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Interactions multisensorielles chez les musiciens

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Résumé

Jouer un instrument de musique demande l'interaction des informations provenant de multiples sens. Cette expérience sensorielle a des effets sur les réseaux corticaux et sur les habiletés comportementales chez les musiciens professionnels qui pratiquent pour plusieurs années. L'entrainement musical semble avoir un effet sur les sens, incluant le toucher, mais peu de recherches se sont penchées sur les habiletés tactiles chez les musiciens. L'objectif de cette thèse est d'évaluer les capacités tactiles unisensorielles et multisensorielles non musicales chez les musiciens à l'aide de méthodologies comportementales. La première étude avait pour objectif d'évaluer les temps de réaction auditifs, tactiles, et audiotactiles chez les musiciens. Les temps de réaction de 16 musiciens et 19 membres d'un groupe témoin ont été évalués. Les résultats de cette recherche suggèrent que les musiciens ont des temps de réaction significativement plus rapide pour des stimulations auditives, tactiles, et audiotactiles. La seconde étude avait comme objectif d'évaluer l'interaction d'informations audiotactiles temporelle et spectrale chez les musiciens. Les interactions audiotactiles de 13 musiciens et de 17 membres d'un groupe témoin ont été évaluées à l'aide d'illusions multisensorielles. Les résultats de cette recherche suggèrent que seulement l'interaction audiotactile temporelle est significative différente entre les groupes. La troisième étude avait pour objectif d'évaluer la localisation spatiale tactile chez les musiciens. La localisation spatiale tactile chez 17 musiciens et 20 membres d'un groupe témoin a été évaluée à l'aide de tâche de jugement d'ordre temporel tactile. Les résultats de cette recherche suggèrent que les musiciens ont un taux d'erreur plus élevé pour localiser des stimulations tactiles quand leurs bras sont croisés, mais qu'ils ont des temps de réaction plus rapides pour cette tâche. Généralement, les résultats de ces recherches suggèrent qu'un entrainement musical à long terme améliore les capacités tactiles unisensorielles et multisensorielles, mais seulement pour certaines tâches. D'autres études sont requises afin de mieux comprendre les facteurs de l'entrainement musical menant à ces changements.

Mot-clés : entrainement sensoriel, audiotactile, tactile, musiciens, temps de réaction, illusions multisensorielles, interactions multisensorielles, cadres de référence.

Abstract

Playing a musical instrument requires the integration of information from multiple senses. The long-term sensory training from playing a musical instrument for many years has effects on cortical networks and behavioral abilities. Touch is a sensory modality that seems to be altered by musical training, but little research has focused on the tactile abilities of musicians. The objective of this thesis is to assess non-musical unisensory and multisensory tactile abilities in musicians using behavioral methodologies. The first study aimed at evaluating simple auditory, tactile, and audiotactile reaction times in musicians. Reaction times of 16 musicians and 19 controls were evaluated. The results of this study suggest that musicians have significantly faster response times for auditory, tactile, and audiotactile stimulations. The second study aimed at evaluating the integration of temporal and spectral audiotactile information in musicians. Audiotactile interactions of 13 musicians and 17 controls were evaluated using multisensory illusions. The results of this research suggest that only temporal audiotactile interactions are different for musicians. The third study aimed at assessing temporal tactile localization in musicians using tactile temporal order judgement task. Temporal tactile localization was evaluated in 17 musicians and 20 members of a control group. The results of this study suggest that musicians have a higher error rate to localize tactile stimulations when their arms are crossed but generally have faster reaction times for this task. All of these results suggest that musicians have altered tactile abilities. Overall, these results suggest that long-term musical training alters specific unisensory and multisensory tactile abilities. Further studies are required to better understand the factors of musical training leading to these changes and why certain interactions remain unchanged.

Keywords: sensory training, audiotactile, tactile, musicians, reaction times, multisensory illusions, multisensory interaction, frames of reference.

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ANOVA : Analysis of variance

CDF : Cumulative Distribution Function

CI : Cochlear implant

CPP : Cortex pariétal postérieur

fMRI : Fonctional magnetic resonance imaging

HF : High frequency

HL : Hearing level

IRMf : Imagerie par résonance magnétique fonctionnelle

MEG : Magnetoencephalography / Magnetoencephalographie

PPC : Posterior parietal cortex

RMI : Race Model Inequality

RT : Reaction time

SD : Standard deviation

SI : Susceptibility Index

SPL : Sound pressure level

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1. Introduction

1.1. Mise en contexte

L’importance des sens ne peut être surestimée. La perception de l’environnement et les mémoires d’expériences vécues découlent toutes des informations provenant de quelques entrées sensorielles. Les informations sensorielles stimulent des récepteurs spécialisés et l’information de ces récepteurs atteint le cerveau où les diverses sources d’informations sensorielles sont combinées pour former notre perception. L’interaction de ces sources sensorielles est dynamique et réciproque. Un changement au niveau d’une source sensorielle peut altérer la perception d’une autre. Pareillement, des situations impliquant simultanément plusieurs sens peuvent changer et renforcer les interactions multisensorielles. Cette amélioration ne change rien au niveau des récepteurs sensoriels, mais peut tout de même améliorer la perception sensorielle. Dans cette thèse, l’entrainement musical est utilisé comme modèle d’environnement sensoriel enrichi. Cette thèse n'aborde donc pas la musique comme expression artistique, mais comme véhicule ayant alloué à l’interaction répétée des sens à long terme. Les données de cette thèse présentent des informations pour mieux comprendre les capacités sensorielles comportementales chez les musiciens, et aussi plus généralement les effets d’un entrainement multisensoriel à long terme sur les capacités sensorielles.

1.2. La perception sensorielle

1.2.1. La perception unisensorielle

Le toucher et l’audition fournissent différentes informations sur l’environnement. Ces deux sources d’informations nous renseignent sur la surface de notre corps et l’espace environnant. Le toucher fournit de l’information endogène et permet au corps de se représenter dans l’espace et de se situer par rapport à une stimulation externe au corps, alors que l'audition informe sur les informations exogènes et permet au corps de se représenter dans son environnement. Malgré leurs différences fonctionnelles et anatomiques, des parallèles existent entre ces modalités. Les cellules cillées et les mécanorécepteurs transmettent des types d'informations similaires : la fréquence et l'intensité d'une force mécanique. En effet, une gamme spectrale peut être détectée par le toucher et l'ouïe (Soto-Faraco & Deco, 2009), bien que l'amplitude du stimulus requis pour engendrer une détection sensorielle soit différente. Cette gamme spectrale partagée par ces deux modalités peut donc produire à la fois une perception tactile et auditive. Il est important de comprendre comment fonctionnent les récepteurs sensoriels de ces deux modalités afin de mieux comprendre l'information qu'ils fournissent.

La peau fournit des informations sensorielles provenant des zones superficielles de l'enveloppe corporelle. L'information cutanée du toucher est traitée par des terminaisons mécanoréceptrices. Quatre types de mécanorécepteurs sont présents au niveau cutané, chacun répondant à une fréquence optimale et à des critères de stimulation différents. Ces mécanorécepteurs peuvent aussi être classifiés selon deux catégories physiologiquement distinctes : ceux ayant une adaptation rapide et ceux ayant une adaptation lente lors de la stimulation (Johansson & Vallbo, 1983). Les mécanorécepteurs ayant une adaptation rapide répondent que lors de l'application ou lors du retrait du stimulus. Les corpuscules de Meissner et les corpuscules de Ruffini sont des récepteurs d'adaptation lente (Iggo & Andres, 1982). Les corpuscules de Meissner répondent aux basses fréquences vibratoires ≤ à 50 Hz (Gescheider et coll., 1994). Les corpuscules de Ruffini répondent aux fréquences vibratoires entre 15 et 400 Hz, par exemple lors d'un étirement de la peau (Sharma et coll., 2014). Les mécanorécepteurs ayant une adaptation lente ne répondent pas lors d'application ou de retrait d'un stimulus. Ces mécanorécepteurs répondent en présence d’une pression sur la peau. Les disques de Merkel et les corpuscules de Pacini sont des récepteurs d’adaptation rapide (Iggo & Andres, 1982). Alors que les disques de Merkel répondent à des fréquences vibratoires allant de 5 à 15 Hz (Gilman, 2002), les corpuscules de Pacini répondent préférentiellement entre 200 et 1000 vibrations à la seconde (Sato, 1961).

La perception auditive provient de compressions et raréfactions aériennes. Ces ondes sont captées par le pavillon de l’oreille qui, par sa forme, modifie les ondes sonores de moyennes et de hautes fréquences (Moore, 2002). Ces ondes sonores font vibrer la membrane tympanique qui relie l’oreille externe à l’oreille moyenne. La disposition des trois osselets de l’oreille interne permet de compenser la différence d’impédance acoustique entre l’air et le milieu liquide de la cochlée (Kurokawa & Goode, 1995). La fenêtre ovale, sur laquelle repose l’étrier de l’oreille moyenne, est le lien cochléaire de l’oreille interne. La cochlée, l’organe sensoriel auditif, est une structure hélicoïdale composée d’un canal replié sur lui-même et remplie de périlymphe. La fenêtre ovale est située à l’une des bases de ce canal replié, nommé la rampe vestibulaire. Au-delà de l’apex cochléaire, le canal forme la rampe tympanique. Le mouvement de la fenêtre ovale par l’onde aérienne mène aux mouvements de périlymphe. Ce mouvement cause des distorsions au niveau de la membrane basilaire, située entre la rampe vestibulaire et la rampe tympanique. L’organe de Corti, qui contient l'ensemble des cellules sensorielles de la cochlée, repose sur la membrane basilaire et se déplace avec le mouvement de périlymphe. Les cellules sensorielles auditives, les cellules ciliées, sont jointes par des structures filamenteuses, les stéréocils, qui transforment ce mouvement en signal bioélectrique (Yost & Nielsen, 1985). Les distorsions de la membrane basilaire sont organisées tonotopiquement. Une vibration par un son de haute fréquence occasionne un mouvement à la base de la membrane basilaire. Une vibration par un son de basse fréquence provoque un mouvement à l'apex de la membrane basilaire. Le système auditif permet la perception de fréquences sonores d'environ 20 Hz à 20 000 Hz chez l'humain (Yost & Nielsen, 1985).

Von Békésy (1959) fut le premier à souligner les similitudes entre les organes tactiles et auditifs. En fait, il suggéra même que le toucher pourrait être utilisé comme modèle pour étudier l'ouïe. Un lien évolutionnaire entre les capteurs sensoriels a même été trouvé chez certains poissons qui ont un organe externe ayant les récepteurs similaires aux cellules cillées (Montgomery & MacDonald, 1987). Cependant, chez l'humain, plusieurs différences existent au niveau des seuils de détection, type de vibrations, et amplitude. Toutefois, le chevauchement des gammes de détection pour le toucher et l'audition suggère une possibilité d'interaction précoce entre ces modalités (Soto-Faraco & Deco, 2009).

1.2.2. La perception multisensorielle

Les sens sont la source d'informations sur notre environnement, mais notre perception globale est fondée sur la combinaison des informations qu'ils fournissent. Le processus par lequel le cerveau combine les informations provenant de nos multiples sens est nommé l'interaction multisensorielle. Ce processus, bien qu'il soit intégral à notre fonctionnement quotidien, passe largement inaperçu. En effet, plusieurs tâches journalières sont beaucoup plus ardues à effectuer sans l'utilisation des processus d'interactions multisensorielle. Par exemple, les interactions multisensorielles sont présentes dans certaines tâches qui pourraient être considérées comme uniquement visuelles; se raser ou discuter avec une autre personne (Campanella & Belin, 2007; Foxe, 2009). De manière générale, l'interaction multisensorielle permet des performances perceptuelles supérieures en diminuant certaines ambigüités qui pourraient être perçues par un seul sens (Green & Angelaki, 2010). Ces améliorations de la perception peuvent être observées dans plusieurs tâches multisensorielles. Par exemple, lors de tâches de détection, le temps de réaction est plus lent lors de la détection d'un stimulus unisensoriel que lors de la détection d'un stimulus multisensorielle (Giray & Ulrich, 1993; Laurienti et coll., 2004; Molholm et coll., 2002). Les stimuli présentés par une modalité unisensorielle sont aussi plus difficilement localisés que les stimuli présentés simultanément à deux modalités (Schröger & Widmann, 1998). L'association entre les modalités est si robuste que des interactions multisensorielles peuvent même être mesurées en combinant un stimulus imaginé à une stimulation réelle (Berger & Ehrsson, 2013; 2017; Landry et coll., 2015 [Annexe I]).

Les modalités sensorielles relatent des informations provenant soit du corps (tactile) ou de l'environnement (audition et vision). La combinaison de ces régions distinctes mène à la création d'une nouvelle région sensorielle : l'espace péripersonnel. L'espace péripersonnel est le résultat de l'interaction des informations tactiles provenant du corps et des informations visuelles sur ce qui se trouve à portée de main (Holmes & Spence, 2004). Cet espace représente la région dans laquelle il est possible d'interagir avec les bras sans se déplacer. Les habiletés sensorielles sont altérées dans cette aire. Par exemple, les signaux prémoteurs d'une tâche de temps de réaction auditive sont plus rapides quand les sons proviennent de l'espace péripersonnel qu'a l'extérieur (Camponogara et coll., 2015).

Puisque l'espace péripersonnel intègre des informations à la fois du corps et de son environnement, il est possible d'induire un conflit entre ces deux. Par exemple, les stimulations provenant de la droite ont une plus forte association avec d'autres stimulations du même côté. Cependant, Spence et coll. (2001) ont trouvé qu'il était possible de modifier cette interaction en se croisant les bras. Dans ce cas, une stimulation tactile du bras droit peut avoir un effet fort sur une stimulation visuelle du champ gauche. Normalement, une stimulation tactile du bras droit aurait un effet fort sur une stimulation visuelle du champ droit. En se croisant les bras, le bras droit se trouve dans l'aire visuelle gauche, ce qui modifie l'interaction visuotactile qui serait habituellement avec une stimulation visuelle dans l'aire droite. Les caractéristiques de latéralités tactiles reflètent donc plutôt les informations provenant de la vision. C'est-à-dire les processus d'interaction multisensorielle sous-jacents la formation de l'espace péripersonnel mélange des informations tactiles provenant du corps et visuelles l'environnement externe (Volcic & Kappers, 2008).

1.3. Comment étudier les interactions multisensorielles

1.3.1. Examiner les interactions multisensorielles avec les temps de réaction

Les temps de réaction sont une méthodologie utile pour examiner les interactions multisensorielles. Les temps de réaction permettent aussi plusieurs analyses statistiques pour mieux comprendre les résultats et supposer les mécanismes neuronaux sous-jacents. Cette méthodologie demande au participant de faire une action quelconque immédiatement au moment de la détection d'une stimulation. Les temps de réaction pour des stimulations multisensorielles sont typiquement plus rapides que pour des stimulations unisensorielles. Cette diminution du temps de réponse a été rapportée pour des stimulations audiovisuelles (Laurienti et coll., 2006), audiotactiles (Nava et coll., 2014), et visuotactiles (Girard et coll., 2011). Ces temps de réponses rapides peuvent être attribués à l'effet de la facilitation intersensorielle (Hershenson 1962) dans l'absence de toute autre facilitation statistique telle la *race model inequality* (RMI : Raab, 1962).

La *RMI* propose que si les temps de réactions multisensorielles sont plus rapides que l'ensemble des temps de réactions unisensorielles, un mécanisme neuronal multisensoriel doive être responsable des temps de réaction plus rapides. C'est-à-dire le *RMI* compare la distribution des temps de réaction unisensoriels à la distribution des temps de réaction multisensoriels. La réponse du participant est imaginée comme une course qui débute du moment de présentation du stimulus et se termine à la réponse du participant. Lors d'une stimulation multisensorielle, la course a deux « coureurs », tandis qu'une stimulation unisensorielle en a qu'un. Si le temps de réaction pour une stimulation multisensorielle est plus rapide que la prédiction statistique selon les temps de réactions unisensorielles combinés, il est probable que le temps de réponse soit le résultat d'un mécanisme distinct activé par la présence d'un stimulus multisensoriel.

Il est aussi possible d'analyser la fonction de distribution cumulative des réponses (Laurienti et coll., 2006). C'est-à-dire, si les réponses pour les temps de réaction ont une différente distribution selon le type de stimulation (uni- ou multisensorielle). Cette analyse permet d'évaluer la probabilité d'un temps de réaction selon le type de stimulation. Il est ensuite possible de comparer les probabilités de temps de réponse selon les modalités entre groupes afin d'évaluer si l'usage d'information sensorielle pourrait être différent.

1.3.2. Examiner les interactions multisensorielles avec les illusions sensorielles

Il est possible d'étudier les interactions présentes entre les systèmes sensoriels en induisant un conflit entre les modalités sensorielles lors de tâches comportementales. Ces tâches provoquent des illusions perceptuelles qui permettent d'examiner l'interaction entre les systèmes sensoriels dans divers contextes, permettant d'examiner les processus d'interactions entre les systèmes sensoriels en cause. L'une des illusions multisensorielles ayant généré le plus d'études est sans doute l'illusion de l'effet McGurk (McGurk & MacDonald, 1976). Cette illusion multisensorielle combine l'information auditive et visuelle de la parole. Pour cette tâche, le participant doit indiquer quelle syllabe il perçoit lors d'une présentation audiovisuelle. Une première syllabe est présentée additivement et, simultanément, une seconde syllabe est affichée visuellement. Ainsi, la combinaison de la stimulation auditive /ba/ et de la stimulation visuelle /ga/ est perçue comme étant /da/. La perception de la syllabe /da/ est dans cette situation le résultat de l'interaction de stimulations auditives et visuelles incongrues. Depuis l'étude de l'effet McGurk, d'autres exemples d'illusions audiovisuelles ont pu être répertoriés.

Parmi les illusions audiovisuelles les plus reconnues, on retrouve l'effet de l'éclair illusoire audiovisuel (Shams et coll., 2000). Dans cette tâche, des stimulations visuelles et auditives de très courtes durées sont présentées simultanément et successivement. Le participant doit alors ignorer les stimulations auditives et se concentrer sur le stimulus visuel uniquement et compter le nombre de stimuli présenté. Dans cette tâche illusoire, il a été révélé que le nombre de stimulations visuelles perçu était augmenté lorsque les stimuli visuels étaient présentés avec un plus grand nombre de stimuli auditifs. Par exemple, deux stimulations visuelles peuvent être perçues lorsque deux stimulations auditives sont présentées simultanément avec une véritable stimulation visuelle.

Les illusions perceptuelles révélant une interaction entre la modalité auditive et tactile sont beaucoup moins nombreuses. Parmi ces illusions, on retrouve la tâche de l'effet de l'éclair illusoire audiotactile (Hötting & Röder, 2004) et l'effet de la peau parcheminée (Jousmäki & Hari, 1998). Ces tâches permettent d'évaluer la capacité d'interaction de l'information auditive temporelle et tactile de même que la capacité d'interaction de l'information auditive spectrale et tactile respectivement.

Le même principe d'interaction multisensorielle retrouvé dans la tâche de l'effet de l'éclair illusoire audiovisuel (Shams et coll., 2000) peut être utilisé afin d'examiner l'interaction du système auditif et somatosensoriel. Cette illusion est nommée l'effet de l'éclair illusoire audiotactile (Hötting & Röder, 2004). Dans ce cas, au lieu de présenter des stimuli par la modalité visuelle, une stimulation vibrotactile au niveau de l'index est présentée simultanément avec la présence de stimuli auditifs de courtes durées. Le participant doit porter attention aux stimuli tactiles en ignorant les stimulations auditives. Similairement à l'effet de l'éclair illusoire audiovisuel, il a été révélé qu'un plus grand nombre de stimulations tactiles est perçu lorsque les stimulations auditives sont plus fréquentes que les stimulations tactiles.

Une autre tâche qui permet efficacement d'étudier les capacités d'interaction des systèmes auditifs et tactiles chez l'humain est l'illusion de la peau parcheminée (Jousmäki & Hari, 1998). Jousmäki et Hari (1998) ont révélé qu'une modification du contenu spectral d'une stimulation sonore peut mener à un changement de sensation au niveau tactile. En effet, les chercheurs ont révélé que lorsqu'une personne se frotte les mains ensemble, la perception tactile peut être altérée si le contenu spectral (plus spécifiquement l'intensité des fréquences sonores supérieures à 2 kHz) est modifié en temps réel. Plus précisément, il a été révélé qu'une diminution de l'intensité des hautes fréquences peut provoquer une perception de mains plus moites alors qu'une augmentation de l'intensité des hautes fréquences peut provoquer une perception de mains plus sèches.

1.3.3. Examiner les interactions multisensorielles entre cadres de référence

Les interactions multisensorielles peuvent aussi combiner des stimuli provenant de cadres de références différents. Par exemple, les stimulations tactiles relatent de l'information provenant du corps tandis que les stimulations visuelles et auditives relatent des informations provenant de l'environnement. Ces deux types d'information peuvent être catégorisés comme étant égocentriques ou allocentriques, respectivement. Ainsi, ces deux catégories forment deux cadres de référence sensorielles : le cadre de référence égocentrique qui relate des informations sensorielles internes et le cadre de référence allocentrique qui relate des informations sensorielles externes (Volcic & Kappers, 2008). L'espace péripersonnel est l'aire dans laquelle convergent ces cadres de référence. L'espace péripersonnel représente une région pouvant être à la fois touchée et vue.

Il est possible d'induire un conflit entre les informations provenant des cadres de références internes et externes. Comme avec les illusions multisensorielles, les résultats perceptifs d'un conflit entre les cadres de références fourni des informations sur les interactions de ces différentes informations sensorielles. L'illusion japonaise (Van Riper, 1935) est l'un des premiers exemples d'une telle illusion perceptive. Le participant se croise les bras avec les pouces pointant vers le bas, entrelace ses doigts puis fait un trois quarts d'une rotation complète. Une fois les mains tournées, le participant doit remuer son index droit. Puisque l'index à droite est maintenant situé à gauche de la main gauche, le participant doit séparer les représentations égocentriques et allocentriques de sa main afin d'accomplir cette tâche. Le cadre égocentrique maintient la latéralité correcte de la main droite. Le cadre allocentrique désigne la main droite comme étant celle à gauche. Ce décalage entre les informations visuelles sur la position de la main et la représentation interne de la main cause un délai significatif de réponse (Hong et coll., 2012). L'illusion japonaise est un exemple des résultats comportementaux résultant d'un décalage des cadres de références égocentriques et allocentriques.

La tâche de jugement d'ordre temporel tactile est une autre méthodologie pour étudier la perception suivant un conflit de cadres de références (Yamamoto et Kitazawa, 2001; Shore et coll., 2002). Dans cette tâche, deux stimulations tactiles consécutives sont présentées une pour chaque main et les participants doivent indiquer quel côté (hémisphère) était le premier à être stimulé. Les participants doivent effectuer ce jugement d'ordre temporel tactile pour deux agencements des bras : décroisés ou croisés. Pour la condition des bras décroisés, la stimulation provient d'un côté de l'hémisphère et de la main concordant. C'est-à-dire la latéralité de main premièrement stimulée est la même que l'hémisphère premièrement stimulé. Cependant, quand les mains sont croisées, la latéralité de la première main stimulée est contraire au premier l'hémisphère stimulé. Le participant doit donc transférer sa réponse d'un cadre égocentrique (main droite premièrement stimulée) à un cadre égocentrique (stimulation était de l'hémisphère gauche) afin de répondre. Ce décalage entre les cadres de référence mène à une augmentation d'erreur du jugement d'ordre temporel tactile. Pour cette tâche, plusieurs délais du début de présentation des stimulations tactiles sont utilisés. Les plus courts délais étant plus difficiles ont les plus hauts taux d'erreur. Il est aussi possible de mesurer les temps de réaction pour cette tâche. Des résultats de recherches suggèrent que les temps de réaction sont plus lents pour les délais de début de présentation plus court (Heed et coll., 2012; Heed et coll., 2016; Yamamoto and Kitazawa, 2001). Ces temps de réaction plus lents pourraient refléter l'effort cognitif que demandent ces conditions plus difficiles. La tâche de jugement d'ordre temporel tactile permet donc d'évaluer plusieurs aspects du processus multisensoriel de l'interaction de cadres de références.

1.4. Facteurs pouvant changer les interactions multisensorielles

1.4.1. Les effets d'une privation sensorielle temporaire sur les interactions multisensorielles

La privation sensorielle est un type d'expérience sensorielle pouvant altérer les interactions multisensorielles. L'individu ayant une privation sensorielle ne perçoit pas les informations provenant d'un sens. Des recherches ont suggéré des changements sensoriels suivant des périodes de privations de plusieurs années (Lee et coll., 2001) ou pouvant être aussi brèves que quelques jours (Kauffman et coll., 2002). Les changements transitoires mesurés lors de courtes périodes de privation sensorielle mettent en évidence la malléabilité des interactions multisensorielles.

Facchini et Aglioti (2003) furent les premiers à présenter des changements sensoriels comportementaux suivant une courte privation visuelle. Leurs résultats suggèrent qu'une privation de 90 minutes pourrait entrainer une amélioration transitoire de l'acuité tactile. Des améliorations semblables furent aussi rapportées au niveau de la localisation auditive (Lewald, 2007), la détection d'harmonicité (Landry et coll., 2013b [voir annexe I]), et la libération du masquage spatial auditif (Pagé et coll., 2016). De plus, des résultats de Fengler et coll. (2015) suggèrent qu'une privation visuelle à court terme pourrait améliorer la discrimination d'informations prosodiques en présence d'une stimulation visuelle contradictoire. La privation sensorielle à court terme semble donc avoir des effets sur les capacités sensorielles fondamentales et de hauts niveaux.

Plusieurs études se sont penchées sur les effets de longues périodes de privation sensorielles sur les interactions sensorielles. Les résultats de Putzar et coll. (2007) suggèrent qu'une privation visuelle congénitale durant les deux premières années de vie pouvait mener à un changement de l'interaction audiovisuelle pouvant perdurer après le rétablissement de la vision. Ces résultats suggèrent que des individus nés avec des cataractes opaques ont une interaction d'informations fondamentales audiovisuelle anormale malgré des habiletés visuelles et auditives liées à la tâche normale (Putzar et coll., 2007).

Une longue période de privation auditive peut aussi avoir des effets sur les interactions sensorielles. Les porteurs d'implant cochléaire sont des individus sourds ayant une neuroprothèse pouvant substituer les signaux électriques provenant de la cochlée par des signaux électriques synthétiques (Wilson & Dorman, 2008). Les porteurs d'implant cochléaire ont typiquement vécu une privation auditive temporaire à long terme. L'ensemble des résultats sur les interactions audiovisuelles chez les porteurs d'implant cochléaire suggère un changement au niveau des interactions audiovisuelles (p. ex. Landry et coll., 2012; Rouger et coll., 2008; Schorr et coll., 2005;

Tremblay et coll., 2010). Des études sur les interactions audiotactiles ont aussi révélé des changements chez les porteurs d'implant cochléaire pour cette modalité multisensorielle (Landry et coll. 2013a; 2014 [voir annexe II]; Nava et coll. 2014). Différents degrés de réorganisation cérébrale seraient responsables pour ces performances altérées. Une plus grande réorganisation cérébrale entrainant une plus grande dominance du système visuel dans des tâches d'interaction multisensorielle auditive, qui mène vers une augmentation d'importance attribuée à la perception des signaux visuelle (Doucet et coll., 2006; Giraud & Lee, 2007; Lee et coll., 2001).

