementaux mesurés par Vieillard et al. (2008) suggérant que les musiciens sont plus précis que les non-musiciens dans l'identification des émotions dans la musique de façon auditive, en plus de la plasticité cérébrale mesurée dans le traitement audiotactile (e.g. Baumann et al. 2007; Schulz, Ross et Pantev, 2003; Zimmerman et Lahav, 2012), nous avions prévu que le pourcentage de bonnes réponses pour la perception des émotions dans la musique pour les stimulations auditives, tactiles, et audiotactiles serait significativement plus grand chez les musiciens que chez les non-musiciens pour tous les types d’émotions mesurées (joyeux, triste, épeurant, apaisant).

Étude 3

La troisième expérience (Chapitre 5) avait pour but d’évaluer l’impact d’une privation auditive permanente dès un bas âge sur la perception tactile dans une tâche sensorielle impliquant un jugement d’ordre temporel de stimuli tactiles liés à la perception du corps et de l’espace. Nous avions prévu que le taux d’erreurs dans la condition bras croisés serait plus élevé chez les sourds que chez les normo-entendants en s’appuyant sur les données obtenues par Noël et Wallace (2016) lors d’une privation auditive temporaire d’individus normo-entendants.

Étude 4

La quatrième expérience (Chapitre 6) avait comme objectif d’évaluer la perception des émotions dans la musique via la modalité tactile chez les individus sourds. Cette tâche permettra d’évaluer la perception de l’émotion joyeux, triste, épeurant et apaisant. Nous avions prévu que le pourcentage de bonnes réponses pour la perception des émotions dans la musique tactile serait significativement plus grand chez les sourds que les individus normo-entendants pour tous les types d’émotions mesurées (joyeux, triste, épeurant, apaisant).

Chapitre 3 – Improved tactile frequency discrimination in musicians

Andréanne Sharp, Marie-Soleil Houde, Maxime Maheu, Iman Ibrahim et François Champoux

Université de Montréal, Faculté de médecine, École d'orthophonie et d'audiologie, C.P. 6128, Succursale Centre-Ville, Montréal, Québec, Canada, H3C 3J7

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3.1 - Abstract

Music practice is a multisensory training that is of great interest to neuroscientists because of its implications for neural plasticity. Music-related modulation of sensory systems has been observed in neuroimaging data, and has been supported by results in behavioral tasks. Some studies have shown that musicians react faster than non-musicians to visual, tactile and auditory stimuli. Behavioral enhancement in more complex tasks has received considerably less attention in musicians. This study aims to investigate unisensory and multisensory discrimination capabilities in musicians. More specifically, the goal of this study is to examine auditory, tactile and auditory-tactile discrimination in musicians. The literature suggesting better auditory and auditory-tactile discrimination in musicians is scarce, and no study to date has examined pure tactile discrimination capabilities in musicians. A two-alternative forced-choice frequency discrimination task was used in this experiment. The task was inspired by musical production, and participants were asked to identify whether a frequency was the same as or different than a standard stimulus of 160 Hz in three conditions: auditory only, auditory-tactile only and tactile only. Three waveforms were used to replicate the variability of pitch that can be found in music. Stimuli were presented through headphones for auditory stimulation and a glove with haptic audio exciters for tactile stimulation. Results suggest that musicians have lower discrimination thresholds than non-musicians for auditory-only and auditory-tactile conditions for all waveforms. The results also revealed that musicians have lower discrimination thresholds than non-musicians in the tactile condition for sine and square waveforms. Taken together, these results support the hypothesis that musical training can lead to better unisensory tactile discrimination which is in itself a new and major finding.

3.2 - Introduction

Musical training is known to enhance multisensory integration (Herholz & Zatorre, 2012) and to alter the anatomy of multisensory structures (for a review, see Münte, Altenmüller & Jäncke, 2002). In link with these cortical changes, modulations in the sensory system in musicians have also been supported by results in behavioral tasks. For example, it has been shown that musicians react faster than non-musicians to visual (Anatürk & Jentzsch, 2015; Chang et al., 2014), tactile

(Landry & Champoux, 2017) and auditory stimuli (Landry & Champoux, 2017; Strait, Kraus, Parbery-Clark & Ashley, 2010). A study from our group used the race model inequality analysis (Raab, 1962) in an auditory and tactile detection task and demonstrated that the gain from adding tactile information to auditory inputs was greater in musicians than in non-musicians (Landry & Champoux, 2017).

Behavioral enhancement in more complex tasks has received considerably less attention in musicians. Spiegel & Watson (1984) and Micheyl, Delhommeau, Perrot & Oxenham (2006) suggested that musicians have better auditory frequency discrimination thresholds compared to non-musicians, and this appeared to be correlated with years of musical practice (or training) (Kishon-Rabin, Amir, Vexler & Zaltz, 2001). These results suggest that auditory frequency discrimination is enhanced in musicians. However, unisensory frequency discrimination capabilities have not been thoroughly explored so far. However, a few studies suggest that such enhancement of the discrimination processing might also extend to multisensory processing. Young, Murphy & Weeter (2017) used a simple two-alternative forced-choice task in which participants had to decide whether two stimuli were the same or different while hearing or hearing and feeling those stimuli with the addition of a vibrotactile glove. Three different kinds of waveforms (sine wave, sawtooth, and square) were presented to evaluate musical vs. non-musical capabilities more independently. The authors showed that adding tactile stimulation significantly improved frequency discrimination in musicians compared to non-musicians for both pure tones (sine wave) and more complex waveforms (sawtooth and square waves). The results are important as they suggest that musicians could make use of the tactile modality for perceiving music, which may have implications for musical practice. However, it is still not clear whether the discrimination capabilities observed in musicians result from an enhanced ability to integrate multisensory information per se, or an enhanced ability to discriminate auditory and tactile information separately, which would necessarily lead to better perception when both unisensory modalities are made available.

The goal of this study is to investigate unisensory and multisensory discrimination capabilities in musicians. More specifically, we aim to examine auditory, tactile and auditory-tactile discrimination in musicians using the procedure developed by Young, Murphy & Weeter (2017).

Besides being the first to examine tactile discrimination capabilities in musicians, the results will add to the scarce literature suggesting better auditory and auditory-tactile discrimination in musicians. A positive result in the tactile-only condition could indicate that the multisensory training that musicians experience has a greater impact on the development of sensory modalities than what was originally assumed. The data could also highlight the need to develop protocols to examine unisensory and multisensory discrimination processing separately in this population.

3.3 - Method

3.3.1 - Participants

Fifteen professional musicians (six women, nine men, average age = 29.5 years, age range 21–59 years) and 15 non-musicians (six women, nine men, average age = 33.6 years, age range 22–62 years) participated in the study (no significant difference between groups for age p = 0.412). Only participants with less than 1 year of musical training were recruited for the control group. All musicians were professionals since they were studying at a university level in music or working in the music field. Musicians reported piano (n = 8), guitar (n = 2), violin (n = 1), percussion (n = 1), flute (n = 1), oboe (n = 1) and trumpet (n = 1). They also reported playing only one instrument (n = 3), playing two instruments (n = 2) and playing more than two instruments (n = 10). The average age of learning of the first instrument was 7 years. The average number of years of active practice of music was 20.2 years. All participants reported have good hearing, vision, no neurological, tactile or other medical condition. A standard audiological procedure was used to ensure that participants had normal hearing. For both groups, pure-tone detection thresholds at octave frequencies ranging from 250 to 4000 kHz were within normal limits in both ears. Hearing thresholds were determined via an audiometer (Astera, GN Otometrics, Denmark). The Research Committee for Health Sciences of the University of Montreal and the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal approved all procedures, and each participant provided written informed consent. All experiments were performed in accordance with relevant guidelines and regulations.

3.3.2 - Stimuli and procedure

Method and stimuli were the same as in Young, Murphy & Weeter (2017). All stimuli were created via Audacity® Version 2.3.0 (Audacity Team 2019). Basically, these corresponded to sinusoidal, square and sawtooth complex waves whose spectrum is infinite and whose fundamental frequency is 160 Hz. Stimuli were presented in pair, one stimulus was an unmodified tone (160 Hz) and the other one was shifted in frequency. Stimulus pairs varied in frequency by ± 0; 0.25; 0.5; 0.8; 1; 1.5; 2; 3; 4; 6; 8; 12; 16; 20; 24; 36; 48 Hz. Wave types were not directly compared to each other within trials (two compared stimuli both had the same wave type, e.g., 160–172 Hz sinusoidal). Each pair of stimuli represented a type of waveforms and were presented randomly twice in a block. Each block was computed by the software Psyscope 1.2.5 (Cohen, 1993) on a Mac computer that was programmed to randomize the presentation of all pair of stimuli.

The purpose of using three types of waveforms was to simulate different musical timbres. Even if a piano and a violin produce a note having the same fundamental frequency, it is possible to determine which instrument produces which note, because they differ by timbre. Using sinusoidal waves (no harmonics), sawtooth waves (odd harmonics) and square waves (even and odd harmonics), the task becomes more representative of the frequency discrimination that occurs during music listening, representing the perception of three artificial musical instruments.

Participants were seated in a soundproof room and stimuli were presented via headphones (TDH-39, Diatec, Canada) for the auditory-only condition, via both headphones and a vibrating glove for the auditory-tactile condition, and only via the vibrating glove device for the tactile-only condition. The masking procedure during tactile stimulation was the same as used previously in our laboratory (see Landry, Guillemot & Champoux, 2013; Landry, Guillemot & Champoux, 2014). During the tactile-only condition, white noise was presented via attenuating circumaural headphones (10 S/DC, David Clark, Worcester, MA, USA) and the participant wore earplugs. A preliminary study was done to make sure that detection via bone-conduction would not be possible with this noise level.

The vibrating glove was a replication of the glove used by Young, Murphy & Weeter (2017), equipped with six independent audio-haptic voice-coil exciters. The voice-coil transducers

(TEAX14C02-8 Compact Audio Exciter) had a diameter of 14 mm and were designed to deliver vibrotactile output at frequencies the hand is most sensitive to. Stimuli were sent via a Dayton Audio DTA3116S Class D Micro Mini Amplifier (2 × 15 W), linked via an audio cable to the software Psyscope 1.2.5 (Cohen, 1993) on a Mac computer.

The participant verbally indicated whether the perceived intensity of the different tactile stimuli was the same while performing the task of discriminating two frequency stimuli during a trial practice period (ten trials). The task was divided into three blocks of 80 trials. The task was repeated three times (auditory, auditory-tactile and tactile). A constant stimuli procedure was used in this experiment to compute threshold and each ΔF was presented four times during each stimulation condition. The number of trials was based on Young, Murphy & Weeter (2017) who used three trials per intervals. One trial per intervals was added to increase the number of trials, taking into account that increasing more would lead to fatigue for participants and create a new bias. The method of constant stimuli used with 100 trials or less is as efficient and less biased that the adaptative method (Simpson, 1988).

In each trial, two stimuli that varied in frequency were presented to the participant. Each stimulus had a duration of 2 s and they were separated in time by a pause of 1 s. The participant had to identify whether the two stimuli presented were the same or different. To answer, the participant made a selection on the screen using the computer mouse.

3.3.3 - Analysis

The just noticeable difference was calculated for all conditions (see Figure 3.1 for a typical case analysis for each group): the difference between the reference frequency (160 Hz) and the frequency where the participant had a recognition score of 75% (above and under 160 Hz taken together) was used as the threshold of recognition (ΔF). Unspeeded reaction times were measured during the experiment via Psyscope software. A multivariate analysis of variance was used to compare the threshold of recognition (ΔF) between groups. Type of waves (sinus, square, saw) and modalities (auditory-only, auditory-tactile, tactile-only) were the dependent variables and group was the independent variable. Another MANOVA with the same variables was used to compare reaction times.

As explained by Gescheider (2013), the 2AFC task is not contaminated by fluctuations in the criterion. Nevertheless, response bias towards one or more observations may still exist. This type of design, however, does not guarantee a complete absence of bias. To control for the sensitivity bias, participants data were verified to ensure that there was no false-positive. If a participant had one false-positive or more (answered “different”, when stimuli were the same), he was eliminated from the study. No participant was eliminated based on that criteria.

3.4 - Results

Figure 3.2 displays the mean thresholds of recognition for auditory, auditory-tactile and tactile conditions for sine waves (Figure 3.2a), square waves (Figure 3.2b) and sawtooth waves (Figure 3.2c). Results from the one-way MANOVA revealed significant differences for ΔF for every condition except for the tactile condition with sawtooth waveform stimulation. As shown in Figure 3.2, there was a statistically significant difference in conditions based on the group [F(9, 20) = 9.534, p < 0.001; Wilk’s Λ = 0.450, partial η2 = 0.811]. Furthermore, group has a statistically significant effect in the following conditions: sinusoid auditory [F(1, 28) = 15.085; p = 0.001; partial η2 = 0.35], sinusoid auditory-tactile [F(1, 28) = 41.902; p < 0.001; partial η2 = 0.60], sinusoid tactile [F(1, 28) = 15.893; p < 0.001; partial η2 = 0.36], square auditory [F(1, 28) = 23.745; p < 0.001; partial η2 = 0.46], square auditory-tactile [F(1, 28) = 40.113; p < 0.001; partial η2 = 0.59], square tactile [F(1, 28) = 6.322; p = 0.018; partial η2 = 0.18], and sawtooth auditory [F(1, 28) = 11.648; p = 0.002; partial η2 = 0.30], sawtooth auditory-tactile [F(1, 28) = 19.349; p < 0.001; partial η2 = 0.41], but not on sawtooth tactile [F(1, 28) = 3.258; p = 0.082; partial η2 = 0.10]. The multivariate analysis of variance was not significant for reaction times [F(9, 16) = 1.341, p = 0.292 Wilk’s Λ = 0.570, partial η2 = 0.430]. In every stimulation condition, average percentage of difference in the thresholds were higher in controls compare to musicians for auditory (sinus: 66.6%; saw: 54.6%; square: 75.1%), auditory-tactile (sinus: 61.7%; saw: 60.2%; square: 56.5%) and tactile (sinus: 54.5%; saw: 34.1%; square: 46.7%).

To provide an estimation of the multisensory benefits compared to unimodal conditions, the gain from adding tactile stimulation to auditory stimulation was calculated. The formula proposed by Rouger et al. (2007) was used to calculate the gain for each participants: (auditory-tactile score − auditory score)/(100 − auditory score). The results showed that there was no gain for musicians (average 0%) in every waveform conditions. For control, there was a gain of 1% for sinus waveform and 2% for square waveform, no gain was found for saw waveform.

3.5 - Discussion

The main goal of this study was to evaluate the effect of musical training on frequency discrimination of auditory-only, auditory-tactile and tactile-only stimuli. We found a significant difference between groups for auditory, tactile, and auditory-tactile stimulation where musicians had smaller discrimination threshold than non-musicians. For the auditory-only condition, these results are consistent with previous studies that have shown that musicians have better performance on simple frequency discrimination tasks (Spiegel & Watson, 1984; Kishon-Rabin, Amir, Vezler & Zaltz et al., 2001; Micheyl, Delhommeau, Perrot & Oxenham, 2006). Other studies investigating spectral aspects of music are using more complex stimuli such as chords or musical instrument samples to show that musicians have superior pitch discrimination or timbre discrimination. For example, Tervaniemi, Just, Koelsch, Widmann & Schröder (2005) have shown that musicians can detect pitch changes faster and more accurately compared to non-musicians; these behavioral differences are accompanied by larger amplitude N2b and P3 responses. Those results combined with our results support the hypothesis that musicians have improved performance for unisensory abilities and, furthermore, support the increased auditory cortical representation in musicians found by imaging studies (Pantev et al., 1998). Our results in the auditory-tactile condition are also consistent with Young, Murphy & Weeter (2017), who used the same device to test frequency discrimination thresholds. Musicians and non-musicians had better discrimination when stimuli were presented in both modalities, but musicians outperformed them in the auditory-tactile condition. Even though musicians outperformed controls in the auditory-tactile condition, no gain was measured for musicians compared to a weak gain measured in controls. This can be explained by a ceiling effect. It is well-known that auditory musical abilities in general in musicians are improved (for a review see Kraus & Chandrasekaran 2010). This can explain why controls were able to use information from tactile stimulation to improve their performance while musicians were already performing too well to improve more. These results are consistent with the fact that in the auditory-only condition, musicians had a much better performance than controls. Finally, the fact that control were able to use output from tactile stimulation to improve their performance in a frequency discrimination is it itself an interesting new finding. The exact neural correlates for the reported frequency discrimination task used here are still open for investigation, since no imaging studies to date have used a protocol that includes haptic stimulation similar to ours. Further studies should use a more sensitive task to avoid the possible ceiling effect found in this study.

The present study was the first to investigate tactile-only discrimination of frequency in musicians. This study revealed that musicians are better in the tactile-only condition, which is in itself a new and major finding. No study to date has shown that the frequency discrimination threshold for simple tactile stimuli is improved in musicians. These results are consistent with the previous investigation, suggesting that musical training enhances performance in less complex tasks, such as stimulus detection (Landry & Champoux, 2017). The present study adds to the existing literature on unisensory processing in musicians by suggesting for the first time that long-term musical training can also improve tactile performance in more complex tasks.

Results for reaction times showed no significant differences between groups. Previous studies have revealed that musicians react faster than non-musicians to visual stimuli (Anatürk & Jentzsch, 2015; Chang et al., 2014), tactile stimuli (Landry & Champoux, 2017) and auditory stimuli (Landry & Champoux, 2017; Strait, Kraus, Parbery-Clark & Ashley, 2010). All these studies used a simple reaction time protocol to report when a stimulus was detected by the participant. The lack of difference between musicians and non-musicians for reaction time may be explained by the complexity of the task. Further studies are needed to investigate reaction time in more complex tasks for auditory and tactile stimuli.

No difference was found between musicians and non-musicians for the tactile-only condition for sawtooth waveform. The sawtooth waveform sound contains both even and odd harmonics of the fundamental frequency, hence it is closer to music compared to the other two stimuli: square waveform (odd harmonics) and sine waveform (pure tone). Because most people have experience discriminating between frequencies while listening to music, this could explain the non-significant difference in performance between musicians and non-musicians. Further studies are needed to validate this hypothesis.

It is well-known that the type of instrument played can influence cortical plasticity. For example, Elbert, Pantev, Wienbruch, Rockstroh & Taub (1995) found that in a group of expert string instrumentalists, the region of the somatosensory cortex that represents input from the left hand was significantly more responsive to tactile stimulation than in non-musicians. Also, Gruhn (2002) found that it is easier to learn in early childhood than in the later years. Researchers suggest that up to 7 years of age there is a sensitive period, beyond which music-induced structural changes and learning effects are less pronounced (for a review see Habib & Besson 2009). Furthermore, Gaser & Schlaug (2003) have demonstrated that the amount of gray matter differs between professional musicians, amateur musicians and non-musicians in the motor, auditory and visual-spatial regions. The more a musician was trained, the larger was the quantity of gray matter. The homogeneity of the group of musicians in this study did not allow us to incorporate covariates such as the degree of musician training, the type of instrument played, the type of music played, the age of learning of the first instrument or the number of hours of practice. The musicians who participated in this study were all professional musicians, most of them played piano as a principal instrument and started to play music around 7 years of age. Further study should investigate if these characteristics influence tactile frequency discrimination in musicians.

In conclusion, this study provides the first investigation of a frequency discrimination task in musicians in the tactile-only modality; results revealed a smaller threshold compared to controls. This major new finding suggests that not only are multisensory abilities improved in musicians, as found in past studies, but that non-auditory unisensory abilities are also improved. The precise nature and cause of this enhanced non-auditory discrimination in musicians will need to be documented in further research. Also, various types of musicians should be investigated in the future to investigate the influence of the type of musical instrument played, the number of instrument played, the age of learning the first instrument, the number of hours of practice and all others characteristics that have been suggested to influence musicians' performance in the past.

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3.7 - Publisher's Note

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3.9- Appendices

Figure 3.1 - Typical psychometric function in response to sine waveform in a control (A) and a musician (B) in the three experimental conditions (auditory, auditory-tactile and tactile).