1.4.2. Les effets d'un entrainement sensoriel sur les interactions multisensorielles

Un entrainement sensoriel, par lequel le lien entre les modalités sensorielles est renforcé par la répétition de stimuli simultanés, peut aussi mener à un changement aux interactions multisensorielles. Par exemple, les résultats de Powers et coll. (2009) suggèrent qu'un entrainement audiovisuel d'une heure pendant cinq jours pouvait étrécir la fenêtre d'interaction audiovisuelle. La fenêtre d'interaction multisensorielle est la période durant laquelle des stimuli de différentes modalités sont perçus comme provenant d'une même source. Ce dernier est un phénomène multisensoriel fondamental et essentiel à notre fonctionnement. Ces résultats démontrent la malléabilité des processus sensoriels fondamentaux suivant une courte période d'entrainement.

Un entrainement multisensoriel réfère à toute situation répétée dans lesquels différents sens sont stimulés simultanément par le même événement. Jouer un instrument de musique est une forme d'entrainement sensoriel (Münte et coll., 2002). Pour l'auditoire, l'ouïe est le sens principal de la musique. Cependant, interagir avec un instrument de musique implique simultanément le toucher, l'audition, et la vision. Les musiciens doivent intégrer de façon optimale les apports sensoriels de l'interaction tactile avec l'instrument, la reconnaissance auditive du son produit et l'apport visuel de ce qui est joué (Herholz & Zatorre, 2012). Les résultats de Paraskevopoulos et coll. (2014) suggèrent que cinq jours d'entrainement musical de 30 minutes étaient suffisants pour améliorer l'identification de stimuli audiovisuels incongrus. Un entrainement musical à long terme, comme le vivent les musiciens, pourrait donc mener à plusieurs changements sensoriels importants.

1.5. Les recherches multisensorielles chez les musiciens

1.5.1. Les temps de réaction chez les musiciens

À jour, qu'une étude a tenté d'étudier les temps de réaction multisensoriels chez les musiciens (Bidelman, 2016). Cependant, la méthodologie n'évaluait pas strictement les temps de réaction. La tâche utilisée demandait aux participants de compter le nombre de stimuli visuels perçus en présence de stimuli auditifs et les temps de réaction pour ces réponses étaient mesurés. Les résultats de cette recherche suggèrent que les musiciens avaient des temps de réaction plus rapides que les non-musiciens. Cette tâche n'était pas une étude explicite des temps de réaction multisensorielle, mais présente toutefois une piste suggérant des réponses plus rapides chez les musiciens.

Plusieurs études ont évalué les temps de réaction unisensoriels chez les musiciens. Des résultats suggèrent que les musiciens auraient des temps de réactions plus rapides pour des stimuli visuels (Anatürk & Jentzsch, 2015; Chang et coll., 2014). Hughes et Franz (2007) ont aussi révélé des améliorations sous la forme d'une plus petite variabilité chez les musiciens pour les temps de réaction aux stimuli visuels. Cependant, un nombre de recherches n'a pu répliquer les résultats de temps de réaction visuels plus rapides (Brochard et coll., 2004; Rodrigues et coll., 2014; Strait et coll., 2010; Woelfle et Grahn, 2013). Une étude de Strait et coll. (2010) au niveau auditif a suggéré que les musiciens avaient des temps de réactions plus rapides, quoique ces résultats ne fussent répliqués par Woelfle et Grahn (2013).

L’ensemble de ces résultats suggère qu’un entrainement musical à long terme pourrait mener à une diminution des temps de réaction pour certaines modalités. À date, aucune recherche n’a examiné les temps de réactions multisensorielles chez les musiciens. De plus, aucune recherche ne s’est penchée sur les temps de réaction tactile chez les musiciens.

1.5.2. L’interaction multisensorielle chez les musiciens

Deux catégories de méthodologies de recherches ont été utilisées pour étudier les interactions multisensorielles chez les musiciens. La première catégorie est les illusions multisensorielles fondamentales (par ex. l’illusion McGurk, l’effet de l’éclair illusoire audiovisuel, etc.). La seconde est les tâches multisensorielles inspirées de la musique.

L’interaction audiovisuelle fondamentale a été évaluée chez les musiciens en mesurant la largeur de la fenêtre d’interaction temporelle; le temps où deux stimuli de modalités distincts seront perçus comme un même événement multisensoriel. Les résultats de ces recherches révèlent que les musiciens ont une fenêtre d'interaction audiovisuelle beaucoup plus étroite pour la parole, la parole avec filtre sinusoïdale, la musique (Lee & Noppenny, 2014) et les sons purs (Bidelman, 2016). Ces résultats pointant à un rétrécissement de la fenêtre d’interaction temporelle sont semblables aux résultats d’entrainement multisensoriel à court terme de Powers et coll. (2009). La capacité de ségrégation audiovisuelle pour les stimuli vocaux chez les musiciens a également été évaluée à l'aide de l'illusion de McGurk (McGurk & MacDonald, 1976). Lorsque des stimuli auditifs et visuels incongrus furent présentés, les musiciens ne percevaient que l’information auditive, tandis que les non-musiciens fusionnaient les informations auditives et visuelles pour en percevoir une illusion multisensorielle (Proverbio et coll., 2016). Ce résultat suggère une modification à l'apport sensoriel dans des situations d'information audiovisuelles conflictuelle pour les musiciens.

Plusieurs tâches multisensorielles inspirées de la musique peuvent évaluer l'interaction des sens dans un contexte semblable à jouer de la musique. Les résultats d'une étude basée sur la production rythmique suggèrent que les percussionnistes sont plus habiles à déterminer des asynchronismes d'informations audiovisuelles relatant la percussion (Petrini et coll., 2009). Pour cette tâche, les participants devaient indiquer des asynchronismes entre des points lumineux générés par les mouvements d'un percussionniste et des sons de percussions. Dans une autre tâche musicale, Paraskevopoulos et coll. (2012) ont révélé une capacité significativement différente entre les musiciens et non-musiciens pour identifier des stimulations audiovisuelles discordantes. Plus spécifiquement, les chercheurs ont évalué la capacité de déterminer des erreurs entre une mélodie et sa représentation visuelle dans une tâche inspirée par la lecture de la musique. Une étude semblable s'est penchée sur la capacité de déterminer des erreurs entre une mélodie et sa représentation tactile dans une tâche inspirée par l'association entre les doigts et la production sonore (ex. jouer de la trompette) (Kuchenbuch et coll., 2014). Les résultats de cette étude audiotactile ont révélé une différence significative entre les musiciens et non-musiciens à trouver des stimulations audiotactiles discordantes. Finalement, les résultats d'une étude menée chez les chefs d'orchestre suggèrent que ceux-ci tirent un avantage significatif de la présence d'informations multisensorielles dans une tâche de localisation d'un stimulus visuel accompagné d'un signal auditif (Hodges et coll., 2005).

Collectivement, les résultats de ces tâches suggèrent que la formation musicale modifie une large gamme d'interactions multisensorielles musicales et non musicales. Malheureusement, ces recherches se sont presque exclusivement penchées sur l'interaction du système auditif et visuel. En fait, qu'une étude s'est encore penchée sur les capacités d'interaction audiotactile (Kuchenbuch et coll., 2014). Il est donc encore trop tôt pour se prononcer sur l'ensemble des processus d'interaction multisensorielle chez les musiciens.

1.5.3. Les cadres de référence sensoriels chez les musiciens

Que deux d'études se sont intéressées à l'interaction des cadres de références sensorielles chez les musiciens. Les deux études ont utilisé la tâche de jugement d'ordre temporel tactile. Les résultats d'une étude chez les pianistes (Kóbor et coll., 2006) et d'une étude chez les percussionnistes (Craig & Belser, 2006) n'ont révélé aucune différence entre musiciens et non-musiciens pour le taux d'erreur de jugement d'ordre temporel tactile. Toutefois, dans leurs analyses Kóbor et coll. (2006) ont éliminé huit des quinze musiciens pour des réponses « anormales ». De leur côté, Craig et Belser (2006) n'ont testé que des participants masculins, qui ont depuis été démontrés à avoir des plus petits effets pour la condition expérimentale de la tâche (Cadieux et coll. 2010). Il se pourrait donc que ces résultats reflètent une erreur de Type II. Au-delà de cette incertitude, les temps de réaction pour cette tâche, qui augmentent typiquement selon la difficulté du stimulus (Yamamoto et Kitazawa, 2001; Heed et coll., 2012, Heed et coll., 2016), demeurent encore inconnus chez les musiciens.

1.6. Objectifs et hypothèses de cette thèse

L'objectif principal de cette thèse est d'évaluer l'interaction des stimulations tactiles unisensorielles et multisensorielles chez les musiciens à l'aide de méthodologies non musicales. Pour se faire, trois expériences ont été réalisées.

La première expérience (Chapitre 2) avait comme objectif d'évaluer les temps de réaction auditifs, tactiles, et audiotactiles chez les musiciens. Nous avions prévu que les temps de réaction des musiciens pour les stimulations auditives, tactiles, et audiotactiles seraient significativement plus rapides que les non-musiciens. Nous avions aussi prévu que les analyses statistiques du RMI et des distributions de probabilités cumulatives suggèreraient une différence entre les musiciens et non-musiciens au niveau des mécanismes neuronaux des interactions multisensorielles audiotactiles.

La deuxième expérience (Chapitre 3) avait comme but d'évaluer les capacités d'interaction audiotactiles temporelles et spectrales chez les musiciens. Nous avions prévu que les capacités de ségrégation audiotactile temporelle seraient significativement différentes dans la tâche de l'effet de l'éclair illusoire audiotactile chez les musiciens. La présence d'un nombre de stimulations auditives supérieures au nombre de stimulations tactiles augmenteraient le nombre de stimulations tactiles perçues chez les participants du groupe témoin, mais pas pour les musiciens. Plus précisément, la présence d'un nombre de stimulations auditives supérieures au nombre de stimulations tactiles n'augmenteraient pas le nombre de sensations tactiles perçues chez les musiciens. Nous n'avions prévu aucune différence entre les effets des changements spectraux des sons autogénérés sur la perception manuelle pour les musiciens et non-musiciens pour l'illusion de la peau parcheminée. Ce résultat serait un reflet des changements sensoriels chez les musiciens qui s'étalent sur une longue période permettant une adaptation au changement sensoriel lié à cette tâche.

La troisième expérience (Chapitre 4) avait comme objectif d'évaluer l'interaction d'informations contradictoires tactiles provenant de cadres de références internes et externes chez les musiciens. Selon des études précédentes, nous n'avions prévu aucune différence du taux d'erreur entre musiciens et non-musiciens pour la tâche de jugement d'ordre temporel tactile. Nous avions toutefois prévu que les musiciens auraient des temps de réponse plus rapides lors des délais de stimulations courts pour les conditions des bras décroisés et croisés, reflétant des améliorations tactiles liées à l'entrainement musical.

Chapitre 2 - Musicians react faster and are better multisensory integrators

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1.7. Abstract

The results from numerous investigations suggest that musical training might enhance how senses interact. Despite repeated confirmation of anatomical and structural changes in visual, tactile, and auditory regions, significant changes have only been reported in the audiovisual domain and for the detection of audio-tactile incongruencies. In the present study, we aim at testing whether long-term musical training might also enhance other multisensory processes at a behavioural level. An audio-tactile reaction time task was administrated to a group of musicians and non-musicians. We found significantly faster reaction times with musicians for auditory, tactile, and audio-tactile stimulations. Statistical analyses between the combined uni- and multisensory reaction times revealed that musicians possess a statistical advantage when responding to multisensory stimuli compared to non-musicians. These results suggest for the first time that long-term musical training reduces simple non-musical auditory, tactile, and multisensory reaction times. Taken together with the previous results from other sensory modalities, these results strongly point towards musicians being better at integrating the inputs from various senses.

Keywords: reaction time, audio-tactile, musical training, multisensory integration, audio-somatosensory

1.8. Introduction

Musical training is often used as a model for the study of cortical plasticity due to its long-term exposure to and strong association between multiple sensory inputs. Musicians undergo long periods of exposure to synchronous auditory, tactile, motor, visual, and emotional components (Munte et al., 2002; Zimmerman & Lahav, 2012). Long-term experience in such a rich multisensory environment has been demonstrated to lead to significant anatomical and structural changes in visual, tactile, and auditory regions (for a review, see Herholz & Zatorre, 2012); changes that extend beyond musical production. For instance, professional piano plays were found to have significantly less activation than non-musicians in the primary sensory motor cortex, supplementary motor, premotor, and superior parietal areas during complex a non-musical finger movement task (Krings et al., 2000). This reduced activation is understood to reflect the reduced effort required by musicians to produce complex finger movements, an ability honed by the complex movements of piano playing. Long-term exposure to multisensory stimuli from musical production also enhances connectivity between sensory and motor cortices (Luo et al., 2012). This enhanced connectivity from long-term exposure to multisensensory inputs and complex motor production suggests an improved low-level connection between these cortices. The behavioural effects of these important cortical changes on sensory abilities have been widely reported for visual (p. ex. Chang et al., 2014; Hughes & Franz, 2007), tactile (p. ex. Ragert et al., 2004; Robinson & Kincaid, 2004; Sims et al., 2015), and auditory processes (Musacchia et al., 2007; Strait et al., 2010).

Significant behavioural enhancements for the integration of multisensory cues have been reported using complex tasks. Audio-visual benefits from musical training include a narrowing of the integration window for musical stimuli (Lee & Noppeney, 2011) and superior detection of rhythmic asynchrony (Petrini et al., 2009). To date, only one study has examined the behavioural effect of musical training on sound and touch. Kuchenbuch et al. (2014) investigated the effect of musical training on the interaction of musically related auditory and tactile cues by studying musicians' ability to detect incongruent audio-tactile signals. Results from this investigation found that musicians were better at identifying auditory and tactile incongruencies. This strongly suggested that musicians were better at computing information coming from these modalities. The data, however, could not reveal whether musicians were better at integrating congruent audio-tactile information at the behavioural level. Furthermore, to this day, audio-visual and audio-tactile processing capacities in musicians have been exclusively examined using tasks involving music related cues. As such, multisensory integration capabilities in musicians for non-musical tasks remains unexplored.

The simple reaction time (RT) task is an effective paradigm to study how the brain integrates basic information coming from the various senses. Previous RT investigations with musicians have focused exclusively on the reactivity to unisensory visual (e.g. Anatürk & Jentzsch, 2015; Brochard et al., 2004; Chang et al. 2014; Hughes & Franz, 2007; Rodrigues et al., 2014; Strait et al. 2010; Woelfle & Grahn, 2013) and auditory (Strait et al. 2010; Woelfle & Grahn, 2013) stimuli. To this day, no study has investigated the impact of long-term musical training on simple tactile or multisensory RTs.

Here, we used a simple RT task to test whether musical training enhances audio-tactile integration at a behavioural level. Furthermore, we used statistical models to analyze whether musical training altered the use of sensory information in the context of this RT task.

1.9. Method

1.9.1. Participants

Thirty-five participants (16 musicians; 19 controls) enrolled in this experiment. Musicians (10 women, 6 men, Mage = 23.8 years, age range: 18-30 years) were recruited from the Université de Montréal Faculty of Music. Control group members (15 women, 4 men, Mage = 25.1 years, age range: 19-34 years) were recruited from the Université de Montréal School of Speech Language Pathology and Audiology. Participants were undergraduate students except for seven musicians (1 collegiate, 5 Master's, 1 Ph.D.) and eight control group members (7 Master's, 1 Ph.D.). All participants were self-reported as neurotypical, had normal or corrected-to-normal vision, and had normal auditory thresholds. All participants self-reported as right-handed except for one musicians and one control. All participants completed a self-reported musical training questionnaire (Müllensiefen et al., 2014) prior to participation to obtain individual musical training scores. The mean control group musical training score was at the 24th percentile (range: 2nd to 58th percentile) while the mean musician group musical training score was at the 91th percentile (range: 76th to 99th percentile). An independent t-test analysis confirmed a statistically significant difference for musical training between groups, $t(33) = -10.998$, $p < 0.001$. Musicians had at least 7 years of formal training on a musical instrument and started playing an instrument between the ages of 3 and 10. The Research Ethics Board of the Université de Montréal approved the study and all the participants provided written informed consent. A sample size of twenty musicians was determined from the median of previous similar RT studies with musicians (Anatürk & Jentzsch, 2015; Brochard et al., 2004; Chang et al. 2014; Hughes & Franz, 2007; Rodrigues et al., 2014; Strait et al. 2010; Woelfle & Grahn, 2013) and was data collection was stopped either once this number of participants was obtained or a significance of $p < 0.02$ was achieved in all three sensory conditions.

1.9.2. Materials and Procedure

A non-musical audio-tactile RT task was used (Nava et al., 2014). Participants were seated comfortably in a quiet well-lit room with their right hand on a standard computer mouse and their left index on a vibrotactile device (Madsen Electronics 03204, Otometrics, Taastrup, Denmark). Participants were instructed to left click on the mouse immediately upon the perception of an auditory, tactile, or simultaneous auditory and tactile stimulation. All stimulations were presented using a custom cognitive evaluation program with PsyScope X software (Cohen et al., 1993). Auditory stimulation consisted of a 50 ms white noise burst presented at 80 dB HL from two speakers (SRS-PC71, Sony, Tokyo, Japan) positioned 60 cm from one another and located 60 cm in front of the participant. Tactile stimulation consisted of a 50 ms vibration of 200 Hz presented by the vibrotactile device. Audio-tactile stimulations were simultaneous presentations of the auditory and tactile stimulation conditions. All participants wore earplugs (Classic Soft, 3M, St. Paul, MN, USA) during the RT task to mask any auditory clues emanating from the vibrotactile device. An ambient white noise from a noise generator was also present to further ensure no auditory clues from the vibrotactile device could be heard. Each of the three conditions was presented 180 times. 36 catch trials in which no stimulus was presented were included to prevent anticipatory responses. A total of 576 stimuli were presented in random order. A random interval of either 1000 ms or 2000 ms was inserted between all stimulations. Responses during catch trials or beyond the inter-presentation interval were considered misses.

1.9.3. Analysis

RTs were transformed to eliminate outlier data (Whelan, 2008). RTs below 100 ms and above 1000 ms, as well as three standard deviations from each condition's individual mean were eliminated from analysis. Each group's average response time for the three conditions was calculated from this transformed data. A repeated measure test was performed with these average times with stimulation type (auditory, tactile, audio-tactile) as within-subject factor and group (control, musician) as between-subject factor. If a significant effect of condition and group was found, a post-hoc ANOVA (3x2) between stimulation types and group was performed to identify the conditions having significant differences.

Audio-tactile redundancy gains were calculated as the difference between each individual's audio-tactile RT and fastest unisensory RT. A t-test was performed between group mean redundancy gains.

The benefit of bimodal stimulation to RT, known as the redundant signals effect, was calculated using Race Model Inequality (RMI: Raab, 1962). The RMI posits that compared to unimodal stimulation, simultaneously stimulating two modalities increases the likelihood of a more rapid response because both modalities "race" to the behavioural task demand. According to RMI, the likelihood of a faster RT is increased for bimodal conditions since input from both modalities increase the likelihood to produce the single desired behavioural response. Combining RTs for unimodal stimulations and comparing them to bimodal RTs can test this hypothesis. To test for RMI violations, individual RTs for unisensory conditions (auditory and tactile) were combined and organized in ascending order. Individual bimodal stimulation (audio-tactile) was also organized in ascending order. These RTs were then divided in ten bins. Each bin's unisensory RTs were combined and compared to multisensory RTs. This process occurs over ten bins, that is to say by comparing the fastest tenth unimodal and multimodal RTs, the second fastest tenth unimodal and multimodal RTs, and so on. Group means of individual RTs for each bin (unimodal and bimodal) were compared using t-test. At least one statistically significant result represented a multisensory RT that could not be accounted by the combination of unimodal RTs and suggested the presence of a neuronal coactivation process. We tested for violations to the RMI using RMITest software (for an in depth description of the applied algorithm, see Ulrich et al., 2007).

Lastly, we further analysed the RT data by performing an analysis on the cumulative distribution function (CDF) using 10 ms time bins (Laurienti et al., 2006). Contrary to the percentile bins from the previous analysis, time bins provided an independent measure with which to compare probability of unisensory and multisensory RT between groups. For this analysis, we calculated individual cumulative likelihood of a RT for each of the three conditions (audio, tactile, audio-tactile) in 10 ms time bins between 100 ms and 1000 ms. A joint probability for unisensory stimuli was then calculated by subtracting the product of the probability for auditory and tactile stimuli from the sum of the probability for auditory and tactile stimuli ((pA + pT) – (pA x PT)). This derived the probability for either an auditory or tactile RT for each 10 ms time bins. This probability for a unisensory RT was subtracted from the multisensory probability at each time bin. Group (control, musician) mean CDF were then calculated. From these, one-sample t-tests were performed to detect a significant probabilities of either multisensory or unisensory RT for each 10 ms time bin. Lastly, an independent-sample t-test was performed between the response probabilities for each group (audio-tactile minus combined unisensory) at all 10 ms time bins to identify group differences for multisensory response likelihood.

1.10. Results

Analyses were performed between mean group RTs obtained from the transformed data for each sensory condition. A repeated-measures analysis for mean individual RTs with stimulation type (auditory; tactile; audiotactile) as within-subject factor and group (controls; musicians) as between-subject factor was performed to detect the presence of group differences in the three conditions. One musicians and one control group member was eliminated from analysis for having over 40 misses in one modality. A significant effect of stimulation type on RT was found, F(2, 30) = 172.986, p < .001, effect size ηp2 = .920. A significant interaction between stimulated modality and group was also found F(2,62) = 3.625, p = 0.032, effect size ηp2 = .105. A test of participant mean RTs revealed a significant effect of group on mean RT, F(1,31) = 9.456, p = .007, effect size ηp2 = .214. Post-hoc single-factor ANOVAs using the Bonferroni adjusted alpha level of .017 revealed significant differences between mean control group auditory RTs (M = 250.13 ms, SD = 71.31 ms) and musicians auditory RTs (M = 193.90 ms, SD = 34.24 ms), F(1, 31) = 7.794, p = .009, between mean control group tactile RT (M = 276.60 ms, SD = 72.43 ms) and musicians tactile RT (M = 208.92 ms, SD = 31.25 ms), F(1, 31) = 11.297, p = .002, and between mean control group audiotactile RT (M = 222.12 ms, SD = 80.63 ms), and musicians audiotactile RT (M = 167.23 ms, SD = 27.11 ms), F(1,31) = 6.326, p = .017 (see Figure 2.1). Average redundancy gains were 28.00 ms (SD = 17.01) for controls and 26.05 ms (SD = 10.76) for musicians, with no significant differences between groups, t(31) = .384, p = .703.

Analysis of RMI revealed significant violations for both groups (see Figure 2.2). The violation occurred in the first two bins for the control group and in the six first bins for the musicians.

CDF were analysed using single-sample t-tests for each group's likelihood for multisensory RTs at each 10 ms time bins (see Figure 2.3 A-B). Control group results revealed a significant likelihood for multisensory RTs between 100 ms and 200 ms ($p < 0.05$) and a significant likelihood for unisensory RTs between 280 ms and 420 ms ($p < 0.05$). Musician group results suggested a significant likelihood for multisensory RTs between 100 ms and 200 ms ($p < 0.05$). This corroborates results from the analysis of RMI and suggests that early RTs for both groups are significantly likely to be from audio-tactile stimulations. Furthermore, later control group RT are more likely to be for unisensory stimuli. An independent sample t-test was performed between the multisensory RT likelihoods for both groups (see Figure 2.3 C). This analysis revealed a significant difference between groups between 100 ms and 130 ms ($p < 0.05$). These results suggest musicians were significantly more likely to have a multisensory RT within this time frame. Another significant difference was found between 210 ms and 320 ms ($p < 0.05$). These results from the earlier timeframe suggest that musicians derive a greater benefit from multisensory coactivation leading to significantly more multisensory RT between 100 ms and 130 ms. Non-musicians are significantly more likely to have unisensory responses between 210 ms and 320 ms.

1.11. Discussion

The main objective of this experiment was to study the effect of long-term musical training on RTs for unimodal (auditory, tactile) and bimodal (audio-tactile) stimulations. We found a significant difference between groups for auditory, tactile, and audio-tactile stimulations. The use of multisensory information was further examined using an analysis of RMI. Results from these analyses revealed significant violations in the first two bins for the control group and first six bins for musicians. This violation of RMI suggests that for both groups, the quicker RTs for the bimodal condition (audio-tactile) were not exclusively the results of statistical facilitation and could be the results of neural co-activation mechanisms. Additional CDF analyses revealed a musician statistical advantage for multisensory stimuli compared to non-musicians. Indeed, the results suggest that musicians derive a greater benefit from multisensory coactivation throughout the early timeframe.

Previous investigations on the effect of musical training on simple RTs have exclusively focused on unisensory stimuli. Brochard et al. (2004) used a simple visual detection RT task and did not find significant differences between musicians and non-musicians; results that were later replicated by Rodrigues et al. (2014) and similar results were also obtained in a study of lateralized visual RT (Woelfle & Grahn, 2013). Strait et al. (2010) used an attentional visual RT task in which participants were instructed to withhold responses if a certain visual stimulus appeared before the visual target and also found no differences between musicians and non-musicians. However, other reports found musicians to have faster visual RTs (Chang et al. 2014), faster visual RTs in a task with pre-stimuli cues (Anatürk & Jentzsch, 2015) and smaller RT variability (Hughes & Franz, 2007).

Auditory RTs were studied by Strait et al. (2010) with a task where participants were instructed to withhold responses if a certain auditory stimulus appeared before the target. Musicians revealed faster auditory RTs and these times were negatively correlated with the years of practice. Conversely, no differences were found between musicians and non-musicians in a lateralized auditory reaction time task (Woelfle & Grahn, 2013). These conflicting results could reflect lateralized or attentional components of the RT methodologies used.