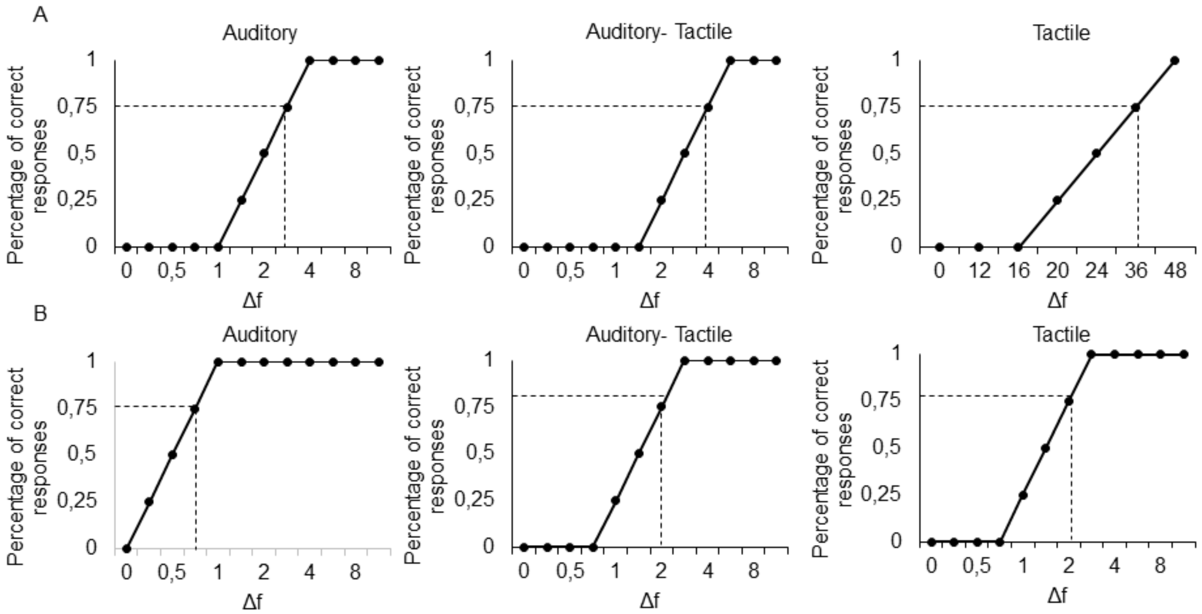
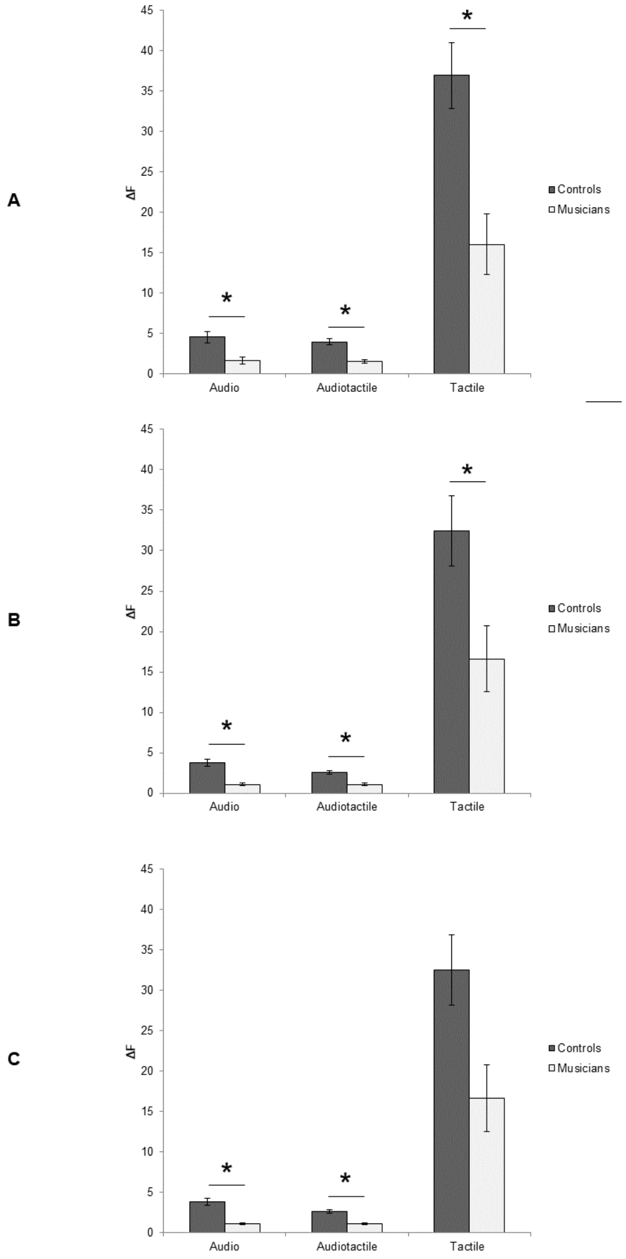


Figure 3.2 - Frequency discrimination threshold average for non-musicians and musicians for the three test conditions (auditory, auditory-tactile, tactile) for a) sine waveform stimuli. b) square waveform stimuli. c) sawtooth waveform stimuli. * = p < 0.05



Chapitre 4 – Musicians show better auditory and tactile identification of emotions in music

Andréanne Sharp, Marie-Soleil Houde, Benoit-Antoine Bacon et François Champoux

Université de Montréal, Faculté de médecine, École d'orthophonie et d'audiologie, C.P. 6128, Succursale Centre-Ville, Montréal, Québec, Canada, H3C 3J7

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4.1 - Abstract

Musicians are better at processing sensory information and at integrating multisensory information in detection and discrimination tasks, but whether these enhanced abilities extend to more complex processes is still unknown. Emotional appeal is a crucial part of musical experience, but whether musicians can better identify emotions in music throughout different sensory modalities has yet to be determined. The goal of the present study was to investigate the auditory, tactile and audiotactile identification of emotions in musicians. Melodies expressing happiness, sadness, fear/threat, and peacefulness were played and participants had to rate each excerpt on a 10-point scale for each of the four emotions. Stimuli were presented through headphones and/or a glove with haptic audio exciters. The data suggest that musicians and control are comparable in the identification of the most basic (happiness and sadness) emotions. However, in the most difficult unisensory identification conditions (fear/threat and peacefulness), significant differences emerge between groups, suggesting that musical training enhances the identification of emotions, in both the auditory and tactile domains. These results support the hypothesis that musical training has an impact at all hierarchical levels of sensory and cognitive processing.

4.2 - Introduction

It is well established that musical training can lead to functional and structural changes in the brain, and that these changes correlate with improved music processing as measured by pitch, timing and timbre discriminations (for a review see Kraus & Chandrasekaran, 2010). Of particular importance to the present study, a number of studies have revealed that long-term musical training promotes brain plasticity and generates reorganization in regions related to audiotactile processing (e.g., Pantev et al., 2003; Baumann et al., 2007; Zimmerman & Lahav, 2012).

At the behavioral level, it has been shown that in detections tasks, musicians react faster to auditory and tactile stimuli (Landry & Champoux, 2017) and are also better at integrating auditory and tactile information (Landry, Sharp, Pagé & Champoux, 2017). In auditory frequency discrimination tasks, musicians have lower threshold compared to controls (Spiegel & Watson, 1984), and this effect appears to be correlated with years of musical expertise (Kishon-Rabin, Amir, Vexler & Zaltz, 2001).

To examine whether such discrimination enhancements extended to multisensory processing, Young, Murphy & Weeter (2017) used a two-alternative forced choice task in which participants had to determine whether a pair of stimuli were the same or different. Participant could hear the stimuli, combined or not with a corresponding tactile stimulation transmitted through a glove. The results revealed that compared to controls, musician frequency discrimination threshold was improved significantly by the addition of tactile stimulation.

Recent results from our laboratory have confirmed such frequency discrimination enhancements in the auditory and audiotactile domains and have extended the latter by demonstrating that musicians were also better at discriminating tactile-only stimuli applied to the hand (Sharp, Houde, Maheu, Ibrahim & Champoux, 2019). Taken together, these results suggest that musical training can have an impact on sensory processing, at least in detection or discrimination tasks. Whether such enhanced abilities can extend to more complex processes remains a matter of debate.

During the last decades, the study of emotions in music has become an increasingly popular research field. It is known that the ability to identify emotion in music starts early in life and that young children base their judgments on basic psychoacoustic cues such as tempo, loudness and pitch (Adachi, Trehub & Abe, 2004). At 3 years of age, children are sensitive to the positive and negative connotations of music but their analysis is not yet sufficiently nuanced to distinguish between more specific emotions (Kastner & Crowder, 1990). It is only around 5 years of age that children begin to discriminate happiness and sadness (Terwogt & Van Grinsven, 1991).

Around 11 years of age, children are able to identify emotions at the adult level (Hunter, Schellenberg & Stalinski, 2011). Since the identification of emotions in music is based on psychoacoustic cues and musical features, the possibility that musical training might enhance this ability has long been surmised. Indeed it appears that musicians are more accurate than non-musicians in the identification of emotions in music (Vieillard et al., 2008). Decline due to age in the identification of emotion in music is also less marked in musicians (Castro & Lima, 2014).

Emotion identification abilities in musicians have not been examined further and the capacity of musicians to better identify emotion in music throughout different sensory modalities also remains to be determined.

The present study aims at investigating the auditory, tactile and audiotactile identification of various emotions in musicians using the stimuli of Vieillard et al. (2008) and tactile stimulation technology developed by Young, Murphy & Weeter (2017). This study will be the first to examine tactile and auditory-tactile identification of emotion abilities in musicians versus controls.

4.3 - Methods

4.3.1 - Participants

Seventeen professional musicians (7 women, 10 men, average age = 28.9 years) and 17 matched non-musicians (8 women, 9 men, average age = 34.4 years) participated in the study. Non-musicians and musicians were matched for age, sex, handedness, educational level, and hearing thresholds. Only participants with less than 1 year of musical training were recruited for the non-musician (control) group. The sample size of this study is justified by the restrictive criteria used for inclusion in the musicians' group. All musicians were working in the music field or studying music at the university level. The musicians specialized in piano (n = 9), guitar (n = 2), trumpet (n = 2), violin (n = 1), percussion (n = 1), flute (n = 1) and oboe (n = 1). They reported playing only one instrument (n = 4), playing two instruments (n = 2) or playing more than two instruments (n = 11). The average age of beginning to learn their first instrument was 7 years old. The average number of years of active practice of music was 20 years. Hearing thresholds were determined with an audiometer (Astera, GN Otometrics, Denmark). For both groups, pure-tone detection thresholds at octave frequencies ranging from 250 to 4000 kHz were within normal limits in both ears. The Research Committee for Health Sciences of the University of Montreal and the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal approved all procedures, and each participant provided written informed consent. All experiments were performed in accordance with relevant guidelines and regulations.

4.3.2 - Stimuli and Procedure

The stimuli used in this study were developed by Vieillard et al. (2008). They are 56 melodies produced by a digital synthesizer in piano timbre. These instrumental stimuli were composed in the tonal musical tradition to express four emotions: happiness, sadness, fear/threat and peacefulness. The stimuli vary in mode, dissonance, pitch range, tone density, rhythmic regularity, and tempo but do not vary in performance-related expressive features (e.g., vibrato or variations of articulation/phrasing). Therefore the identification of emotions was based exclusively on the compositional structure. The mean duration of each stimuli was 12.4 s. All stimuli were originally validated by Vieillard et al. (2008) and were also cross-culturally validated by Fritz et al. (2009). These stimuli have been designed to elicit specific emotions that can be universally recognized.

The battery of Vieillard et al. (2008) was selected for this experiment because the four emotions evoked by the melodies are easily recognized and discriminated. Furthermore, all stimuli were validated cross-culturally by Fritz et al. (2009), and across age groups by Lima & Castro (2011). Finally, peacefulness is the most likely stimulus in this experiment to avoid a ceiling effect in musicians which show near perfection identification for better known emotions such has happy and sad.

Each of the 56 melodies were presented in a randomized order in three stimulation conditions: auditory-only, tactile-only and auditory-tactile. There were 14 stimuli for each type of emotion. For each stimuli, participants had to rate how much the melody expressed each of the four emotions on a 10-point intensity scale ranging from 0 (absent) to 9 (present). The four scales were presented immediately after each stimulus, and always in the same order (happy/sad/scary/peaceful). Each melody was presented only once in random order during each block (auditory only, tactile only and auditory-tactile) and no feedback was given. All conditions for stimulation and emotion were randomized. For example, one participant started in the tactile condition with a peaceful stimulus, while another started in the auditory condition with a sad stimulus. To exactly replicate the standardized task of Vieillard et al. (2008), the order of the scale presented after each stimulus was not counterbalanced.

Participants were seated in a soundproof room and stimuli were presented via headphones (TDH-39, Diatec, Canada) for the auditory-only condition, via a vibrating glove device for the tactile-only condition, and via both headphones and a vibrating glove for the auditory-tactile condition. During the tactile-only condition, white noise was presented via headphones and the participant wore earplugs. The participant had to adjust the volume during practice trials so as not to hear the vibrating glove.

The vibrating glove was a replication of the glove used by Young, Murphy & Weeter (2017) and was equipped with six independent audio-haptic voice-coil exciters. The voice-coil transducers (TEAX14C02-8 Compact Audio Exciter) had a diameter of 14 mm and were designed to deliver vibrotactile output. The frequency range of these speakers is 300 to 20,000 Hz. Stimuli were sent via a Dayton Audio DTA3116S Class D Micro Mini Amplifier (2 × 15 W), linked via an audio cable to the software Psyscope 1.2.5 (Cohen, 1993) on a Mac computer.

4.3.3 - Analysis

The percentage of accurate responses, defined as the highest rating score for a melody corresponding to the intended emotion, was calculated for each participant for each emotion. For example, given a happy melody and a rating of Happy = 7, Sad = 3, Fear = 2, Peaceful = 6, the response would be counted as correct, whereas Happy = 6, Sad = 3, Fear = 2, Peaceful = 7 would be counted as incorrect. The same rating could never be used twice for any of the melody ratings.

An ANOVA was used as an omnibus test to compare the percentage of accurate responses for stimulation conditions and emotions as within-subject factors and groups as a between-subject factor. A multivariate analysis of variance was used to compare the percentage of accurate responses between groups. To provide an estimation of multisensory benefits compared to unimodal stimulation, the increase in performance was measured by subtracting the score in the auditory only condition from the score in the auditory-tactile condition. The results provide an estimation of the contribution of tactile stimulation.

4.4 - Results

Figure 4.1 displays the percentage of accurate responses for auditory, tactile and auditory-tactile conditions for each of the emotions. An ANOVA for stimulation conditions, emotions and groups was used as an omnibus test. There was a significant difference between groups ($F(1,32) = 10.834$, $p = 0.002$). There was also a significant interaction between the condition and emotion variables ($p < 0.0001$).

The multivariate analysis of variance used to compare the percentage of accurate responses revealed a statistically significant difference in conditions based on Group ($F(12, 21) = 2.585$, $p = 0.027$; Wilk's $\Lambda = 0.404$, partial $\eta 2 = 0.596$). Table 4.1 shows that there were significant differences between groups for fear/threat auditory, peacefulness auditory and peacefulness tactile whereas no significant differences between groups were found in the other conditions.

Uncorrected t-tests revealed that for both groups, mean percentage of responses was above chance for auditory and auditory-tactile stimulation conditions for all type of emotions ($p < 0.001$). For tactile stimulation, uncorrected t-tests revealed that the mean percentage of responses was above chance for both groups for happy ($p < 0.001$) and fear/threat emotions (controls: $p = 0.002$, musicians: $p < 0.001$), but not for sad (controls: $p = 0.153$, musicians: $p = 0.747$). Finally, an uncorrected t-test showed that musicians were performing above chance for tactile stimulation for peaceful emotion ($t(16) = 2.170$, $p = 0.045$) while on the contrary, another uncorrected t-test showed that controls were performing below chance for tactile stimulation for peaceful ($t(16) = -4,629$, $p < 0.001$).

For the happiness and sadness conditions, no increases in performance were observed in the auditory-tactile compared to the auditory-only condition in either groups (mean under 0%). For sadness and peacefulness, there were increases measured for controls (Sadness: 4% and Peacefulness: 12%), but not for musicians (mean under 0%). After correcting for multiple comparisons he increase in performance between auditory and auditory-tactile stimulation was not significant for either musicians or controls (see Table 4.2 for more details).

ANOVAs were used as an omnibus test to compare the number of errors between groups for each expected emotion (4). The dependent variable was the number of errors and independent variables were groups, stimulation conditions and categories of the emotion scale. The ANOVAs for happiness (F(1,32) = 0.141, p = 0.710), sadness (F(1,32) = 0.196, p = 0.661) and fear/threat (F(1,31) = 3.061, p = 0.090) revealed no differences between groups. There was a significant difference between groups for peacefulness (F(1,32) = 10.691, p = 0.003). t-Test analysis revealed differences between groups for sadness when the expected emotion was peacefulness. This emotion had the higher rate of error for both groups. The difference between groups was the number of error, but not the type of emotion wrongly associated with peacefulness. In all conditions, both group were doing the same kind of errors for each type of emotion as shown in Table 4.3. In the auditory stimulation condition, for both groups, the emotion with which happiness and sadness was most often confused with was peacefulness. Similarly, for both groups, the emotion with which fear/threat and peacefulness were most often confused with was sadness. Results were the exact same in the auditory-tactile stimulation. In the tactile stimulation condition, for both groups, the emotion with which happiness was most often confused with was fear/threat. For all other emotions in the tactile stimulation condition, errors were distributed across the other three type of emotions. The missing values in Table 4.3 are due to the fact that it was not possible to categorize some errors, because some participants were giving a 0 score to all types of emotions in the scale for a few trials.

4.5 - Discussion

The main objective of the present study was to investigate auditory, tactile and auditory-tactile identification of emotion in musicians versus non-musicians. A significant difference between groups was found, with musicians showing better emotion identification for fear/threat in the auditory condition and for peacefulness in both the auditory and tactile conditions. Additionally, even if the difference does not remain significant after correcting for multiple comparisons, the trend indicates a possible gain from adding tactile stimulation to the auditory stimuli in peacefulness condition for controls (12%), but not for musicians (under 0%).

The significant differences found between controls and musicians can be linked to the complexity of the emotions displayed. It is well-known that happiness and sadness are the easiest emotions to identify because they are mainly based on tempo (see Terwogt & Van Grinsven, 1991). As such it is not surprising that results revealed no difference between controls and musicians for happy (auditory, auditory-tactile and tactile) and sad (auditory and auditory-tactile) conditions as there were ceiling effects. The average performance for sad for tactile stimulation did not differ between groups, but also, did not differ from chance for both groups. A more sensitive task would be needed to determine whether musical expertise can lead to more accurate identification of these emotions via auditory, tactile and auditory-tactile stimulation. Fear/threat is a musically less straightforward emotion than happiness and sadness (Vieillard et al., 2008; Tan, Pfordresher & Harré, 2017). Hence, compared to controls, musicians more accurately identified that emotion in the auditory condition. In the same vein, the most complex and ambiguous emotion displayed in the sample melodies, namely peacefulness (Vieillard et al., 2008; Tan, Pfordresher & Harré, 2017), was more accurately identify by musicians than by controls in both the auditory and the tactile conditions.

Results from the auditory condition are consistent with the extensive literature demonstrating that musical training leads to brain plasticity and can improve music processing as measured by pitch, timing and timbre discriminations (for a review see Kraus & Chandrasekaran, 2010). Since the identification of emotions in music is based on psychoacoustic cues and musical features, the enhanced performance of musicians in the auditory condition was also to be expected. Furthermore, an important component of musical training is aimed at understanding and experiencing the full range of emotional meaning and expressiveness, however faint, of a musical performance (Castro & Lima, 2014). As such, it is not surprising that improved performance was only found in conditions where musicians had to identify subtle emotional qualities.

One recent study have investigated recognition of emotions in an auditory-only stimulation condition. They suggest a correlation between years of musical training and accuracy at identifying emotion in music and revealed a significant difference between groups for older musicians with respect to sad and fear emotions (Castro & Lima, 2014). It should be noted that a major limitation of this study was that the range of musical expertise of participants as measured in years was large (8–18 years), and that the average age of training onset was over 7 years of age, the known threshold beyond which music-induced structural changes and learning effects become less pronounced (for a review see Habib & Besson, 2009). As such the lesser musical expertise of their younger participants may explain why they could not find any significant differences between groups. In contrast, results from the present study were obtained with participants whose average age of learning onset was 7 years of age, and whose average number of years of active practice of music was 20.2 years. All participants were working or studying full-time in the field of music and can be considered professional musicians. In addition, the average age of the participants was 34.4 years for controls and 28.9 years for musicians, which corresponds to the younger group of Castro & Lima (2014).

The present study was the first to investigate the tactile identification of emotions in music. Results revealed that both musicians and controls were able to identify emotions via tactile stimulation only, which is in itself a new and major finding. No study to date has investigated purely tactile identification of emotion in music. The only existing study along these lines was performed by Branje, Nespoil, Russo & Fels (2013) and suggests that multisensory stimulation can increase emotion perception in film. By using the Emoti-Chair, a device that induces vibration in the back of normal-hearing participants, they found increases in skin conductance levels when vibrotactile stimuli were added to audio/visual film content. They also observed that not only the intensity of vibration but also the frequency of the vibrotacile stimuli was playing a role in the observed reactions. The present study results are consistent with Branje, Nespoil, Russo & Fels (2013) and further support the hypothesis that both controls and musicians are able to extract meaningful information from the frequency characteristics of a signal presented through vibrations only. Furthermore, for the emotion of peacefulness, results revealed a significant difference between musicians and controls for tactile stimulation. These results are consistent with a previous study from our laboratory, the first to demonstrate that musicians were better at discriminating frequencies via tactile stimulation applied to the hand (Sharp, Houde, Maheu, Ibrahim & Champoux, 2019). The enhanced ability to identify peaceful emotions in music via tactile stimulation suggests that more complex processes are improved following long-term musical training. This hypothesis should be verified using other types of complex emotions that are easier to identify via tactile stimulation than peacefulness. Indeed, results in the peacefulness condition are above chance for musicians, but not for controls and the comparison of performance would be easier to interpret if both groups were above chance.

It is well-known that the frequency spectrum treated is more limited than that of the hair cells of the cochlea (1 to 1000 kHz) (Rovan & Hayward, 2000). Which musical components is perceived though the tactile modality remains a question of debate. Some studies suggest that non-musicians can detect different musical notes via the tactile modality (Hopkins, Maté-Cid, Fulford, Seiffert & Ginsborg, 2016) and that they can discriminate timbre (Russo, Ammirante & Fels, 2012). Furthermore, low frequencies in music are important to understanding beat and can be transmitted via vibrotactile devices (Van Dyck et al., 2013; Tranchant et al., 2017). All these psychoacoustic cues are known to be transmitted via the tactile modality and are all important for emotion identification in music. Further study should investigate if other cues are used in the identification of emotion in the tactile domain or if some of these cues are more important than the others. All these studies support our results suggesting that non-musicians and musicians are able to identify emotion via tactile stimulation only.

Finally, the lack of significant difference between musicians and non-musicians in the auditory-tactile condition can be explained by the trend for controls toward exhibiting gain from tactile stimulation compared to musicians, as the latter were already too skilled in the auditory domain to benefit from tactile stimulation. Further studies should use more complex emotional stimuli to assess whether there could be a tactile gain for musicians, and investigate whether non-musicians' performance could become similar to that of musicians with training and feedback.

4.6 - Data Availability

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

4.7 - Ethics Statement

This study was carried out in accordance with the recommendations of Research Committee for Health Sciences of the University of Montreal and the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Research Committee for Health Sciences of the University of Montreal and the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal.

4.8 - Author Contributions

AS and FC designed and performed the experiment. All authors wrote the manuscript, discussed the results and implications, and commented on the manuscript at all stages.

4.9 - Funding

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4.10 - Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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4.12 – Appendices

Tableau 4.1 - Statistical results from the multivariate analysis of variance used to compare percentage of accurate responses between groups (auditory, tactile, auditory-tactile) for all four emotions.

	Auditory	*Tactile*	*Auditory-Tactile*
Happy	F(1, 32) = 0.313 p = 0.579 partial η2 = .0.010	F(1, 32) = 0.023 p = 0.881 partial η2 = .0.001	F(1, 32) = 0.020 p = 0.887 partial η2 = .0.001
Sad	F(1, 32) = 3.010 p = 0.092 partial η2 = .0.086	F(1, 32) = 1.859 p = 0.182 partial η2 = .0.055	F(1, 32) = 0.797 p = 0.379 partial η2 = .0.024
Fear/Threat	F(1, 32) = 4.23 **p = 0.048*** partial η2 = 0.117	F(1, 32) = 2.379 p = 0.133 partial η2 = .0.069	F(1, 32) = 1.940 p = 0.173 partial η2 = .0.057
Peacefulness	F(1, 32) = 15.838 **p < 0.001*** partial η2 = .0.331	F(1, 32) = 8.432 **p = 0.007*** partial η2 = 0.209	F(1, 32) = 1.531 p = 0.225 partial η2 = .0.046

Tableau 4.2 - Mean percentage of increase in performance from adding tactile stimulation to auditory stimulation (Auditory-tactile performance – Auditory only performance).

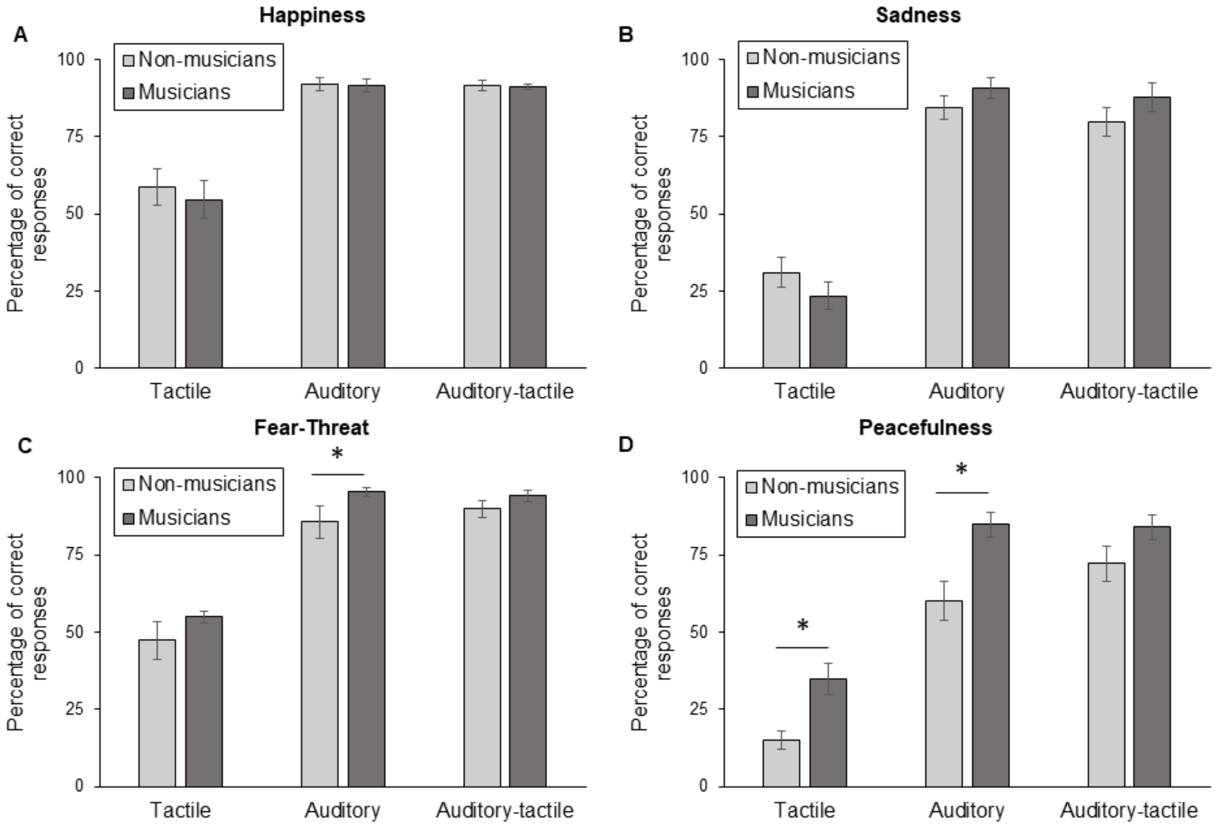
	Group	*Mean (%)*	*Standard error of the mean*	*T-test: Auditory versus Auditory-tactile performance*
Happiness	Controls	-0.50	2,04	t(16) = 0.833, p = 0.417
	Musicians	-0.39	2,15	t(16) = 0.190, p = 0.851
Sadness	Controls	-4.59	5,96	t(16) = 2.048, p = 0.057
	Musicians	-2.87	3,00	t(16) = 0.975, p = 0.344
Fear/Threat	Controls	4.24	3,51	t(16) = -1.357, p = 0.193
	Musicians	-1.20	1,52	t(16) = 0.824, p = 0.422
Peacefulness	Controls	12.19	5,73	t(16) = 2.318, p = 0.034
	Musicians	-0.78	3,50	t(16) = 0.235, p = 0.818

Tableau 4.3 - Mean percentage of correct responses and mean percentage of errors per emotion classified by the type of emotion wrongly identified.

	Auditory							
	Happiness				Sadness			
	Correct	Sadness	Fear/Threat	Peacefulness	Correct	Happiness	Fear/Threat	Peacefulness
Controls	92,02	0,84	0,84	6,72	86,98	0,42	2,10	7,14
Musicians	91,61	0,84	0,00	7,56	90,76	0,42	2,10	7,14
	Fear/Threat				Peacefulness			
	Correct	Happiness	Sadness	Peacefulness	Correct	Happiness	Sadness	Fear/Threat
Controls	84,45	7,14	10,50	1,68	61,77	19,75	**23,93***	0,84
Musicians	95,38	0,00	3,36	0,42	84,87	6,30	**8,86***	0,00
	Auditory-tactile							
	Happiness				Sadness			
	Correct	Sadness	Fear/Threat	Peacefulness	Correct	Happiness	Fear/Threat	Peacefulness
Controls	90,23	0,00	0,00	3,78	76,47	0,42	2,94	10,50
Musicians	91,19	1,26	0,00	6,30	87,84	0,00	4,62	5,46
	Fear/Threat				Peacefulness			
	Correct	Happiness	Sadness	Peacefulness		Happiness	Sadness	Fear/Threat
Controls	89,50	0,42	3,36	0,84	75,64	9,24	17,65	0,84
Musicians	94,12	0,42	4,20	0,42	84,05	6,30	8,82	0,00

	Tactile							
	Happiness				Sadness			
	Correct	Sadness	Fear/Threat	Peacefulness	Correct	Happiness	Fear/Threat	Peacefulness
Controls	55,87	8,82	26,07	8,82	33,18	21,43	25,63	18,49
Musicians	54,63	6,30	19,71	16,81	23,51	15,97	25,21	31,93
	Fear/Threat				Peacefulness			
	Correct	Happiness	Sadness	Peacefulness	Correct	Happiness	Sadness	Fear/Threat
Controls	45,78	21,85	24,79	13,39	13,85	41,60	3,00	23,11
Musicians	55,03	9,24	19,33	13,03	35,71	27,31	16,39	17,65

Figure 4.1 - Percentage of correct responses for non-musicians and musicians for the three test conditions(Tactile, Auditory, Auditory-tactile) for (A) happy, (B) sad, (C) fear/threat, (D) peacefulness. Error bars represent the mean standard error. * = p < 0.05



Chapitre 5 – Deafness alters the spatial mapping of touch

Andréanne Sharp, Simon P. Landry, Maxime Maheu et François Champoux

Université de Montréal, Faculté de médecine, École d'orthophonie et d'audiologie, C.P. 6128,

Succursale Centre-Ville, Montréal, Québec, Canada, H3C 3J7

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5.1 - Abstract

Auditory input plays an important role in the development of body-related processes. The absence of auditory input in deafness is understood to have a significant, and even irreversible, impact on these processes. The ability to map touch on the body is an important element of body-related processing. In this research, the crossed-arm TOJ task was used to evaluate the spatial mapping of touch. This task elicits a conflict between visual and somatosensory body-related information through a change in posture. We used the crossed-arm TOJ task to evaluate the spatial mapping of touch in deaf participants. Results suggested that a change in posture had a greater impact on congenitally deaf participant TOJ than for hearing participants. This provides the first evidence for the role of early auditory exposure on spatial mapping of touch. More importantly, most deaf participants had auditory prosthetics which provided auditory input. This suggests an important, and possibly irreversible, impact of early auditory deprivation on this body-related process.

5.2 - Introduction

The representation and control of our body relies on the ability to perceive and distinguish our limbs in space, independent of their posture (Maravita, Spence & Driver, 2003). This process requires the interaction of somatosensory and retinotopic inputs (Heed & Röder, 2012). Somatosensory inputs provide information on the body's position in relationship to itself. This sensory information forms the internal frame of reference. Retinotopic input provides information on the body's position in relationship to the environment. This sensory information forms the external frame of reference. Combining these complementary frames of reference forms a body representation that allows us to interface with our surroundings (Heed & Röder, 2012).

The crossed-arm TOJ task (Yamamoto & Kitazawa, 2001), (Shore, Spry & Spence, 2002) is a complex tactile task used to study the spatial mapping of touch by creating a conflict between internal and external frames of reference. In it, participants are asked to identify the laterality of the hands to be first stimulated (left hand or right hand) using buttons placed under their feet. Participants must perform this with their arms either uncrossed or crossed. For the crossed-arm condition stimulating the right hand first requires the participant to respond with the left foot, as the hand is located left of the body-midline. This creates a conflict between the information from internal somatosensory and external retinotopic frames of reference. Perceptual results from the task are compared using the cumulated percentage of correct responses over all stimulus onset asynchronies (SOA) in uncrossed and crossed conditions. This can then be analyzed to determine the presence of a significant increase of the TOJ error rate when crossing the arms (Heed & Azañón, 2014).

The crossed-arm TOJ task is a multisensory task where vision plays an important role along with touch (see, e.g. Gallace & Spence, 2005; Ley, Bottari, Shenoy, Kekunnaya & Röder, 2013; Röder, Rösler & Spence, 2004). Vision provides such crucial information for this task that the crossed-arm deficit can be nearly eliminated by simply seeing uncrossed rubber hands (Azañón & Soto-Faraco, 2007). Results from previous investigations suggest that the interaction between frames of reference develops in early infancy through sensory and motor experience (Ali, Spence & Bremner, 2015; Bremner, Mareschal, Lloyd-Fox & Spence, 2008). Moreover, congenitally blind participants were found to have significantly lower TOJ error rates when crossing the arms (Röder, Rösler & Spence, 2004). Studies have since tested the crossed-arm TOJ task with blindfolded participants (Crollen, Albouy, Lepore & Collignon, 2017; Kóbor, Füredi, Kovács, Spence & Vidnyánszky, 2006; Schicke & Röder, 2006). Results from these short-term sensory deprivation studies have revealed that temporary visual deprivation does not seem to have a similar effect on the task as congenital blindness since TOJ errors were not significantly different from the control group. This suggests that early sensory exposure plays an essential role in the development of the automatic interaction of internal and external coordinates for touch processing.

A recent investigation by Noël & Wallace (2016) on the impacts of temporary sensory deprivation revealed a significant increase to crossed-arm TOJ error rate for auditory deprivation. In their study, participants were temporarily deprived of audition, vision, or both and performed the TOJ task. Their results suggest that auditory and audiovisual deprivation led to a significant increase in error rates, while visual deprivation did not lead to significant changes. It would seem that audition plays a crucial, but under studied, role in the spatial mapping of touch. Indeed, there are several evidences of disturbed neural representation of the body following deafness (for a review, see Houde, Landry, Pagé, Maheu & Champoux, 2016). In this study, we investigated spatial mapping of touch in the deaf using crossed-arm TOJ task (Cadieux, Barnett-Cowan & Shore, 2010; Cadieux & Shore, 2013). We calculated the results from the crossed-arm TOJ task using the PCD. The PCD is a reliable performance metric that provides information on uncrossed and crossed responses error rates in a single score (Cadieux, Barnett-Cowan & Shore, 2010). A low PCD represent a similar error rate between the crossed and uncrossed posture, while a higher PCD represents a large difference in error rates between postures. Due to the demonstrated importance of auditory input on the spatial mapping of touch (Noël & Wallace, 2016), we hypothesise that crossing the arms will lead to a significantly greater error rate in deaf participants. This increase in error rates will be reflected by a higher means group PCD score.

5.3 - Materials and methods

5.3.1 - Participants

13 deaf (9 women, 4 men, mage = 38.4 years, range: 29–57 years) and 13 hearing group participants (9 women, 4 men, mage = 33.4, range = 20–59 years) took part in the study (see Table 5.1 for more details). Participants underwent a hearing test and a comprehensive vestibular evaluation by a certified audiologist. Two deaf participants chose to opt out of the vestibular evaluation. Hearing thresholds were determined using an audiometer (Astera, GN Otometrics, Denmark). All deaf participants suffered from congenital profound bilateral hearing loss (mean hearing thresholds from 250 Hz to 8 kHz > 100 dBHL). Hearing group pure-tone detection thresholds at octave frequencies ranging from 250 to 8000 kHz were within normal limits in both ears (mean hearing thresholds from 250Hz to 8kHz: 4.44±0.91 dBHL). A comprehensive peripheral vestibular evaluation of all six semi-circular canals using the video head impulse test (vHIT: Eyeseecam, Interacoustics, Denmark), both saccules with the cervical vestibular evoked myogenic potential (cVEMP: Eclipse EP-25/VEMP Interacoustics, Denmark) and both utricules using ocular vestibular evoked myogenic potential (oVEMP: Eclipse EP-25/VEMP Interacoustics, Denmark) was

performed. We identified 7 deaf participants with a vestibular deficit of the 11 tested (64%). This proportion is consistent with previous studies assessing the vestibular function of hearing impaired participants, with or without cochlear implants (see, e.g. Cushing, Gordon, Rutka, James & Papsin, 2013; Kaga, Shinjo, Jin & Takegoshi, 2008; Tien & Linthicum, 2002; Handzel, Burgess & Nadol, 2016; Xu et al., 2015). All other participants (including normal-hearing participants) had normal bilateral vestibular function. Twelve deaf participants communicated primarily through oral language and lip reading, and used auditory amplification (mean age of acquisition of hearing aids: 5.9 years ± 5.2). One deaf participant communicated primarily through sign language. Twelve deaf participants used hearing aids (mean age of acquisition: 5.9 years ± 5.2) and four used cochlear implants (mean age of acquisition: 40.3 years ± 9,7). The Research Committee for Health Sciences of the University of Montreal and the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal approved all procedures and each participant provided written informed consent. All experiments were performed in accordance with relevant guidelines and regulations.

5.3.2 - Procedure and stimuli

As previously used in our laboratory (Landry & Champoux, 2018), we used a crossed-arm TOJ task (Cadieux, Barnett-Cowan & Shore, 2010; Cadieux & Shore, 2013) and recorded non-speeded reaction times (Heed, Blackhaus & Röder, 2012; Heed, Blackhaus, Röder & Badde, 2015; Yamamoto & Kitazawa, 2001). Participants held 4cm3 foam cubes between both thumbs and indexes. For each trial, 20-ms vibrations were delivered to each foam cube. Stimulations were separated by a variable SOA: ± 400, ± 200, ± 100, ± 50 ms, where negative SOAs indicated that the vibration was presented to the left index first. Two 20 trial practice blocks, one in each posture, were performed before the start of the experiment. Each of the eight SOAs were presented randomly 40 times over 20 blocks. Arm posture alternated between crossed and uncrossed for each block. Starting postures were counterbalanced across participants; odd numbered participants started in an uncrossed posture, even numbered participants started in a crossed posture. Two response buttons, one under each foot, were used to record participant responses. Participants were instructed to indicate the side of the cube having first vibrated with the response buttons, regardless of the arm posture.

Participant comprehension was verbally confirmed many times throughout the procedure. The task was first explained before the practice blocks. Participants were instructed to press on the pedal located on the same side of space as the cube that first vibrated. It was further specified that the side in space of the cube and the hand would be different for the crossed posture and that the side in space was the correct answer. Participants then performed the practice blocks with the experimenter at their side, clarifying any ambiguities and confirming their understanding of the task. Furthermore, task comprehension was verbally verified for all participants after the first crossed and uncrossed postures. Participants demonstrating a misunderstanding of the task during this last comprehension evaluation were eliminated from analysis. All participants confirmed their correct understanding of the task demand.

5.3.3 - Analysis

A PCD score was calculated to compare the crossed and uncrossed error rates (Cadieux, Barnett-Cowan & Shore, 2010; Cadieux & Shore, 2013; Wada, Yamamoto & Kitazawa, 2004). The PCD is a single performance metric that reliable represents the entire curve of uncrossed and crossed responses (Cadieux, Barnett-Cowan & Shore, 2010). This value is calculated by summing up the differences between the proportion of correct response for the crossed and uncrossed postures at each SOA. PCD scores range from 0 to 8. A score of 0 represents the exact same response for uncrossed and crossed postures at each SOA. This would occur if the participant were completely accurate in the uncrossed and crossed postures. A score of 8 represents exact opposite response for uncrossed and crossed postures at each SOA. This would occur if the participant were completely accurate in the uncrossed posture and completely inaccurate in the crossed posture. An indepedant t-test between mean group PCD will be used as statistical test. Furthermore, a repeated measure analysis will be used to compare unspeeded reaction times with two within subject factors (SOA and posture) and the between subject factor group. All analysis will be done with IBM SPSS statistics 23 software.

5.4 - Results

Individual scores for proportion of right-hand first answers across different SOA are shown in Figure 5.1 We performed an independent t-test between the mean group PCD score for deaf (M

= 4.59, SD = 1.91) and hearing group participants (M = 2.49, SD = 1.19). Results from this analysis suggested significant different PCD scores between groups (t(20.146) = -3.373, p = .003). This result indicates that deaf participants had significantly higher TOJ error rates for the crossed posture (see Figure 5.2). Mean group unspeeded reaction times were analyzed using a repeated measure analysis with two within subject factors (SOA and posture) and the between subject factor group. Results from this analysis failed to reveal a significant between-subjects effect of group for reaction times (F(1,24) = 1.035, p = 0.319, ηp2 = 0.041).

5.5 - Discussion

The objective of this study was to investigate spatial mapping of touch in the deaf using the crossed-arm TOJ task. Results for the task revealed that deaf participants had a higher mean PCD group score, indicating more TOJ errors when crossing the arms, compared to hearing control group members. Results from the non-speeded reaction times for the crossed-arm task revealed no difference between groups. These results suggest that a period of deafness permanently alters spatial mapping of touch, but does not alter the time required to provide that judgment.

Many deaf participants provided inverted TOF responses when they crossed their arms (see Figure 5.1), which could be interpreted as a misunderstanding of the instructions. However, all participants provided verbal confirmation for understanding the task demands before and during the experiment, for both crossed and uncrossed postures. We also maintained a strict task comprehension inclusion criterion. Results from any participant demonstrating misunderstanding of task demand after the instruction sessions would have been removed from analysis. Thus eliminating the possibility of a misunderstanding, the increased error rate could be associated with the widely reported changes in body-related processes for deaf individuals (for review see Houde, Landry, Pagé, Maheu & Champoux, 2016). More specifically, deaf individuals have been found to have significantly lower temporal tactile discrimination abilities (Bolognini et al., 2012). It seems unlikely that the larger error rates stem from participants not understanding the task requirement due to our strict inclusion criteria.

Our results provide an important insight on deafness and the spatial mapping of touch for SOA up to 400 ms. However, future analysis on deaf participants will benefit from longer SOAs to reveal if deaf error rates are along an N-curve (Yamamoto & Kitazawa, 2001; Wada, Yamamoto & Kitazawa, 2004), or an inverted psychometric function. It would also be worth investigating with methodologies where answers are given manually or vocally (Pagel, Heed & Röder, 2009) as foot answers can lead to increased error rates (Noël & Wallace, 2016).

Our findings are consistent with the crossed-arm TOJ results from Noël & Wallace (2016) where participants could be temporarily deprived of either auditory or visual information. Their results suggest that only a period of short-term auditory deprivation lead to an increase in crossed-arm TOJ. This suggests that even short-term auditory deprivation is sufficient to alter spatial mapping of touch. Results from Noël & Wallace (2016) also suggest that short-term visual deprivation can lead to a non-significant tendency towards reduced crossed-arm TOJ errors. Similarly, Röder, Rösler & Spence (2004) found that congenitally blind participants had significantly less cross-arm TOJ errors than a sighted control group. It thus seems that vision, unlike audition, requires a longer period of sensory deprivation, perhaps even a congenital blindness, to lead to a significant different in crossed-arm TOJ.