The present results add to the existing literature on unisensory processing in musicians by suggesting for the first time that long-term musical training reduces tactile RTs. Our results also find that musicians have faster RTs for auditory stimuli. Most importantly, these results are the first to find that musicians are better at integrating congruent audio-tactile information at the behavioural level. To date, only two neuroimaging studies have investigated the anatomical substrates of audiotactile interaction in musicians. Schulz et al. (2003) first reported the effect of musical training on audio-tactile processes using MEG. Control participants and professional trumpet players were presented trumpet tones and tactile stimulations to either the lower lip or the index, separately or simultaneous. Musicians displayed significantly increased cortical source signal strength amplitude for audio-tactile stimuli, but only when the tactile stimulation was on the lower lip. The significant difference was thus only present for condition most similar to playing the instrument. This result suggested a qualitatively different processing of audiotactile information in musician, in line with the RMI results in the present study. Kuchenbuch et al. (2014) later found significant MEG responses in musicians for incongruent auditory and audio-tactile stimuli. In this study, participants were simultaneously presented five-note melodies composed of four possible tones along with synchronous fingertip stimulations. The tones were associated with specific fingers in a manner similar to playing a musical instrument. Audiotactile stimulations revealed greater incongruency responses generated in the left uncus, premotor gyrus and cerebellum for musicians. Behavioural results corroborated this increased activation by revealing that musicians were better at identifying incongruencies between auditory and tactile stimulations than non-musicians. Taken together with investigations examining behavioural multisensory processing in musicians (Kuchenbuch et al., 2014; Lee & Noppeney, 2011; Petrini et al., 2009), these results provide additional evidence that musicians are better at integrating the inputs coming from various senses. A simple advantage possessed by musicians to process musical-related stimuli can be ruled out to explain these results considering that multisensory processing capabilities were examined in the present study with a tasks involving non-musical cues. Regardless of these differences, the long-term playing of an instrument is sustained exposure to an enriched sensory environment which leads to changes in cortical connectivity and behavioral ability. While the exact neural correlates for the reported faster RTs are yet to be determined, they are likely similar to the changes found in the aforementioned neuroimaging studies with musicians. Indeed, as both the present study and the existing body of research have consistently suggested, musical training alters sensory ability, whether for a single sensory system or the integration of multiple sensory systems.

Musical training causes many structural neurological changes (for a review, see Herholz & Zatorre, 2012) and consequently, it is difficult to determine the neural substrates underlying enhancement in perception and action. The anatomical substrates responsible for the reported faster audiotactile RTs are not yet clearly defined. However, several investigations of the cortical substrates responsible for interactions between auditory and tactile stimulations might provide hints as to the areas involved in the reported results. Neuroimaging studies have revealed possible neural correlates of audiotactile integration in auditory belt areas, secondary somatosensory cortex, and posterior parietal cortex (Foxe et al., 2000; Foxe et al., 2002; Lütkenhöner et al., 2002; Gobbelé et al., 2003). However, it is difficult to conclusively implicate these regions with faster RTs, as these investigations used did not require a similar speeded behavioural response. Though the enhanced use of audiotactile information as suggested by the RMI analysis implies an enhanced use of the multisensory information that could potentially take place in one of these regions. Moreover, studies have revealed a strengthening effect of piano playing between auditory and motor regions (Bangert et al., 2006; Jancke, 2012). Using neuroimagery, Bangert et al. (2006) found that pianists had co-activation of areas involved in auditory and sensorymotor integration during normal and muted piano playing. This enhanced connectivity was explained as likely being task-specific for a repeated task, in this case, piano playing. Janke (2012) demonstrated a strong coupling between the auditory cortex and the premotor cortex during piano playing, but not during rest. It is unlikely that the enhanced audiomotor connectivity demonstrated in these study is involved in faster RT due to their tight association with piano playing. However, changes to neural oscillations following musical training could be linked to the results from this investigation. Musical training has been reported to enhance beta band activity (Doelling & Poeppel, 2015; Kühnis et al., 2014) and larger beta band activation has been correlated with faster unisensory and multisensory RTs (Senkowski et al., 2006). While the mechanisms underlying beta band generators is not fully understood, they could reflect a significant clue as to the cortical origin of these faster RTs.

In our experimental paradigm, tactile input was delivered to the left hand and the response was provided by the right hand. For this reason, the role of the structure responsible for interhemispheric transmission should also be considered in the context of our results. Some data suggest that the size of the anterior corpus callosum (CC), which mainly connects motor areas, is enlarged in musicians (Lee et al., 2003; Öztürk et al., 2002; Schlaug et al., 1995). Several morphometric studies suggest that callosal volume predicts interhemispheric transfer capacity (Jäncke & Steinmetz, 1994; Witelson, 1985). Thus, it is possible that such important structural changes in the interhemispheric structure following musical training could account for the reported enhancement in RTs.

Several factors can influence the cortical plasticity following musical training (for a review, see Brown et al., 2015). Gaser & Schlaug (2003) first reported differences between musicians and non-musicians for sensory regions grey matter volume. Results from this investigation found significant increases in grey matter volume for musicians in primary motor and somatosensory, premotor, and anterior superior parietal areas, and inferior temporal gyrus. This increase in grey matter volume was correlated with the level of musical expertise. Groussard et al. (2014) further explored the effect of musical training on grey matter volume in a regression study and found a correlation between increased grey matter volume and the musical experience. This gradual increase was first observable in the left hippocampus and right middle and superior frontal regions. Prolonged musical training was then linked to an increase in grey matter volume in the right insula, supplementary motor area, left superior temporal, and posterior cingulate areas. A similar study by Vaquero et al. (2016) revealed volume grey matter differences between non-musicians and professional pianists. Results from this study found greater bilateral grey matter volume for the putamen and lingual gyri, along with the right thalamus and left superior temporal gyrus. Interestingly, they also reported a decrease in grey matter volume for the right supramarginal, superior temporal and postcentral gyri. These changes in grey matter volume are presumably caused by long-term exposure to the sensory, motor, and emotional aspects of music and its production. These increases in grey matter could be linked to the faster RT found in this study, but further studies are required to confirm this hypothesis and identify the specific structures involved.

Results from the repeated measures analysis revealed an interaction between group and the tested modality. Future research on the effect of musical training on non-musical abilities will benefit greatly from looking at factors having an impact on these perceptual enhancements. For instance, some have suggested heredity as a significant factor for musical expertise and the development of these skills (see Brown et al., 2015). While our study was not designed to directly investigate all the characteristics of musical training in relation with multisensory performance, it would be worthwhile further examining the impact of these features on performances. Future examinations should use groups with a more homogeneous distribution in order to isolate structures or features that might account for the reported effect. This would also provide insight as to whether sensory benefits of musical training are progressive or abrupt in regard to multisensory integration and RTs. Moreover, future investigations should look at instrument-specific improvements. In the current study, instruments played by participants were considerably heterogeneous with most participants reporting playing multiple instruments. Piano was reported most frequently as the primary instrument (n=6). The specificity of enhancement for instrument, in relation to the musically involved hand and experimentally tested hand, could provide great insights on the pervasiveness of any enhancements. Future investigations on the non-musical impact of musical training should try to test more homogeneous groups for instruments played. It is also possible these results reflect another unmeasured variable. Investigations have reported correlations between musical training and general intelligence (IQ) (Schellenberg, 2004) and a correlation has been reported between general intelligence and RTs (Jensen, 1993). Despite having groups with similar levels of education, it is possible the reported greater IQ in musicians could have played a role in observed faster RTs.

1.12. Acknowledgement

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1.13. References

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Figure 2.1

Mean reaction time (in ms) for each condition (auditory, tactile, audio-tactile) for control group members and musicians. Error bars represent standard error. Asterisks indicate a significant difference between groups (* = p > .02).

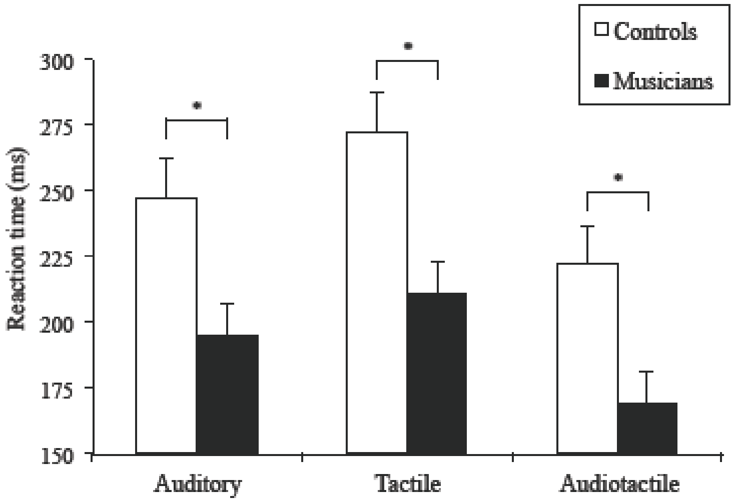


Figure 2.2

Predicted multisensory facilitation violations of the RMI for the (A) non-musician and (B) musician group. Distributions of cumulative group mean reaction times for auditory, tactile, audiotactile, and combine unisensory stimulations. Reaction times are segmented in 10 percentile bins. Asterisks represent bins with violations to RMI.

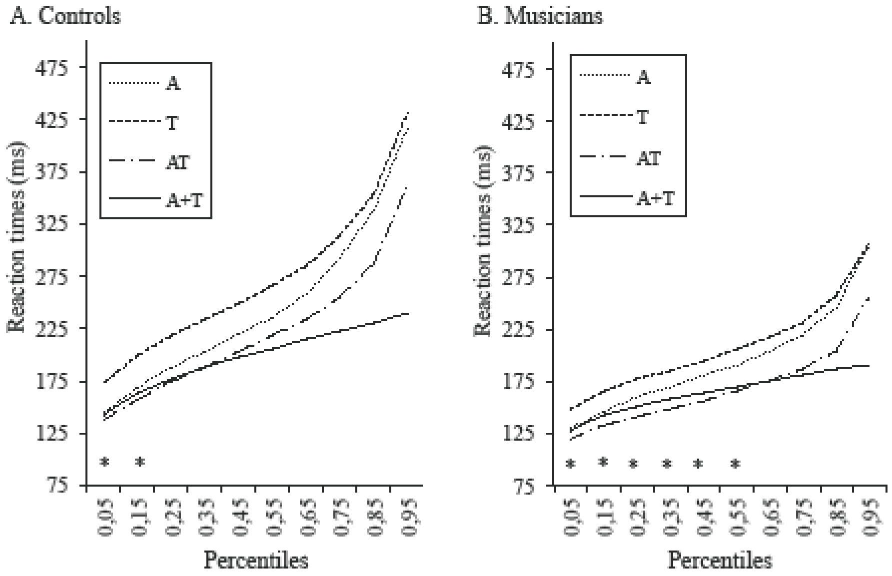
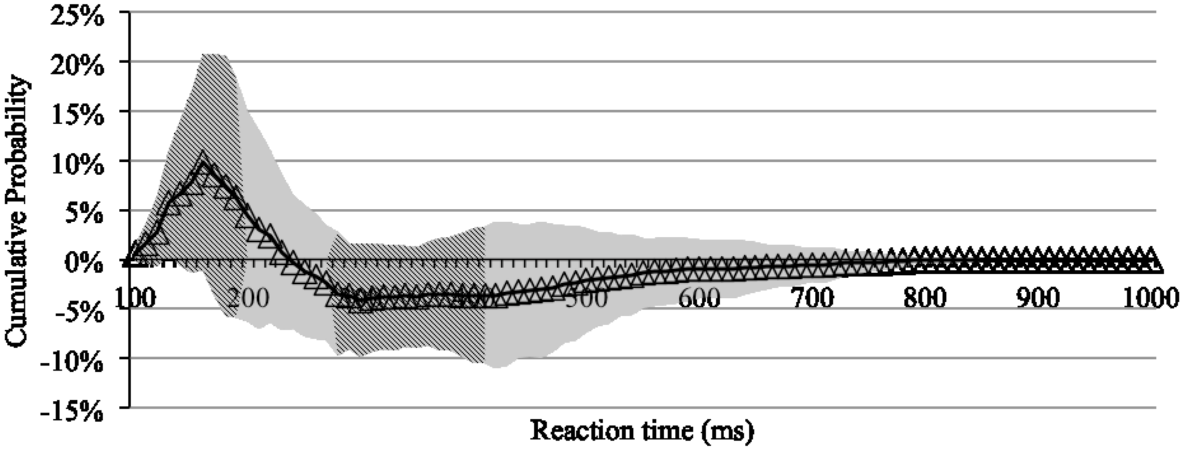


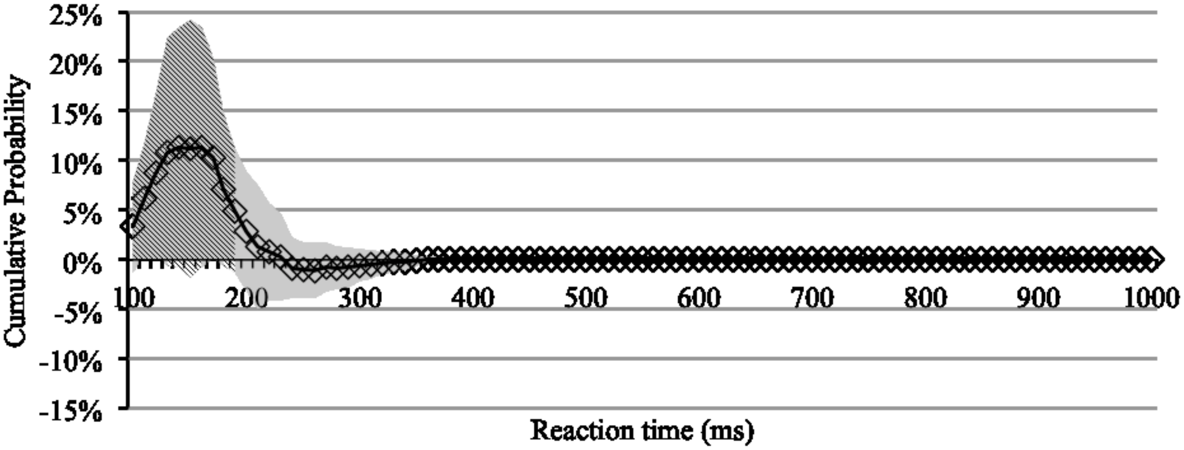
Figure 2.3

Cumulative distribution functions (CDF) for 10ms bins for the control group (A) and musicians (B) with standard deviation. Hashed area represents RTs with a significant probability ($p < 0.05$) for multisensory (> 0%) or unisensory (< 0%) responses. (C) The subtraction of the musician CDF from the control group CDF. A positive value can represent higher musician multisensory response likelihood while a negative response can represent higher non-musician multisensory response likelihood. Similarly, a negative value can represent higher musician unisensory response likelihood while a positive response represents higher non-musician unisensory response likelihood.

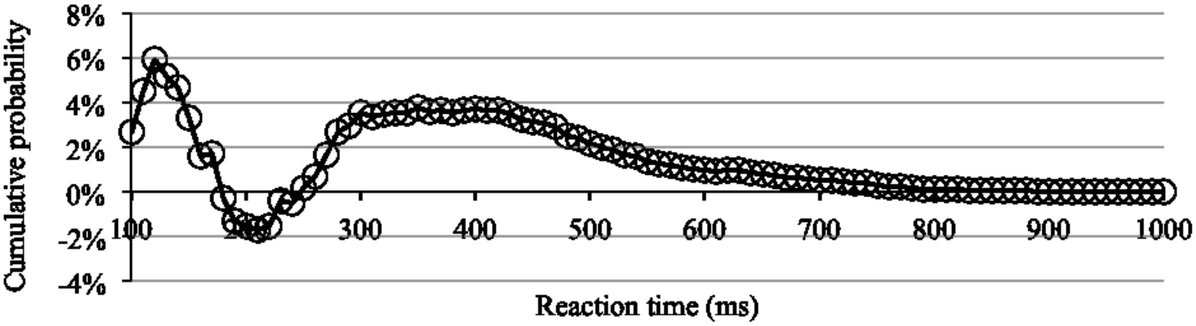
A. Controls



B. Musicians



C. Difference between musician CDF and control CDF



Chapitre 3 - Temporal and spectral audiotactile interactions in musicians

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3.1. Abstract

Previous investigations have revealed that the complex sensory exposure of musical training alters audiovisual interactions. As of yet, there has been little evidence on the effects of musical training on audiotactile interactions at a behavioural level. Here, we tested audiotactile interaction in musicians using the audiotactile illusory flash and the parchment-skin illusion. Significant differences were only found between musicians and non-musicians for the audiotactile illusory flash. Both groups had similar task-relevant unisensory abilities, but unlike non-musicians, the number of auditory stimulations did not have a statistically important influence on the number of perceived tactile stimulations for musicians. Musicians and non-musicians similarly perceived the parchment-skin illusion. Spectral alterations of self-generated palmar sounds similarly altered the perception of wetness and dryness for both groups. These results suggest that musical training does not seem to alter multisensory interactions at large. The specificity of the sensory enhancement suggests that musical training specifically alters processes underlying the interaction of temporal audiotactile stimuli and not the global interaction between these modalities. These results are consistent with previous unisensory and multisensory investigations on sensory abilities related to audiotactile processing in musicians.

Keywords: Multisensory training; musical training; multisensory segregation; multisensory interaction

3.2. Introduction

The interaction of input from our multiple senses forms our perception of the world (Stein & Stanford, 2008). This process of combining sensory information into a cohesive percept is a culmination of our continuous perceptual experiences (Wallace & Stein 2007). Audiotactile interaction, the combination of tactile and auditory inputs, is understood to play an important yet little understood role in everyday behaviour. Indeed, it is involved in a wide variety of daily tasks such as musicianship (Wollman et al. 2014), speech production (Nasir & Ostry 2008), and even shaving (Foxe 2009). The capacity to integrate or segregate multisensory information can be studied through the use of multisensory illusions. By provoking a perceptual conflict between typically congruent sensory information, it is possible to study the brain's weighing of each modality involved in a given process of multisensory interaction. One of the most popular examples of this process is the McGurk illusion (McGurk & MacDonald 1976) in which conflicting auditory and visual speech stimuli are simultaneously presented. Perception can be either of the discrete visual or auditory stimulus or of a novel percept combining auditory and visual characteristics, depending on individual interactions between modalities (Schwartz, 2010). As such, individuals for whom vision is more heavily weighed will report perception of the vision stimulus. The two most prevalent audiotactile illusions are the audiotactile illusory flash (Hötting & Röder 2004) and the parchment-skin illusion (Jousmäki & Hari 1998). The audiotactile flash illusion, in which an illusory percept typically occurs when the number of ignored auditory stimulations is larger than the number of attended tactile stimulation, studies temporal audiotactile interaction. The parchment-skin illusion, in which attenuating specific spectral information can lead participants to perceive a wet illusory palmar sensation while augmenting specific spectral information can induce a dry palmar sensation, studies spectral audiotactile interaction.

Musical training is recognized to be a complex form of multisensory training due to its interacting auditory, tactile and visual components (Münte et al. 2002). The interaction between what is heard and felt is especially important when playing a musical instrument. Subtleties in the vibrations from the instrument, which become sounds, can alter the musical expression. As such, long-term training with a musical instrument relies heavily on audiotactile interactions. This long-term training can lead to anatomical and structural changes in the cortical regions associated with these senses (for a review, see Herholz & Zatorre 2012). Behavioural data examining sensory capabilities are consistent with the findings suggesting structural and anatomical changes following long-term musical training. Indeed, previous investigations on the effects of musical training on multisensory interactions have revealed an effect of training for several audiovisual processes (e.g. Petrini et al. 2009; Hodges et al. 2005; Musacchia et al. 2007; Musacchia et al. 2008; Lee & Noppeney 2011; Lee & Noppeney 2014; Pantev et al. 2015). However, there has been little evidence on the effects of musical training in the audiotactile domain at a behavioural level. The results from Kuchenbuch et al. (2014) suggest musicians possess a superior ability to detect incongruent auditory and tactile stimuli in a task inspired by music production.

To our knowledge, audiotactile interactions have not been investigated further in musicians. As such, it is unsure whether musical training has an impact on audiotactile processing at large or if the changes are specific only to detection of audiotactile incongruences (Kuchenbuch et al. 2014). Moreover, since the previous investigation used a musically inspired methodology, multisensory capabilities for musicians in non-musical audiotactile tasks remain unexplored. The use of non-musical tasks provides critical information as to the pervasiveness of sensory changes in musicians. While differences between groups in musically inspired tasks can be explained by repeated exposure to musical stimuli, using a non-musical task evaluates whether sensory changes exist beyond the abilities directly related the familiar musical context.

The objective of this study is to explore the effects of long-term musical training on temporal and spectral audiotactile interaction using widely used non-musical paradigms, namely the audiotactile illusory flash (Hötting & Röder 2004) and the parchment skin illusion (Jousmäki & Hari 1998).

3.3. Method

3.3.1. *Participants*

Thirty individuals (13 musicians; 17 controls) participated in this study. Thirteen musicians (10 women, 3 men, m_{age} = 25 years, age range: 18-30 years) were recruited from the Université de Montréal Faculty of Music. Participants reported piano (n=6), percussions (n=2), double bass (n=1), harp (n=1), trombone (n=1), violin (n=1), and viola (n=1) as their primary instrument. Seventeen control group members (13 women, 4 men, m_{age} = 23.7 years, age range: 19-34 years) were recruited from the Université de Montréal Faculty of Medicine. All participants completed a self-reported musical training questionnaire (Müllensiefen et al. 2014) to ensure a significant difference in musical training between groups.

Twenty-four of these individuals, 12 musicians (8 females, 4 males, mean age = 23.8 years, range = 18-30 years) and 12 controls (8 women, 4 men, m_{age} = 24.6 years, age range = 19-34 years) participated in Experiment 1. The mean musical training scores for the control group was representative of the 34th percentile (range: 5th to 58th percentile) while the mean musical training score for the musician group was representative of the 92nd percentile (range: 81st to 99th percentile).

The difference between group mean musical training scores was significantly different, $t(22) = -8.045$, $p < 0.001$.

Twenty-six individuals, 13 musicians (9 women, 4 men, $m_{age} = 23.7$ years, age range: 18-30 years) and 13 controls (10 women, 3 men, $m_{age} = 24.5$ years, age range: 19-34 years), participated in Experiment 2. The mean musical training scores for the control group was representative of the 28th percentile (range: 5th to 58th percentile) while the mean musical training score for the musician group was representative of the 92nd percentile (range: 81st to 99th percentile). The difference between group mean musical training scores was significantly different, $t(24) = -9.626$, $p < 0.001$.

All participants reported no history of tactile disorders, concussions, or taking any medications. All participants had normal or corrected-to-normal vision, and had normal auditory pure tone detection thresholds for octave frequencies ranging from 0.5 to 8 KHz. The study conformed to the World Medical Association Declaration of Helsinki and the Research Ethics Board of the Université de Montréal approved the study. All participants provided written informed consent.

3.3.2. *Experiment 1: The audiotactile illusory flash*

Materials and procedures

Control auditory condition. Participants were seated comfortably in a quiet well-lit room in front of a computer with attenuating circumaural headphones (10 S/DC, David Clark, Worcester, MA, USA). An auditory control task (Landry et al. 2013) was first performed using 10 trials of one, two, three, and four auditory stimuli (2100 Hz, 10-ms duration, 100 ms between stimuli). The 40 trials were presented in random order. These auditory stimulations were presented at a comfortable level (60–70 dB hearing level) via the headphones. Participants were instructed to count the number of auditory stimulations and report them on a computer running a custom cognitive evaluation program using PsyScope X software (Cohen et al. 1993). A white-noise generator was used to provide an aural environment comparable to the subsequent experimental condition.

Experimental condition. Participants were seated in a room in front of the computer with attenuating circumaural headphones. They had their right index finger on a vibrotactile device (Madsen Electronics 03204, Otometrics, Taastrup, Denmark). We replicated the experimental condition from Hötting & Röder (2004) where twelve trial types combining auditory and tactile stimulations were used. Trial types were as follows: one tactile stimulus was paired with zero, one, two, three, or four auditory stimuli; two tactile stimuli were paired with zero, one, or two auditory stimuli; three tactile stimuli were paired with zero or one auditory stimulus; and four tactile stimuli were also paired with zero or one auditory stimulus. Each trial type was presented 25 times and the 300 trials were presented in random order over five blocks of 60 trials. Auditory stimulations (2100 Hz, 10-ms stimuli) were presented with an interstimulus interval of 100 ms and at a comfortable level (60–70 dB hearing level) via the headphones. The first auditory stimulation always preceded the first tactile stimulation by 25 ms. Tactile stimulations (1000 Hz, 50-ms stimuli) were presented with an interstimulus interval of 200 ms at an individually calibrated level slightly above threshold. Participants were instructed to report the number of tactile stimulations on the computer keyboard and ignore the auditory stimulations. A white-noise generator was used to mask any auditory hints emanating from the vibrotactile stimulator.

Analysis

For the auditory control condition, an ANOVA was performed on each group's average perceived auditory stimulations with group (control or musician) as a between-subjects factor and number of auditory stimuli (one, two, three, or four) as a within-subjects factor. This analysis of the auditory control condition was to ensure that both groups were able to accurately discriminate numbers of auditory stimuli and had comparable task-relevant auditory abilities.

To control for tactile perception, an ANOVA was performed on each group's average perceived tactile stimulations for one, two, three, and four tactile stimulations in the presence of no auditory stimuli. The analysis had group (control or musician) as a between-subject factor and number of tactile stimuli (one, two, three, or four) as a within-subjects factor. This analysis of tactile perception was to ensure that both groups were able to accurately discriminate differing numbers of tactile stimuli and had comparable task-relevant tactile abilities.

For the experimental condition, an analysis was performed on the effect of the number of auditory stimulations on a single tactile stimulation to determine if both groups perceived the tactile illusory percept. A repeated measure ANOVA on each group's average perceived tactile stimulations was performed. For this, group (control or musician) was the between-subjects factor and number of auditory stimuli (zero, one, two, three, or four) was the within-subjects factor. Subsequent post hoc analysis for group (control or musician) and the perceived number of tactile stimuli for conditions with a single tactile stimulus and auditory stimuli (one, two, three, or four) were performed if a significant interaction was found for the number of auditory stimuli.

A susceptibility index (SI) (Stevenson et al. 2012) was calculated for all participants. The SI is an individual value that represents the participant's susceptibility to having the target modality (tactile) altered by another sensory input (auditory). A SI value of one signifies that the perception of the target modality was constantly altered by the other modality while a SI value of zero signifies that the presence of the other modality had no effect of the perceived number of target stimuli. The SI was calculated from individual mean perceived tactile stimulations for conditions with: one auditory and one tactile ($A1T1$); two auditory and one tactile ($A2T1$); three auditory and one tactile ($A3T1$); and four auditory and one tactile ($A4T1$) stimulations. The following formula was used to calculate SI: $SI = [(A2T1\text{-}A1T1)/1+(A3T1\text{-}A1T1)/2+(A4T1\text{-}A1T1)/3)]/3$

Mean group SI results were then compared using an independent t-test with SI as the dependent variable and group (control or musician) as the independent variable.

All degrees of freedom and p values associated with the analyses of variance (ANOVAs) were adjusted using the Greenhouse-Geisser correction when Mauchly's test of sphericity was significant.

3.3.3. *Experiment 2: The parchment skin illusion*

Materials and procedures.

The parchment skin illusion, an illusory task investigating spectral audiotactile interaction, was used (Jousmäki & Hari 1998; Champoux et al. 2010). Participants were comfortably seated in a quiet well-lit room and wore attenuating circumaural headphones (10 S/DC, David Clark, Worcester, MA, USA). They were asked to rub the palms of their hands in front of a microphone six times at a rate of approximately two cycles per second. The sound of their hands rubbing was captured by a microphone (Neumann, TLM 103, Berlin, Germany) and processed through an equalizer (Realistic, model 31-2018A, Fort Worth, Texas, USA) and mixing board (Yamaha, MG10/2 mixing console, Hamamatsu, Shizuoka, Japan). The processed sound was played through the circumaural headphones in real-time at a comfortable volume. As per Jousmäki and Hari (1998), three conditions were used. For the control condition, the captured sound was not modified before being presented to the participant. For the first experimental condition (augmented condition), all captured frequencies were augmented by 20 dB and the frequencies above 2 kHz were augmented by an additional 12 dB. For the second experimental condition (attenuated condition), all captured frequencies were attenuated by 20 dB and the frequencies above 2 kHz were decreased by an additional 12 dB. These three conditions were each presented ten times in a pseudo-random order. Participants were asked to rate their perceived tactile sensation after each manipulation, independent of auditory perception, on a dry/moist scale of /+5/ to /-5/ (Guest et al. 2002). The rating of /+5/ represented the perception of having dry palmar skin and /-5/ represented the perception of having moist palmar skin. Palmar sensation rating was verbally reported to the experimenter after each trial.

Analysis

A Mann-Whitney U non-parametric test comparing the average reported palmar sensation for both groups in each condition was performed. This analysis was used to find any significant differences between groups for any of the three conditions. We also performed a Wilcoxon Signed-Rank test to analyse between condition results to ensure that participants had significantly different palmar sensation for the difference conditions.

3.4. Results

3.4.1. *Experiment 1*

The repeated measure ANOVA for the control auditory condition revealed a significant main effect for auditory stimuli ($F_{(1.113, 23.372)} = 6502.844$, $p < .001$, $\eta_p^2 = .997$) and no main effect of group ($F(1, 21) = 1.871$, $p = .082$, $\eta_p^2 = .082$). Moreover, the interaction between the factors was not significant ($F_{(1.113, 23.372)} = 2.375$, $p = .135$, $\eta_p^2 = .102$). Thus, both groups were able to discriminate differing numbers of task-relevant auditory stimuli (Figure 3.1 a).

An ANOVA was performed with group (control or musician) as a between-subjects factor and number of tactile stimuli (one, two, three, or four) as a within-subjects factor. One control participant was eliminated from analysis for having an average response of 1.76 for the single tactile without auditory condition. This analysis revealed that the main effect of the number of tactile stimuli was significant, ($F_{(3,\,63)} = 32.792$, $p < .001$, $\eta_p^2 = .993$). Again, there was no main effect of group ($F_{(1,\,21)} < 0.001$, $p = .925$, $\eta_p^2 < .001$), and, most notably, the interaction between the factors was not significant ($F(3, 63) = 0.249$, $p = .861$, $\eta_p^2 = .012$). Thus, both groups were able to discriminate differing numbers of tactile stimuli (Figure 3.1 b).

A repeated measure ANOVA between both groups for the perceived number of tactile stimulations in presence of a single tactile stimulation and zero to four auditory stimulations was performed. Statistically significant main effects of the number of auditory stimuli ($F_{(1.281,\,26.891)} = 7.756$, $p = .006$, $\eta_p^2 = .270$), and group ($F_{(1,\,21)} = 4.995$, $p = .036$, $\eta_p^2 = .192$), were found. Most important, the interaction between these factors was significant ($F_{(1.281,\,26.891)} = 4.386$, $p = .037$, $\eta_p^2 = .173$). Results from post hoc analyses revealed that the perceived number of tactile stimuli differed significantly between the groups whether the single tactile stimulus was presented along with two auditory stimulations ($t_{(21)} = 3.030$, $p = .006$, $d = 1.442$), or three auditory stimulations ($t_{(21)} = 2.176$, $p = .041$, $d = 0.950$). However, it did not differ significantly when a single tactile stimulation was paired with zero auditory stimulation ($t_{(21)} = -.629$, $p = .536$, $d = -0.275$); one auditory stimulation, ($t_{(21)} = -.309$, $p = .761$, $d = -0.135$), or four auditory stimuli ($t_{(21)} = 1.884$, $p = .073$, $d = 0.380$). Thus musicians were significantly less influenced by the presence of two or three auditory distractors on a single tactile percept than non-musicians (Figure 3.2).

A t-test was performed between groups and susceptibility indexes. As expected, this revealed a significant difference between groups ($t_{(21)} = 2.574$, $p = .005$, $d = 1.123$) meaning musicians were less susceptible to the illusory percept.

3.4.2. *Experiment 2*

There was no significant difference between groups for the control condition without any auditory manipulation ($U = 72$, $p = 0.589$). Results from the Mann-Whitney U non-parametric test also revealed no significant differences between groups for the augmented auditory condition ($U = 74$, $p = 0.739$) or the attenuated condition ($U = 76.5$, $p = 0.837$) (Figure 3.3). As expected, results from the Wilcoxon Signed-Rank test revealed a significant difference between palmar sensation for the attenuated and control condition ($Z = -3.363$, $p = .001$), attenuated and augmented condition ($Z = -2.722$, $p = 0.06$), and control and augmented condition ($Z = -2.487$, $p = .013$).

3.5. Discussion

The main objective for Experiment 1 was to evaluate temporal audiotactile interaction in musicians using the audiotactile illusory flash. Our results suggest that musicians are better at segregating auditory stimuli from tactile sensation than non-musicians. The number of auditory stimulation did not influence the number of tactile percept for musicians whereas it did for non-musicians. This significant difference between groups was found in the presence of two and three auditory stimulations with a single tactile stimulation. These results cannot be explained by differences in unisensory abilities, as both task specific unisensory abilities were found to be similar between groups. This difference of susceptibility to multisensory illusion between groups was further confirmed by a significant SI difference between groups. Our results reveal a significant interaction between group and number of auditory stimulations (zero to four) for the single tactile stimulation condition. However, beyond the expected similar results for zero and one auditory stimulations, our post hoc analysis found no significant difference between groups in the presence of four auditory distractors. This could be attributed to the large variability of perceived tactile stimuli for this condition (mean = 1.49, SD = 0.73), a finding that was similarly reported by Hötting & Röder (2004) for the condition with four auditory stimulations. These results might be explained by the temporal disparity between auditory and tactile stimulation duration. The threshold for multisensory asynchrony is reported to be shorter for audiotactile than for audiovisual and visuotactile information (Fujisaki & Nishida 2009). Because of this high sensitivity, it is possible the four auditory stimuli were beyond the window of audiotactile interaction for some participants since the single tactile stimuli lasted 50 ms while the total auditory stimulation train was 340 ms. Further explorations on the effect of musical training on multisensory interactions of sequential conflicting sensory stimuli (ex. Bresciani et al. 2006) will help deepen our understanding of this sensory weighing and whether it extends to other multisensory interactions.

The main objective of Experiment 2 was to study the effects of musical training on spectral audiotactile interaction using the parchment-skin illusion. We found no significant difference between musicians and non-musicians in any of the conditions, whether control or experimental. Both groups perceived the palmar illusory effect produced by auditory manipulation without significant differences between groups for intensity of illusory percept. Both groups also similarly perceived the control condition. These results suggest that the palmar percept from manipulating spectral information does not change following musical training.

Both findings from this study, along with other investigations of multisensory abilities in musicians, help paint a picture of the impact of a very specific long-term sensory training (playing music) on abilities that are not directly related the trained skill. The null finding from the parchment skin illusion is informative in that it suggests musical training does not alter multisensory interactions at large. In fact, because of this null finding, it is possible that musical training alters a specific mechanism underlying temporal multisensory integration, while leaving other, more passive forms of non-musical integration, in this case spectral, unaltered.

An important distinction between the audiotactile illusory flash and the parchment-skin illusion are the tasks' temporal and spectral auditory components. Processing spectral and temporal auditory information is understood to occur through distinct pathways in humans (Zatorre & Belin 2001). Indeed, Zatorre and Belin (2001) found that spectral auditory components activated anterior superior temporal regions while temporal components activated the primary cortices. These different pathways could provide clues towards understanding the differences in the two types of audiotactile interactions reported in this study. Further investigations should look at the effects of musical training on temporal frequency channels with more sensitive tasks (Yau et al. 2009). Indeed, this task could simultaneously investigate spectral and temporal audiotactile interaction, thus providing greater context for these results.

Neuroimaging studies with musicians have revealed significantly altered early-stage audiotactile processing (Schultz et al. 2003) as well as greater connectivity between the primary auditory and somatosensory cortices (Luo et al. 2012). Such anatomical changes from long-term musical training could provide clues towards the neuroanatomical basis for the obtained results. Significant cortical plasticity has been reported in children after as little as 15 months of musical training (Hyde et al. 2009). Structural differences were reported in the precentral gyrus, the corpus callosum, and the right primary auditory region. However, while these changes led to behavioural enhancement for musically related tasks, they did not extend to non-musical behavioural task.

Taken with our results, it can be assumed that the reported ability to segregate auditory input from tactile stimuli is acquired only after several years of intense musical training. Neuroimaging studies have revealed that long-term musical training can increase cortical representations of the fingers (Elbert et al. 1995) and result in a larger area of auditory activation for musical stimuli (Pantev et al. 1998). These results from professional musicians were unfortunately not linked to behavioural enhancements. To date, only Kuchenbuch et al. (2014) investigated audiotactile cortical changes in relation to behavioural improvement. The authors found an enhanced MEG response for incongruent audiotactile stimuli and an improved behavioural ability to detect audiotactile incongruencies. Further investigations between enhanced fundamental behavioural sensory abilities and neuroimaging results in musicians are required to better understand the non-musical sensory impact of musical training. Functional near-infrared spectroscopy (fNIRS) could prove to be a valuable tool in such investigations due to its demonstrated usefulness in testing paradigms with musical (Santosa et al. 2014) and sound (Hong et al. 2016) stimuli.

It has been demonstrated using EEG that children can already benefit from musical training within as little as 6 months (Moreno et al. 2009). It would be worth investigating whether this relatively rapid change also occurs for multisensory interactions in adults. A study comparing the unisensory and multisensory aspects of musical production in adults found significant training-induced plasticity after only 2 weeks (Lappe et al. 2008). In this study, participants were trained using either an auditory or sensorimotor-auditory musical production paradigm for two weeks. The sensorimotor-auditory group had greater musically elicited mismatch negativity after training. These results suggest a rapid effect of musical training-induced plasticity for musical stimuli. Future investigations should investigate if a correlation exists between susceptibility to illusory precepts and factors related to musical training. This was not possible in this study since the musical training score used is a compound measure of several factors and musicians had a concentration of high musical training scores while controls were highly dispersed below the 58th percentile. Future investigations on correlations between multisensory illusory susceptibility and factors of musical training could provide evidence as to whether the alterations of audiotactile interaction are progressive or occur abruptly past a level of musical training.

3.6. Acknowledgment

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Figure 3.1

Results from the controls conditions. **(a)** Perceived number of auditory stimulus from the auditory control conditions containing no tactile stimuli plotted for the actual number of auditory stimulations. **(b)** Perceived number of tactile stimuli presented during the experimental task plotted for the actual number of tactile stimulations. Error bars represent standard deviation.

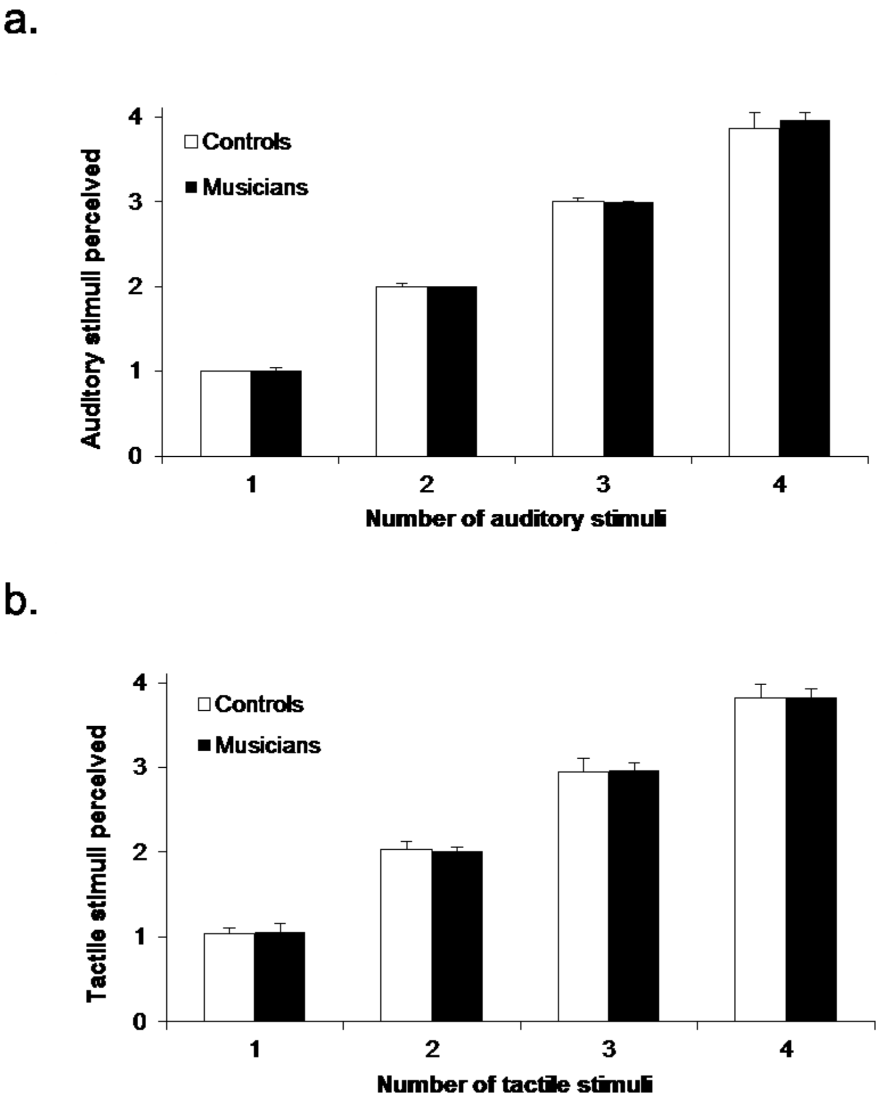


Figure 3.2

Perceived number of tactile stimulus for the trials containing a single tactile stimulation in function of the number of auditory stimulus. Error bars represent standard error. An asterisk indicates a significant difference between groups ($p < 0.05$)

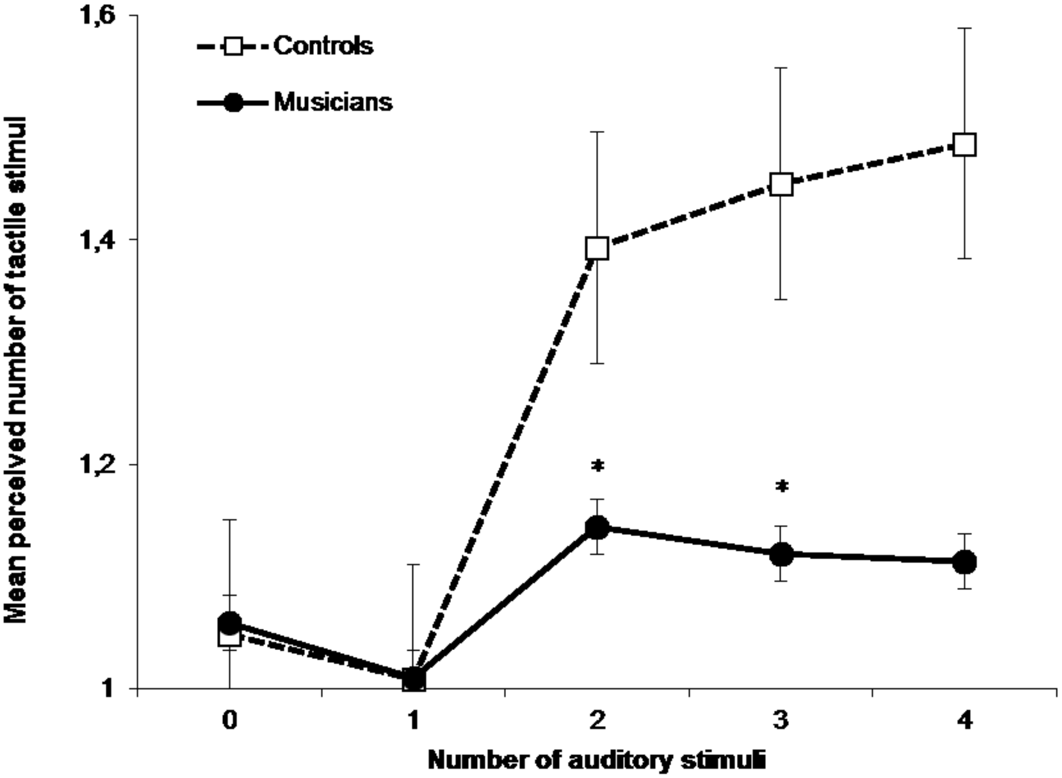
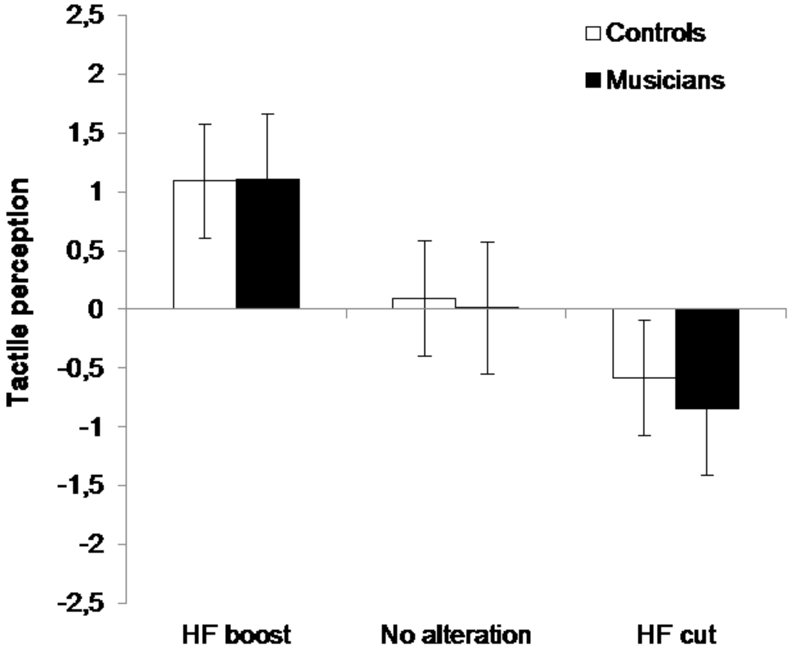


Figure 3.3

Changes in palmar skin perception for control and musician groups for the control condition (no alteration), augmented condition (HF boost), and attenuated condition (HF cut). A positive value in tactile perception represents a "dry" palmar sensation while a negative value represent a "wet" palmar sensation. Error bars represent standard error



Chapitre 4 - Long-Term Musical Training Alters Tactile Temporal-Order Judgment

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5.7. Abstract

Long-term musical training is an enriched multisensory training environment that can alter uni- and multisensory substrates and abilities. Amongst these altered abilities are faster reaction times for simple and complex sensory tasks. The crossed arm temporal-order judgement (TOJ) task is a complex tactile task in which TOJ error rate increases when arms are crossed. RTs for this task are typically proportionate to the difficulty of the stimulus onset asynchrony (SOA) and increase more when the arms are crossed than when uncrossed. The objective of this study was to study the impact of musical training on RTs and accuracy for the crossed arm TOJ task. 17 musicians and 20 controls were tested. Musicians had significantly faster RTs for all crossed arm conditions and half of the uncrossed conditions. However, musicians had significantly more TOJ errors for the crossed posture. We speculate that faster musician TOJ RTs leaves little time to consolidate conflicting internal and external task-related information when crossing the arms, leading to increased incorrect responses. These results provide novel insights on the potential mechanisms underlying the increased TOJ error rates when crossing the arms. Moreover, it adds to the growing literature of altered sensory ability in musicians and proposes an unexpected consequence of faster reaction times.

Keywords: musicians, tactile, temporal-order judgement, crossed arm, reference frame

5.7. Introduction

Playing musical instruments provides a rich multisensory environment. Musicians must optimally integrate sensory inputs from the tactile interaction with the instrument, the auditory recognition of the sound produced, and the visual input from reading sheet music or seeing one's own arms while playing the instrument (Herholz and Zatorre, 2012). Research on the effects of musical training on sensory abilities has revealed improved multisensory interactions for tasks inspired by the processes involved in playing a musical instrument. One of these research methodologies presents explicitly associated multimodal information and asks participants to identify when asynchronies occur. For instance, a sensation of touch on each finger would be associated with a different tone in ascending order for both the sound and touch. This particular methodology is especially similar to playing a musical instrument where different fingers are associated with specific sounds such as a trumpet. Participants must then identify when the tactile and auditory inputs are discordant. Using this type of methodology, Kuchenbuch et al. (2014) revealed that musicians were better at identifying when auditory and tactile information were incongruent. Paraskevopoulos *et al.* (2015) further demonstrated this altered ability in musicians, this time suggesting musicians are also better at identifying when auditory and visual information are similarly incongruent in a task inspired by the association between the height of visual marker and the frequency of a tone, similar to reading sheet music. Taken together, these two studies suggest that musical training does indeed strengthen the interaction between individual senses for musical contexts.

Musicians were also revealed to have enhanced abilities beyond a musical context. Fundamental audiovisual integration has been evaluated in musicians by measuring the duration of the time window in which auditory and visual information are bound as a single percept. Results from these investigations reveal musicians have a significantly narrower audiovisual integration window for speech, sinewave speech, music (Lee and Noppenny, 2015), and tones (Bidelman, 2016). Musicians have also been evaluated using the McGurk illusion (McGurk and MacDonald, 1976) in a study of audiovisual segregation abilities for speech stimuli. When incongruent auditory and visual speech stimuli were presented, musicians perceived only the auditory stimuli whereas non-musicians fused auditory and visual inputs and perceived an illusory multisensory percept (Proverbio *et al.*, 2016). This result suggests altered weighing of sensory input in situations of conflicting sensory information for musicians. Musicians were also found to have altered audiotactile integration (Landry *et al.*, 2016). In this study, participants were asked to ignore auditory input and solely report the number of tactile stimuli perceived. Control group participants reported a number of tactile stimuli influenced by the presented number of auditory stimuli while musicians were able to report the number of tactile stimuli without such an interference. These results suggest an enhanced ability to segregate temporal auditory and tactile information. Collectively, results from these musical and non-musical tasks suggest that musical training alters a wide range of musical and non-musical multisensory interactions. Indeed, results from these latter non-musical tasks are especially interesting as they reveal the wide-reaching effects of the sensory training provided by playing a musical instrument.

Improved multisensory interactions in musicians were also reported using reaction times (RTs) (Landry and Champoux, 2017). Musicians were revealed to have faster simple reaction time for simultaneously presented auditory and tactile stimuli than non-musicians. Improved interactions between senses for musicians were also reported for unspeeded reaction times during an audiovisual simultaneity judgement task (Bidelman, 2016). For this task, RTs were measured while participants were asked to indicate the number of perceived visual stimuli in the presence of auditory stimuli. Musicians were found to more accurately report the number of visual stimuli, but more interestingly, their RTs were faster for most conditions. These results suggest that musicians seem to have faster RTs for multisensory stimuli even when unspeeded.

Playing a musical instrument provides rich multisensory training that can improve the interaction between senses and benefits have also been reported for unisensory abilities. Some have found musicians to have faster visual RTs (Anatürk and Jentzsch, 2015; Chang *et al.* 2014) and smaller RT variability for visual stimuli (Hughes and Franz, 2007), though others have failed to replicate such findings (Brochard *et al.*, 2004; Rodrigues *et al.*, 2014; Strait *et al.*, 2010; Woelfle and Grahn, 2013). Similarly, some studies found musicians to have faster auditory RTs (Landry and Champoux, 2017; Strait *et al.*, 2010), while others failed to replicate these findings (Woelfle and Grahn, 2013). Most recently, musicians were revealed to have faster tactile reaction times (Landry and Champoux, 2017), suggesting that musical training potentially leads to faster RTs for simple unisensory and multisensory stimuli, as well as unspeeded multisensory tasks.

Faster unisensory and multisensory RTs reflect the pervasiveness of musical training-based sensory improvements. Musical training seems to improve several sensory abilities not explicitly associated with playing an instrument. Tactile abilities in both unisensory and multisensory contexts appear significantly altered due the extensive tactile interaction between musicians and their instrument. The crossed arm TOJ task is a testing paradigm to investigate the multisensory process of tactile localization (Heed *et al.*, 2015). In this task, the two hands are stimulated successively and participants must indicate which hand was first stimulated. Tactile stimuli are delivered over several stimulus onset asynchronies (SOAs) and participants must perform a TOJ when their arms are either uncrossed or crossed. For the crossed arm condition, participants must indicate whether the hand located to the right or to the left of the participant was first stimulated.

When participants crossed their arms, tactile TOJ accuracy is significantly reduced (Shore *et al.*, 2002; Yamamoto and Kitazawa, 2001). Increased error rate in the crossed arm posture in understood to be a result of a conflict in internal and external frames of reference (Heed *et al.,* 2015). The internal frame of reference maps sensory input in relation to the body while the external frame of reference maps sensory inputs pertaining to the environment beyond the body. For example, when crossing the arms, the internal frame of reference maps the tactile stimuli to the right hand while the external frame of reference maps the source of the stimuli to the left side of the body, as that is the location of the hand. This conflict in stimuli lateralization between frames of reference would lead to increased localization errors.

Investigations on the unspeeded RTs for this task suggest that RTs are significantly slower for the shorter more difficult SOAs. Moreover, the RTs for short SOAs increase more for the crossed-arm condition compared to uncrossed arm condition (Heed *et al.*, 2012; Heed *et al.*, 2016; Yamamoto and Kitazawa, 2001). Pianists and drummers have been tested with the crossed arm TOJ task without significant differences between groups in terms of TOJ error rate (Craig and Belser, 2006; Kóbor *et al.*, 2006), though the effect of musical training on TOJ RTs is still unknown.

Touch plays an important role in musical performance, as it is how musicians physically interact with their instrument. Yet little is known on the effect of musical training on tactile abilities. More specifically, how does having enhanced tactile ability from long-term interaction an instrument translate to passive tactile skills as measured with some research methodologies? Results from some investigations suggest that musical training leads to altering tactile abilities as well as tactile substrates. Indeed, musicians were found to have higher spatial tactile acuity (Ragert *et al.*, 2004) and imaging studies revealed that musical training could lead to increased cortical representation of the hands (Elbert *et al.*, 1995; Pantev *et al.*, 1998). These changes, taken with the reduced unspeeded RTs for audiovisual stimuli in musicians (Bidelman, 2016), suggest possible changes to unspeeded RTs in a complex tactile task. Indeed, evaluating the effect of musical training on the unspeeded tactile RTs of the crossed arm TOJ task could further reveal the pervasiveness of musical training on non-musical abilities. Moreover, it would provide more evidence on altered tactile abilities of musicians.