Indeed, two studies have now indicated unimpaired crossed-arm performance in the early blind adults (Crollen, Albouy, Lepore & Collignon, 2017; Röder, Rösler & Spence, 2004). This unimpaired performance of early blind adults has been suggested by Crollen, Albouy, Lepore & Collignon (2017) to reflect that touch localization in this population relies mainly on the internal reference frame. The alignment of external and internal frames of references seen in sighted controls could hinge on early experience with seeing and feeling the arm interact with the environment. Our results with deaf individuals suggest an opposite alignment of frames of reference. Deafness thus seems to shift the balance for frames of reference leading to a heavier reliance on the external frame of reference for this touch localization task.

Yamamoto & Kitazawa (2001) proposed that hands must be localized in space before the temporal order can be determined. In the crossed hands posture with short SOAs, the stimulations occur before remapping is completed, leading to the higher error rates. Our results suggest that this remapping takes longer in deaf individuals as their error rates in the crossed posture are higher than normal hearing-individuals. In contrast, Shore, Spry & Spence (2002) proposed that the internal and external frames of reference remain active after a frame of reference transformation. Per this hypothesis, the higher error rate found in the crossed-arm condition would be attributed to a greater cognitive effort required to resolve conflicting frame of reference information. As it takes time for information from the first stimulation to be localized, if the second stimulus is presented before the first is located, TOJ errors can occur. Were the Shore, Spry & Spence (2002) hypothesis the only factor explaining the lower performance in the crossed-arm condition, we would expect both reaction times and error rates to be higher for deaf participants. However, an analysis of mean group unspeed reaction times failed to reveal a significant difference between deaf and hearing groups.

The effects of deafness on tactile abilities are highly variable. Some investigations on body perception in the deaf have reported no differences in tactile perception (see, e.g., Heimler & Pavani, 2014; Moallem, Reed & Braida, 2010), while others have suggested improvements (Levänen & Hamdorf, 2001; , Kappers & Postma, 2013) or even declines (Bolognini et al., 2012). Investigations on abilities closer related to the cross-arm TOJ task on movement and posture have revealed a more consistent effect of deafness. These results suggest that deafness leads to impairments in tasks related to motor behavior or action (for review see Houde, Landry, Pagé, Maheu & Champoux, 2016). Our results show that even in the absence of a motor component, deaf individuals can experience difficulties in tasks involving correctly judging the position of their body in space. This altered spatial mapping of touch provides a direction to better explain the deficits in tasks related to motor behavior or action in the deaf. The impact of individual characteristics of deafness on this reported altered spatial mapping of touch also merits further investigation.

These results are the first to investigate the interaction of internal and external frames of references in deaf individuals. The posterior parietal cortex (PPC) has been suggested to play a key role in the interaction of frames of reference in hearing individuals (Azañón, Longo, Soto-Faraco & Haggard, 2010). Several studies have demonstrated significant changes to PPC activation for visual stimuli in the deaf (Bavelier et al., 2000; Bavelier et al., 2001; Seymour et al., 2017). While these studies investigated visual processes, they highlight a plasticity in the PPC caused by a period of auditory deprivation. These neuroimaging studies suggest an increased presence of visual information in the PPC in the absence of auditory input. As vision represents information from an external frame of reference, this increased importance of visual information in the PPC could help explain why deaf participant provided externally-based responses for the TOJ task. Future studies are required to better understand the cortical mechanisms underlying this effect and the role of the PPC for the increased TOJ error rate in deaf individuals.

Participants all had similar onset of hearing loss, duration of hearing loss, hearing aids use, and modes of communication. These factors have been revealed to critically impact plasticity and performance in the deaf (see, e.g. Kral & Sharma, 2012). Further studies should investigate the link between TOJ task performance and hearing gain using information including hearing thresholds with amplification, hearing aid data logging, and hearing aid adjustments parameters. We acknowledge that these factors have not been measured in our study and while this impact is not fully yet understood, it can impact plasticity leading to altered performances. Also, future research needs to examine the effect of these characteristics on the task results and also to evaluate whether there exists a critical period during which auditory input is required for normal-like spatial mapping of touch. Finally, in the present study, most deaf participants had vestibular impairments. Since vestibular function has an influence on body-related processes, such as body awareness and perception (for review see Lopez, 2016), the deficit of the vestibular function might explain some of the results. Moreover, investigations using passive body rotation revealed an impact of rotation on TOJ (Figliozzi, Guariglia, Silvetti, Siegler & Doricchi, 2005) The impact of vestibular impairment on the representation of the body in space needs to be explored further in order to disentangle if the lack of postural control observed in the congenitally deaf is the result of early auditory deprivation or vestibular impairment.

5.6 - References

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5.7- Appendices

Tableau 5.1 - Deaf participant’s individual characteristics.

Participant	Age	Sex	Duration of deafness (years)	Duration of hearing aid use (years)	Duration of cochlear implant use (years)
Deaf 1	29	M	29	26	1
Deaf 2	52	M	52	37	3
Deaf 3	51	F	51	48	4
Deaf 4	41	F	30	29	4
Deaf 5	32	F	32	26	N/A
Deaf 6	37	F	36	36	N/A
Deaf 7	34	F	34	31	N/A
Deaf 8	34	F	34	20	N/A
Deaf 9	33	F	33	29	N/A
Deaf 10	34	M	34	31	N/A
Deaf 11	29	F	29	28	N/A
Deaf 12	57	F	57	25	N/A
Deaf 13	36	M	30	20	N/A

Figure 5.1 - Proportion of right-hand first answers across different SOA : SOA represent left presented first and + SOA represent right presented first. Individual scores are the gray lines and the group mean is the black line. A) Hearing control group in the uncrossed posture. B) Hearing control group in the crossed-arm posture. C) Deaf group in the uncrossed posture. D) Deaf group in the crossed-arm posture.

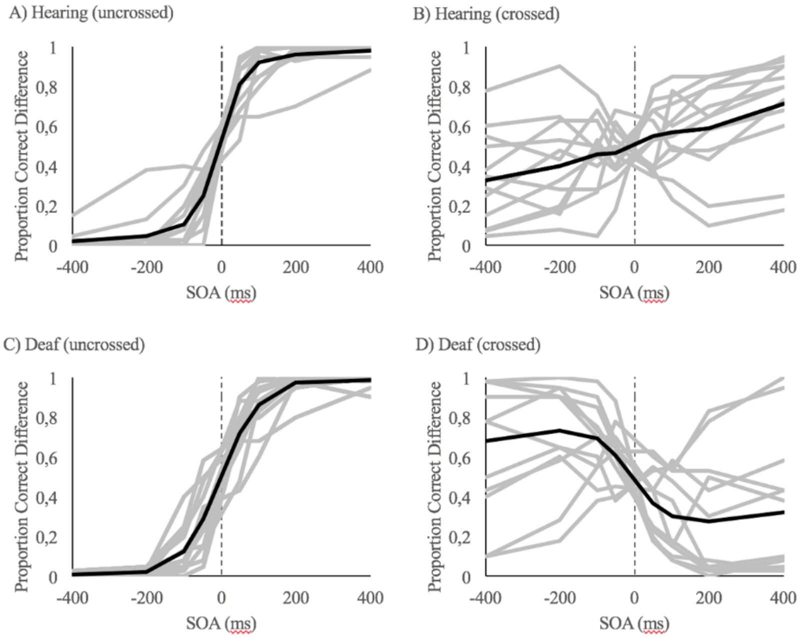
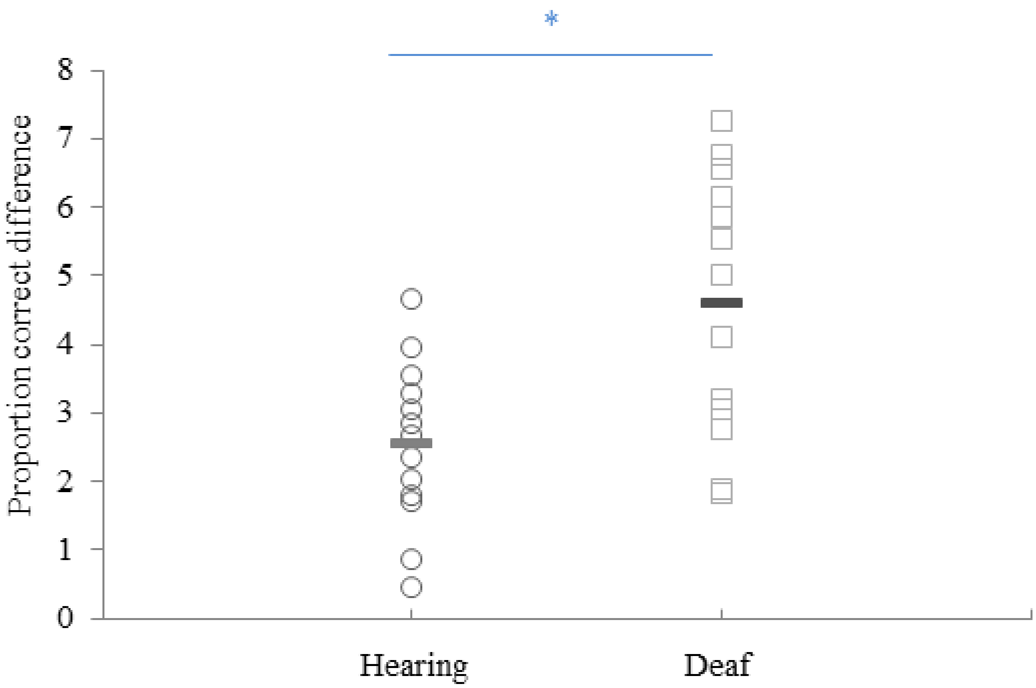


Figure 5.2 - Individual PCD scores for hearing (n = 13), deaf participants (n = 13). Circles represent individual PCD scores for hearing and squares individual PCD scores for deaf. Lines represent mean scores calculated for each group. * represents p = .003.



Chapitre 6 – Enhanced tactile identification of musical emotion in the deaf: More complex tactile tasks can better reveal the behavioral correlate of tactile activation of auditory areas following deafness

Andréanne Sharp, Benoit-Antoine Bacon et François Champoux

Université de Montréal, Faculté de médecine, École d'orthophonie et d'audiologie, C.P. 6128, Succursale Centre-Ville, Montréal, Québec, Canada, H3C 3J7

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6.1 - Abstract

Functional neuroimaging studies have demonstrated that following deafness, auditory regions can respond to tactile stimuli. However, research to date has not conclusively demonstrated the behavioral correlates of these functional changes, with most studies showing normal-like tactile capabilities in the deaf. It has recently been suggested that more cognitive and complex tactile processes, such as music perception, could help to uncover superior tactile capabilities in the deaf. Indeed, following deafness music seems to be perceived through vibration, but the extent to which they can perceive musical features though the tactile modality remains undetermined. The goal of this study was to investigate tactile identification of musical emotion in the deaf so as to uncover the behavioral correlates of the auditory area activation by tactile stimuli. Participants had to rate melodies based on their emotional perception. Stimuli were presented through an haptic glove. Data suggest that deaf and controls are comparable in the identification of the more complex emotions (sad, fear/threat, peacefulness). However and most importantly, for the simplest emotion (happiness), significant differences emerged between groups, suggesting an improved tactile identification of musical emotion in the deaf. Results support the hypothesis that brain plasticity following deafness can lead to improved complex tactile ability.

6.2 - Introduction

Several studies have shown that cross-modal reorganization generally occurs following sensory deprivation. In the widely studied visual domain, multiples studies have showed that such neurophysiological reorganization is accompanied by significant behavioral correlates (e.g. Bavelier et al., 2000; 2001; Bavelier & Neville, 2002; Bosworth & Dobkins, 2002; Burnstine, Greenough & Tees, 1984; Neville, 1990; Neville et al., 1998; Neville & Lawson, 1987; Neville, Schmidt & Kutas, 1983; Parasnis & Samar, 1985; Proksch & Bavelier, 2002; Rettenbach, Diller & Sireteanu, 1999).

In the deaf, functional neuroimaging data has shown that multiples auditory regions can become activated by visual stimulation (e.g. Hirano et al., 2000; MacSweeney et al., 2002; Nishimura et al., 1999; Petitto et al., 2000; Sadato et al., 2005). Similarly to what has been found in the visual domain, functional neuroimaging data has also showed that tactile stimulation generates activation in the secondary auditory cortex of deaf people (Auer, Bernstein, Sungkarat & Singh, 2007; Levänen, Jousmäki & Hari, 1998; Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, 2006). However, behavioral correlates of this reorganization remain to be confirmed, with most research suggesting normal-like tactile capabilities in the deaf (e.g. Bolognini et al., 2012; Conway et al., 2011; Donahue & Letowski, 1985; Hauthal, Debener, Rach, Sandmann & Thorne, 2015; Heimler & Pavani, 2014; Moallem, Reed & Braida, 2010; Rosenstein, 1957; Schiff et Dytell, 1971) and only a few studies showing enhanced performance (Chakravarty, 1968; Schiff & Dytell, 1972; Levänen & Hamdorf, 2001; Nava et al., 2014).

It has recently been suggested that the failure to convincingly demonstrate the behavioral correlates of the neuroanatomical reorganization observed in the deaf might be related to the lack of complexity of the task used. Indeed, Pagagno et al. (2016) suggested that more cognitive and more complex tasks should be investigated to better understand tactile perception in deaf individuals. Among the multiple tactile process that could be examined in the deaf, music perception has been overlooked.

Music is generally considered a source of enjoyment (Dubé & Le Bel, 2003) and studies have shown that listening to music is sufficient to activate brain circuits involved in pleasure and reward. Indeed, similar brain structures are activated by listening to a pleasant musical stimulus as by eating chocolate, which is known to be highly pleasurable (Blood & Zatorre, 2001; Small, Zatorre, Dagher, Evans & Jones-Gotman, 2001). Agreeable music also leads to a greater release of dopamine, a neurotransmitter well-known to be involved in pleasure and reward mechanisms (Salimpoor, Benovoy, Larcher, Dagher & Zatorre, 2011). Furthermore, several studies suggest that music is used across cultures to elicit emotional responses (Panksepp, 1995; Sloboda, 1991; Trainor & Trehub, 1992). Indeed, music is often characterized as the language of emotions (Langer, 1959; Meyer, 1956; Peretz, Gagnon & Bouchard, 1998).

It is a common misconception that deaf individuals do not care for music, but in fact the majority of individuals in the deaf community report some engagement in musical activities (Good, Reed & Russo, 2014). Most studies investigating music perception following deafness focus on auditory perception in hearing aids or cochlear implants users, and in conventional hearing aids users, challenges with musical perception is one of the most common complain (e.g. Feldmann & Kumpf, 1988). Indeed, hearing aids users report that musical sounds are distorted, that melodies are difficult to recognize and that the lyrics of songs are at time not intelligible (Chasin & Russo, 2004; Feldmann & Kumpf, 1988). In cochlear implant users, only tempo and basic rhythm patterns seem to be preserved (Cooper, Tobey & Loizou, 2008; Gfeller, Witt, Stordahl, Mehr & Woodworth, 2000; Gfeller et al., 2007; Kong, Cruz, Jones, & Zeng, 2004; Limb, 2006), and users usually experience poor perception of melody, pitch, harmony and timber (Gfeller, Witt, Stordahl, Mehr & Woodworth, 2000; Limb, 2006; Limb & Roy, 2014; McDermott, 2004). Those limitations are not occurring only because of the technological and acoustic limitations of the device, but also because of the neurophysiological alterations that usually accompany deafness (for a review see Limb & Roy, 2014).

Besides the examination of the auditory limitations in using these technological devices, music perception and especially perception using other sensory modalities has received little attention in the deaf. Like their hearing counterparts, deaf individuals, can perceive music through vibration. For example, a high intensity sound can induce vibrations into objects such as the floor, walls and furniture (Good, Reed & Russo, 2014). Interestingly, the vibrotactile receptors of the skin are biomechanically similar to the hair cells of the cochlea (Good, Reed & Russo, 2014). How much of the complex components of music can be perceived though the tactile modality remains a question of debate.

Indeed, vibrations perceived through the skin cannot carry as much information as those perceived thought the cochlea. Indeed, the frequency spectrum perceived through the skin differs according to the types of tactile receptors present, and is considerably more limited (1 to 1000Hz) than that of the hair cells of the cochlea (Rovan & Hayward, 2000). However, one could expect that the tactile-to-auditory brain reorganization repeatedly observed in profoundly deaf individuals (e.g. Auer, Bernstein, Sungkarat & Singh, 2007; Levänen, Jousmäki & Hari, 1998; Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, 2006) could potentialize such tactile processing of musical vibrations. Unfortunately, only a few studies have examined the tactile perception of music in the deaf.

It appears that the tactile intensity needed for the detection of different musical notes in the deaf is comparable to that of normally hearing individuals (Hopkins, Maté-Cid, Fulford, Seiffert & Ginsborg, 2016). The deaf also show normal-like rhythmic pattern (Rosenstein, 1957) and musical timbre discrimination capabilities (Russo, Ammirante & Fels, 2012). Low frequencies in music are important in experiencing beat and can be well transmitted via vibrotactile devices (Van Dyck et al., 2013; Tranchant et al., 2017). Indeed, two recent studies suggest that deaf individuals can move to a beat transmitted via vibrations (Phillips-Silver et al., 2015; Tranchant et al., 2017) just as well as hearing individuals. Altogether, these studies suggest that deaf individuals can perceive basic aspects of music via tactile perception. Whether they are able to perceive more complex elements in music, such as musically conveyed emotions, is still unknown. The goal of the present study was therefore to examine the tactile identification of emotions following long-term auditory deprivation.

6.3 - Material and methods

6.3.1 - Participants

10 deaf participants (7 women, 3 men, mage = 43.3 years) and 10 hearing participants (7 women, 3 men, mage = 38.6) took part in the study. Participants underwent a hearing test to determine hearing thresholds using an audiometer (Astera, GN Otometrics, Denmark). All deaf participants suffered from congenital profound bilateral hearing loss (mean hearing thresholds from 250 Hz to 8 kHz > 100 dBHL). Hearing participants pure-tone detection thresholds at octave frequencies ranging from 250 to 8000 kHz were within normal limits in both ears (mean hearing thresholds from 250Hz to 8kHz: 4.44±0.91 dBHL). Eight deaf participants communicated primarily through oral language and lip reading, and used auditory amplification. Two deaf participants communicated primarily through sign language. Two deaf participants used hearing aids and six used cochlear implants. The Research Committee for Health Sciences of the University of Montreal and the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal approved all procedures and each participant provided written informed consent. All experiments were performed in accordance with relevant guidelines and regulations.

6.3.2 - Control task

6.3.2.1 - Stimuli and procedures

A control evaluation was conducted to confirm that there was no significant difference between deaf and control participants in a simple musical discrimination task. A two-alternative forced-choice frequency discrimination task was used to compare both groups.

Stimuli and procedures were the same as in Young, Murphy & Weeter (2017). All stimuli were created via Audacity® Version 2.3.0. (Audacity Team, 2018), and were sinusoidal, square and sawtooth complex waves with infinite spectrum and a fundamental frequency of 160 Hz. Stimuli were presented in pairs: One stimulus was an unmodified tone (160Hz) and the other was shifted in frequency. Stimulus pairs varied in frequency by ± 0; 0.25; 0.5; 0.8; 1; 1.5; 2; 3; 4; 6; 8; 12; 16; 20; 24; 36; or 48 Hz. Wave types were not directly compared to each other within trials (i.e both stimuli in a pair always had the same wave type, e.g. 160Hz-172Hz sinusoidal). Each pair of stimuli represented a waveform type and were presented randomly twice in a block. Each block was programmed in the software Psyscope 1.2.5. (Cohen, MacWhinney, Flatt & Provost, 1993) on a Mac computer so that the presentation of all pairs of stimuli was randomized.

The purpose of using three types of waveforms was to simulate different musical timbres. Even if a piano and a violin produce a note having the same fundamental frequency, it is possible to determine which instrument produces which note, because they differ in timbre. By using sinusoidal waves (no harmonics), sawtooth waves (odd harmonics) and square waves (even and odd harmonics), the task becomes more representative of the frequency discrimination that occurs during music listening, and represents the perception of three artificial musical instruments.

Participants were seated in a soundproof room and stimuli were presented through the vibrating glove device. The masking procedure during tactile stimulation was the same as used previously in our laboratory (see Landry, Guillemot & Champoux, 2013; Landry, Guillemot & Champoux, 2014). White noise was presented via attenuating circumaural headphones (10 S/DC, David Clark, Worcester, MA, USA) and the participant wore earplugs. A preliminary study was conducted to ensure that detection via bone conduction would not be possible at this noise level.

The vibrating glove was a replication of the glove used by Young, Murphy & Weeter (2017) and was equipped with six independent audio-haptic voice-coil exciters. The voice-coil transducers (TEAX14C02-8 Compact Audio Exciter) had a diameter of 14mm and were designed to deliver vibrotactile output. The frequency range of these speakers is 300Hz to 20 000Hz. Stimuli were sent via a Dayton Audio DTA3116S Class D Micro Mini Amplifier (2 x 15W), linked via an audio cable to the software Psyscope 1.2.5. (Cohen, MacWhinney, Flatt & Provost, 1993) on a Mac computer.

The task was divided into three blocks of 80 trials. A constant stimulus procedure was used in this experiment to compute the threshold and each Δf was presented 4 times during each stimulation condition. The number of trials was based on Young, Murphy & Weeter (2017) who used 3 trials per intervals. One trial per intervals was added to increase the number of trials, taking into account that increasing more would lead to fatigue for participants and create a new bias. The method of constant stimuli used with 100 trials or less is as efficient and less biased that the adaptative method (Simpson, 1988).

In each trial, a pair of stimuli were presented. Each stimulus of the pair had a duration of two seconds, and they were temporally separated by a pause of one second. Participants had to identify whether the two stimuli had the same or different frequencies by making a selection on the screen using the computer mouse.

6.3.2.2 - Analysis

The just noticeable difference was calculated for all conditions: the difference between the reference frequency (160Hz) and the frequency where the participant had a recognition score of 75% (above and under 160Hz taken together) was used as the threshold of recognition (ΔF). A multivariate analysis of variance was used to compare the threshold of recognition (ΔF) between groups. Type of waves (sinus, square, saw) and modalities were the dependent variables and group was the independent variable.