The goal of this study was to evaluate the effect of musical training on complex tactile unspeeded RTs using the crossed arm TOJ task. At the same time, we aimed to evaluate the effect of musical training on the integration of conflicting information from internal and external frames of reference using crossed arm TOJ accuracy.

5.7. Method

5.4.1. *Participants*

Thirty-seven participants, 17 musicians and 20 control group members, took part in this study. Control group members (15 women; 5 men, M_{age}= 24.0 years, age range = 19 -34 years) were recruited from the Université de Montréal's faculty of medicine. None of the control group members self-identified as musicians. Musicians (11 women; 6 men, M_{age}=23.7 years, age range = 18 – 30 years) were recruited from the Université de Montréal faculty of music. All participants self-reported as right-handed except one control group member and two musicians. Educational backgrounds were similar for both groups. All participants reported normal hearing, normal or corrected-to-normal vision, normal tactile abilities, and no history neurological issues. All participants completed the Goldsmiths Musical Sophistication Index (Müllenseifen *et al.*, 2014). This questionnaire provides a score that reflects individual musical training and provides a percentile ranking. This allowed us to verify a significant difference for musical training between groups. Results from this revealed a significant difference between controls (mean percentile of musical training = 29th) and musicians (mean percentile of musical training = 93rd), $t(35) = -11.266$, $p < .001$. Primary instruments were piano (n=8), violin (n=3), percussions (n=2), double bass (n=1), harp (n=1), and viola (n=1) and all musicians, except one violinist, reported playing at least two instruments. Musicians had a mean of 14.4 years of formal training (range = 7 to 20 years) and mean starting age for musical training was 6.6 years old (range = 3 to 10 years old). All participants provided written and informed consent.

5.4.2. *Materials and Procedures*

Participants were comfortably seated in a quiet well-lit room in front of a laptop. They were instructed to hold a 4 cm^3 foam cube between their index and thumb. The two cubes were held at a distance of 18 cm from each other. Each foam cube contained a bone conduction transducer (Madsen Electronics 03204, Otometrics, Taastrup, Denmark) connected to the computer. Custom response pedals were placed beneath the feet of the participants. For each trial, a 20 ms 250-hz vibration at a clearly detectable intensity was delivered to each cube separated by a stimulus onset asynchrony (SOA) of either ±400 ms, ±200 ms, ±100 ms, or ±50 ms (negative SOAs represent left-first stimulation while positive SOAs represent right-first stimulations). Custom evaluation software was designed using Psyscope X (Cohen *et al.*, 1993) where participants were instructed to press on the response pedal to initial the trial. Vibrations with a randomly selected SOA were presented after an 800 ms delay. Participants were instructed to indicate which cube vibrated first using the pedals located under each of their feet. They were then cued to press any pedal to cue the next trial. A total of 64 SOAs were presented per block. After each arms-crossed block, participants were instructed to assume the uncrossed posture and after each arms-uncrossed block, participants were instructed to assume the crossed arm posture. Participants were instructed to press the pedal on the same side as the cube that first vibrated, regardless of arm posture. Starting posture was counterbalanced with even numbered participants starting with their arms uncrossed and odd numbered participants starting with their arms crossed. Participants performed a total of ten blocks and understanding of the experimental demand was confirmed at least once between blocks (e.g. when in the crossed posture, answer for the side in space that first vibrates, not the hand that first vibrates). Two 20 trial practice blocks, one in each posture, were performed before the start of the experiment. A white noise generator was used and participants wore earplugs to mask any auditory cues emanating from the vibrotactile devices.

5.4.3. *Analysis*

Mean group unspeeded RT were compared between groups for each of the SOAs for the two postures. A repeated-measures analysis of variance was performed with SOA and postures as within-subject factors and group as between-subject factor. We also performed an analysis with answer veracity as a between-factor to investigate if this had an effect on RT. A posthoc analysis was performed with group means for individual SOA RTs as a dependent variable and group as the independent variable. Greenhouse-Geisser corrections were used in the event of a violation of sphericity.

A proportion correct difference (PCD) score was calculated for all participants by summing the difference between correct answers for uncrossed and crossed postures for each SOA (Ali *et al.*, 2015; Cadieux *et al.*, 2010; Cadieux *et al.*, 2013). The PCD allows an individual's performance to be reduced to a single value and is a reliable representation of individual uncrossed and crossed

TOJ response curves (Cadieux *et al.,* 2010). PCD scores can be between 0 and 8. A PCD score of 0 represents no difference in TOJ error rate between the crossed and uncrossed postures. A PCD score of 8 represents a completely accurate TOJ for the uncrossed posture but completely inaccurate TOJ for the crossed posture. We performed an independent t-test with PCD as the test variable and group as the grouping variable. All participants were included in this analysis.

A first secondary analysis was performed to take into account TOJ "veracity", as defined by Kóbor *et al.* (2006). Participants were placed in "veridical" or "inverted" groups. We calculated the slope of the crossed-arm answers to separate participants. Individuals with a positive slope were placed in the "veridical" group while participants with a negative slope were placed in the "inverted" group. A two-way ANOVA was performed to examine the effect of musical training and answer veracity on PCD score. Furthermore, we performed an independent t-test to compare PCD scores between musician and controls with veridical or inverted answers.

A second secondary analysis was performed between PCD scores of musicians based on the use of feet for their primary instrument (feet: piano, drums, harp; non-feet: double bass, trombone, violin, viola) due to the feet being used to input answers. We segregated musicians into feet (n=11) and non-feet (n=6) sub-groups and performed an independent t-test on their PCD scores. Mean group unspeeded RT were compared between groups (feet; non-feet) for each of the SOAs for the two postures. A repeated-measures analysis of variance was performed with SOA and postures as within-subject factors and group as between-subject factor.

5.7. Results

Results from the repeated measure analysis with SOA and posture as within-subject variable and group as between-subject factor revealed a significant effect of group on RT, *F*(1,35)=10.734, *p*=.002, η_p^2=.235. However, veracity did not have a significant effect on RT, *F*(1,33)=.470, *p*=.498, η_p^2=.014. As expected, a significant interaction was revealed between SOA and RT, *F*(1.584, 55.441)=60.110, *p*<.001, η_p^2=.632. Posthoc analyses were performed between RTs for crossed and uncrossed SOAs (see Table 4.1 and Figure 4.1). These revealed a significant difference for RTs between control and musician groups for all crossed SOAs and -200ms, -100ms, -50ms, and 50ms uncrossed SOAs.

Results from the analysis comparing mean control (*M*=2.77, *SD*=1.14) and musicians (*M*=3.99, *SD*=1.71) group PCD scores revealed a significant difference, *t*(27.184)=-2.509, *p*=.018, *d*=0.840 (Figure 4.2). Results from the two-way ANOVA to examine the effect of musical training and answer veracity on PCD did not reveal a statistically significant interaction, *F*(1, 33)=2.793, *p*<.104, η_p^2=.078. As expected, simple main effect analysis suggested that musicians had a significantly higher PCD score, *F*(1, 33)=17.761, *p*<.001, η_p^2 =.350. Simple main effect analysis also suggested a significant difference for PCD scores between individuals with veridical and inverted responses, *F*(1, 33)=69.442, *p*<.001, η_p^2 = .678 (Figure 4.3).

Results from the analysis comparing mean veridical control (n=13, *M*=2.11, *SD*=0.68) and musicians (n=10, *M*=2.83, *SD*=1.09) group PCD scores did not revealed a significant difference, *t*(21)=-1.927, *p*=.068, *d*=.793 (Figure 4.3). However, results from the analysis comparing mean inversed control (n=7, *M*=3.99, *SD*=0.72) and musicians (n=7, *M*=5.64, *SD*=0.71) group PCD scores revealed a significant difference, *t*(12)=-4.303. *p*=.001, *d*=2.307 (see Figure 4.3).

Results from the second secondary analysis revealed that the feet group (n=11) had a larger PCD score (*M*=4.59, *SD*=1.52) than non-feet musicians (n=6; *M*=2.89, *SD*=1.56). An independent t-test between feet musicians and non-feet musicians revealed a significant difference, *t*(15)=-2.188, *p*=.045, *d*=1.104. Results from the repeated measure analysis with SOA and posture as within-subject variable and group as between-subject factor did not reveal a significant effect of group on RT, *F*(1,15)>.000, *p*=.993, $\eta_p^2 > .000$.

5.7. Discussion

In the present study, we examined the effects of musical training on the unspeeded RT and error rate for the crossed arm TOJ task. Results from the cross-armed TOJ task revealed that musicians were significantly faster than non-musicians for all crossed-arm SOAs and for half uncrossed SOAs. Musicians were also found to have a significantly higher TOJ error rate when crossing their arms than non-musicians.

RT data from the crossed arm TOJ task suggests that musicians have faster unspeeded RTs for complex tactile tasks. Indeed, musicians had significantly faster RTs for all crossed arm SOAs and for the -200ms, -100ms, -50ms, and 50ms uncrossed SOAs. There were no significant differences between mean group RTs for -400ms, 100ms, 200ms, and 400ms uncrossed SOAs. Taken together, these results suggest that when the task is more difficult, such as for the crossed arm posture and the short SOAs, musicians have enhanced tactile abilities leading to faster RTs. These results are in accordance with results from Bidelman (2016) in an audiovisual task suggesting faster unspeeded RTs for more difficult SOAs. Indeed, Bidelman (2016) found no significant difference for musicians RTs for the -200ms and -300ms, two easier SOAs. As such, it seems musical training decreases RTs for difficult sensory situations that may otherwise require more time to process.

These results find that musicians have faster non-speeded RTs for a complex tactile task. This adds to the existing evidence of faster non-speeded audiovisual RTs (Bidelman, 2016) and faster simple tactile RTs (Landry and Champoux, 2017). Faster tactile RTs are likely helpful for musicians when playing in an improvised context where they must quickly adapt to new musical cues. These finding highlight the pervasiveness of cognitive changes from musical training in non-musical contexts. It is worth noting that the methodology of the present used a passive tactile stimulus whereas musicians are normally actively tactile. As such, it is difficult to directly relate these results to musical production. More complex RT tasks could be used in more homogenous groups of musicians to measure tactile ability as it more directly relates to their specific instrument. An appropriate real-world application of the increased crossed-arm error rate remains unknown. However, previous research with musicians have consistently reported enhanced sensory abilities. Future research will need to critically investigate musical abilities with RT components, be it speeded or un-speeded, to increase our understanding of this issue.

Results from the crossed arm TOJ task suggest that musicians are poorer at judging the tactile TOJ with their arms crossed than non-musicians. This result differs from previous investigations with musicians that found no differences between musicians and non-musicians for the crossed arm TOJ task (Craig and Belser, 2006; Kóbor *et al.*, 2006). However, unlike in our study, Kóbor *et al.* (2006) removed participants from analysis based on the veracity of their answer. Participants were eliminated from analysis if they had a majority of incorrect responses in the crossed arm posture. Through this, 8 of the 15 pianists and 10 of the 18 non-musicians were eliminated from analysis for having such inverted responses. However, eliminating participants for inverted responses can increase the risk for a type II error as demonstrated by further analysis for results from Cadieux et al (2010). In their article, Cadieux *et al.* (2010) reported a significant difference between genders for the crossed arm TOJ error rate. However, by removing the individual results with estimated inversed scores (1 male; 6 females), the previously significant effect of gender is rendered non-significant, *F*(1,39)=1.523, *p*=.225. As such, results from Kóbor *et al.* (2006) suggesting no differences between non-musicians and pianists for the crossed arm TOJ task may reflect a Type II error. The TOJ crossed arm task was also studied with percussionists where no participants were eliminated and failed to find a significant difference between groups (Craig *et al.*, 2006). This could reflect a particularity of percussion training compared to other musical instruments, though investigations have found both groups to have similar cognitive and sensorimotor abilities (Krause *et al.*, 2010; Matthews *et al.*, 2016). Results from Craig and Belser, (2006) could also reflect a gender effect as they tested 13 male and one female percussionists and males are less susceptible to errors when crossing the arms (Cadieux *et al.*, 2010).

One important difference between the present study and the previous investigations of musicians with the crossed-arm TOJ task is musician heterogeneity. Kóbor *et al.* (2006) and Craig and Belser (2006) exclusively investigated pianists and drummers whereas the present research focused on general musical expertise, regardless of instrument. The diversity in instruments played could influence results since certain instruments such as piano and drums require crossing the arms, similar to the task's cross-arm condition. Future investigations should also pay particular attention to the level of expertise and amount of practice for all instruments played since Craig and Belser (2006) suggested that training can enhance TOJ performance and expertise level has been correlated with anatomical changes in musicians (Gaser and Schlaug, 2003; Groussard *et al.*, 2014).

We performed a secondary analysis where we separated participants based on veracity of crossed-arm TOJ answers. We found no interaction between groups and crossed-arm TOJ veracity. We did however find a significant difference between PCD scores of veridical and inverted participants. This result is to be expected, as the PCD score is calculated using the crossed-arm error rate. A higher crossed-arm error rate, as in the inverted group, will have the impact of raising the PCD score. We also parsed groups based on veracity and analysed differences between mean group PCD scores. We found no significant difference between controls and musicians for the veridical group. We did however find a significant difference between controls and musicians for the inverted group. These results suggest that the presence of participants with inverted answers can produce group differences for this task due to their PCD scores are higher. As such, it is possible Kóbor *et al.* (2006) would have found similar results to ours had they not eliminated the inverted group. Future analyses on veracity of answers for the crossed-arm TOJ task will need to use larger groups to better understand the role of answer veracity on PCD group differences.

It could be argued that the faster RTs and increased crossed-arm TOJ errors reflect a speed-accuracy trade-off (Wickelgren, 1977). That is to say, musicians would have answered more quickly, resulting in a reduction in accuracy. However, musicians and controls were similarly accurate at identifying TOJ with arms uncrossed for SOAs ranging from -200ms to 100ms. In these SOA, musicians had significantly faster RTs. Presumably, if the increased error rates reflected a speed-accuracy trade-off, these faster uncrossed RTs would have a significantly higher error rate. It is also worth noting that participants were not instructed to speed their responses. RTs reflect the time required for participants to make what they considered to be an accurate judgement without methodological time constraints. This being said, increased crossed-arm TOJ errors as a reflection a speed-accuracy trade-off cannot be ruled out. Further testing of the speed-accuracy trade-off for this task is required to better understand the impact of speeded judgements on crossed-arm error rates.

We used foot pedal responses instead of a manual response procedure. For some, making responses with pedals can be a novel process. Previous investigations of TOJ-task RTs used manual responses (Heed *et al.,* 2012; Heed *et al*., 2016; Sambo *et al.,* 2013; Shore *et al*., 2001; Wada *et al.,* 2004; Yamamoto and Kitazawa, 2001). Previous investigations of musicians used foot pedals (Kóbor *et al.,* 2006; Craig and Belser, 2006), but did not record RT. Musicians might have an advantage with pedals since some instruments such as piano, drums, and harp require input from the feet. We compared PCD scores between "feet using" and "non-feet using" musicians. Results from this analysis suggest a significant difference between musicians that use their feet and those who do not. We found that musicians who use their feet have a larger PCD. No significant differences were found between these groups for any RTs. This analysis suggests foot-using musicians have more crossed-arm TOJ errors than non-feet musicians. These results are in conflict with the results from Kóbor *et al*. (2006) and Craig and Belser (2006) that suggested pianists and drummer had similar crossed-arm TOJ error rates than non-musicians. Further investigation looking at RT differences between response methods (hand versus feet) will help further our understanding of the crossed-arm TOJ task and these results.

Three models have been proposed to explain the crossed arm deficit (Heed *et al*., 2015; Shore *et al.,* 2002; Yamamoto and Kitazawa, 2001). Most notably, Shore *et al.* (2002) proposes that the crossed arm deficit arises from a conflict between the internal tactile frame of reference and external visuo-spatial frame of reference and that it is the integration of conflicting information from these frames of reference gives rise to this conflict. Recent evidence from Cadieux *et al.* (2013) supports this second hypothesis. Faster unspeeded RTs for this complex tactile task are in line with previous results suggesting that musicians have faster unspeeded RT for audiovisual tasks (Bidelman, 2016). In accordance with the model proposed by Shore *et al.* (2002), the decreased musician RT for the crossed arm TOJ task could eliminate the presence of the time required to consolidate the conflicting information from the internal and external frames of reference, leading to more TOJ errors. Following research will need to look at the PCD scores of other populations with faster tactile RTs. These future investigations will provide critical information to discern if a reduced crossed arm TOJ RT does indeed increase crossed arm error rate.

The anatomical substrates involved in these results from musicians were not evaluated in the present study. However, in a functional magnetic resonance imaging (fMRI) study, Takahashi *et al.* (2012) compared the areas of activation of the crossed and uncrossed posture for the TOJ task. These areas, which include the medial frontal gyrus, dorsolateral prefrontal gyrus, supramarginal gyrus, and medial prefrontal gyrus, are similar to areas of activation identified using fMRI with professional pianists processing piano playing (Bangert *et al.*, 2006). The strengthening of these networks by long-term musicianship could lead to a more efficient processing of information during the crossed arm TOJ task. Future research should explicitly compare areas of activation between playing an instrument and the crossed-arm TOJ task. Since these tasks seemingly share several activation pathways, isolating substrates involved exclusively in one tasks could provide insight on the effects of musical training on the crossed-arm TOJ task. Moreover, such a study could shed a light on any neural underpinning of inverted cross-arm TOJ responses. As per the model proposed by Shore *et al.* (2002), the faster processing of crossed arm TOJ information, leading to faster RTs, could have led to more crossed arm TOJ errors.

To give the correct answer in the crossed arm TOJ task, participants must temporally and spatially transform the tactile stimuli. Imaging studies have revealed activation in the posterior parietal cortex (PPC) for temporal and spatial manipulation of information in pianists (Zatorre *et al.*, 2010). Activation of the PPC was also found for real, but not imagined, piano playing in pianists

(Meister *et al.*, 2004). Ostensibly, long-term musical training heavily recruits the PPC. Beyond music, the PPC is also understood to play a role in motor planning (Scherberger *et al.*, 2005), in transforming motor frames of reference (Cohen and Andersen, 2002), and more specifically, in processes requiring TOJ such as the crossed arm TOJ task (Miyazaki *et al.*, 2016). This shared activation of the PPC for piano playing and the crossed arm TOJ task could lead to a higher TOJ error rate. Hermosillo *et al.* (2011) found that simply planning to cross the arms could increase error for the TOJ task. While the substrates involved in the increased error rate reported by Hermosillo *et al.* (2011) are still unknown, it is possible the PCC is involved due to its role in planning movements. Musicians could have increased PPC activation during the crossed arm TOJ task, due to long-term musical training involving the substrate, leading to an increase error rate. However, further investigations looking at whether the increased TOJ error rate in still present for musicians without PPC activation using techniques such as transcranial magnetic stimulation is required.

Results from the present study suggest for the first time that the benefits from musical training could have unexpected secondary effects. We found that musicians had faster unspeeded RTs for crossed SOAs and faster RTs for half uncrossed SOAs. We also found that musicians had a more TOJ errors when crossing the arms. Here we propose that reduced musician RTs lead to an increased crossed arm TOJ error rate. However, this hypothesis, which also supports a model of the increased crossed arm TOJ error rate from Shore *et al.* (2002), still needs further study.

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5.7. References

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Table 4.1

Mean reaction times for SOA for both postures in ms with standard deviation for controls and musicians. Asterisks represents a statistically significant difference between groups for the unspeeded RT.

	Controls		Musicians		
	M	*SD*	*M*	*SD*	*p*
Uncrossed SOA					
-400 ms	536.51	168.72	415.75	211.17	.061
-200 ms	643.36	221.91	494.67	164.56	.029*
-100 ms	850.29	295.92	627.92	195.56	.012*
-50 ms	1118.72	435.71	797.97	319.58	.017*
50 ms	1067.51	355.93	757.62	246.91	.005*
100 ms	803.80	263.20	625.11	234.77	.038*
200 ms	612.05	201.51	494.84	181.97	.074
400 ms	494.95	186.52	397.50	177.54	.122
Crossed SOA					
-400 ms	1033.05	330.16	722.30	325.71	.007*
-200 ms	1091.27	347.08	749.96	281.37	.003*
-100 ms	1230.61	443.15	844.45	284.24	.004*
-50 ms	1352.91	486.16	938.56	336.45	.005*
50 ms	1423.68	517.29	986.94	370.25	.006*
100 ms	1229.63	385.33	866.69	255.52	.002*
200 ms	1131.37	345.64	766.84	239.76	.001*
400 ms	996.75	314.69	716.61	261.06	.006*

Figure 4.1

Mean group RTs (in ms) for each SOA (in ms) for crossed and uncrossed postures.

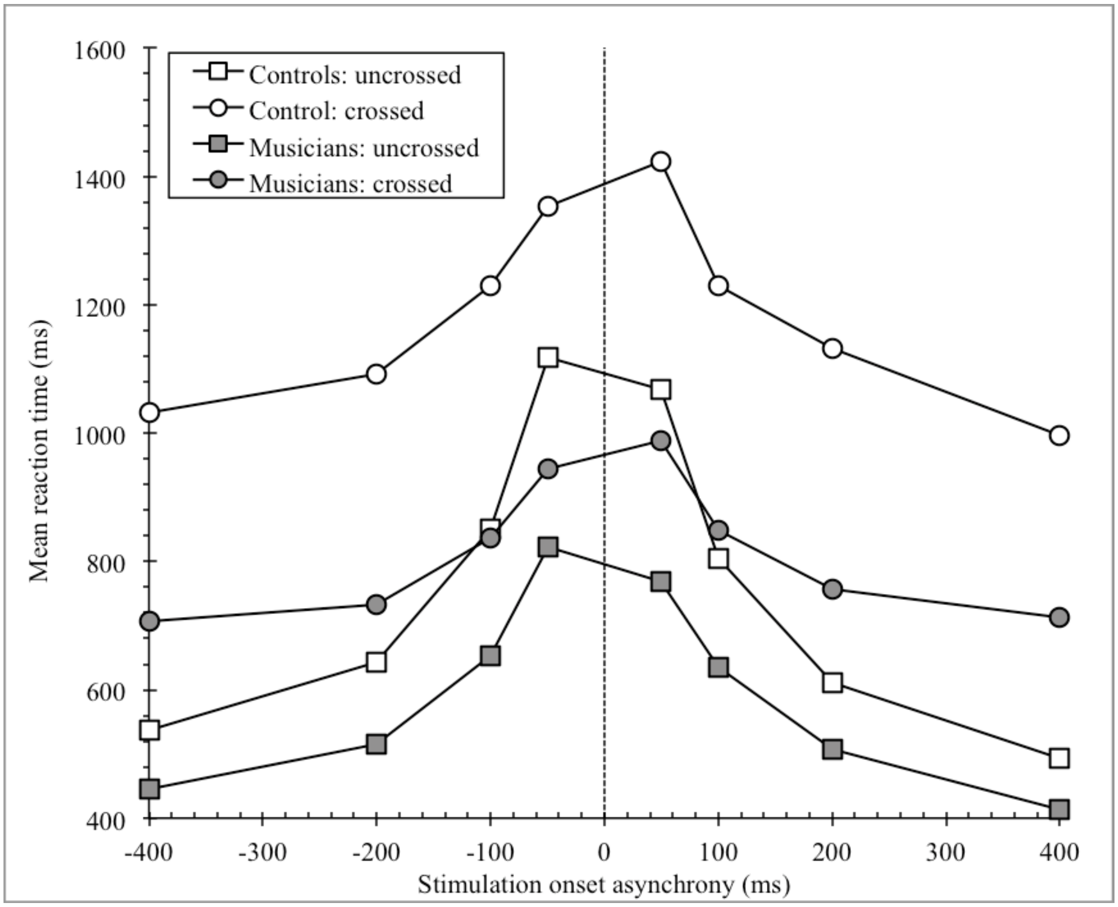


Figure 4.2

The average group proportion of “right first” responses for each SOA (in ms) for crossed and uncrossed postures. Inset: Average group PCD score for controls (white) and musicians (grey) with error bars representing standard error. Asterisk represents a significant difference, *p*=.018.

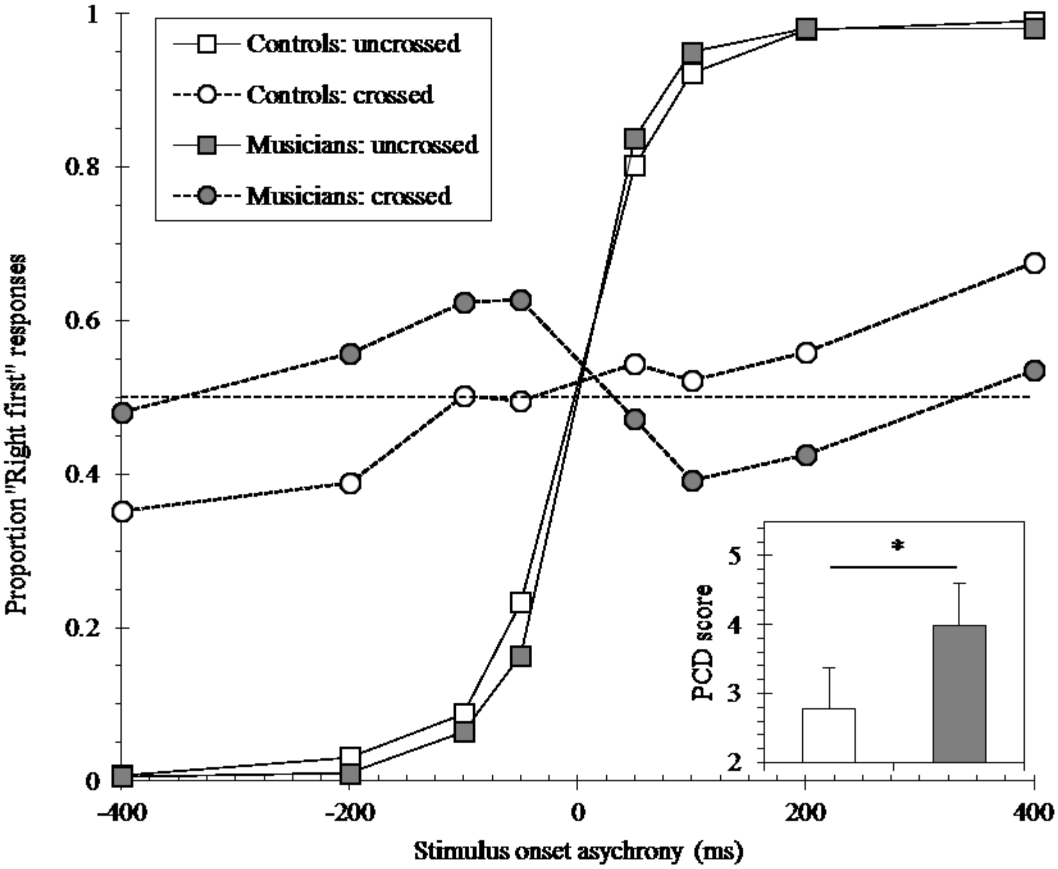
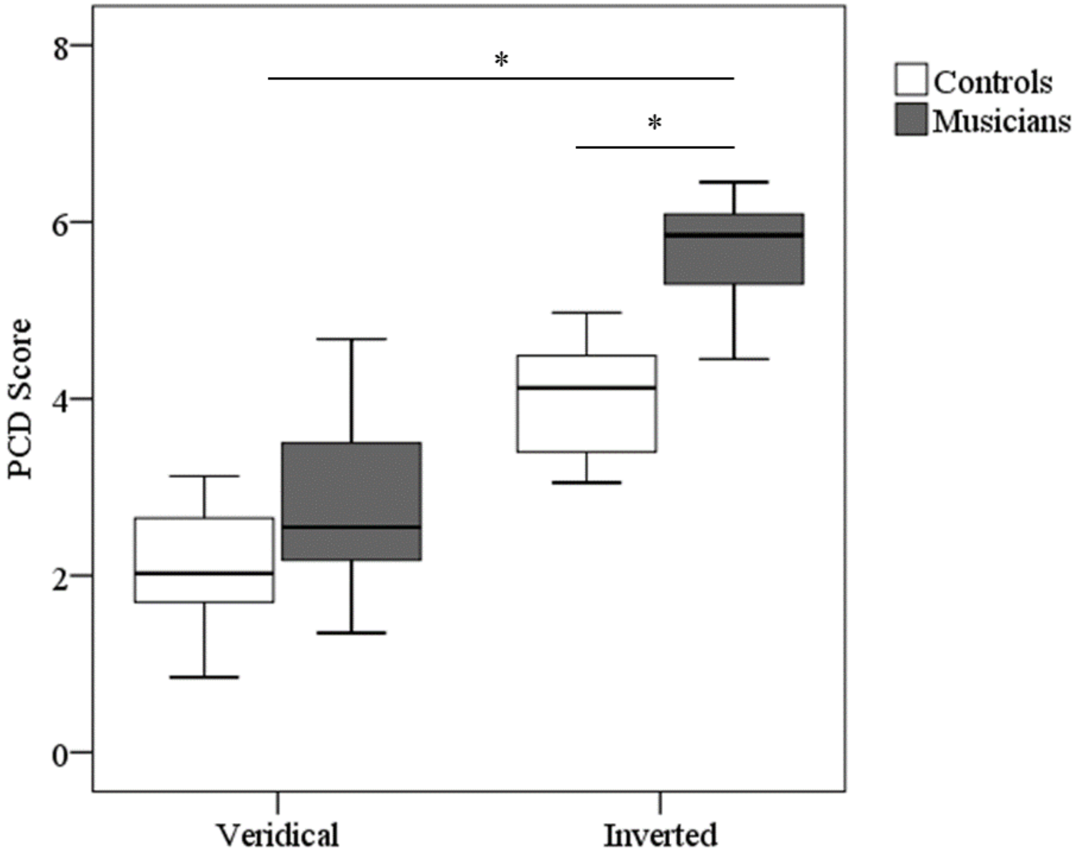


Figure 4.3

Boxplot of individual PCD scores for controls having veridical answers (n=13) and inverted answers (n=7) and musicians having veridical answers (n=10) and inverted answers (n=7). Boxes represent between 25th and 75th percentile of the scores and the line within the box represents the median. Whiskers range from the 10th to the 90th percentile. Outlier points represented with circles fall farther than 1.5 box-lengths from the box edge while asterisks represent outliers that fall father than 3 box-lengths from the box edge. Asterisks represent a significant difference, *p*<.001.



Chapitre 5 - Discussion générale

5.7. Introduction à la discussion

Jouer un instrument de musique demande l'interaction d'informations provenant de plusieurs modalités sensorielles. Une exposition à long terme à cet environnement sensoriel enrichi peut mener à des changements aux interactions sensorielles chez les musiciens. Plusieurs recherches se sont penchées sur les habiletés unisensorielles et multisensorielles chez les musiciens. Par exemple, selon les résultats des certaines recherches unisensorielles, les musiciens ont des temps de réaction visuels (Chang et coll., 2014; Anatürk & Jentzsch, 2015) et auditifs plus rapides (Strait et coll., 2010), une meilleure acuité tactile (Ragert et coll., 2004), et une meilleure analyse de la scène auditive (Strait et coll., 2010). Les résultats des recherches sur les habiletés multisensorielles suggèrent de nombreuses améliorations au niveau audiovisuel (Bidelman, 2016; Hodges, et coll., 2005; Lee & Noppenny, 2014; Paraskevopoulos et coll., 2012; Petrini et coll., 2009). Malgré ces évidences de plusieurs changements unisensorielles et multisensorielles, qu'une étude s'est penchées sur l'interaction audiotactile chez les musiciens. Dans leur étude, Kuchenbuch et coll. (2014) suggèrent que les musiciens sont meilleurs à détecter des stimulations auditives et tactiles asynchrones. Plusieurs investigations au prêt des musiciens demeurent pour mieux comprendre les effets d'un entrainement musical à long terme sur l'interaction des informations auditives et tactiles. Ces connaissances offrent une fenêtre sur le potentiel de l'amélioration des capacités sensorielles à l'aide d'un environnement multisensoriel enrichi. Une meilleure compréhension de ces effets ouvre la porte à des applications d'entrainement musical chez des populations pouvant profiter d'améliorations sensorielles multisensorielles tactiles.

5.7. Résumé des résultats

5.4.1. *Étude 1*

La première étude (Chapitre 2) avait comme but d’évaluer les temps de réaction auditifs, tactiles, et audiotactiles chez les musiciens à l’aide d’une tâche de temps de réaction audiotactile (Nava et coll., 2014). Les stimulations auditives et tactiles simples n’avaient aucune composante musicale et la méthodologie était une mesure de temps de réaction simples. Les résultats de la première étude suggèrent que les musiciens ont des temps de réactions significativement plus rapides que des non-musiciens pour toutes les modalités sensorielles évaluées. Les résultats de l’analyse statistique *RMI* suggèrent la présence d’un mécanisme neuronal différent entre musiciens et non-musiciens pour des stimulations multisensorielles. Les temps de réaction audiotactiles des musiciens seraient le résultat d’un processus cortical distinct pour la moitié des temps de réaction les plus rapides selon l’analyse *RMI*. Quant aux non-musiciens, ce processus cortical d’interaction multisensorielle ne compterait que pour le 20% des réponses plus rapides. De plus, les résultats d’une seconde analyse statistique suggèrent que les musiciens ont une probabilité significativement plus importante d’avoir des temps de réponse entre 100ms et 130ms pour une stimulation audiotactile. L’ensemble de ces résultats ajoutent aux évidences qu’un entrainement musical à long terme peut avoir des effets sur les capacités sensorielles sans aspects musicaux. Ces résultats présentent les premières évidences que les musiciens ont des temps de réactions plus rapides pour des stimulations tactiles et audiotactiles. De plus, les analyses statistiques secondaires offrent des pistes sur un mécanisme neuronal distinct sous-jacent ces changements.

5.4.2. *Étude 2*

La seconde étude (Chapitre 3) avait comme but d'étudier les capacités d'interaction multisensorielles tactiles chez les musiciens à l'aide d'illusions audiotactiles. L'effet de l'éclair illusoire audiotactile pour a été utilisé pour évaluer l'interaction audiotactile temporelle (Hötting & Röder, 2004; Landry et coll., 2013) et l'effet de la peau parcheminée pour évaluer l'interaction audiotactile spectrale (Jousmäki & Hari, 1998; Champoux et coll., 2010). L'ensemble des résultats de ces recherches suggère qu'un entrainement musical a un effet l'interaction audiotactile temporelle, mais pas spectrale.

Les résultats des conditions contrôles de l'effet de l'éclair illusoire audiotactile suggèrent des capacités auditives et tactiles semblables pour musiciens et non-musiciens. La condition expérimentale demandait aux participants d'ignorer des séquences de stimulations auditives tout en comptant une séquence de stimulations tactiles. Les résultats de cette tâche suggèrent que les musiciens sont capables de compter le nombre de stimulations tactiles avec plus grande précision sans être influencés par le nombre de stimulations auditives. Contrairement, le nombre de stimulations auditives présentées avait un effet sur le nombre de stimulations tactiles perçu chez les non-musiciens. Les résultats de la condition contrôle suggèrent que les deux groupes ont des habiletés sensorielles semblables pertinentes à la tâche. Ces résultats reflètent donc un changement au traitement d'informations audiotactiles temporelles chez les musiciens.

L'effet de la peau parcheminée est une tâche illusoire dans laquelle des modifications spectrales à un son autogénéré mènent à des changements à la sensation tactile palmaire. Les résultats de cette tâche n'ont révélé aucune différence significative entre musiciens et non-musiciens pour aucune des deux conditions expérimentales ou la condition contrôle. Les musiciens auraient donc la même interaction du contenu spectral auditif sur la perception tactile que les non-musiciens.

5.4.3. *Étude 3*

La troisième étude (Chapitre 4) avait comme but d'évaluer la localisation d'une stimulation tactile chez les musiciens. Les taux d'erreurs et les temps de réaction dans une tâche de jugement d'ordre temporel tactile ont été enregistrés (Yamamoto & Kitazawa, 2001; Cadieux et coll., 2010). Deux stimulations tactiles consécutives de délai variable étaient présentées une à chaque main et les participants devaient identifier dans quel hémisphère de l'espace (droite; gauche) se trouvait la main ayant été premièrement stimulée. Les temps de réaction pour ce jugement furent enregistrés, mais les participants n'avaient pas l'instruction de répondre rapidement. Les bras des participants avaient deux agencements durant la tâche, les bras décroisés et les bras croisés. Avec les bras décroisés, les musiciens et non-musiciens avaient des taux d'erreurs de jugement temporel semblables. Cependant, avec les bras croisés, les musiciens avaient significativement plus d'erreurs de jugement temporel que les non-musiciens. L'analyse des temps de réaction non accélérés suggère que les musiciens ont des temps de réactions plus rapides pour toutes les stimulations avec les bras croisés et la moitié des délais de présentations plus courts pour les bras décroisés. Un entrainement musical semble diminuer les capacités de jugement d'ordre temporel tactile en présence d'un conflit de cadre de référence interne et externe. Cependant, les temps de réactions plus rapides chez les musiciens pourraient suggérer un mécanisme dans lequel il n'y aurait pas le temps de consolider des informations des cadres de références discordantes.

5.7. Effets d'un entrainement musical à long terme sur les capacités multisensorielles tactiles

Les résultats des recherches de cette thèse suggèrent plusieurs changements importants au niveau des interactions tactiles unisensorielles et multisensorielles chez les musiciens. Ces résultats suggèrent des changements aux capacités tactiles plus répandus qu'entretenus auparavant. Notamment, ces changements tactiles sont pour des habiletés sensorielles n'ayant aucun lien direct à l'entrainement sensoriel vécus par les musiciens en production musicale.

5.4.1. *Les temps de réaction*

Nos résultats de la tâche de temps de réaction sont les premiers à suggérer une amélioration au temps de réactions pour des stimulations tactiles et audiotactiles. Nos résultats du temps de réaction audiotactile sont les premiers à suggérer une amélioration pour cette modalité sensorielle, mais aussi à l'ensemble des temps de réactions multisensorielles simples. Ces résultats correspondent aux résultats de Bidelman (2016) qui suggéraient que les musiciens ont des temps de réactions multisensorielles rapides pour des tâches sans critères de réponse accélérée. Nos résultats des temps de réaction auditifs ajoutent aux évidences d'amélioration chez les musiciens (Strait et coll., 2010). Cependant, les résultats d'une étude de Woelfle et Grahn (2013), qui se penchait sur la latéralisation des temps de réaction, n'ont pas trouvé de telles augmentations pour les temps de réaction auditifs. Il est donc possible qu'une amélioration pour les stimulations auditives ne soit que pour des temps de réaction simples.

5.4.2. *Les interactions audiotactiles temporelle et spectrale*

Les résultats pour l'effet de l'éclair illusoire audiotactile ont deux interprétations. Les musiciens étaient capables d'ignorer les stimulations auditives et compter le nombre de stimulations tactiles avec précision. Ils pourraient donc avoir une meilleure habileté de ségrégation audiotactile. Cependant, ces résultats suggèrent également que les musiciens ont une interaction audiotactile anormale puisqu'ils ne percevaient pas l'illusion multisensorielle. Prenant cette optique, les musiciens auraient une déficience au niveau de l'interaction audiotactile puisqu'ils ne perçoivent pas le percept illusoire. Toutefois, les résultats de cette recherche dans le contexte des études existantes chez les musiciens sont plus probablement une évidence d'une meilleure capacité de ségrégation. Les recherches sur l'interaction audiotactile (Kuchenbuch et coll., 2014; Schultz et coll., 2003; Luo et coll., 2012) suggèrent que les musiciens ont des habiletés améliorées. Il est donc fort probable que nos résultats suivent cette tendance. Par exemple, une meilleure habileté de ségrégation des informations auditives et tactiles pourrait servir à jouer un instrument tout en chantant ou en écoutant les informations auditives provenant d'autres musiciens.

Les résultats de l'interaction audiotactile spectrale représentent un processus sensoriel distinct des informations audiotactiles temporelles. Dans cette catégorie d'interaction, les musiciens auraient des habiletés semblables aux non-musiciens. Le lien entre la production sonore de ses mains et la sensation tactile de ses mains est une association acquise sur une longue période (Landry et coll., 2014 [voir annexe III]). Puisque les musiciens entendent toujours leurs mains, comme le font les non musiciens, tout changement lié à l'entrainement musical serait graduel sur une étendue de temps. Les changements multisensoriels n'auraient donc aucun effet sur les liens entre la sensation tactile et le son associé.

5.4.3. *Les interactions des cadres de référence*

Les résultats de la troisième étude demandent une interprétation plus nuancée qu'une simple amélioration chez les musiciens. Nos résultats suggèrent que les musiciens ont un taux d'erreur plus élevé quand ils croisent leurs bras. Ces résultats vont à l'encontre des résultats de deux études précédentes (Craig et Belser, 2006; Kóbor et coll., 2006). Ce résultat est particulièrement intéressant puisque plusieurs instruments demandent au musicien de se croiser les bras. Les musiciens devraient donc avoir une aise pour des tâches aux bras croisés, comme démontré chez les percussionnistes (Craig et Belser, 2006) et les pianistes (Kóbor et coll., 2006). Cependant, une analyse supplémentaire a été effectuée chez les musiciens d'instruments aux bras croisés, et ce sous-groupe présentait significativement plus d'erreurs dans la condition des bras croisés. À la surface, ces résultats suggèrent que les musiciens présenteraient des difficultés à jouer des instruments exigeant de se croiser les bras. Aussi, les réponses étaient données par des boutons sous les pieds. Il serait possible qu'un musicien d'un instrument impliquant les pieds ait un avantage pour répondre à cette méthodologie. Une analyse comparant des musiciens d'instruments qui impliquent l'usage des pieds et ceux qui utilisent uniquement leurs mains n'a révélé aucune différence significative entre ces groupes.

Puisque les musiciens sont capables de jouer avec leurs bras croisés sans confusion, les résultats sont surprenants. Des analyses supplémentaires ont été effectuées pour mieux comprendre les résultats. Une explication possible pour ces résultats pourrait se trouver dans l'interprétation des temps de réactions plus rapides chez les musiciens. Il est possible qu'une réponse fournie dans un délai plus court puisse empêcher la consolidation d'informations provenant des cadres de référence égocentriques et allocentriques (Shore et coll., 2002). C'est-à-dire, la réponse des musiciens pour le côté stimulé serait fondée uniquement sur l'information de la main stimulée (cadre égocentrique). L'information sur le côté de la stimulation n'aurait pas le temps de transférer du cadre égocentrique de la stimulation au cadre de référence allocentrique pour donner la bonne réponse. Les musiciens perçoivent une stimulation de la main droite et répondent avant d'avoir pris en considération la position de la main droite qui se trouve maintenant à la gauche. Chez les non-musiciens, pour les réponses avec les bras croisés plus lentes il y aurait assez de temps pour transférer l'information sur la stimulation du cadre égocentrique (tactile) à l'allocentrique (critère de réponse).

Il serait intéressant de répliquer la tâche et demander aux participants de répondre rapidement. Les résultats de cette recherche pourraient éclairer le rôle du temps de réaction sur le taux d'erreur dans la tâche de jugement d'ordre temporel tactile. De plus, des études à venir devraient utiliser des délais de présentations plus longues afin de voir si les réponses inverses perdurent en présence d'un délai entre les deux stimulations extrêmement long (ex. 1000 ms). Il serait aussi pertinent de répliquer l'étude avec une méthodologie où la réponse est fournie manuellement afin d'évaluer si l'usage des pieds eut un effet sur les résultats.

Cette étude est la première à trouver une tâche dans laquelle les musiciens n'ont pas des habiletés semblables ou améliorées aux non-musiciens. Il est trop tôt pour savoir si ces résultats sont isolés à cette méthodologie ou si les musiciens ont des difficultés générales au niveau la localisation tactile corporelle. Une analogie à cette méthodologie est difficile à repérer hors du contexte expérimental. Il est donc difficile d'établir comment ces résultats pourraient être observés dans un contexte écologique.

5.7. Corrélats anatomiques

L'entrainement multisensoriel à long terme que vivent les musiciens mène à des changements au niveau cortical (Herholz & Zatorre, 2012). Des changements corticaux en lien à l'entrainement musical ont été rapportés chez les enfants après seulement 15 mois de formation musicale (Hyde et coll., 2009). Suivant cette période d'entrainement, des différences structurelles furent révélées dans le gyrus précentral, le corps calleux et la région auditive primaire droite. Cependant, les chercheurs ont rapporté des améliorations pour les tâches musicales, mais pas pour les tâches non musicales. Cette étude souligne la rapidité des changements corticaux liés à l'entrainement musical. Tous les musiciens des recherches de cette thèse avaient au moins sept ans d'expérience musicale, une période permettant plusieurs changements corticaux. Nos résultats reflètent donc probablement des changements corticaux induits par l'entrainement musical, tels que ceux rapportés par Hyde et coll. (2009).

5.4.1. *Changements corticaux audiotactiles*

Des études de neuro-imagerie ont révélé que la formation musicale à long terme peut accroître les représentations corticales des doigts (Elbert et coll., 1995) et entraîner une plus grande zone d'activation auditive pour les stimuli musicaux (Pantev et coll., 1998). Ces études n'ont malheureusement pas présenté d'analogues d'améliorations comportementales. À ce jour, seuls Kuchenbuch et coll. (2014) ont étudié les corrélats corticaux des interactions audiotactiles avec les habiletés comportementales. Les auteurs ont trouvé une plus grande réponse MEG pour les stimuli audiotactiles incongrus ainsi qu'une améliorée de la détection d'incongruités audiotactiles. Une étude de neuro-imagerie chez des musiciens a révélé un changement significatif au début du traitement audiotactile (Schultz et coll., 2003). Une plus grande connectivité entre les cortex auditifs primaires et somatosensoriels a aussi été mise en évidence (Luo et coll., 2012). De tels changements anatomiques chez les musiciens pourraient fournir des indices sur la base neuroanatomique des résultats obtenus.

5.4.2. *Matière grise*

Schlaug et coll. (1995) furent les premiers à trouver des changements anatomiques chez les musiciens. Leurs résultats suggèrent des différences au volume cortical des régions auditives, motrices, et visuospatiales. Gaser et Schlaug (2003) ont aussi révélé des différences au niveau du volume de la matière grise des régions sensorielles chez les musiciens. Cette augmentation a aussi été corrélée avec le niveau d'expertise musicale. Leurs résultats suggèrent des augmentations significatives du volume de matière grise chez les musiciens dans les zones primaires motrices et somatosensorielles, prémotrice et supérieure pariétale antérieure, et le gyrus temporal inférieur. Groussard et coll. (2014) de leur part ont exploré le volume de matière grise chez les musiciens à l'aide de régressions. Les résultats de cette recherche ont suggéré une corrélation entre le volume de matière grise et l'expérience musicale. Cette augmentation a d'abord été observée dans l'hippocampe gauche et dans les régions frontales moyennes et supérieures droites. Une longue période d'entrainement musicale menait aussi à une augmentation du volume de la matière grise dans l'insula droite, la zone motrice supplémentaire, la zone temporale gauche supérieure et les zones cingulaires postérieures. Semblablement, une étude de Vaquero et coll. (2016) a révélé des différences de matière grise entre les non-musiciens et les pianistes professionnels. Les résultats de cette étude ont révélé un volume bilatéral de matière grise plus important pour le putamen et le gyrus lingual, ainsi que le thalamus droit et le gyrus temporal supérieur gauche. Ces changements au volume de la matière grise sont possiblement causés par une exposition à long terme aux aspects sensoriels, moteurs et émotionnels de la production musicale. Ces augmentations de matière grise pourraient être liées aux résultats de cette thèse. Cependant, d'autres études seront nécessaires pour identifier les structures impliquées et confirmer cette hypothèse.

5.4.3. *Les temps de réaction*

Les substrats anatomiques responsables des temps de réaction audiotactiles rapides rapportés dans cette thèse ne sont pas encore clairement définis. Cependant, plusieurs études des substrats corticaux responsables des interactions auditives et tactiles pourraient fournir des indications sur les régions impliquées. Les études de neuro-imagerie ont révélé des corrélats d'interaction audiotactile dans les zones de la ceinture auditives, le cortex somatosensoriel secondaire et le cortex pariétal postérieur (Foxe et coll., 2000; Gobbelé et coll., 2003; Lütkenhöner et coll.., 2002). Bien qu'il soit trop tôt pour conclure du rôle de ces régions sur la diminution des temps de réaction. Des études chez les pianistes ont révélé un renforcement entre les régions auditives et les régions motrices pour des tâches associées à jouer du piano (Bangert et coll., 2006; Jancke, 2012). Il est possible que le changement des connexions audiomotrices puisse mener au temps de réaction plus rapide. L'entrainement musical pourrait aussi augmenter l'activation des bandes bêta (Doelling & Poeppel, 2015; Kühnis et coll., 2014). Une plus grande activation de la bande bêta serait corrélée au temps de réactions unisensorielles et multisensorielles plus rapides (Senkowski et coll., 2006). Les mécanismes sous-jacents la génération de bande bêta ne sont pas entièrement compris, mais elles offrent une piste vers un indice quant à l'origine corticale des temps de réaction rapportés dans cette thèse.

5.4.4. *Illusions audiotactiles*

Les tâches utilisées au Chapitre 3 impliquaient deux différentes composantes de l'interaction audiotactiles : la composante temporelle pour flash illusoire audiotactile et la composante spectrale pour l'illusion parchemin-peau. Cette distinction est importante puisque le traitement des informations auditives spectrales et temporelles se fait par des voies distinctes (Zatorre et Belin

2001). Zatorre et Belin (2001) ont découvert que les composantes auditives spectrales activaient les régions temporales antérieures supérieures tandis que les composantes temporales activaient les régions temporales primaires. Ces différentes voies pourraient fournir des indices pour comprendre les résultats différents rapportés dans le Chapitre 3.

5.4.5. *Les interactions des cadres de référence*

Les résultats d'une étude d'imagerie par résonance magnétique fonctionnelle (IRMf) par Takahashi et coll. (2012) ont comparé les zones d'activation de la posture croisée et non croisée pour la tâche de jugement d'ordre temporel tactile. Ces zones, qui incluent le gyrus frontal médian, le gyrus préfrontal dorsolatéral, le gyrus supramarginal et le gyrus préfrontal médian, sont similaires aux zones d'activation identifiées par l'IRMf chez les pianistes professionnels exerçant leur instrument (Bangert et coll., 2006).

De plus, des études d'imagerie ont révélé une activation dans le cortex pariétal postérieur (CPP) pour la manipulation temporelle et spatiale de l'information chez les pianistes (Zatorre et coll., 2010). L'activation du CPP a également été trouvée chez les pianistes jouant leurs instruments, mais pas quand ce mouvement était imaginé (Meister et coll., 2004). Les musiciens semblent donc avoir un recrutement important du CPP. Le CPP joue aussi un rôle dans la planification motrice (Scherberger et coll., 2005), dans la transformation des cadres moteurs de référence (Cohen et Andersen, 2002), et dans les processus nécessitant un jugement d'ordre temporel (Miyazaki et coll., 2016).

Ainsi, il se pourrait que l'activation partagée du CPP pour jouer au piano et de la tâche de jugement d'ordre temporel puisse mener à un taux d'erreur de la tâche de jugement d'ordre temporel tactile plus élevé rapport dans le Chapitre 4. En fait, Hermosillo et coll. (2011) ont constaté que la simple planification de croiser les bras pourrait augmenter l'erreur pour la tâche de jugement d’ordre temporel tactile. Hermosillo et coll. (2011) n'ont pas évalué les substrats neuronaux impliqués, mais il est possible que le CPP soit impliqué en raison de son rôle dans la planification des mouvements. Les musiciens pourraient avoir une augmentation d’activation du CPP lors de la tâche de jugement d’ordre temporel en raison d'une formation musicale à long terme impliquant le substrat. Cette augmentation d’activation du CPP pourrait ensuite mener au taux d'erreur plus élevé. D'autres études devront examiner si l'augmentation du taux d'erreur pour les jugements d'ordre temporel est encore présente pour les musiciens sans activation de CPP en utilisant des techniques telles que la stimulation magnétique transcrânienne. Les corrélats anatomiques sous-jacents des temps de réaction rapides du Chapitre 4 pourraient être attribués à des changements similaires à ceux du Chapitre 2.

5.7. Apports cliniques

Les résultats présentés dans cette thèse fournissent des évidences sur les interactions multisensorielles fondamentales chez les musiciens. Bien que se soient pour des processus fondamentaux, des recherches subséquentes pourraient mener à des usages cliniques d’environnements multisensoriels enrichis. Les jeux vidéo, un environnement multisensoriel enrichi, ont déjà fait preuve d’amélioration cognitive chez les personnes âgées (Anguera et coll., 2013). Une étude sur 6 mois d’enseignement au piano chez les personnes âgées a aussi révélé des améliorations cognitives (Bugos et coll., 2007). Une formation musicale pourrait donc être une intervention efficace pour éviter les pertes cognitives associées au vieillissement.