6.3.4 - Experimental task

6.3.4.1 - Stimuli and procedures

The stimuli used in this study were developed by Vieillard et al. (2008). They consist of 56 melodies produced by a digital synthesizer in piano timbre. These instrumental stimuli were composed in the tonal musical tradition to express four emotions: happiness, sadness, fear/threat and peacefulness. The stimuli vary in mode, dissonance, pitch range, tone density, rhythmic regularity and tempo, but do not vary in performance-related expressive features (e.g. vibrato or variations of articulation/phrasing). Therefore, the identification of emotions was based exclusively on the compositional structure. The mean duration of each stimulus was 12.4 s. All stimuli were originally validated by Vieillard et al. (2008) and were also cross-culturally validated by Fritz et al. (2009). These stimuli have been designed to elicit specific emotions that can be universally recognized.

The battery of Vieillard et al. (2008) was selected for this experiment because the four emotions evoked by the melodies are easily recognized and discriminated. Furthermore, all stimuli were validated cross-culturally by Fritz et al. (2009), and across age groups by Lima & Castro, 2011.

For each stimuli, participants had to rate to what degree the melody expressed each of the four emotions on a 10-point intensity scale ranging from 0 (absent) to 9 (present). The four scales were presented immediately after each stimulus, and always in the same order (happy/sad/scary/peaceful). To exactly replicate the standardized task of Vieillard et al. (2008), the order of the scale presented after each stimulus was not counterbalanced. Each melody was presented only once, in random order.

Participants were seated in a soundproof room and stimuli were via a vibrating glove. During the task, white noise was presented via headphones and the participant wore earplugs. Participants had to adjust the volume of the white noise during practice trials so as not to hear the vibrating glove.

6.3.4.2 - Analysis

The percentage of accurate responses, defined as the highest rating score for a melody corresponding to the intended emotion, was calculated for each participant for each emotion. For example, given a happy melody and a rating of Happy = 7, Sad = 3, Fear = 2, Peaceful = 6, the response would be counted as correct, whereas Happy = 6, Sad = 3, Fear = 2, Peaceful = 7 would be counted as incorrect. The same rating could never be used twice for any melody. A multivariate analysis of variance was used to compare the percentage of accurate responses between groups (2) for each category of emotion (4).

6.4 - Results

The results of the control discrimination task are shown in Figure 6.1. The MANOVA revealed no significant differences between groups (F(3, 20) = 0.260, p = 0.853). The results of the experimental task, namely the percentage of accurate responses for each of the four tested emotions, are displayed in Figure 6.2. The multivariate analysis of variance used to compare the percentage of accurate responses revealed a statistically significant difference in conditions based on Group (F(4,15) = 5.413, p = 0.007; Wilk's Λ = 0.409). Specifically, there were significant differences between groups for happy (F(1, 19) = 2.344, p < 0.001), whereas no significant differences between groups were found for sad (F(1, 19) = 2,004, p = 0.174), fear/threat (F(1, 19) = 1.308, p = 0.268) and peacefulness (F(1, 19) = 0.851, p = 0.368).

6.5 - Discussion

The goal of the present study was to investigate the tactile perception of musical emotion in the deaf. A significant difference between deaf and normally hearing participants was found, with deaf individuals showing better tactile identification in one of the experimental conditions, namely the identification of happiness. Our results support the hypothesis that more demanding and more complex tactile tasks can help to more convincingly demonstrate superior tactile capabilities in the deaf, the neural correlates of tactile activation of auditory areas.

Imaging studies suggest that tactile stimulation causes activation in the secondary auditory cortex of deaf people (Auer, Bernstein, Sungkarat & Singh, 2007; Levänen, Jousmäki & Hari, 1998;

Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, 2006). When vibration is presented to the palms and fingers, activation of the secondary auditory cortex is larger and more extensive in deaf participants than in hearing participants (Auer, Bernstein, Sungkarat & Singh, 2007; Levänen, Jousmäki & Hari, 1998). The impact of those anatomical changes on behavioural capabilities are, however, highly variable. Some suggested enhanced skin sensitivity (Chakravarty, 1968; Schiff & Dytell, 1972; Levänen & Hamdorf, 2001) and faster tactile reaction times in deaf-born cochlear implant users (Nava et al., 2014), whereas other failed to reveal such difference between controls and deaf-born (Heimler & Pavani, 2014) or late-deaf cochlear implant users (Hauthal, Debener, Rach, Sandmann & Thorne, 2015; Rosenstein, 1957). Better performance in a vibrotactile line and two-point discrimination measures were also reported in congenitally deaf children (Schiff & Dytell, 1972).

However, several other studies failed to report any enhancement in tactile perception in the deaf. Indeed, deaf and control have been found to be similar in tasks involving i) tactile detection (Conway et al., 2011; Donahue & Letowski, 1995; Moallem, Reed & Braida, 2010), ii) the discrimination of spatial length (Bolognini et al., 2012), temporal onset-offset-order (Moallem, Reed & Braida, 2010), frequency (Levänen & Hamdorf, 2001) and rhythmic patterns (Rosenstein, 1957), or iii) object identification (Schiff & Dytell, 1971). One study even reported that deaf individuals in fact showed inferior tactile performance in a tactile temporal discrimination task (Bolognini et al., 2012), suggesting that the tactile-to-auditory reorganization found in some deaf individuals could be maladaptative. Papagno, Cecchetto, Pisoni & Bolognini (2016) have recently suggested that the difficulty of the task could have been a major limitation in the majority of past investigations. The authors suggested that more cognitive and complex tasks should be investigated to better understand tactile perception in deaf individuals and our results are in line with this hypothesis.

The fact that a performance enhancement was found for one emotion but not for the others could be linked to happiness having previously been showed to be the easiest emotion to identify auditorily in music (see Terwogt & van Grinsven, 1991). The results in this condition, taken in isolation, suggest that deaf individuals might be better at discriminating more subtle features in music with tactile stimuli as compared to normally-hearing individuals, and to associate them with an emotion.

One may then wonder why such enhanced performance was only found in the easiest identification condition. One hypothesis is that deaf participants, due to the early onset of their condition, simply did not have the musical knowledge to associate the less obvious musical features felt through the tactile modality with a specific emotion. Indeed, the ability to identify emotion in music starts early in life and young children base their judgments on basic psychoacoustic cues such as tempo, loudness and pitch (Adachi, Trehub & Abe, 2004). As early as 3 years of age, children are sensitive to the positive and negative connotations of music, but their analysis is not yet sufficiently nuanced to distinguish between more specific emotions (Kastner & Crowder, 1990). Later in development, around 5 years of age, children begin to discriminate sadness (Terwogt & van Grinsven, 1991). Finally, it's only around 11 years of age that children are able to identify emotions at the adult level (Hunter, Schellenber & Stalinski, 2011).

In the present study, all except one participant had early-onset hearing loss (< 7 years-old). The lack of exposure (and training) in the deaf would arguably have impede the formation of well-defined associations between specific features of sensory stimuli and emotion while listening to music. In contrast, deaf individuals performed at a normal level in the most difficult tactile identification conditions. In retrospective, these results rise important questions when considering a somewhat more limited level of musical exposition. Indeed, it would be of interest to examine whether tactile performance could be improved in deaf individuals with basic musical tutoring.

Considering that tactile perception of music is somewhat limited as compared to auditory perception, any improvement might have a significant impact in the appreciation of music in the deaf. Recent results from our lab using the exact same procedure suggest that such enhancement might be achieved with a relatively high level of multisensory training in the normally-hearing (Sharp, Houde, Bacon & Champoux, 2019). It would be interesting to examine whether this level of performance could be achieved with only tactile training in the deaf.

Of course, one should consider the specific characteristics of hearing loss (e.g. Dietrich, Nieschalk, Stoll, Rajan & Pantev, 2001; Lambertz, Gizewski, de Greiff & Forsting, 2005; McDermott, Lech, Kornblum & Irvine, 1998; Thai-Van, Micheyl, Norena & Collet, 2002; Thai-Van, Micheyl, Norena & Collet, 2003) in the examination of tactile performance following deafness. In the present study, participants were similar in terms of onset of hearing loss and mode of communication; nearly all had early-onset hearing loss, were oralists and used auditory amplification. Considering that these specific characteristics could have a significant impact on brain plasticity (e.g. Kral, Hartmann, Tillein, Heid, & Klinke, 2001; Kral & Sharma, 2012) and consequently on the performance reported here, they should be studied further independently before the results could be generalized to the entire deaf community.

6.6 - Conclusion

The present results support the notion that more complex and cognitive tasks would better reveal enhance tactile capabilities in the deaf – the expected correlate of tactile activation of auditory areas following deafness. These results also provide important insights as to why the majority of individuals in the deaf community report engagement in musical activities and report music as a pleasurable activity. Indeed, it appears that their ability to perceived music through the tactile modality might have been underestimated. Further studies should investigate whether other complex musical abilities (e.g. melody contour discrimination, major or minor mode discrimination) could be elicited via tactile stimulation to determine the limits of music perception with vibrotactile devices in this population. In addition, further work should be conducted to assess whether the use of such devices early in life, which would expose deaf individuals to the more complex features of music at a younger age, could enhance these capabilities even further.

6.7 - Disclosure statement

No potential conflict of interest was reported by the authors.

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6.9 - References

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6.10- Appendices

Figure 6.1 - Tactile frequency discrimination threshold average for control group and deaf group for the three test conditions (sine waveform stimuli, square waveform stimuli, sawtooth waveform stimuli). Error bars represent the standard deviation.

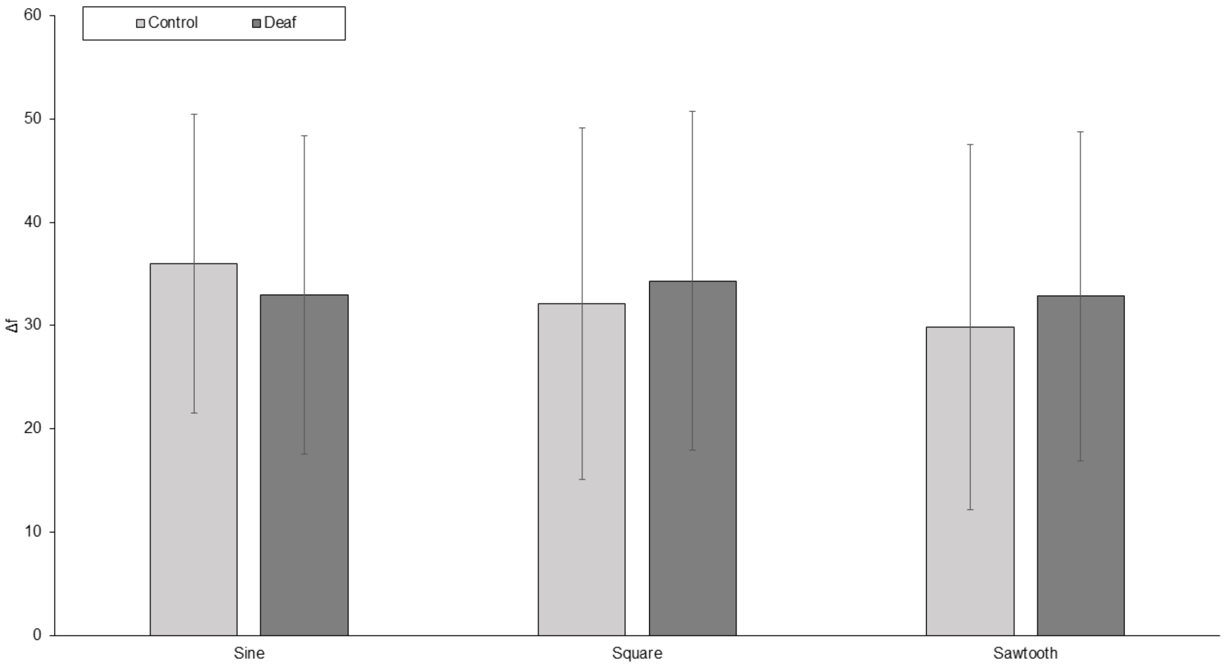
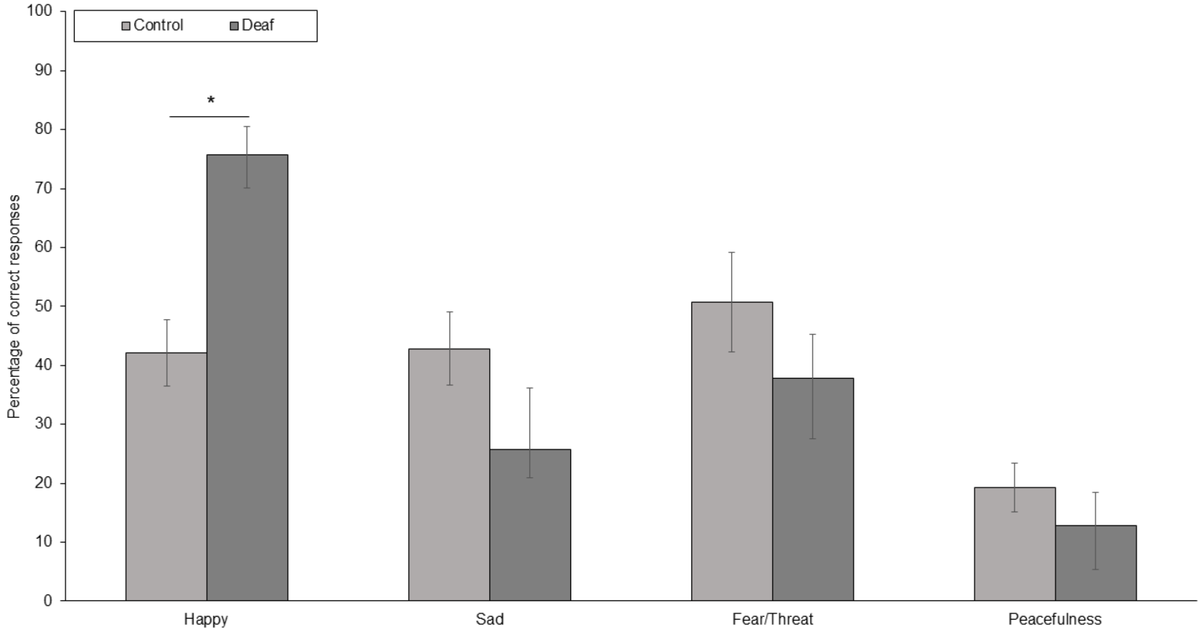


Figure 6.2 - Percentage of correct responses for control group and deaf group for tactile stimulation condition for each type of emotions (Happy, sad, fear/threat, peacefulness). Error bars represent the mean standard error. * = p < 0.05



Chapitre 7 – Discussion

Les résultats des recherches de cette thèse confirment l'hypothèse générale selon laquelle les capacités sensorielles peuvent être augmentées chez l'humain, soit i) à la suite d'un entraînement ou ii) à la suite d'une privation sensorielle précoce.

7.1 - Effet de l'entraînement musical

Les études de cette thèse suggèrent qu'un entraînement musical peut non seulement augmenter les capacités de détection ou de discrimination auditive, mais aussi tactile. Les résultats sont aussi les premiers à suggérer une meilleure reconnaissance tactile des émotions musicales.

7.1.1 - Amélioration de la discrimination fréquentielle

L'étude 1 avait comme objectif d'évaluer la discrimination fréquentielle auditive, tactile, et audiotactile chez les musiciens à l'aide d'une tâche à choix forcé à deux alternatives permettant de mesurer le seuil de discrimination fréquentielle (Young, Murphy et Weeter, 2017). Les résultats suggèrent des différences significatives entre les groupes pour la stimulation auditive, audiotactile et tactile, où les musiciens ont un seuil de discrimination plus bas que les non-musiciens à l'exception de la condition tactile utilisant les stimuli d'ondes en dents de scie. Aucune différence n'a été trouvée entre musiciens et non-musiciens pour cette dernière condition. De plus, même si les résultats suggèrent des performances améliorées chez les musiciens dans la condition audiotactile, aucun gain de l'addition de la modalité tactile à la stimulation auditive n'a été mesuré pour les musiciens. Pourtant, un faible gain a été mesuré chez les contrôles. Finalement, aucune différence significative entre les groupes n'a été mesurée pour les temps de réaction.

7.1.2 - Habiletés auditives

Ces données sont compatibles avec les études antérieures suggérant de meilleures performances auditives dans des tâches simples de discrimination fréquentielle chez les musiciens (Spiegel et Watson, 1984; Kishon-Rabin, Amir, Vexler et Zaltz, 2001; Micheyl, Delhommeau, Perrot et

Oxenham, 2006) et appuient les études suggérant que la plasticité corticale chez les musiciens est responsable de l'amélioration mesurée (par ex. Pantev et al. 1998; Pantev et Herholz, 2011).

7.1.3 - Habiletés tactiles

Les résultats sont les premiers à suggérer une amélioration de la discrimination fréquentielle tactile unisensorielle chez les musiciens. L'amélioration a été mesurée pour les stimuli d'onde sinusoïdale et carrée. Les résultats concordent avec l'étude de Landry et Champoux (2017), qui suggère des meilleurs temps de réaction dans la condition tactile unisensorielle chez les musiciens. La présente étude s'ajoute à la littérature existante sur les capacités unisensorielles des musiciens en suggérant pour la première fois qu'une formation musicale à long terme peut également améliorer la performance tactile dans des tâches d'un niveau plus complexe que la simple détection tactile. Les résultats concordent aussi avec les données d'imagerie concernant la perception tactile chez les musiciens. L'étude de Elbert, Pantev, Wienbruch, Rockstroh et Taub (1995) a révélé que chez des violonistes professionnels, la représentation corticale de la main gauche mesurée en magnétoencéphalographie est plus étendue lors du doigté des cordes, tel que l'indiquent l'amplitude mesurée et l'emplacement des réponses évoquées par la stimulation tactile. Cette différence de mesure est significative en comparaison aux contrôles, mais aussi par rapport à la représentation de la main droite mesurée chez les violonistes. De plus, la plasticité cérébrale chez les musiciens dans le domaine tactile serait plus facilement modulable que chez les contrôles selon Ragert, Schmidt, Altenmüller et Dinse (2004). Ceux-ci suggèrent que, suite à une stimulation tactile passive de 3 heures, les musiciens ont une plus grande diminution de leur seuil de discrimination tactile comparativement aux contrôles, donc une amélioration de performance générée par l'entraînement passif.

Aucune différence n'a été trouvée entre musiciens et non-musiciens pour la condition tactile avec les stimuli représentant l'onde en dent de scie. Ce type d'onde contient des harmoniques paires et impaires de la fréquence fondamentale. L'onde carrée ne contient que des harmoniques impaires. L'onde sinusoïdale ne contient aucune harmonique. L'onde en dents de scie est donc la plus représentative de ce qui est retrouvé comme type d'ondes en musique. Considérant que la plupart des gens ont l'habitude de faire de la discrimination fréquentielle lors de l’écoute de musique, il est possible de faire l’hypothèse que les non-musiciens sont donc plus entraînés à discriminer des ondes en dents de scie que les autres types d’ondes. Cette proposition expliquerait pourquoi aucune différence n’a été mesurée entre les musiciens et les contrôles pour la condition de l’onde en dents de scie. Des études supplémentaires sont nécessaires pour valider cette hypothèse.

Une amélioration de performance tactile chez les musiciens a aussi été mesurée dans une tâche musicale de plus haut niveau. L’étude 2 est la première à ce jour à mesurer l’identification tactile des émotions dans la musique. Le fait que les musiciens et non-musiciens sont capables d'identifier des émotions dans la musique uniquement par stimulation tactile constitue une découverte nouvelle et majeure en soi. L’étude de Branje, Nespoil, Russo et Fels (2013) va dans le même sens en suggérant qu'une stimulation multisensorielle peut augmenter la perception des émotions dans un film. Les auteurs ont utilisé « l’Emoti-Chair », un appareil qui induit des vibrations au niveau du dos. Les résultats de cette étude suggèrent que les individus normaux ont une augmentation des niveaux de conductance cutanée lorsque des stimuli vibrotactiles sont ajoutés au contenu d'un film audiovisuel. Ils ont observé que c’était non seulement l'intensité de la vibration qui jouait un rôle dans les réactions observées, mais également la fréquence des stimuli vibrotactiles. L’ajout de stimulation tactile pourrait donc être une avenue à explorer pour offrir une expérience émotionnelle améliorée, par exemple lors d’un concert musical.

De plus, les résultats ont révélé une différence significative entre les musiciens et les contrôles pour la stimulation tactile dans la condition de l’émotion apaisante. Celle-ci représente l’émotion la plus complexe à identifier dans la tâche présentée. Les musiciens se démarquent donc par rapport aux contrôles dans la condition qui demandent une analyse plus fine de la mélodie. Il est donc possible de faire l’hypothèse que l’entraînement musical à long terme permet une meilleure identification des subtilités musicales dans une mélodie permettant de distinguer des émotions complexes via la modalité tactile seulement. Ces résultats sont cohérents avec l’étude 1, qui est la première à ce jour à démontrer que les musiciens font une meilleure discrimination fréquentielle tactile que les contrôles. Ces résultats supportent l’hypothèse qu’une formation musicale à long terme entraîne une amélioration des capacités unisensorielles tactiles, mais surtout que celle-ci s’étend à des processus tactiles complexes.