La recherche présentée au Chapitre 2 est un bon point de départ pour des usages éventuels de cette thèse en réadaptation clinique. Les personnes âgées ont des temps de réaction plus lents

(Fozard et coll., 1994; Hultsch et coll., 2002; Laurienti et coll., 2006). Bien que ce ne soit pas un lien causal, il est aussi notable qu'il existe une corrélation entre temps de réaction et habileté cognitive (Jakobsen et coll., 2011). Les résultats présentés au Chapitre 2 suggèrent que les musiciens ont des temps de réaction plus rapide. Les résultats de recherches suggèrent que les musiciens âgés pourraient tirer des bénéfices de leur entrainement musical pour prévenir des déclins cognitifs (Amer et coll., 2013; Moreno et coll., 2011) et auditifs (Zendel et coll., 2009; 2012). Il serait donc intéressant d'évaluer si les temps de réactions plus rapides sont encore présents chez les musiciens âgés. Une telle étude pourrait dresser un meilleur portrait des effets d'un entrainement musical à long terme sur le vieillissement et la cognition. Une autre étude subséquente pourrait aussi évaluer les effets d'un entrainement musical chez les personnes âgées sur les temps de réaction et les habiletés cognitives.

Les résultats présentés au Chapitre 3 présentent un autre potentiel clinique de l'entrainement musical. Les résultats de l'effet de l'éclair illusoire audiotactile suggèrent que les musiciens sont meilleurs à ségréger les informations provenant de ces deux modalités. Ces résultats sont semblables aux résultats pour cette tâche chez les personnes sourdes (Hötting & Röder, 2004) et les porteurs d'implant cochléaire (Landry et coll., 2013a). Toutefois, l'interprétation de ces résultats chez les porteurs de l'implant cochléaire suggère un manque d'intégration et non une meilleure habileté de ségrégation multisensorielle. Il se pourrait qu'un entrainement musical puisse améliorer l'intégration audiotactile chez les porteurs d'implant cochléaire. Cependant, toute amélioration serait impossible à mesurer avec cette tâche puisque les deux groupes ont des résultats semblables. L'illusion de la peau parcheminée pourrait être utile pour évaluer l'évolution d'interaction audiotactile chez les porteurs d'implant cochléaire qui suivent un entrainement musical. Les résultats de Landry et coll. (2014 [voir Annexe III]) suggèrent que l'interaction audiotactile spectrale, telle qu'évalué par la peau parcheminée, évolue avec l'expérience auditive. Un entrainement musical pourrait être bénéfique pour renforcer les interactions entre le toucher et l'audition et accélérer cette interaction.

5.7. Recherches suivantes

Plusieurs nouvelles questions découlent des recherches de cette thèse. L'hétérogénéité des musiciens mérite particulièrement l'attention des recherches à venir. Il serait intéressant pour les recherches subséquentes à évaluer des musiciens ayant des profils d'entrainement plus semblables. Les musiciens ayant participé aux recherches de cette thèse furent choisis pour leur niveau d'expertise musicale déterminé par le questionnaire *Goldsmiths Musical Sophistication Index* (Müllensiefen et coll. 2014). Cependant, des groupes ayant certains facteurs semblables tel l'âge au début de l'entrainement musical, années d'entrainement musical, et durée de session d'entrainement musicale seraient intéressants. Ces recherches pourraient éclaircir l'importance des différents facteurs d'entrainement musicale sur les améliorations comportementales. De telles informations pourraient être utiles pour mieux comprendre les facteurs ayant un rôle sur la plasticité cérébrale chez les musiciens. Ces analyses pourraient aussi fournir de nouvelles pistes pour mieux comprendre les paramètres importants pour améliorer l'efficacité d'entrainement musical en réadaptation. Aussi il serait important d'évaluer des musiciens jouant le même instrument. Il est possible que les effets d'un entrainement musical dépendent de l'instrument. Contrôler ces multiples facteurs dans les recherches à venir permettra de mieux comprendre quels facteurs mènent aux changements sensoriels mis en évidence dans cette thèse. Aussi, puisque les méthodologies utilisées dans cette thèse produisent toutes des scores individuels, évaluer des groupes plus hétérogènes permettrait le calcul de corrélations. Ces corrélations pourraient alors fournir des informations sur l'évolution des changements sensoriels chez les musiciens.

Il est difficile de déterminer si les nombreuses améliorations sensorielles et cognitives chez les musiciens sont résultantes d'un entrainement musical ou si ceux ayant de meilleures habiletés sensorielles gravitent vers la musique. Cette question est difficile à résoudre. Les résultats des recherches sur les effets d'un entrainement musical à court terme suggèrent des améliorations après la musique (Hyde et coll., 2009). Il semble donc que la musique ait un effet important. Toutefois, le paradoxe d'améliorations innées ou acquises peut toujours être relevé dans les études chez les musiciens. Afin d'y trouver une réponse, une recherche longitudinale serait requise.

5.7. Conclusion

Cette thèse répond à l'objectif d'évaluer l'interaction des stimulations tactiles unisensorielles et multisensorielles chez les musiciens à l'aide de méthodologies non musicales. Ces résultats suggèrent que les musiciens ont des interactions pour les stimulations tactiles unisensorielles et multisensorielles significativement différentes comparées aux non-musiciens. Parmi les changements trouvés 1) les musiciens ont des temps de réaction significativement plus rapides pour des stimulations auditives, tactiles, et audiotactiles simples, 2) les musiciens ont des capacités d'interaction audiotactiles altérées pour les stimulations temporelles, mais intègrent les informations audiotactiles spectrales semblablement aux non-musiciens et 3) les musiciens ont une diminution des temps de réaction pour une tache la localisation tactile spatiale, mais avec plus d'erreurs de localisation avec les bras croisés.

Ces résultats suggèrent des changements pour plusieurs habiletés tactiles unisensorielles et multisensorielles non musicales chez les musiciens. Des études subséquentes devront évaluer des groupes de musiciens ayant des caractéristiques plus hétérogènes. Ces recherches futures permettront de mieux comprendre l'importance des caractéristiques d'un entrainement musical sur les habiletés sensorielles. Les résultats de cette thèse proposent qu'un entrainement musical, qui est un entrainement sensoriel complexe, ait un effet de grande envergure sur les habiletés sensorielles de base.

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Annexe I – Auditory imagery forces motor action

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I.i Abstract

A large number of neuroimaging studies have investigated imagined sensory processing and motor behaviours. These studies have demonstrated neural activation patterns for imagined processes that resemble those of real sensory and motor events. The widespread use of such methods has raised questions about the extent to which imagined sensorimotor events mimic their overt counterparts, including their ability to elicit sensorimotor interactions. Direct behavioural evidence of imagery-induced multisensory interactions has been recently revealed in tasks involving auditory and visual processing. An influence of sensory imagery on the control of motor action, however, has not been previously investigated. Here, we demonstrate that both real and imagined moving sounds induce involuntary ocular movement in a non-visual tracking task. The present data build on the results of prior studies of sensory imagery by showing that such conditions activate sensory neural areas. Moreover, we demonstrate an engagement of functional sensorimotor networks for imagined stimuli in a manner similar to the processing of real auditory stimuli.

Keywords: Auditory motion tracking; audio-motor interaction; oculomotor behaviour; physiological recording.

I.ii Introduction

A large number of neuroimaging studies have investigated imagined (or covert) motor and sensory processing. These investigations have demonstrated neural activation patterns for imagined processes that often resemble those of real sensory and motor events (Kosslyn et coll., 2001; Bunzeck et coll., 2005; Kraemer et coll., 2005; Hunter et coll., 2006). The widespread use of such methods has raised a number of questions regarding the extent to which imagined sensorimotor events mimic their overt counterparts, including their ability to elicit cross-modal or sensorimotor interactions.

Multisensory studies have demonstrated the importance of fusing or segregating information from different sensory modalities in order to correctly interpret our surroundings (e.g. McGurk & MacDonald, 1976; Sekuler et coll., 1997; Shimojo & Shams, 2001; Alais & Burr, 2004; Stein & Stanford, 2008). Recently, Berger & Ehrsson (2013) demonstrated that imagining an auditory stimulus while observing real visual stimuli or imagining a visual stimulus while listening to real auditory stimuli can induce a variety of audio-visual illusory percepts such as the McGurk Effect and the cross-bounce illusion. These results provide the first direct behavioural evidence of imagery-induced multisensory integration, indicating that the neural processing of imagined sensory signals might be more similar to the processing of real sensory signals than previously considered (Berger & Ehrsson, 2013).

Multiple sensory inputs are tightly coupled with motor systems to allow for the control of specialized sensory-guided behaviours. Numerous species, including humans, possess specialized neural circuitry for rapidly localizing and tracking the spatial location of objects on the basis of their auditory signals. Indeed, a tight functional coupling between auditory and oculomotor systems has been demonstrated in numerous studies (e.g. Schaefer et al., 1981; Petrides & Pandya, 1988;

2006; Van Grootel & Van Opstal, 2009). Reciprocal sensory-motor influence in spatial tasks appears involuntary. For example, the presentation of a moving sound elicits clear and detectable changes in eye position even when participants are specifically instructed not to move their eyes (Schaefer et al., 1981). However, it remains unclear whether imagery-induced multimodal interactions extend to the domain of functional sensorimotor couplings. In the present study, we explore whether evidence of a coupling between auditory sensory processing and motor control remains evident during imagined sensory input. Specifically, we investigate whether imagined moving auditory signals elicit oculomotor changes as robust as with real auditory signals.

I.iii Method

I.iii.i Participants

19 healthy volunteers (12 females, mean age: 24.16, SD=2.95) participated in this study. Pure-tone detection thresholds were within normal limits at octave frequencies ranging from 125 to 8000 Hz for all participants. The Research Ethics Board of the Université de Montréal approved the study and all the participants provided written informed consent.

I.iii.ii Materials and Procedures

The procedures and stimuli were selected in accordance with previous investigations suggesting that auditory-induced eye movements are most pronounced *i*) for sounds in motion *ii*) in darkness and *iii*) when there is no fixation (Schaefer et al., 1981). Two auditory stimuli were used (Fig. I.i). The first stimulus was a binaural recording of a moving automobile (duration: 5 sec; from http://www.universal-soundbank.com) that gave an impression of spatial motion from left to right due to the presence of interaural time and intensity differences. For the second stimulus, a static version of the first stimulus was generated using audio editing software (Logic Pro 8, Apple, USA) so that the left channel from the binaural track was presented to both ears. This stimulus gave the impression of a static sound source as both ears were subjected to identical sounds. This ensured, as much as possible, that the characteristics of the static (Figure I.i A) and moving (Figure I.i B) sounds were similar. All stimuli were presented binaurally at 80 dB SPL through ER 3A insert earphones (Etymotic Research, Elk Grove). Participants were seated in a completely darkened room during the task with their heads positioned on a chin rest in front of an eye tracking camera with an infrared light to allow tracking of any eye-movement in darkness (ISCAN Eye-tracker system, Burlington, MA). The visual field was sampled at a resolution of 512 pixels in the horizontal plane, each pixel representing 0.4 degree of visual angle.

An objective evaluation was performed before proceeding with the experimental conditions to confirm participants did not have involuntary eye movements and understood the instructions. Four auditory stimuli conditions were used in this pre-experimental task: real static sound, real moving sound, imagined static sound, and imagined moving sound. For the real sound conditions, participants were asked to listen to static and moving sounds and track the sound with their eyes. For the imaginary moving sound condition, participants were asked to imagine the static and moving sounds from the previous condition and track them with their eyes. Participants were expected to reliably replicate the ocular pursuit movement from real-motion sound stimuli as measured by the pace and range of ocular movement. As expected, measured shifts in eye position were almost nil for all participants for the real and imagined static sounds (Figure I.i C). The real and imagined moving auditory stimuli induced motion-related changes in gaze angle (Figure I.i D).

Overall, ocular activity was found to be similar for auditory imagery and real-stimuli for all participants, both for the static condition and moving stimuli conditions. Eye gaze was found to start at the same maximal left position and progressively shift to the maximal opposite direction for the imagined moving sound condition and for the real sound condition (Figure I.i D). The similarity in eye movement for real and imagined stimuli suggests that the participants were able to correctly imagine the speed and location of the moving sound. Results from these preliminary objective evaluations confirmed that participants were both free of involuntary eye-movement and capable of accurately replicating ocular pursuits of static and moving sounds with an imagined sound.

For the main task, three listening conditions were used in a pseudorandom order: real static, real moving and imagined moving stimuli. However, contrary to the pre-experimental task, participants were specifically instructed not to move their eyes during the presentation of real or imagined auditory stimuli. Participants closed their eyes before the start of each experimental condition. At the presentation of a binaural tone, participants opened their eyes and completed the task according to a recorded set of instructions presented before beginning each individual trial. Between each condition, participants were exposed to light (500 lux) for a period of 60 seconds to prevent dark adaptation. Each of these three experimental conditions was presented 10 times. Ocular movement was averaged for each condition. The mean eye shift for each condition was calculated by averaging the difference between the maximal left and right ocular positions from each trial. Shifts in eye position during the moving sound and the auditory imagery conditions were compared to the static condition. This comparison was made to reveal if the presence of a moving sound (real or imaginary) had an effect on oculomotor behaviour.

I.iv Results

Typical results from five individuals in the non-visual tracking task are shown in Figure I.ii (A-E). Measured shifts in eye position were almost nil for all participants during the presentation of the static sound (green lines). The presentation of the moving sound generated a different pattern of results across participants (blue lines). In most individuals, the moving sound generated an eye movement (right to left) in the opposite direction (Figure I.ii A, B, and C). However, for some participants changes occurred in the direction (left to right) of the eye movement for the moving sound condition (Fig I.ii D and E). Participants also showed a detectable change in eye position during moving sound imagery (red lines). Interestingly, unlike the real moving sound condition, ocular movement always occurred in the direction of the sound movement for moving sound imagery.

One-way repeated measures ANOVA showed a main effect of conditions (static, motion, imaginary) on shifts in eye position, $F(2, 36) = 16.253$, $p < .001$, $\eta_p^2 = .475$. Post-hoc analyses using Bonferroni corrections indicated that the motion sound ($p = .005$) and auditory imagery ($p < .001$) conditions were both significantly different from the static condition (Fig. I.ii F). After the experiment, most participants reported that they were aware of their oculomotor behaviour during the presentation of real or imagined stimuli. Several testified that they felt an involuntary motor movement toward the sound source during the presentation of moving stimuli and that they had to force oculomotor activity in the opposite direction in order to remain still. Moreover, most affirmed that it was “extremely difficult”, even “impossible”, to imagine a moving sound in the dark without moving their eyes towards the fictional sound source.

I.v Discussion

In the present study, we demonstrated that the perception of an imagined moving auditory stimulus interacts with oculomotor control. This interaction occurs in a manner similar to the effects of real auditory stimuli in terms of detectable changes of eye position. Specifically, we showed that mental imagery of moving sounds elicits large oculomotor activity under conditions of voluntary visual tracking, and smaller, involuntary visual pursuit movements under conditions in which subjects were instructed to not move their eyes. The data are consistent with prior results suggesting a close relationship between auditory signals and oculomotor behaviours in spatial tasks (e.g. Schaefer et al., 1981; Van Grootel & Van Opstal, 2009). These results suggest that auditory imagery is capable of altering perception in multisensory tasks involving auditory and visual elements (Berger & Ehrsson, 2013).

The question of demands characteristics to explain the results might be questioned at first. Indeed, one may argue that the aim of the experiment would appear to be fairly transparent to participants. Some results are, however, contradictory with the assumption of demands characteristic to explain the outcomes. Indeed, most participants displayed the opposite of the expected ocular movement directionality (see blue lines in Fig. 2. A-C). If participants were aware of the experimental demands and complied with them, it would be expected that the participants would produce more directionally consistent results.

This experiment's principal objective was to ascertain where or not is it possible to hear or imagine a moving sound without ocular movement. Due to the nature of our experimental design, however, we do not reveal factors responsible for this sensory-motor interaction nor do we expose whether these factors were similar for real and imagined sounds. Due to the distinct nature of the stimuli used between conditions, such a comparison might not be feasible. Indeed, our results suggest that sound imagery induces oculomotor action that is more difficult to inhibit than the action induced by an actual sound. Participants had more difficulty suppressing oculomotor impulses caused from the imagined sensory stimuli than they did from a real stimulation (see red bars vs. blue bars in Fig. 2F). More specifically, most participants seemed to over-compensate the impulse to move their eyes in for the actual moving sound condition. This overcompensation generated the reverse-pattern of oculomotor activity observed in Fig. 2A-C (blue lines). In contrast, participants consistently generated oculomotor motion in the direction of the imagined sound, from left-to-right, for the illusory sound condition (Fig. 2A-E). Taken together, these results seem to suggest that the underlying perceptual mechanisms of moving illusory and passive sounds cannot be directly related. With the currently available data, we can only speculate as to which neural substrates are involved in such interactions and whether these are related for imagined and real auditory simulations.

The "premotor theory of attention" stipulates that the mechanisms involved in programming ocular saccades and the mechanisms responsible for spatial attention, including those involved in auditory tasks, are the same (Rizzolatti et al., 1994). This theory is supported by multiple behavioural, neurophysiological, and neuroimaging studies (e.g. Rizzolatti et al., 1994; Kustov & Robinson, 1996; Moore & Fallah, 2001; Stoyanova et al., 2010; Ganis et al., 2004). The present data suggest a close relationship between auditory imagery and oculomotor activity in line with the premotor theory of attention. Specifically, the results from our study are consistent with those indicating functional or neuroanatomical connectivity between auditory and oculomotor processing (e.g. Petrides & Pandya, 1988; 2006).

Investigations on the modulation of activity in auditory areas during auditory imagery have provided useful information regarding the involvement of top-down processes in conscious perception (Ganis et al., 2004; King, 2006). Auditory imagery can activate auditory brain regions in the absence of any external stimulation (Bunzeck et al., 2005; Kraemer et al., 2005; Hunter et al., 2006) and imaging studies have found activation in the secondary auditory cortex and frontal cortical areas in anticipation of sound when none was presented (King, 2006). As for the structures or path that may be responsible for the interaction reported in the present study, the answer could be found at any hierarchical stage having a convergence of multisensory signals. More specifically, the reported interaction could take place at the level of association cortices (Stein & Stanford, 2008) or even as low as midbrain structures. Indeed, the results suggest that auditory imagery might initiate activity in multisensory structures responsible for orienting behaviour, such as the superior colliculus. Neurons in this multisensory structure are organized to form auditory and visual space maps that are topographically aligned (Knudsen. 1982; Meredith & Stein, 1983). Indeed, responses in animal models found neural correlate for auditory and visual representation of space in the superior colliculus (Knudsen, 1982). This shared sensory maps was found to share multiple factors, such as orientation and position, for auditory and visual stimuli. This representation, which extends to the most peripheral regions of represented space, could suggest a neural correlate for the observed illusory phenomenon. It has been shown that a target in a given region of visual or auditory space can activate neurons to orient eyes towards that target via motor output neurons (Meredith & Stein, 1983). Hence, the effect reported here may result from the close and repetitive matching of stimuli from different sensory modalities accomplished by such low-level processing.

I.vi Conclusion

Whereas past investigations have considered the interaction between imagined and actual stimuli within the same modality (Brockmole et al., 2002; Lewis et al., 2011) or in processes that are multisensory in nature (Berger & Ehrsson, 2013), our results are the first to demonstrate that mental imagery can interact with motor processes in tasks that are purely unisensory. Such data builds on the results of prior studies of sensory imagery (Kosslyn et al., 2001) by showing that such conditions not only activate sensory neural areas, but also engage functional sensorimotor networks in a manner similar to the processing of real auditory stimuli.

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I.vii.i Author Contributions

F.C. conceived the experiment; S.L., collected and analyzed the data, S.L., S.P., D.M.S., J.F.L., H.T. and F.C. wrote the manuscript.

I.viii Acknowledgments

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Figure I.i

Pre-experimental observation. (A-B) Spectrograms (upper pictures) and illustrations of typical oculomotor activity (lower pictures) in response to the static (A) and moving (B) sounds (real or imaginary) and (C-D) mean shifts pattern (n=19) in eye position in response to the three sounds. Participants were very efficient in fixating the static sound (C). Ocular activity was similar for moving sound and auditory imagery conditions (D), starting at the same maximal left position and progressively shifting to the maximal opposite direction.

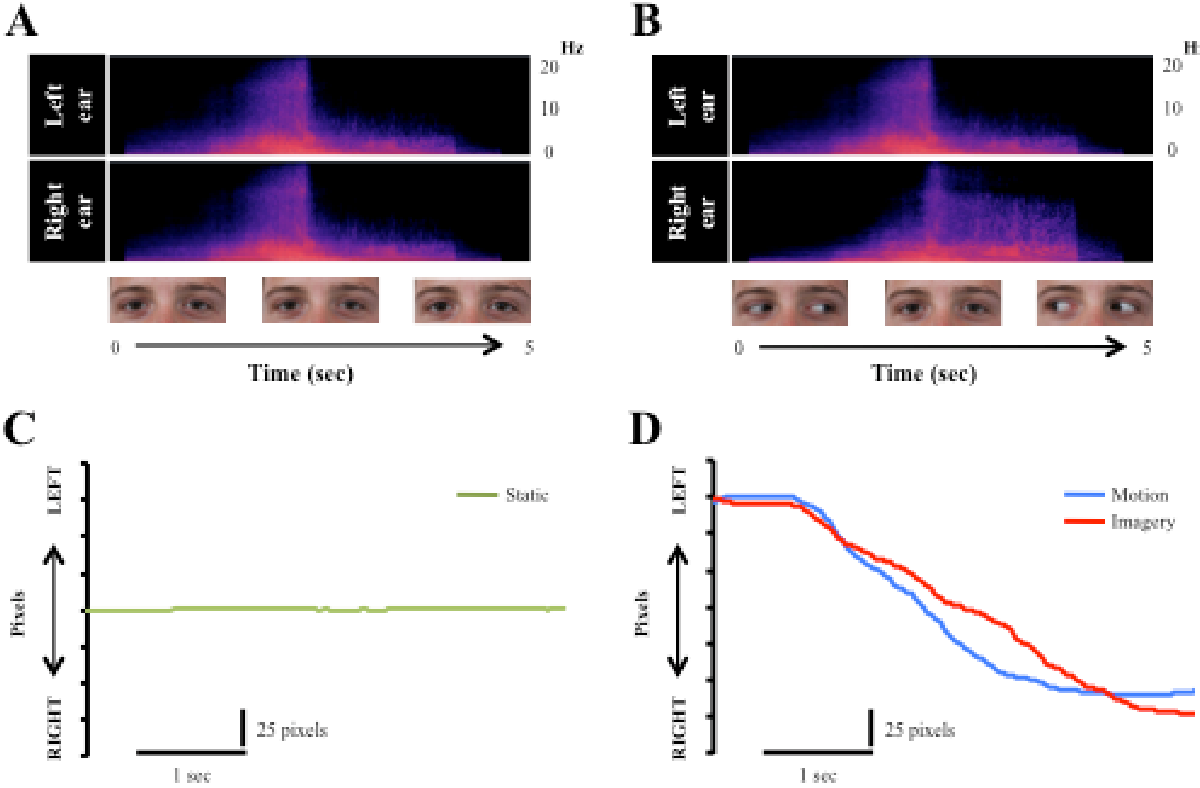
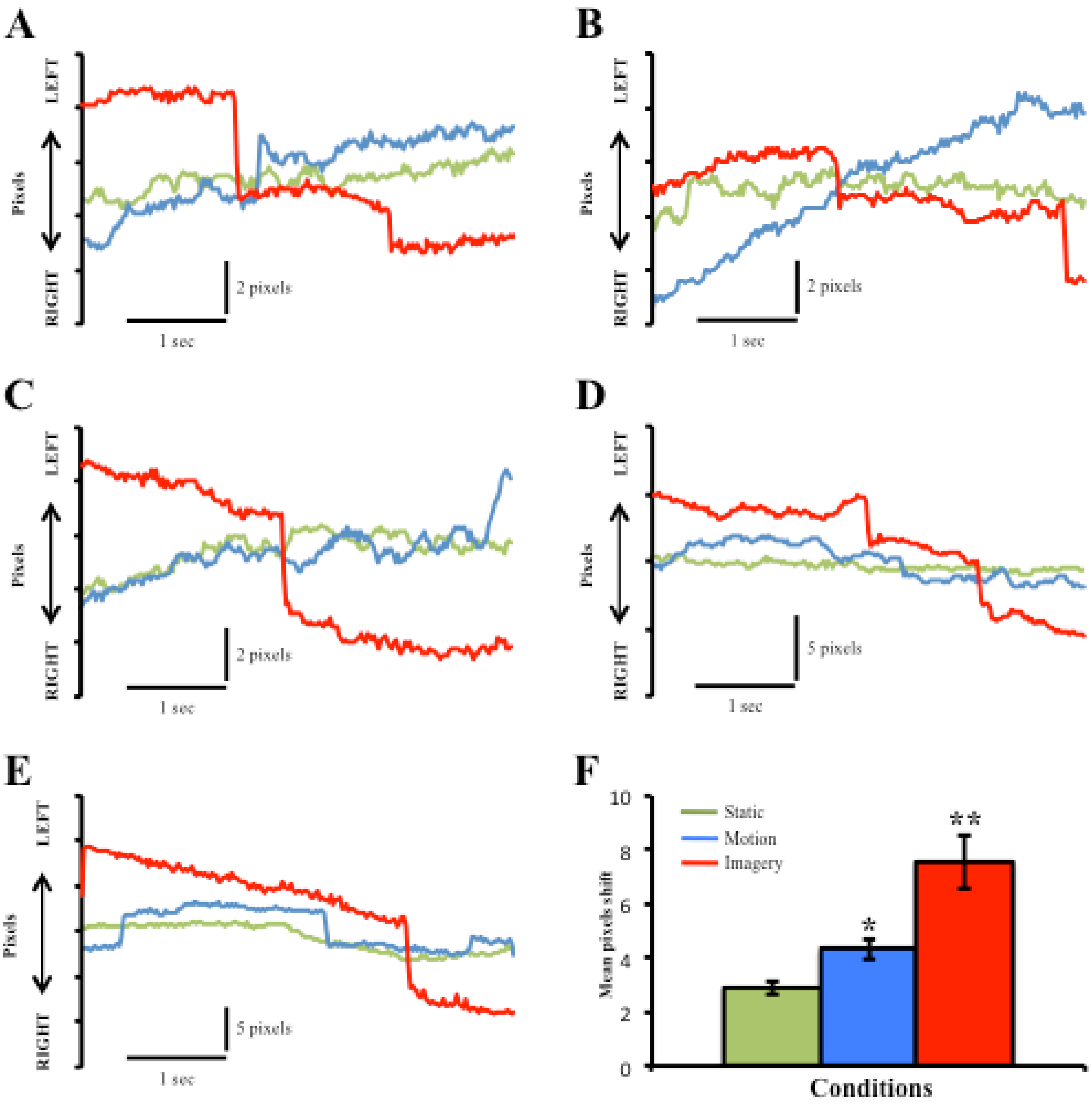


Figure I.ii

Experimental task. (A-E) Typical results from five individuals in response to the three sounds conditions and (F) mean pixels shift. Error bars: SEM. *: *p* < .05; **: *p* < .001.