7.1.4 - Habiletés audiotactiles

Le seuil de discrimination fréquentielle (étude 1) des musiciens était significativement plus petit que celui des contrôles dans la condition audiotactile. Ces résultats concordent avec l'étude de Young, Murphy et Weeter (2017) ayant utilisé le même protocole. Par contre, aucun impact significatif sur la performance de l'ajout de la modalité tactile à la modalité auditive (calcul du gain) n'a été mesuré. Un faible gain a été mesuré chez les contrôles comparativement à un gain nul chez les musiciens. Ce résultat pourrait être expliqué par un effet plafond. Considérant que, d'un point de vue comportemental, tel que discuté précédemment, les habiletés auditives de discrimination sont améliorées de façon générale chez les musiciens (Chartrand et Belin, 2006; Kishon-Rabin, Amir, Vexler et Zaltz, 2001; Micheyl, Delhommeau, Perrot et Oxenham, 2006 ; Pitt, 1994 ; Spiegel et Watson, 1984; Tervaniemi, Just, Koelsch, Widmann et Schröger, 2005). Il est possible que la performance dans la condition auditive seulement soit tellement améliorée qu'elle représente une valeur plafond, c'est-à-dire à partir de laquelle il n'est plus possible de s'améliorer davantage même lors de l'ajout d'indices supplémentaires provenant d'autres modalités sensorielles. Considérant que les contrôles performent à la base moins bien, il est donc possible pour eux de s'améliorer davantage par l'ajout du tactile. Cette hypothèse concorde avec les résultats obtenus dans l'étude pour la condition auditive seulement.

Contrairement à la discrimination fréquentielle, les performances pour l'identification des émotions dans la musique ne diffèrent pas entre les groupes dans la condition audiotactile. Par contre, un phénomène similaire à celui de l'étude 1 est observé concernant le gain. Le pourcentage d'amélioration de performance entre la condition auditive seulement et tactile seulement était près de 0 ou inférieur à 0 pour tous les types d'émotions chez les musiciens. Par contre, un gain a été mesuré chez les contrôles pour les émotions épeurante et apaisante. L'hypothèse d'un effet plafond est donc applicable pour cette tâche aussi. Les musiciens étant déjà trop bons dans la condition auditive seulement, ils ne peuvent pas s'améliorer par l'ajout du tactile. Ils ont donc possiblement une performance plafond comparativement aux contrôles qui eux, ayant place à s'améliorer, performent mieux dans la condition audiotactile qu'auditive seulement.

7.1.5 - Amélioration de la reconnaissance des émotions

Les résultats de l'étude 2 suggèrent que l'entraînement musical permettrait aussi d'améliorer des habiletés musicales de plus haut niveau comme la perception des émotions dans la musique. En effet, l'étude 2 avait comme but d'évaluer la perception des émotions musicales par des stimulations auditives, tactiles, et audiotactiles chez les musiciens. Les mélodies développées par Vieillard et al. (2008) comme exprimant la joie, la tristesse, la peur et l'apaisement ont été utilisées pour la tâche. Les participants devaient évaluer chaque extrait sur une échelle de 10 points pour indiquer leur appartenance à chacune des quatre émotions. Les résultats suggèrent un pourcentage d'identification adéquat des mélodies exprimant la peur qui est plus grand chez les musiciens que chez les contrôles dans la condition auditive. De plus, une amélioration de l'identification des mélodies exprimant la tranquillité a été mesurée dans les conditions auditive et tactile. Par contre, l'ajout de la stimulation tactile aux stimuli auditifs a apporté un gain de performance pour les contrôles, mais pas pour les musiciens. Ces données suggèrent que l'identification auditive des stimuli musicaux épeurants et apaisants est améliorée chez les musiciens. Ces résultats concordent avec l'étude de Vieillard et al. (2008) suggérant que les musiciens sont plus précis que les non-musiciens dans l'identification des émotions dans la musique. Le différent degré de difficulté associé aux types d'émotions utilisées dans la tâche pourrait expliquer la performance observée. La joie et la tristesse sont des émotions de base facilement identifiables (Terwogt et van Grinsven, 1991). Par exemple, il est possible de discriminer une émotion joyeuse versus triste en se basant seulement sur le tempo (rapide = joyeux, lent = triste) ou sur le mode (majeur = joyeux, mineur = triste) (Dalla Bella, Peretz, Rousseau et Gosselin, 2001), tandis que la peur est une émotion musicale moins directement identifiable considérant qu'elle est dans un mode mineur comme la tristesse, mais avec comme subtilités des dissonances ainsi qu'un rythme plus irrégulier (Vieillard et al., 2008; Tan, Pfordresher et Harré, 2017). Dans le même ordre d'idée, l'émotion la plus complexe et la plus ambiguë exprimée dans les mélodies de la tâche était l'apaisement. Cette émotion est évoquée en utilisant un mode majeur comme pour les stimuli joyeux, mais avec un tempo intermédiaire (entre joyeux et triste). De plus, les stimuli apaisants contiennent des arpèges et sont joués avec la pédale (Vieillard et al., 2008; Tan, Pfordresher et Harré, 2017). Les résultats pour la joie et la tristesse pourraient s'expliquer par un effet plafond considérant que la performance des musiciens atteignait près du cent pourcent de bonnes réponses dans ces conditions, ces émotions étant trop facilement identifiables pour eux tout en étant des conditions plutôt faciles aussi pour les contrôles. Il est possible de poser l'hypothèse que ces deux conditions ne sont donc pas assez sensibles pour déceler des différences entre les groupes.

7.2 - Effet de la privation auditive précoce

En marge des données suggérant que les habiletés sensorielles puissent être modifiées à la suite d'un entraînement musical, les données émanant de deux autres études suggèrent qu'une telle amélioration puisse survenir afin de compenser une perte sensorielle. En effet, les données suggèrent la présence d'une réorganisation sensorielle chez les personnes sourdes de naissance, ces dernières démontrant une capacité accrue dans certaines tâches tactiles musicales et non-musicales.

7.2.1 - Détection tactile chez l'individu sourd

L'étude 3 avait pour but d'évaluer l'impact d'une privation auditive permanente dès un bas âge sur la perception tactile dans une tâche sensorielle impliquant un jugement d'ordre temporel de stimuli tactiles lié à la perception du corps et de l'espace. Dans cette étude, la tâche de jugement d'ordre temporel tactile des bras croisés utilisée est la même que celle de Cadieux, Barnett-Cowan et Shore (2010). Les résultats de la tâche ont révélé que les participants sourds avaient un taux d'erreurs plus élevé lors du croisement des bras par rapport au groupe contrôle, ce qui concorde avec l'étude de Noël et Wallace (2016). Celle-ci suggère qu'une privation auditive de court terme est suffisante pour augmenter le taux d'erreurs dans la tâche des bras croisés. Aucune différence significative entre les groupes n'a été mesurée pour les temps de réaction.

Deux hypothèses permettent d'expliquer les résultats obtenus dans la tâche. Il est important de comprendre que l'augmentation du taux d'erreurs dans la position posturale des mains croisées lors de cette tâche a été attribuée à un conflit existant entre les cadres de référence permettant la perception du corps et de l'espace. Il existe un référent interne (égocentrique) et externe (allocentrique) associés au corps lorsqu'un individu tente de localiser la main de provenance d'un stimulus tactile. La première théorie de Yamamoto et Kitazawa (2001) propose que la main doit être localisée tout d'abord dans l'espace avant que l'ordre temporel d'arrivée des stimulations tactiles puisse être déterminé. Dans la posture des mains croisées, lorsque le délai est court entre les stimulations tactiles, les stimuli ont lieu avant que le cerveau ait procédé à une nouvelle cartographie spatiale du toucher. C'est ce qui conduirait à des taux d'erreurs plus élevés. Les résultats de l'étude 3 suggèrent donc que la génération d'une nouvelle cartographie spatiale du toucher prendrait plus de temps chez les individus sourds considérant que leur taux d'erreurs dans la posture bras croisés est plus élevé que celui des personnes normo-entendantes.

D'autre part, Shore, Spry et Spence (2002) proposent, dans une seconde théorie, que les cadres de référence interne et externe restent actifs après une transformation du cadre de référence. Selon cette hypothèse, le taux d'erreurs plus élevé constaté dans la condition des bras croisés serait attribué au fait qu'il est nécessaire de fournir un effort cognitif plus important pour résoudre les informations contradictoires entre les cadres de référence. Considérant qu'il faut un certain temps pour que les informations de la première stimulation soient localisées, si le deuxième stimulus est présenté avant que le premier stimulus ne soit localisé, des erreurs dans la position des bras croisés peuvent se produire. L'hypothèse de Shore, Spry et Spence (2002) devrait donc mener à des temps de réaction plus grands et des taux d'erreurs plus élevés pour les participants sourds. Cependant, l'analyse des temps de réaction ne suggère pas une différence significative entre les groupes sourds et contrôles.

L'étude 3 supporte les recherches sur le mouvement et la posture qui ont révélé un effet plus homogène chez les sujets sourds que les études s'intéressant seulement à la détection tactile. La littérature sur le sujet suggère que la surdité mène à la présence de déficits lors de la réalisation de tâches liées aux comportements moteurs ou à l'action motrice (Conway et al., 2011; Savelsbergh, Netelenbos et Whiting, 1991; Gayle et Pohlman, 1990; Gheysen, Loots et Van Waelvelde, 2007; Hartman, Houwen et Visscher, 2011; Lévesque, Théoret et Champoux, 2014; Schlumberger, Narbona et Manrique, 2004; Wiegersma et Velde, 1983). Les résultats obtenus dans l'étude 3 suggèrent que même en l'absence d'une composante motrice, les individus sourds présentent des difficultés dans une tâche impliquant un jugement adéquat de la position de leur corps dans l'espace. De ce point de vue, le fait que la cartographie spatiale du toucher soit altérée chez ces individus suggère une piste d'explication du déficit mesuré dans les tâches impliquant les comportements moteurs et l'action motrice chez les sourds. Tel que discuté précédemment, à la suite d'une privation auditive prolongée, le cerveau tend à se réorganiser par lui-même de façon à ce que le cortex sensoriel privé traite de plus en plus des stimuli habituellement régis par d'autres modalités. Les données en imagerie suggèrent que certaines régions typiquement associées à la modalité auditive sont activées par des stimulations tactiles chez les individus sourds (Levänen, Jousmäki et Hari, 1998; Schürmann, Caetano, Hlushchuk, Jousmäki et Hari, 2006). Par contre, il est possible que d'autres aires corticales soient altérées chez les individus sourds et puissent expliquer les résultats obtenus dans l'étude 3. Il a été suggéré que le cortex pariétal postérieur joue un rôle-clé dans l'interaction des cadres de référence chez les personnes entendantes (Azañón, Longo, Soto-Faraco et Haggard, 2010). Plusieurs études ont mis en évidence des modifications significatives de l'activation du cortex pariétal postérieur pour les stimuli visuels chez les sourds (par ex. Bavelier et al, 2000; Bavelier et al., 2001; Seymour et al., 2017). Bien que ces études aient porté sur les processus visuels, elles mettent en évidence une plasticité du cortex pariétal postérieur provoquée par une période de privation auditive. Ces études de neuroimagerie suggèrent une présence accrue d'informations visuelles dans le cortex pariétal postérieur en l'absence d'entrée auditive. Comme la vision représente des informations provenant d'un cadre de référence externe, cette importance accrue des informations visuelles dans le cortex pariétal postérieur pourrait aider à expliquer pourquoi un participant sourd fournit des réponses en se basant sur son référent externe lors de la tâche d'ordre temporel de détection tactile.

7.2.2 - Perception des émotions tactile chez l'individu sourd

Enfin, l'étude 4 avait comme objectif d'évaluer la perception des émotions dans la musique via la modalité tactile chez les individus sourds. Une tâche contrôle de discrimination fréquentielle tactile a été réalisée préalablement à l'étude à l'aide du même protocole expérimental que celui de l'étude 1. Les résultats suggèrent une discrimination fréquentielle tactile similaire chez les sourds et les contrôles. La tâche principale de l'étude 4 est la même que celle utilisée lors de l'étude 2 pour la condition tactile seulement. Les résultats suggèrent une performance améliorée pour l'identification des mélodies représentant la joie chez les individus sourds.

Contrairement à ce qui est retrouvé chez les musiciens, la seule émotion dans laquelle la performance des individus sourds était augmentée par rapport aux contrôles pour la condition tactile était la joie. Ceci est explicable par le fait que cette émotion est la plus facile à identifier au sein des quatre présentées dans la tâche (Terwogt et Van Grinsven, 1991). Le fait que des améliorations n'aient pas été observées chez les sourds pour les autres types d'émotions pourrait s'expliquer par leur manque d'exposition auditive à des stimuli musicaux complexes. L'habileté à identifier des émotions dans la musique débute à un jeune âge chez les individus normo-entendants. Par exemple, les enfants de 3 ans sont déjà sensibles à la connotation positive ou négative de la musique, mais ils ne sont pas suffisamment habiles pour identifier des émotions (Kastner et Crowder, 1990). Les enfants de 5 ans et moins sont limités à la discrimination des émotions joie et tristesse (Terwogt et Van Grinsven, 1991). Leur jugement est principalement basé sur des traits psychoacoustiques simples tels que le tempo, l'intensité et la hauteur (Adachi, Trehub et Abe, 2004). C'est seulement autour de l'âge de 11 ans que les enfants parviennent à identifier les émotions dans la musique comme le fait un adulte (Hunter, Schellenber & Stalinski, 2011). Considérant que la perception auditive de la musique des individus sourds est limitée par leur déficit auditif, il ne serait donc pas surprenant que leur capacité à percevoir des émotions dans la musique soit moins développée.

7.3 - Limites des études et recherches futures

7.3.1 - Tâche d'identification des émotions dans la musique

Tel que rapporté dans l'étude 2, les résultats des musiciens pour la tâche d'identification des émotions auditive et audiotactile sont tellement élevés qu'il est possible que des différences subtiles n'aient pas pu être décelées entre les groupes en raison d'un effet plafond. Un moyen d'éviter cet effet serait par l'utilisation d'une tâche plus sensible. Par exemple, l'utilisation de stimuli représentant une gamme émotionnelle plus large permettrait de déterminer à quel moment cet effet plafond disparaît. Par exemple, la Geneva Emotional Music Scales contient 45 étiquettes permettant de décrire les émotions ressenties lors de l'écoute de musique (Zentner Grandjean et Scherer, 2008). Il faudrait par contre créer des stimuli musicaux associés à chacune de ces étiquettes et les valider préalablement au sein de la population pour pouvoir mesurer ces subtilités, considérant qu'ils n'existent pas à l'heure actuelle. Cette échelle permettrait de mesurer des différences subtiles comme, par exemple, une musique amusante versus dansante, toutes deux des émotions au sein du spectre de la joie. Des études supplémentaires sont donc nécessaires pour explorer davantage l'identification des émotions chez les musiciens.

7.3.2 - Mesures électrophysiologiques et en imagerie

La réalisation d'études supplémentaires utilisant des mesures objectives (par exemple, électrophysiologiques) serait aussi une solution envisageable afin d'éviter l'effet plafond suggéré dans l'étude 2. Ces études permettraient non seulement d'éviter ce biais, mais aussi d'identifier les corrélats neuroanatomiques sous-jacents à la perception auditive, audiotactile et tactile chez les musiciens qui demeurent inconnus à ce jour, autant pour la discrimination fréquentielle que l'identification des émotions dans la musique.

Des études électrophysiologiques ou en imagerie sont aussi nécessaires pour mieux comprendre les mécanismes corticaux sous-jacents à la détection tactile chez l'individu sourd. Tout d'abord, celles-ci permettraient de comprendre le rôle du cortex pariétal postérieur dans l'augmentation du taux d'erreurs lors de la tâche d'ordre temporel de détection tactile chez les sourds ainsi que de comprendre l'origine des limites mesurées lors de la tâche d'identification des émotions musicales chez l'individu sourd.

7.3.3 - Temps de réaction

Les temps de réaction ont été mesurés chez les musiciens pour la tâche de discrimination fréquentielle. Les résultats pour les temps de réaction n'ont montré aucune différence significative entre les groupes. Des études antérieures ont révélé que les musiciens réagissent plus rapidement que les non-musiciens aux stimuli visuels (Anatürk et Jentzsch, 2015; Chang et al., 2014), aux stimuli tactiles (Landry et Champoux, 2017) et aux stimuli auditifs (Landry et Champoux, 2017; Strait, Kraus, Parbery-Clark et Ashley, 2010). Toutes ces études ont utilisé un protocole de temps de réaction simple, ce qui n'est pas représentatif de la tâche utilisée dans l’étude actuelle. L'absence de différence entre les musiciens et les non-musiciens en ce qui concerne les temps de réaction peut s'expliquer par la complexité de la tâche utilisée, qui consiste en de la discrimination et non de la simple détection. Des études complémentaires sont nécessaires pour étudier le temps de réaction dans des tâches plus complexes de stimuli auditifs et tactiles.

7.3.4 - Caractéristiques des musiciens

Il est bien connu que le type d’instrument joué par le musicien a une influence sur la plasticité corticale. Par exemple, Elbert, Pantev, Wienbruch, Rockstroh et Taub (1995) ont suggéré que dans un groupe de violonistes experts, la région du cortex somatosensoriel qui représente la main gauche était significativement plus sensible à la stimulation tactile que chez les non-musiciens. De plus, Gruhn (2002) a révélé qu’il est plus facile d’apprendre un instrument de musique en bas âge. La période sensible serait autour de l’âge de 7 ans selon plusieurs études (pour une revue, voir Habib et Besson, 2009). Si un instrument de musique est débuté à un âge plus avancé, les changements structurels induits par la musique et les effets d'apprentissage seraient moins prononcés. De plus, la quantité de matière dans les régions motrice, auditive et visuo-spatiale grises différerait entre les musiciens professionnels, amateurs et les non-musiciens (Gaser et Schlaug, 2003). Plus un musicien est entraîné, plus la quantité de matière grise dans ces régions serait grande.

L’étude de Castro et Lima (2014) suggère une corrélation entre le nombre d’années d’expertise musicale et la précision à identifier des émotions dans la musique. Cette étude a révélé que chez les participants plus âgés, il y avait une différence significative entre les musiciens et non-musiciens. Les personnes âgées entraînées à la musique faisaient une meilleure identification des émotions triste et épeurante. Cette différence entre les groupes n’est pas reproduite chez les plus jeunes. Une limitation importante de cette étude est que le nombre d’années d’expertise musicale des participants était grandement variable d’un participant à l’autre (8-18 ans) et l’âge de début de l’entraînement musical était au-dessus de 7 ans. Considérant que l’expertise musicale des participants plus jeunes était moindre, c’est possible que ce simple facteur explique qu’aucune différence significative n’a été trouvée entre les groupes plus jeunes. De ce point de vue, les résultats de nos études sur les musiciens représentent mieux le profil du musicien expert. De plus, la moyenne d’âge du groupe de musiciens correspondait au groupe plus jeune de Castro et Lima (2014). Tous les participants étaient des musiciens professionnels avec, en moyenne, un âge de début d’apprentissage de la musique de 7 ans et une vingtaine d’années de pratique de leur instrument. Ces résultats soulèvent l’importance de considérer les caractéristiques des musiciens lors de l’étude de leur performance sensorielle.

Le même groupe de musiciens a été évalué dans le cadre de l’étude 1 et 2. L’homogénéité des caractéristiques des participants n’a pas permis d’évaluer l’impact sur la performance de différents portraits de musiciens. Les musiciens qui ont participé aux deux études étaient tous des professionnels. La plupart d'entre eux jouaient du piano comme instrument principal et ont commencé à jouer de la musique vers 7 ans. Dans le cadre de futures recherches, il serait intéressant d’aller mesurer l’impact du degré d’entraînement musical, du type d’instrument joué, du style de musique le plus fréquemment joué, de l’âge de début d’entraînement pour le premier instrument de musique ou encore du nombre d’heures de pratique par semaine sur la performance.

7.3.5 - Caractéristiques des individus sourds

Les participants des études 3 et 4 avaient tous des caractéristiques similaires (âge de début de la surdité, durée de la surdité, utilisation d’aides auditives et mode de communication). Certaines caractéristiques sont pourtant bien connues comme influençant la réorganisation corticale (voir, par exemple, Kral et Sharma, 2012). Par exemple, la privation auditive peut modifier le développement du langage et ces changements peuvent être irréversibles si la stimulation auditive n'est pas restaurée avant l'âge de 7 ans (pour une revue, voir Kral, Hartmann, Tillein, Heid et Klinke, 2001). Sur la base de ces études, nous pouvons émettre l'hypothèse que les résultats obtenus pour les sourds ayant une perte d'acuité auditive après 7 ans seraient différents de ceux des participants ayant participé aux études 3 et 4 qui étaient principalement des sourds congénitaux. Des études ultérieures devraient examiner l'impact de l'apparition tardive d'une perte auditive sur la performance afin de comparer les résultats obtenus dans cette thèse chez les sourds de naissance.

De plus, pour l’étude 3, il y avait un seul participant communiquant via la langue des signes et il y en avait deux pour l’étude 4. Tous les autres participants communiquaient oralement. Nishimura et al. (1999) ont suggéré que la langue des signes active des régions du cerveau habituellement réservées à l'audition, ce qui suggère que ces régions peuvent être activées par d'autres modalités sensorielles. Cette plasticité neuronale constatée chez les utilisateurs de la langue des signes suggère que ces participants devraient être différents des sourds qui communiquent oralement. Il n'y avait pas de différence entre les utilisateurs de la langue des signes et les autres participants pour les études 3 et 4. Par contre, des études ultérieures devraient prendre en compte cette caractéristique et constituer un groupe de sourds gestuels de plus grande envergure pour confirmer l’absence de différence entre les groupes. Tous les participants communiquant oralement faisaient usage de l’amplification auditive.

Pour les deux études, il serait intéressant d’examiner l’effet de l’amplification auditive sur la performance lors de la tâche en tenant compte de différentes caractéristiques telles que les seuils auditifs avec amplification, le « data logging » de l’aide auditive et les paramètres d’ajustement des appareils auditifs. Il est bien connu que ces facteurs peuvent avoir un impact important sur la plasticité cérébrale et la performance des personnes sourdes (Kral et Sharma, 2012). De plus, concernant la tâche des bras croisés plus spécifiquement, il serait intéressant d’évaluer s’il existe une période critique au cours de laquelle une entrée auditive est requise pour que la cartographie spatiale du toucher demeure normale.

La majorité des participants sourds présentaient aussi des dommages au niveau du système vestibulaire. Étant donné qu’il est bien connu que la fonction vestibulaire a une influence sur les processus liés au corps, tels que la conscience du corps et la perception du corps (pour une revue de la littérature, voir Lopez, 2016), un déficit de la fonction vestibulaire pourrait expliquer certains des résultats. Les investigations utilisant la rotation passive du corps ont révélé un impact de la rotation sur la tâche d’ordre temporel tactile (Figliozzi, Guariglia, Silvetti, Siegler et Doricchi, 2005). L'impact de la déficience vestibulaire sur la représentation du corps dans l'espace doit être approfondi afin de démêler si l'absence de contrôle postural observée chez le sourd congénital résulte d'une privation auditive précoce ou d'une déficience vestibulaire.

Finalement, l'identification tactile des émotions dans la musique doit être étudiée chez des individus sourds présentant une apparition tardive de leur surdité versus des sourds congénitaux. Ces résultats pourraient aider à déterminer s’il existe une période critique pendant laquelle la privation auditive est nécessaire pour générer l’amélioration de la performance telle que mesurée chez les individus sourds de naissance de l’étude 4.

7.4 - Intégration d’aides vibrotactiles dans les technologies d’aide auditive

Les technologies tactiles sont utilisées en réadaptation dans le cadre de l’adaptation de domicile des individus sourds pour les alerter des sonneries telles que la porte, l’alarme de feu, etc. Ce type de technologies est en constante évolution et un prototype permet même de donner des signaux visuels et tactiles à l’individu sourd grâce à son téléphone portable (Ketabdar et Polzehl, 2009). Les nouvelles recherches sur l’ajout d’aides vibrotactiles pour aider les individus sourds vont au-delà de la simple détection de sons dans l’environnement. La possibilité de perception tactile de la musique suggère que les technologies tactiles pourraient apporter beaucoup plus dans la vie des individus sourds. Considérant le peu de connaissances actuelles sur la perception de la musique tactile, les technologies existantes pour l’instant demeurent à l’état de prototype.

Pour mener leurs études sur l’ajout d’indices tactiles aux réactions à un film (Karam, Nespoli, Russo et Fels, 2009) et la perception tactile du timbre musical (Russo, Ammirante et Fels, 2012), l’équipe du chercheur Frank Russo a développé une chaise permettant de transmettre des indices tactiles via le dos. Cette chaise reproduit l’organisation tonotopique de la cochlée (Branje, Maksimouski, Karam, Fels et Russo, 2010). Deux autres équipes ont développé des technologies similaires de chaises vibrotactiles pour transmettre la musique (Jack, McPherson et Stockman, 2015; Nanayakkara, Taylor, Wyse et Ong, 2009). Ce genre de prototype pourrait être utilisable dans une salle de spectacle pour transmettre la musique via le dos lors d’un concert d’un orchestre, par exemple. Cette technologie n’est par contre pas pratique pour une utilisation personnelle au quotidien.

L'équipe de Yao, Shi, Chi, Ji et Ying (2010) a plutôt développé une aide vibrotactile pour les danseurs présentant une surdité. Les indices de rythme et de tempo sont transmis via des souliers vibrotactiles. Ce genre de technologies répond à un besoin spécifique, mais ne peut pas permettre d'aider tous les individus sourds présentant une problématique avec la perception de la musique.

Finalement, le gant utilisé dans les études 1, 2, 3 et 4 est aussi une autre avenue technologique pour transmettre la musique via le sens du toucher (Young, Murphy et Weeter, 2017). Malheureusement, le gant n'est pas non plus un outil pratique, considérant qu'il prive l'utilisateur de la possibilité d'utiliser ses mains pour faire une autre tâche.

Considérant que les connaissances sur la perception de la musique tactile sont en constante évolution, les chercheurs devraient débuter l'intégration du tactile aux aides auditives déjà existantes. Cette option, si fonctionnelle et efficace, pourrait permettre de répondre au besoin d'ajout d'un sens supplémentaire pour mieux percevoir la musique pour les individus sourds, tout en étant pratique pour le porteur.

7.5 - Conclusion

Les résultats de cette thèse soutiennent l'hypothèse que la plasticité cérébrale entraîne des changements sensoriels à la suite d'un entraînement auditif et une privation auditive depuis la naissance. Par contre, l'impact de cette plasticité sur la performance comportementale diffère entre ces deux populations. Tout d'abord, la plasticité cérébrale améliore la performance pour des processus sensoriels de bas et de haut niveau chez les musiciens tandis qu'elle améliore seulement la performance pour des processus de haut niveau chez les individus sourds. Les études de cette thèse sont les premières à révéler des améliorations tactiles pour des processus de haut niveau chez les musiciens et les individus sourds. Des études supplémentaires utilisant des mesures objectives (par exemple, des mesures électrophysiologiques ou en imagerie) sont donc nécessaires pour identifier les corrélats neuroanatomiques associés à ces altérations mesurées dans la performance chez ces deux populations.

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Annexes

Annexe 1 - Auditory event-related potentials associated with music perception in cochlear implant users

Andréanne Sharp, Audrey Delcenserie et François Champoux

Université de Montréal, Faculté de médecine, École d'orthophonie et d'audiologie, C.P. 6128, Succursale Centre-Ville, Montréal, Québec, Canada, H3C 3J7

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Abstract

A short review of the literature on auditory event-related potentials and MMN in cochlear implant users engaged in music-related auditory perception tasks is presented. Behavioral studies that have measured the fundamental aspects of music perception in CI users have found that they usually experience poor perception of melody, pitch, harmony as well as timbre (Limb & Roy, 2014). This is thought to occur not only because of the technological and acoustic limitations of the device, but also because of the biological alterations that usually accompany deafness. In order to improve music perception and appreciation in individuals with cochlear implants, it is essential to better understand how they perceive music. As suggested by recent studies, several different electrophysiological paradigms can be used to reliably and objectively measure normal-hearing individuals' perception of fundamental musical features. These techniques, when used with individuals with cochlear implants, might contribute to determine how their peripheral and central auditory systems analyze musical excerpts. The investigation of these cortical activations can moreover give important information on other aspects related to music appreciation, such as pleasantness and emotional perception. The studies reviewed suggest that cochlear implantation alters most fundamental musical features, including pitch, timbre, melody perception, complex rhythm, and duration (e.g., Koelsch, Wittfoth, Wolf, Müller & Hahne, 2004; Limb & Roy, 2014; Timm et al., 2012, 2014; Zhang, Benson & Fu, 2013; Zhang, Benson & Cahn, 2013). A better understanding of how individuals with cochlear implants perform on these tasks not only makes it possible to compare their performance to that of their normal-hearing peers, but can also lead to better clinical intervention and rehabilitation.

Introduction

Listening to and playing music are pleasurable activities of everyday human life. However, in order to be able to enjoy music, a complex analysis of the musical excerpt has to be done by the peripheral and central auditory systems, which then elicits emotions and/or meaning.

In both normal-hearing and cochlear implant listeners, MMN patterns in event-related neural electrical potentials can be used to assess basic auditory perceptual discriminations most critical for music perception (pitch, timbre, loudness as well as melodic, and rhythmic patterns). The

MMN component is a deviant-minus-standard difference waveform that is computed by subtracting the averaged event-related potential waveform in response to a repeated “standard” stimulus from that produced by a different, rarely presented novel, “deviant” stimulus (oddball paradigm). In general, the MMN is a reliable neural marker for the perceptual contrast (discriminability) between the rare novel stimulus and the much more probable standard one (see Näätänen, Gaillard & Mäntysalo, 1978 for more details).

More complex processes, such as pleasantness, emotions or meaning, usually associated with music, can be evaluated using electrophysiological measurements of cortical activations– including the N400 component or frontal alpha asymmetry correlates. The N400 component is an event-related potential associated with the meaning of a stimuli and, in the case of music, meaning corresponds to the ability to associate a concept with musical excerpts. One type of protocol used to elicit the N400 component is to compare a prime stimulus with a target stimulus. For example, a fast song that contains a lot of high frequencies is usually more closely associated with the concept of a mouse than that of an elephant. The closer the association between these two stimuli, the less negative the amplitude of the N400 will be. The other technique, namely, the frontal alpha asymmetry measurement, is a relatively recent technique that has been used to examine the perceived pleasantness of a stimulus. This protocol consists in placing electrodes on each side of the head over the frontal area in order to obtain an imbalance index (Maglione et al., 2015).

In contrast to their normal-hearing peers, deaf individuals need an auditory compensation device in order to access an auditory experience of music. The typical way to restore hearing is to insert electrodes in the cochlea to directly stimulate the auditory nerve. This process, called cochlear implantation, can convert a severe-to-profound sensorineural hearing loss into near-normal hearing. Although implants successfully provide access to speech perception, CI users usually complain about the fact that implantation impairs their perception of music—specifically in cases of acquired deafness (e.g., Limb & Roy, 2014). Behavioral studies have confirmed this by assessing basic aspects of music perception in CI users and showing that these listeners have very poor perception of pitch, melody, harmony, and timbre (Limb & Roy, 2014). However, their perception of rhythm is generally well preserved (e.g., Looi, Gfeller & Driscoll, 2012; McDermott, 2004).

On the one hand, it is well known that the signals that individuals are able to perceive with implants are degraded—an important limitation that may contribute to music perception deficits mentioned above (for a review see Limb & Roy, 2014). The spectral resolution that can be conveyed through CIs is much reduced compared to spectral resolution in the normal hearing system. Also, the possible interaction between electrodes is a limiting factor, because it decreases the quantity of possible independent channels for conveying information. The characteristics of the implants are leading to a bad replication of place-coded information. Finally, another problem is that CIs are not replicating temporal firing patterns that are essential for the representation of musical pitch and spectral fine structure, resulting in a bad replication of temporally-coded information by CI users.

Furthermore, studies suggest that the prolonged period of auditory deprivation that deaf individual experience prior to implantation may lead to brain alterations. For example, research shows that deprivations experienced in a given sensory modality can lead to the reorganization of the sensory cortex associated with this modality, known as cross-modal plasticity (e.g., Bavelier & Neville, 2002; Good, Reed & Russo, 2014; Houde, Landry, Pagé, Maheu & Champoux, 2016). Similarly, a recent neuroimaging study has found that, in deaf individuals, auditory regions are activated by vibrotactile stimuli (Schürmann, Caetano, Hlushchuk, Jousmäki & Hari, 2006). These studies indirectly suggest that the altered perception of music experienced by CI users is possibly due, in part at least, to this cross-modal plasticity.

To date, no review has looked specifically at the auditory event-related correlates associated with CI users' music perception. The main goal of the present short review was to examine these electrophysiological responses that can be really useful to better understand music perception in CI users. An emphasis will be put on studies that have examined perception of musical pitch, melody, harmony, timbre, rhythm, tempo, meter, duration, and intensity by using auditory event-related potentials.

Moreover, and as mentioned earlier, electrophysiological measurements, such as the N400, frontal asymmetry measurement, and the MMN, are useful to examine the complex processes associated with music perception in normal-hearing individuals. Similarly, using electrophysiological measurements in hearing-impaired individuals could be useful to investigate the causes of CI users' impaired music perception. Thus, a secondary goal of the present review was to investigate the electrophysiological markers that can be used to document CI users' impaired music perception. The present review will focus on two electrophysiological techniques that have been used to investigate music perception, that is, measurements of the pleasantness and of the meaning of music. Overall, the present review aims to help clinicians by allowing them to plan their interventions with CI users more effectively. Since music perception is often a priority of CI users, clinicians must be properly trained to offer them appropriate and efficient rehabilitation.

Perception of Musical Pitch, Melody, and Harmony

The present review will focus mainly on pitch perception and, to a smaller extent on melody. It is however important to highlight that it is pitch perception that makes it possible for people to have a good understanding of music harmony, thus explaining why so many studies have investigated this ability.

On the one hand, behavioral studies suggest that CI users' performance on tasks assessing pitch perception is generally poor because of factors related to the technological limitations of the implant, including the implant processor and the design of its electrode (see Limb & Roy, 2014 for a review).

A study by Zhang, Benson & Fu (2013) used electrophysiological measurements, specifically the MMN, in order to examine pitch perception patterns. They compared 10 CI users to 10 normal-hearing controls (NH) using four different oddball paradigms. The participants were either exposed to a sequence of five notes with a standard pitch contour pattern [4 conditions: pattern in which each note was separated by one semi-tone starting at 440 Hz (1) rising or (2) falling or by five semi-tone (3) rising or (4) falling] or to a deviant pitch contour pattern [4 conditions paired with the equivalent standard stimuli (rising-flat or falling-flat): the 3 first notes followed the pattern separated by one or five semi-tone, but the last two notes of the pattern were the same as the third]. The presence of an MMN in participants indicated that they were able to detect the change in pitch contour pattern. However, in the one semi-tone pitch contour paradigm, none of the CI users exhibited an MMN response. An MMN was found in 30% of the CI users and in 80% of the NH controls in the rising pitch condition, whereas, in the falling pitch condition, 60% of the CI users and 80% of the NH controls had an MMN. This suggests that individuals with CIs have more difficulty discriminating pitch contour patterns than their NH peers (see also Timm et al., 2014 for similar results).

Studies have also investigated more complex musical features related to pitch perception, but these studies have used different electrophysiological paradigms. For example, Sandmann et al. (2009) examined pitch perception. To do so, they compared 12 CI users to 12 NH controls using an oddball design in two different conditions—a dyadic tonal interval condition and a passive listening condition. Dyadic tonal intervals consisted of two sinusoidal tones, sampled at 44.1 kHz and tuned to the equal-tempered chromatic scale in the range of A4 (440 Hz) and Eb6 (1,245 Hz). These simple tones were paired at pitch intervals of 1 (minor second) and 18 (minor duodecim) semitones, resulting in two different dyadic tonal intervals. During this task, they looked specifically at the elicitation of the N1 component. This component is usually elicited when an unpredictable stimulus is detected, suggesting that a change in the auditory stimulus has been perceived (in that case, a difference in pitch). The dyadic tonal intervals could be defined as a simple frequency relationship between two notes. Sequences of musical intervals are fundamental features that constitute melodies. The results showed that the CI users exhibited smaller N1 amplitudes over their fronto-central area as well as altered hemispheric asymmetries when required to process dyadic tones. Effectively, the results showed that CI users exhibit a contralateral dominance for right-ear stimulation, while NH individuals exhibit a contralateral dominance for left-ear stimulation.

Given that, as already mentioned, pitch perception makes it possible to understand music harmony, CI users' pitch perception difficulties reviewed in the electrophysiological and behavioral studies described above may explain why they have an impaired appreciation of music (see also Limb & Roy, 2014 for a review).

Perception of Timbre

An extensive number of behavioral studies show that CI users experience difficulties with timbre perception (for a review, see McDermott, 2004). Timbre is the set of auditory qualities that distinguishes two different instruments playing the same note (i.e., the same pitch). A task in which subjects have to identify musical instruments is thus a task that relies on timbre perception.

Electrophysiological studies, on the other hand, generally report that, in normal hearing individuals, music-syntactic irregularities elicit negative electric brain potentials (around 200 and 500 ms). These negative brain potentials include the ERAN, the N5, the MMN, and the P3 components. In general, these components are elicited when an individual detects novel or deviant stimuli. For example, a study by Koelsch, Wittfoth, Wolf, Müller & Hahne (2004) has used music-syntactic irregularities; a concept associated with pitch, and timbre deviation to compare CI users and NH individuals on electroencephalogram responses for different negative electric brain components—the ERAN, the N5, the MMN, and the P3 components. The participants included 12 CI users and 12 NH who were instructed to count the number of deviant instruments in a sample of 216 chord sequences that each consisted of five chords. Note that, here, a deviant instrument refers to an instrument that differs from the piano (in this experiment deviant instruments were: trumpet, organ and other instruments sample available). In each chord sequence, there was a 25% chance that the third chord was irregular (syntactic irregularities: expected elicitation of the ERAN and the N5), a 25% chance that the fifth chord was irregular (syntactic irregularities: expected elicitation of the ERAN and the N5), and a 15% chance that the chords two to five were played by another instrument (expected elicitation of the MMN and the P3). In terms of syntactic irregularities, there was a significant group difference was found for ERAN and N5 responses. For the CI group, the amplitude of both complexes was smaller, but only for the fifth chord irregularity. As well, no ERAN or N5 responses were found in the CI users when the third chord was irregular. However, the amplitude of CI users' response was significantly smaller, suggesting diminished neural responses to violations of harmonic expectancy. In CI users, the timbre deviation condition also elicited an MMN response that was smaller in amplitude than that of NH individuals (by a factor of three). The latter results are not only consistent with those reported in the previous section, namely that CI users experience altered pitch perception, but they also suggest that basic timbre perception is a weakness of CI users.

More recently, Timm et al. (2012) focused on the perception of temporal features related to timbre. They used an oddball paradigm in which the length of the stimuli were either shortened, by cutting off the first 60 ms (referred to as shortened attack time), or prolonged (prolonged attack time) in comparison to a standard normal stimulus (a 360 Hz French horn sound). The authors also examined basic auditory features using evoked potentials, specifically N1 and P2 amplitudes as well as latencies. The N1-P2 complex is known to be associated with the encoding of the physical attributes of sound in normal hearing individuals, such as the detection of stimulus onset (Weise, Bendixen, Müller & Schröger, 2012). They recruited 12 CI users and 12 NH controls. In both groups, some participants had some musical training while others did not. The groups were matched on age and gender. The results showed that, in the NH group, a significant MMN response was elicited when the stimulus was presented in the prolonged attack time, but no significant MMN response was measured for the shortened attack time. In contrast, no MMN response was elicited in the CI group—this for all conditions. An absence of MMN response suggests that individuals with CIs experience reduced timbre perception. In terms of the N1 response, two interesting findings were reported. First, it was found that the amplitude of the N1 response in the CI users was significantly smaller than that of the control. Second, the amplitude of N1 responses in the CI users with prior musical training was more similar to that of the normal-hearing controls (with and without musical training) than to that of the CI users without musical training. These results suggest that musical training has an important impact on hearing experience.

Similarly, Zhang, Benson & Cahn (2013) used MMN responses to look at timbre discrimination in CI users and their NH peers. To do so, they used three different oddball paradigms in which CI users and NH controls heard a musical note played by three different pairs of musical instruments (i.e., saxophone/piano, cello/trombone, and flute/French horn). In this protocol, a sequence of repetitive standard stimuli (saxophone, cello or flute) was infrequently interrupted by a deviant stimulus (piano or trombone or French horn). An MMN response, evoked by the presentation of the deviant stimulus, was measured for each of the three different pairs of musical instruments.

Interestingly, the CI users exhibited MMN peaks that were significantly smaller and shorter in terms of both amplitude and duration than those of the NH group. These results corroborate those of previous electrophysiological studies in showing that timbre discrimination is altered in CI's users (Koelsch, Wittfoth, Wolf, Müller & Hahne, 2004; Timm et al., 2012).

Although interesting, the studies described above have used a paradigm that is relatively simple in order to measure timbre perception, that is, the ability to discriminate between two musical instruments. Rahne, Plontke & Wagner (2014) recently used a more complex paradigm to investigate timbre perception, namely, a multifaceted protocol. In contrast to the protocols described earlier, the multifaceted protocol is particularly innovative since it allows the investigation of both spectral and temporal aspects of timbre at the same time. This more complex protocol was created to show that MMN responses could more objectively reflect timbre discrimination thresholds in groups of CI and NH individuals. Note that, given its complexity, only a brief description of the protocol will be provided below (see Rahne, Plontke & Wagner, 2014 for the complete procedure). The task was an adaptive three-alternative forced-choice procedure in which just noticeable differences (JND) for temporal envelope modulation differences as well as spectral distribution differences were measured for each participant. Each participant's JND was then used to compute individual tone pairs, including (a) temporal envelope modulation/spectral distribution timbre discrimination and (b) above and below JND. Using these tone pairs, four oddball paradigms were created in order to elicit MMN. Specifically, Rahne, Plontke & Wagner (2014) used the MMN amplitudes at the Fz electrode, representing the midline frontal area, which reflects one's ability to automatically detect acoustic change.

First, the behavioral results showed that CI users' performance on spectral distribution and temporal envelope modulation were significantly lower than that of the NH controls. For CI users, a mean JND of 30.0 dB (TE tones in "good performers," standard deviation [SD]: 8.6 dB) and 0.67 (S tones in all CI users, SD: 0.37) was found. For NH listeners, the mean JNDs were 7.2 dB (TE tone, SD: 4.7 dB) and 0.21 (S tones, SD: 0.28). Indeed, only four CI users out of fifteen were able to successfully complete the temporal envelope modulation condition. In terms of electrophysiological results, the authors report that both groups exhibited a significant MMN response in the above JND condition. However, no significant MMN response was found in the “below JND” condition—this for both groups. These results suggest electrophysiological measurements represent an effective way to evaluate timbre discrimination.

Overall, no difference was found between the CI and NH participants on the electrophysiological part of the study—which is coherent with the nature of the protocol, because the stimuli were adapted for each participant by being presented above or below their own just noticeable difference. In contrast, the CI users performed significantly worse than the NH controls on behavioral measures, which evaluated the discrimination of spectral distribution differences as well as temporal envelope modulation.

Indeed, the fact that the electrophysiological results can reveal the thresholds for both spectral distribution difference and temporal envelope modulation difference suggests that it might be an effective way to measure timbre discrimination in individuals whose understanding of the behavioral tasks, like prelingually deaf CI users, is more demanding. In sum, the study of Rahne, Plontke & Wagner (2014) suggests that more complex protocols might be more effective to monitor timbre discrimination abilities than tasks that simply require participants to discriminate between musical instruments.

It is important to emphasize here that studies do not consistently report altered timbre discrimination in CI users. For example, some studies have found no significant differences between CI users and NH controls on MMN amplitudes and/or latencies for saxophone timbre (standard stimulus: piano; deviant stimulus: saxophone), although significant differences were found for guitar timbre (standard stimulus: piano; deviant stimulus: guitar). These results suggest that, following implantation, some aspects of timbre discrimination might be preserved. Importantly, these studies have often used simple tasks in which timbre discrimination is easier or more obvious, thus allowing CI users to perform similarly to NH controls. However, when studies require participants to make more refined auditory analyses of the musical stimuli, the CI users usually experience more difficulties.

Overall, the present section seems to confirm that CI users experience difficulties with timbre perception, but also that the degree of their difficulties depends on the nature of the tasks that are used. More research needs to be done in order to better understand CI users' weaknesses and this has to be done with tasks that are demanding enough to better characterize CI users' difficulties with timbre perception.

Perception of Rhythm, Tempo, Meter, Duration, and Intensity

The behavioral studies that have investigated CI users' rhythm perception have shown that their perception of simple rhythm patterns is relatively good (Drennan and Rubinstein, 2008). Only one study has found that CI users perform significantly worse than controls on a rhythm task using a short inter-pulse interval in a six-pulse auditory pattern (Gfeller, Woodworth, Robin, Witt & Knutson, 1997).

On the other hand, electrophysiological studies that have examined rhythm, tempo, meter, duration, and intensity of music in CI users have used multi-feature paradigms. For example, Sandmann et al. (2010) investigated musical sound perception in CI and NH individuals using an MMN paradigm. As mentioned earlier, the MMN component is elicited when an individual detects a different (or deviant) auditory stimulus among the “standard” stimuli that are presented. The MMN paradigm measured participants' ability to notice variations in music frequency, intensity, and duration. The task included different types of variations, namely, increments in frequency (493, 554, 622, and 698 Hz), decrements in intensity (61, 57, 53, 49 dB), and variations in stimuli duration (130, 110, 90, 70 ms). The results showed that, on deviations in duration, none of the groups showed a robust MMN response. However, the CI users exhibited MMN components of smaller amplitudes than the NH controls when exposed to variations in frequency and intensity. The CI users did not significantly differ from the NH controls when behavioral measures were used to examine variations in frequency, intensity, and duration of musical sounds (see Timm et al. (2014) for similar results).

Thus, the above results suggest that CI users' ability to detect/notice variations in musical rhythm could be worse than that of NH individuals, which is consistent with the findings of behavioral studies showing that CI users experience difficulties with complex rhythm patterns.

Musical Meaning

It is interesting to reflect on the fact that songs often allow people to feel emotions, such as pleasantness. The cognitive ability that makes it possible to derive pleasantness from music has often been investigated in CI users. For example, Maglione et al. (2015) compared CI users and NH controls on the pleasantness that they felt while looking at a music video. The CI group was evaluated when they had only one implant and were evaluated again a few months later, after their second implantation. Perceived pleasure was assessed using an electroencephalogram measurement technique comparing the electrical activity in the different prefrontal areas (see Maglione et al., 2015 for the complete procedure). This technique made it possible to calculate an electrical imbalance index between left and right frontal regions while the participants were listening to the music video in three different conditions: (a) unmodified sound, (b) distorted sound, and (c) no sound. The results suggest that participants with bilateral implants experience a fluctuation in their perceived pleasures between the three different conditions similar to the variation found in the NH group (i.e., perceived pleasure: unmodified sound > distorted sound > no sound). Similar findings were found when the participants had only one implant.

A more recent procedure allows researchers to investigate relations between musical and lexical meaning. This procedure, which includes both behavioral and electrophysiological measures, consists in determining whether a musical stimulus is congruent or incongruent with a word (see Koelsch et al., 2004 for the detailed procedure). This word can be associated or not to the semantic sense of the musical piece an individual is listening to. For example, a fast musical except with a high pitch can easily be related to the word bird (i.e., related prime), but less to the word king (i.e., an unrelated prime). In terms of electrophysiological measurements, the procedure intends to elicit an N400 component. This component is an event-related brain potential that is related to meaning processing. Thus, it provides an objective evaluation of the congruence judgment of musical stimuli that the procedure entails (Koelsch et al., 2004).

A recent study has used this technique, including N400 measurements, in order to investigate CI users' comprehension/understanding of the meaning of music. Both pre-lingual CI users implanted before language acquisition (i.e., early childhood) and post-lingual CI users implanted after adolescence (i.e., long period of hearing deprivation before implantation) were included in this study. The results showed that the amplitude of the N400 component elicited by musical stimuli is positively and significantly correlated with the ability to make appropriate musical discriminations in NH individuals—but also in some CI users (Bruns et al., 2016). Indeed, an N400 was elicited in the post-lingual CI users, but not in the pre-lingual CI users. This is particularly relevant because it suggests that access to auditory input prior to deafness and, thus, to implantation is necessary to access the meaning of music.

Discussion

The goal of the present short review was to identify the auditory event-related potential correlates underlying CI users' music perception. Reviewing the existing literature on CI users' music perception also highlighted the insufficient research on this topic and, accordingly, the scarcity of available evidence on the variables that might impact music perception in CI users. Moreover, the review shows that CI users' music perception can be measured objectively—with effective and demanding protocols. Indeed, the oddball paradigm was found to be an effective technique to measure CI users' perception of most fundamental musical features. Interestingly, the studies reviewed here clearly suggest that cochlear implantation alters most fundamental musical features, including pitch, timbre, melody perception, complex rhythm, and duration (e.g. Koelsch, Wittfoth, Wolf, Müller & Hahne, 2004; Limb & Roy, 2014; Timm et al., 2012, 2014; Zhang, Benson & Cahn, 2013; Zhang, Benson & Fu, 2013). For a summary of how CI listeners fare on music perception tasks, see Table 8.1 In other words, the review confirms CI users' complaints about their reduced appreciation of music and, thus, stresses the importance of investigating the impact of deafness on music perception.

There are several limitations in the tasks that have been used and further studies should take them into consideration. A basic problem with interpreting the MMN studies is that there may be a perceptual contrast, but one does not necessarily know that the difference being perceived uses the same dimensions as the NH listener. For example, CI listeners could conceivably hear differences between musical instruments as changes in loudness, which will also produce an MMN. The studies need to probe not only the differences in performance, but also the perceptual dimensions that are involved. We know what those dimensions are for NH listeners, but they are ill-defined in the case of CI users. Also, further studies should probe MMN experiments with transposed melodies or chords. That would address issues related to pitch contours vs. musical intervals.

Several other important points can be made from the above review. First, it is essential to properly investigate CI users' characteristics when evaluating their music perception. The quality of the acoustic signals provided by implants, the duration of deafness, and length of CI use are important variables that should be considered. Indeed, the studies reviewed differ greatly in terms of length of deafness. For example, the participants of Timm et al. (2014) and those of Zhang, Benson & Cahn (2013) and Zhang, Benson & Fu (2013) have a mean length of deafness of 5.93 and 35.5 years, respectively. It is, however, clear that length of deafness can greatly affect individuals' appreciation of music. Accordingly, Sandmann et al. (2010) found a significant negative correlation between duration of deafness and MMN responses for music frequency and intensity.

Although outside the scope of the present review, evidence shows that early cochlear implantation leads to better music perception than later cochlear implantation. Torppa et al. (2012) have investigated music perception in children with CIs. Interestingly, they found that the ERP activation patterns of children with CIs closely resembled that of normal hearing children—this on all musical dimensions, except intensity increment deviants. This further suggests that studies on CI users' musical perception abilities have to carefully control for the variables related to deafness and implantation.

Additional important variables to take into account include musical experience prior to implantation and number of implants. On the one hand, evidence shows that a background in musical perception prior implantation has a positive effect on music perception after implantation, making it possible to activate the concepts that are essential to access the meaning of music—as measured by the N400 protocol (Bruns, Mürbe & Hahne, 2016). In terms of the number of implants, the few studies that have been done to date suggest that bilateral implantation has positive effects on music perception (Maglione et al., 2015). Studies must thus go further and contrast the music perception abilities of individuals with one implant to those of individuals with two implants (see Maglione et al., 2015 for an example). These studies would be helpful for clinicians who have to help patients decide whether or not they should get a second CI, by giving them arguments about the possible gains of bilateral implantation in terms of music perception. Further studies are, however, needed before any firm conclusion can be made on the positive impacts of bilateral implantation.

The present review also highlights the importance of using complex electrophysiological protocols to examine CI users' complaints about music perception. Many of the studies reviewed above have used multi-feature paradigms that make it possible to investigate music perception rapidly and easily (e.g., Koelsch et al., 2004; Koelsch, Wittfoth, Wolf, Müller & Hahne, 2004; Sandmann et al., 2010; Timm et al., 2014). Adding this type of paradigm in routine evaluations of deaf individuals' music perception might eventually lead to a better understanding of the effectiveness of implants. Moreover, despite being rarely used, other electrophysiological protocols offer interesting knowledge on more complex musical features. For example, the imbalance index and the N400 are efficient electrophysiological techniques that make it possible to simultaneously evaluate several musical characteristics. The fact that they give information about several musical features at the same time make these measures particularly effective. Although more studies are needed before these techniques can be used in clinical contexts, they still make it possible to better understand musical perception in CI users.

Conclusion

In summary, the presence of MMNs in CI users that are related to musical percepts indicates that they do possess some residual capacities for music perception after implantation. Although this gives hope for their future rehabilitation, there is still a substantial amount of work to do in order to improve CI users' music perception. As mentioned earlier, it is essential to determine which technique can be used to properly evaluate CI users' complaints about their music perception abilities. It is also important to better characterize the impact of their music perception complaints on their everyday life. To do so, paradigms measuring the pleasantness and/or the meaning of music appear to be particularly promising (see Bruns, Mürbe & Hahne, 2016 and Maglione et al., 2015). As well, oddball and multi-feature paradigms were found to be particularly effective. It is, however, important to remember that multi-feature paradigms allow for more complete evaluations of musical perception abilities than oddball paradigms, which focus on more specific features.

Altogether, the present review suggests that cochlear implantation alters most fundamental musical features, including pitch, timbre, melody perception, complex rhythm, and duration (e.g. Koelsch, Wittfoth, Wolf, Müller & Hahne, 2004; Limb & Roy, 2014; Timm et al., 2012, 2014; Zhang, Benson & Cahn, 2013; Zhang, Benson & Fu, 2013). Also, the results discussed here suggest that auditory event-related potentials are an effective technique to investigate CI users' music perception. Future studies using these techniques, however, need to take more variables into consideration, including prior musical training, duration of deafness, and number of implants.

Author Contributions

AS wrote the first draft of the manuscript. AD and FC provided critical feedback to improve it.

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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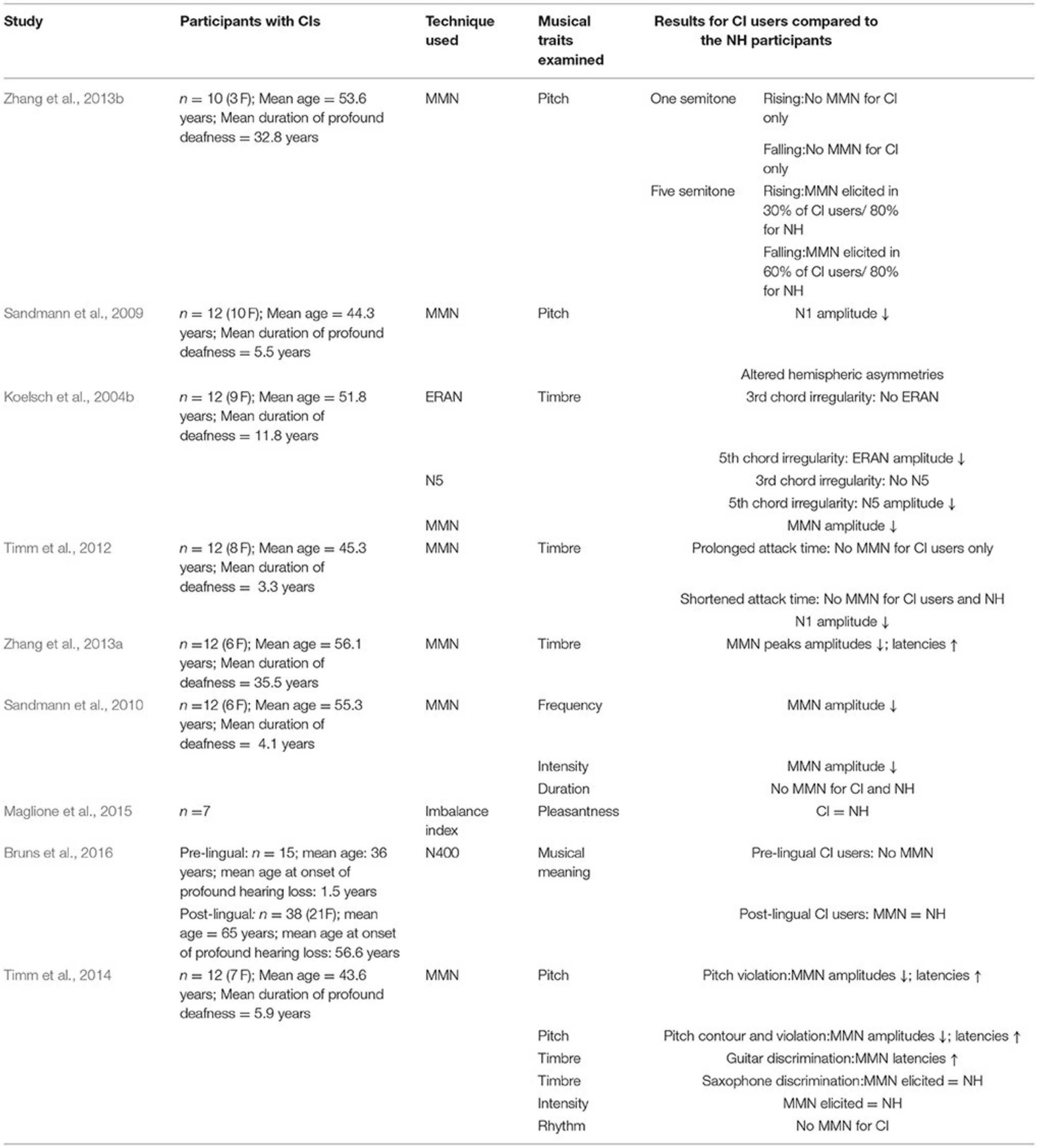
Appendices

Tableau 8.1 - Summary table of how CI listeners fare on music perception tasks.



Study	Participants with CIs	Technique used	Musical traits examined	Results for CI users compared to the NH participants	
Zhang et al., 2013b	*n* = 10 (3 F); Mean age = 53.6 years; Mean duration of profound deafness = 32.8 years	MMN	Pitch	One semitone	Rising:No MMN for CI only
					Falling:No MMN for CI only
				Five semitone	Rising:MMN elicited in 30% of CI users/ 80% for NH
					Falling:MMN elicited in 60% of CI users/ 80% for NH
Sandmann et al., 2009	*n* = 12 (10 F); Mean age = 44.3 years; Mean duration of profound deafness = 5.5 years	MMN	Pitch	N1 amplitude ↓	
				Altered hemispheric asymmetries	
Koelsch et al., 2004b	*n* = 12 (9 F); Mean age = 51.8 years; Mean duration of deafness = 11.8 years	ERAN	Timbre	3rd chord irregularity: No ERAN	
				5th chord irregularity: ERAN amplitude ↓	
		N5		3rd chord irregularity: No N5	
				5th chord irregularity: N5 amplitude ↓	
		MMN		MMN amplitude ↓	
Timm et al., 2012	*n* = 12 (8 F); Mean age = 45.3 years; Mean duration of deafness = 3.3 years	MMN	Timbre	Prolonged attack time: No MMN for CI users only	
				Shortened attack time: No MMN for CI users and NH	
				N1 amplitude ↓	
Zhang et al., 2013a	*n* =12 (6 F); Mean age = 56.1 years; Mean duration of deafness = 35.5 years	MMN	Timbre	MMN peaks amplitudes ↓; latencies ↑	
Sandmann et al., 2010	*n* =12 (6 F); Mean age = 55.3 years; Mean duration of deafness = 4.1 years	MMN	Frequency	MMN amplitude ↓	
			Intensity	MMN amplitude ↓	
			Duration	No MMN for CI and NH	
Maglione et al., 2015	*n* =7	Imbalance index	Pleasantness	CI = NH	
Bruns et al., 2016	Pre-lingual: *n* = 15; mean age: 36 years; mean age at onset of profound hearing loss: 1.5 years	N400	Musical meaning	Pre-lingual CI users: No MMN	
	Post-lingual: *n* = 38 (21F); mean age = 65 years; mean age at onset of profound hearing loss: 56.6 years			Post-lingual CI users: MMN = NH	
Timm et al., 2014	*n* = 12 (7 F); Mean age = 43.6 years; Mean duration of profound deafness = 5.9 years	MMN	Pitch	Pitch violation:MMN amplitudes ↓; latencies ↑	
			Pitch	Pitch contour and violation:MMN amplitudes ↓; latencies ↑	
			Timbre	Guitar discrimination:MMN latencies ↑	
			Timbre	Saxophone discrimination:MMN elicited = NH	
			Intensity	MMN elicited = NH	
			Rhythm	No MMN for CI	

Annexe 2 – Curriculum Vitae

Éducation

(2016 – présent) - Doctorat en Sciences Biomédicales option Audiologie - Université de Montréal. Titre de la thèse : Réorganisation audiotactile suite à un entraînement multisensoriel ou à une privation auditive congénitale. Directeur : François Champoux, PhD.

(2015 – 2016) - Maîtrise professionnel en Audiologie - Université de Montréal. Titre du travail dirigé : Les effets d'une privation et d'un entraînement sensoriel sur la perception et l'intégration d'information sensorielle en espace proximal et distal. Directeur : François Champoux, PhD

(2012-2015) - Baccalauréat en Audiologie - Université de Montréal

Publications avec comité de pairs

Sharp, A., Bacon B.A., & Champoux, F. (2019). Enhanced tactile identification of musical emotion in the deaf. Brain & Cognition (**Under Review)**

Sharp, A., Delcenserie, A., & Champoux, F. (2018). Auditory event-related potentials associated with music perception in cochlear implant users. Frontiers in Neuroscience, 12, 538.

Sharp, A., Houde, M.S., Bacon B.A., & Champoux, F. (2019). Musicians show better auditory and tactile identification of emotions in music. Frontiers Psychology, 10, 1976.

Sharp, A., Houde, M.S., Beaudoin, D., Dufour, J., Maheu, M., & Champoux, F. (2019) Cochlear Implant International **(Submitted)**

Sharp, A., Houde, M.S., Maheu, M., Ibrahim, I., & Champoux, F. (2019). Improve tactile frequency discrimination in musicians. Experimental brain research, 237(6), 1575-1580.

Sharp, A., Landry, S.P., Maheu, M., & Champoux, F. (2018). Deafness alters the spatial mapping of touch. PloS one, 13(3), e0192993.

Sharp, A., Turgeon C, Johnson A.P., Pannasch S., Champoux F., & Ellemberg D. (2019). Congenital deafness leads to altered overt oculomotor behaviors. Frontiers in Neurosciences **(Submitted)**

Landry, S.P., Sharp, A., Pagé S. & Champoux, F. (2016). Temporal and spectral audiotactile interactions in musician. Experimental Brain Research, 1-8.

Maheu M., Pagé S., Sharp A., Delcenserie A. & Champoux F. (2017). The impact of vestibular status prior to cochlear implantation on postural control : a multiple case-study. Cochlear Implants International, 18(5), 250-255.

Maheu, M., Sharp, A., Pagé, S. & Champoux, F. (2017). Congenital deafness alters sensory weighting for postural control. Ear & Hearing, 38(6), 767-770.

Maheu, M., Sharp, A., Landry, S.P. & Champoux, F. (2016). Sensory reweighting after loss of auditory cues in healthy adults. Gait & Posture, 151-154.

Pagé, S., Sharp, A., Landry, S. P., & Champoux, F. (2016). Short-term visual deprivation can enhance spatial release from masking. Neuroscience Letters, 628, 167-170.

Prix et bourses

(2019) - Professeure de la session – Association des étudiants en orthophonie et en audiologie

(2018-2020) - Conseil de Recherches en Sciences Naturelles et Génie du Canada - (CRSNG) – Bourse d’études supérieures du Canada Alexander-Graham-Bell - doctorat (BESC-D)

(2018-2021) - Fonds de recherche du Québec - Santé (FRQS) - Programme de bourses de formation de doctorat

(2018) - Prix du mérite de l'École d'orthophonie et d'audiologie, Université de Montréal

(2017) - Bourse d’excellence, Sciences biomédicales, Université de Montréal

(2016-2017) - Bourse du Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

(2017) - Prix Cardozo-Coderre, Ordre professionnelles des orthophonistes et des audiologistes

(2017) - Prix du mérite de l'École d'orthophonie et d'audiologie, Université de Montréal

(2016) - Prix d’excellence en recherche, Congrès international en orthophonie et en audiologie, Université de Montréal

(2016) - Bourse d’excellence, Sciences biomédicales, Université de Montréal

(2016) - Bourse au mérite du Centre de recherche en neuropsychologie et cognition

(2016) - Prix du Challenge étudiant - Académie Canadienne d'audiologie

(2016) - Prix d'excellence étudiant - Académie Canadienne d'audiologie

(2015) - Prix de l'étudiante exceptionnelle - École d'orthophonie et d'audiologie, Université de Montréal

(2015) - Prix de communication affichée – Soirée de la recherche étudiante, École d'orthophonie et d'audiologie, Université de Montréal