Annexe II - Short-term visual deprivation improves the perception of harmonicity

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II.i Abstract

Neuroimaging studies have shown that the perception of auditory stimuli involves occipital cortical regions traditionally associated with visual processing, even in the absence of any overt visual component to the task. Analogous behavioral evidence of an interaction between visual and auditory processing during purely auditory tasks comes from studies of short-term visual deprivation on the perception of auditory cues, however the results of such studies remain equivocal. Although some data suggest that visual deprivation significantly increases loudness and pitch discrimination and reduces spatial localization inaccuracies, it is still unclear whether such improvement extends to the perception of spectrally complex cues, such as those involved in speech and music perception. Here we present data demonstrating that a 90-minute period of visual deprivation causes a transient improvement in the perception of *harmonicity*: a spectrally complex cue that plays a key role in music and speech perception. The results provide clear behavioral evidence supporting a role for the visual system in the processing of complex auditory stimuli, even in the absence of any visual component to the task.

Keywords: Visual deprivation; multisensory interaction; auditory perception; auditory scene analysis.

II.ii Introduction

There is an increasingly accepted notion in neuroscience that the primary sensory cortices are in fact multisensory in nature (e.g. Cappe & Barone, 2005; Schroeder & Foxe, 2005; Ghazanfar & Schroeder, 2006). Corticocortical connections between the primary visual cortex and auditory areas have been revealed in numerous studies of sighted subjects using retrograde tracing and neuroimaging techniques (e.g. Falchier et al., 2002; Hall & Lomber, 2008; Charbonneau et al., 2012; Liang et al., 2013). These findings are complemented by behavioral studies demonstrating that auditory processing may be enhanced by short- and long-term visual deprivation, even during tasks that are purely auditory in nature.

The impact of sensory deprivation on the function of intact sensory modalities has mainly been investigated following long-term sensory deprivation in the congenitally blind, and has primarily focused on auditory or tactile functions (e.g., Théoret, Merabet, & Pascual-Leone, 2004; Merabet & Pascual-Leone, 2010). However, the duration of sensory deprivation required in order to obtain enhanced perceptual abilities is still not clear. The enhancements in tactile perception observed in the congenitally blind can be reproduced in the tactile perception of sighted individuals who have undergone short-term visual deprivation ranging from 90 minutes (Facchini & Aglioti, 2003) to days (Kauffman, Théoret, & Pascual-Leone, 2002). To our knowledge, only two studies have investigated the effects of short-term visual deprivation on auditory processes. These investigations have suggested that visual deprivation significantly increases loudness and pitch discrimination (Gibby et al., 1970) and reduces spatial localization inaccuracies (Lewald, 2007). Such data are unique in the exploration of auditory-visual interactions as they suggest that the visual system is implicated in the processing of auditory stimuli even in the absence of a visual component to the task. Unfortunately, such critical explorations regarding the interaction between auditory and visual systems in the hearing have not received further investigation. In particular, it is unknown whether such improvement extends to perceptual abilities involved in the analysis of spectrally complex cues, such as those involved in speech and music perception.

In normal aural environments, the auditory system has to segregate multiple overlapping and concurrent sounds sources. Under everyday listening conditions, loudness, frequency and localization represent only a fraction of the various simultaneous auditory cues available for the analysis of the acoustic scene. Many sounds that are important to humans are harmonic or quasi-harmonic (Micheyl & Oxeham, 2010), thus one of the most powerful cues used by the auditory system to segregate concurrent sounds is *harmonicity*: the harmonic relation between acoustic components (Bregman, 1990). The analysis of harmonicity, involving the processing of multiple tonal elements on the basis of periodicity, is not only recognized as a primary ability in the identification and segregation of sounds originating from different sources (e.g., Alain et al., 2001; 2002; Alain, 2007), but also plays a key role in both music and speech perception (e.g., Micheyl & Oxeham, 2010; Plack, 2010). The perception of harmonicity can be examined using discrimination tasks that involve the fusion of multiple tonal elements into a single sound "object" or the segregation of a mistuned element as a separate auditory object (e.g., Moore et al., 1986; Chalikia & Bregman, 1989; Hartmann et al., 1990; Lin & Hartmann, 1998).

Here, we aim to study the effect of short-term visual deprivation on performance in a harmonicity discrimination task. As short-term temporary visual deprivation has been shown to enhance other auditory abilities (Gibby et al., 1970; Lewald, 2007), we hypothesized that a 90-minute period of visual deprivation would also significantly improve the perception of harmonicity (i.e., decrease harmonicity discrimination thresholds). The results support the hypothesis, suggesting that a perceptual auditory enhancement of spectrally complex sounds can be triggered following a short period of visual deprivation. Moreover, our results highlight the transiency of such an enhancement in temporarily blindfolded participants.

II.iii Method

II.iii.i Participants

74 healthy volunteers (36 males and 38 females; 18-32 years of age) participated in this study. Pure-tone detection thresholds were within normal limits at octave frequencies ranging from 125 to 8000 Hz for all participants. All participants reported normal or corrected-to-normal vision. The Research Ethics Board of the Université de Montréal approved the study and all the participants provided written informed consent.

II.iii.ii Materials and procedures

All participants completed a harmonicity discrimination task and were naïve as to the objectives of the research and to their group assignment (experimental vs. control). The auditory stimuli consisted of a fundamental frequency (220 Hz) and five additional harmonically related tonal elements (i.e., integer multiples of the fundamental frequency; see Zendel & Alain, 2009). Each component (220, 440, 660, 880, 1100 and 1320 Hz) was a 150 msec pure tone sine wave with a 10 msec rise/fall time. The third frequency component of the series was either tuned (precisely 660 Hz) or mistuned in steps of 1 Hz. Participants were asked to report verbally whether each stimulus presented was perceived as "tuned" (the percept resulting from all components being in tune with the others) or "mistuned" (the percept resulting from one component tone not being in tune with the others). Before running the experiment, participants had the chance to hear the tuned and a mistuned sound.

The minimum frequency step needed by subjects to detect a change in harmonicity (tuned vs. mistuned) was determined using a 3-down/1-up adaptive staircase procedure (for further description, see Levitt et al., 1971; Amitay et al., 2006). The initial amount of mistuning was set well above the expected threshold (50 Hz), corresponding to a stimulus clearly identified by subjects as 'mistuned'. The third frequency component was then reduced in 3-Hz steps until the stimuli were perceived as 'tuned', at which point the direction of stimulus change was reversed (increased in 1-Hz steps). Following the subsequent judgment of the stimulus as 'mistuned', the direction was again reversed and the process repeated. The run was terminated after six reversals. The threshold was calculated as the average of the last four reversals. The stimuli were generated using Logic Pro (Logic Pro 8, Apple, USA) and were presented binaurally at a comfortable level (55-60 dB SPL) through headphones (10 S/DC, David Clark, Worcester, MA, USA). The output of the acoustic system was calibrated using a sound level meter (model 2230, Brüel and Kjaër, Denmark) and artificial ear (6cc coupler, model 4153, Brüel and Kjaër, Denmark).

The discrimination task was administered twice to two groups of participants who were matched for age and gender. Each evaluation lasted approximately 5 minutes. All participants, including those in the control group, were blindfolded at the time of the evaluation (Mindfold, Mindfold Incorporated, Tucson, AZ, USA). After the first test of discrimination (pre-test), participants waited 90 minutes during which one group of participants (n=32) remained visually deprived, while the other group (n=32) had their blindfolds removed. During this interval, participants were asked to view or listen to a movie. Participants were kept alert by the examiner who remained in the room. Participants' thresholds were measured again immediately following this 90-minute interval (post-test)[1]. No feedback about the correctness of the responses was given to the participants at any time.

Complementary data was collected for 34 of the 74 participants in order to assess the transiency of the effect. Additional measures of the harmonicity discrimination threshold were carried out following 15 minutes, 30 minutes and 60 minutes of visual restoration in 17 non-deprived and 17 visually deprived individuals. These successive testing sessions were conducted to evaluate both the transiency of effect and to better control for some of the cognitive factors that could account for a change in measured harmonicity discrimination threshold, such as habituation or learning. Changes in performance were computed as the difference between the first evaluation and those conducted after visual deprivation.

II.iv Results

Overall, the performance of non-visually deprived participants remained relatively constant between the pre-test and post-test (Figure II.i a), whereas the visually deprived participants

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[1] The period of 90 minutes of visual deprivation was based upon the results of a preliminary study from our laboratory conducted with 60 individuals. In this study, as in the main study described above, the discrimination task was administered twice. For one group (n=30), the tasks were separated by an interval of 60 minutes, while for the other group (n=30) the tasks were separated by 90 minutes. In each group, 15 participants were blindfolded and 15 had normal or corrected-to-normal vision. The interaction between factors was significant ($F(1, 28) = 10.538$, $p = .003$, $\eta_p^2 = .273$). Specifically, the shorter period of visual deprivation (60 minutes) was found to be insufficient to elicit a significant change in auditory perception compared to controls ($t(28) = 0.560$, $p = .580$). In contrast, a period of 90 minutes induced a significant change in auditory perception between control and visually deprived groups ($t(28) = -6.607$, p □ .001). This pilot study confirmed a previous estimation of the period required to elicit a change in perception established by Facchini & Aglioti (2003) and concomitantly lessened the implication of a change in response strategy to explain any improvement in performance (see Durgin et al. 2009).

exhibited an improvement in performance during their second discrimination test (Figure II.i b). More specifically, 31 of the 32 visually deprived participants showed an improvement (i.e., decrease) in their discrimination threshold, ranging from 7% to 85% (mean = 28.7%) relative to their initial discrimination score. A 2X2 ANOVA with *group* (Group 1: control; Group 2: visually deprived) as the between-subjects factor and *condition* (Condition 1: before visual deprivation; Condition 2: after visual deprivation) as a within-subjects factor was conducted. The interaction between factors was significant ($F(1, 62) = 41.298, p < .001, \eta_p^2 = .400$), reflecting group-specific changes from pre-test to post-test. Post hoc tests with Bonferroni correction (alpha value = 0.025) revealed no significant difference in the ability to discriminate auditory stimuli prior to visual deprivation between the two groups ($t(62) = -0.026$; $p = 0.979$). Results from the subsequent testing session revealed a significant improvement for the visually deprived individuals' discrimination ability compared to the non-visually-deprived group ($t(62) = 3.786$; $p < 0.001$).

Additional data were collected in order to examine the transiency of the effect (Figure II.ii). A 2X5 ANOVA with *group* (control; visually deprived) as the between-subjects factor and *condition* (Condition 1: prior to visual deprivation; Condition 2: after visual deprivation; Condition 3: 15 minutes of visual restoration; Condition 4: 30 minutes of visual restoration; Condition 5: 60 minutes of visual restoration) as a within-subjects factor was conducted. The interaction between factors was significant ($F(1, 32) = 6.338, p < .001, \eta_p^2 = .165$), reflecting group-specific changes from pre-test to post-tests. Specifically, t-tests with Bonferroni correction (alpha value = 0.01) showed no significant difference in the ability to discriminate auditory stimuli prior to visual deprivation between the two groups (Condition 1: $t(32) = 0.252$; $p = 0.803$). A significant enhancement in performance for the sensory deprived group (relative to control) was observed following 90 minutes of visual deprivation (Condition 2: $t(32) = 3.018$; $p = 0.005$), however no significant differences were observed in the subsequent conditions (Condition 3: $t(32) = 2.288$; p = 0.029; Condition 4 : $t(32) = 1.681$; $p = 0.103$; Condition 5 : $t(32) = 0.454$; $p = 0.653$). Within group analyses comparing performance among the different time points revealed a similar pattern. As expected, there were no significant differences across time-points (relative to baseline) for the control group (Condition 2: $t(16) = -0.841$; $p = 0.413$; Condition 3: $t(16) = -1.737$; $p = 0.102$; Condition 4: $t(16) = -0.895$; $p = 0.384$; Condition 5: $t(16) = 0.517$; $p = 0.612$). In accordance with the previous results (see Figure II.i), the data showed a significant enhancement in performance (relative to baseline) following 90 minutes of visual deprivation (Condition 2: $t(16) = 5.548$; $p < 0.001$). The enhancement in performance was still significant after 15 minutes of visual recovery (Condition 3: $t(16) = 3.266$; $p = 0.005$) and progressively returned to normal at 30 and 60 minutes recovery time (Condition 4 : $t(16) = 2.519$; $p = 0.023$; Condition 5 : $t(16) = 1.701$; $p = 0.108$).

II.v Discussion

The present study aimed to investigate the effect of short-term visual deprivation on the perception of a primary auditory scene analysis cue. Using a harmonicity discrimination task, we demonstrated that 90 minutes of visual deprivation results in an enhancement of auditory acuity. These results are consistent with recent findings suggesting short-term changes in auditory perception in blindfolded-sighted individuals in a variety of tasks, including spatial localization and the discrimination of frequency and loudness (Gibby et al., 1970; Lewald, 2007). It should be noted, however, that not all auditory perceptual tasks previously investigated have revealed such changes (e.g., a frequency modulation discrimination task; Lazzouni, Voss et Lepore, 2012). Our results also revealed the transiency of the effect, demonstrating a washout of the enhancement effect 30 minutes after the removal of the blindfold.

It has long been suggested that blind individuals have enhanced auditory sensory abilities, though demonstrations of such enhancements have been limited to a relatively small set of auditory skills (e.g., Lessard et al., 1998; Röder et al., 1999; Gougoux et al., 2004; Lewald, 2013). To date, the effect of short-term visual deprivation on auditory skills in sighted individuals has also remained underexplored. The results of the present study confirm that short-term visual deprivation can significantly enhance auditory perception. To our knowledge, this is the first demonstration of such an auditory perceptual enhancement involving the analysis of a spectrally complex cue, such as those involved in speech and music perception.

These results highlight the extent and relative swiftness of neural changes in response to sensory deprivation. Considering that the enhanced auditory capability reported here can be triggered after only 90 minutes of visual deprivation and begins to return to a normal level soon after the visual input is restored, it is of interest to consider the mechanisms that might be responsible for such changes. One possibility is that existing auditory neural pathways are rapidly "unmasked" following the loss of visual input. Merabet & Pascual-Leone (2010) have suggested that, unlike cortical plasticity following long-term visual deprivation, changes following short-term visual deprivation may not be related to a compensatory process. Rather, such changes are consistent with a *metamodal* model of cortical function in which cortical regions, including primary sensory areas, receive multiple sensory inputs and are organized on the basis of task requirements rather than unique sensory modalities (Pascual-Leone & Hamilton, 2001). According to the metamodal model, visual sensory dominance in the striate cortex occurs because the assigned computation of the area is more efficiently utilized for retinal information. Therefore, in case of the removal of visual input, non-visual inputs (i.e. auditory and tactile) in visual cortex may be rapidly unsuppressed. This model has been used to explain the rapid neural plasticity observed in the tactile domain in temporarily blindfolded participants (Kauffman, Théoret, & Pascual-Leone, 2002; Facchini & Aglioto, 2003), and may be applicable to other neural systems as well (Merabet et al., 2008). The model is also consistent with the increasingly accepted notion that primary sensory cortices receive input from other sensory modalities, and are thus not limited to unimodal processing of sensory information (e.g., Cappe & Barone, 2005; Schroeder & Foxe, 2005; Ghazanfar & Schroeder, 2006: Liang et al., 2013). Unfortunately, the functional implications of such intermodal projections remain unclear. Considering that different auditory processes have been associated with distinct cortical pathways (e.g., Romanski et al. 1999; Alain et al. 2001; Maeder et al., 2001), it would be of interest to further explore the characteristics of neural activity in response to sound in the primary visual cortex in sighted individuals in relation to short-term sensory deprivation, possibly using neuroimaging techniques. Such future work is necessary to explain why some types of auditory processing, such as the perception of harmonicity, exhibit improvement following short-term visual deprivation, while other auditory processes exhibit changes only in the case of congenital or prolonged blindness.

In the present study, an adaptive staircase procedure was used to measure auditory discrimination thresholds. Several aspects of our results indicate that the changes in measured thresholds following 90 minutes of visual deprivation reflect a true change in perceptual sensitivity, and not simply a response bias (toward a greater proportion of "tuned" responses) somehow introduced by the visual manipulation. First, it should be noted that all participants (including controls) were perceptually tested while blindfolded, hence any immediate influence of visual deprivation on responses was balanced between the groups. Further, the influence of visual deprivation on harmonicity discrimination was found to be highly time sensitive: no improvement in discrimination was observed in participants who were visually deprived for 60 minutes, and the perceptual enhancement in participants who were visually deprived for 90 minutes was found to dissipate 30-60 minutes following the restoration of visual input. Such specificity in the observed auditory-perceptual change following visual deprivation cannot readily be explained as a change in response strategy.

While the mechanisms underlying the reported enhancement in harmonicity perception remain unknown, the results of the present study suggest that the potential for change in auditory scene analysis in sighted individuals is much greater than previously assumed. Future psychophysical and neuroimaging studies exploring other acoustic cues related to auditory scene analysis are necessary to further our understanding of the effect of temporary visual deprivation on auditory capacities.

II.vi References

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Figure II.i

Individual performance of the control group and the visually deprived group before and after an interval of 90 minutes. Error bars are SEM. ** : $p < 0.001$.

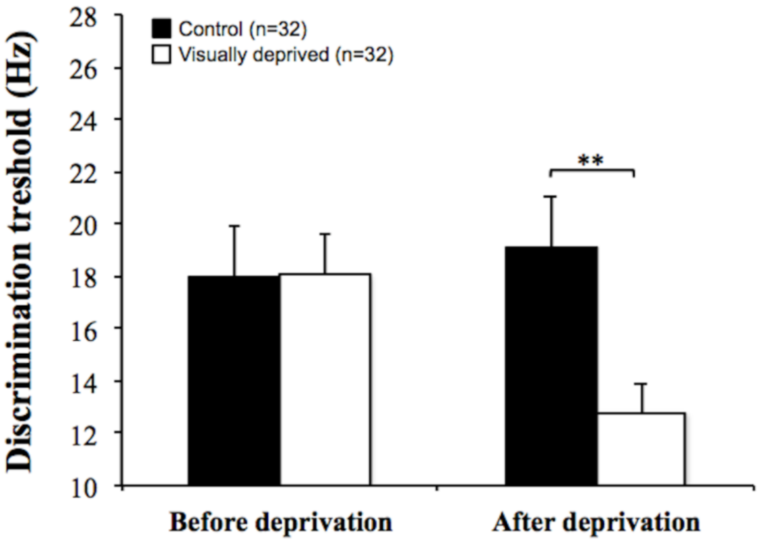
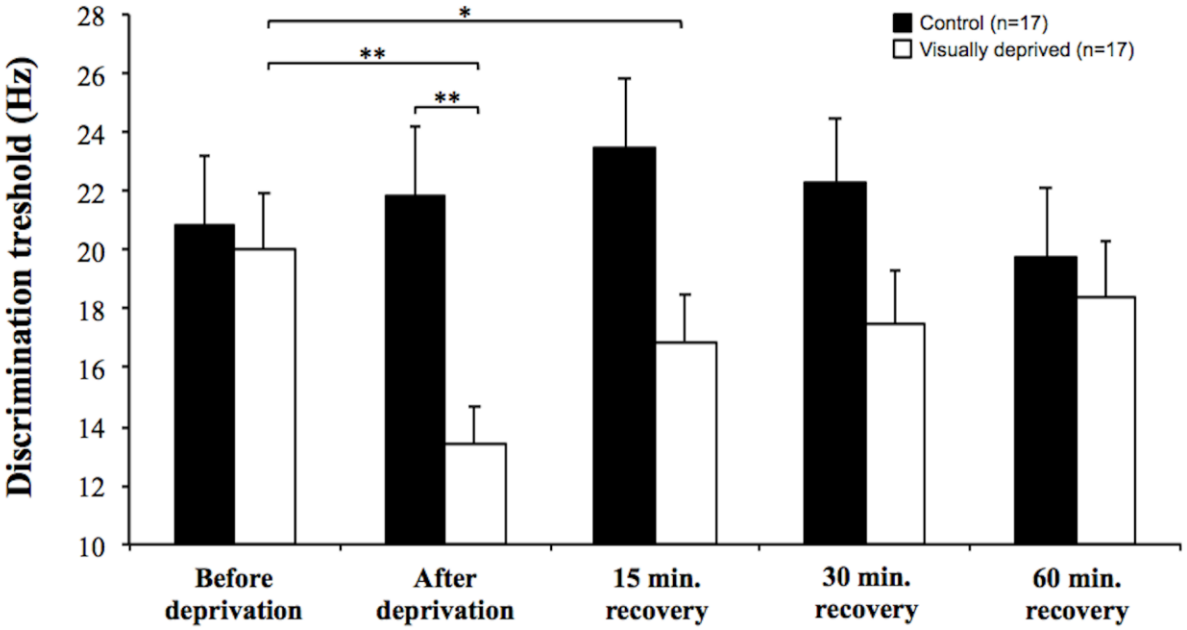


Figure II.ii

Results of the harmonicity discrimination task before visual deprivation, immediately following 90 minutes of visual deprivation, and then 15, 30 and 60 minutes after the recovery of visual input. Error bars are SEM. ** : $p < 0.001$; * : $p < 0.01$.



Annexe III - Audiotactile interaction can change over time in cochlear implant users

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III.i Abstract

Recent results suggest that audiotactile interactions are disturbed in cochlear implant (CI) users. However, further exploration regarding the factors responsible for such abnormal sensory processing is still required. Considering the temporal nature of a previously used multisensory task, it remains unclear whether any aberrant results were caused by the specificity of the interaction studied or rather if it reflects an overall abnormal interaction. Moreover, although duration of experience with a CI has often been linked with the recovery of auditory functions, its impact on multisensory performance remains uncertain. In the present study, we used the parchment-skin illusion, a robust illustration of sound-biased perception of touch based on changes in auditory frequencies, to investigate the specificities of audiotactile interactions in CI users. Whereas individuals with relatively little experience with the CI performed similarly to the control group, experienced CI users showed a significantly greater illusory percept. The overall results suggest that despite being able to ignore auditory distractors in a temporal audiotactile task, CI users develop to become greatly influenced by auditory input in a spectral audiotactile task. When considered with the existing body of research, these results confirm that normal sensory interaction processing can be compromised in CI users.

Keywords: Audiotactile interaction; multisensory interactions; cochlear implant; parchment-skin illusion; sensory deprivation; cross-modal plasticity; deafness; hearing loss.

III.ii Introduction

Audiovisual interactions have been extensively studied in the hearing. Resulting evidence put forth that interaction between senses enhances overall perceptual accuracy and saliency through cooperative advantages in congruent situations (e.g. Calvert and Thesen, 2004; Stein and Stanford, 2008) and provides the redundancy of cues that is necessary to fully characterize objects in our environment (e.g. Driver and Noesselt, 2008). Audiovisual processing has also been widely examined in cochlear implant (CI) users (p. ex. Champoux et al., 2009; Geers, 2004; Kaiser et al., 2003; Landry et al., 2012; Moody-Antonio et al., 2005; Tremblay et al., 2010; Tyler et al., 1997;). However, multisensory interaction in CI users outside of the audiovisual domain has not received the same attention. This neglect is unfortunate as it has been recently proposed that several unexplained day-to-day life difficulties observed in the deaf could be related to deficits in audiotactile processing (Nasir and Ostry, 2008).

The sense of touch can be altered if another sense is simultaneously stimulated. Motivated by the fact that tactile and auditory modalities are both sensitive to environmental oscillations, interactions between these modalities have recently gained attention from some researchers (Yau et al., 2009a; 2009b; 2013). Such multisensory interactions can be examined using different tasks. Arguably, the most robust cases of cross-modal fusion between auditory and tactile modalities are the audiotactile illusory flash effect (Hötting and Röder, 2004) and the parchment skin illusion (Jousmäki and Hari, 1998), for the temporal domain and the spectral domain respectively. The audiotactile illusory flash effect is a non-speech illusory percept in which the simultaneous presentation of a single somatosensory stimulus with two successive sounds can lead to the perception of two distinct tactile sensations in normally hearing individuals. The parchment skin illusion (Jousmäki and Hari, 1998) is also a non-speech illusory percept in which an amplification or reduction of high-frequency content from the sound generated by rubbing hands together results in an alteration of the experienced palmar dryness/moistness. This sound-induced alteration of touch perception appears to be a robust case of cross-modal fusion in the spectral domain (see also Champoux et al., 2011; Guest et al., 2002). The parchment skin illusion is one of the earliest demonstrations of the importance of spectral auditory inputs on tactile perception. This task demonstrates the potential perceptual effect of auditory frequency manipulation on palmar sensation of roughness and moistness.

Recently, we investigated whether temporal audiotactile processes were disturbed in CI users (Landry et al., 2013). The audiotactile illusory flash effect was administered to a group of normally hearing individuals and a group of CI users. Control conditions revealed that auditory and tactile discrimination capabilities were identical for both groups. Whereas normally hearing individuals integrated auditory and tactile information in the context of an audiotactile illusion, CI users were not influence by the presence of auditory stimuli and thus did not perceive the audiotactile illusion. This gives strength to the hypothesis by which CI users may have audiotactile interactions deficits (Nasir and Ostry, 2008).

However, two important questions remain before such a sweeping statement can be substantiated. First, it remains unclear whether these results can be attributed exclusively to the specificity of the interaction investigated. Until now, CI user audiotactile interaction has only been examined in a temporal task (Landry et al., 2013). Thus, it remains unclear whether the observed change is related to the specificity of the interaction investigated. In order to examine whether a period of prolonged deafness can have an impact on the development of audiotactile processing at large, the performance of CI users needs to be investigated in relation to other features of the stimuli, namely spectral characteristics. Second, audiotactile performance has not yet been examined in relation to features related to cochlear implantation such as duration of CI use. In order to examine whether temporary deafness has an impact on the development of audiotactile processes at large, the performance of CI users needs to be investigated in relation to other features of the multisensory stimuli, including spectral characteristics. Moreover, duration of experience with the implant has been found to have a strong positive effect on auditory performance in various behavioral and electrophysiological tasks (e.g. Nicholas and Geers, 2006; Pantev et al., 2006). These results suggest that longer experience with the implant might help with the restoration of sensory functions after prolonged deprivation. Long-term follow-up investigations of CI patients suggest that long-term perception performance improves over time and reaches a plateau 4-5 years post-implantation (O'Donoghue et al., 1998). Furthermore, approximately 6 years of experience with the implant is required to acquire excellent results in perception performance (e.g. Allen et al., 1998; Damen et al., 2007).

In the present study, we aim at examining spectral audiotactile interaction capabilities of CI users in relation to the duration of experience with the CI. Previous investigations have demonstrated that temporal audiotactile integration is abnormal in CI users (Landry et al., 2013), yet it is unknown if this is applicable to other domains of audiotactile integration such as frequency. We used the parchment skin illusion (Jousmäki and Hari, 1998) to further the knowledge of audiotactile integration capabilities in CI users. In addition to this illusory task, control tasks provide the means for the separation of unisensory performance from multisensory performance.

III.iii Method

III.iii.i Participants

Thirty-eight participants (19 CI users and as many normal-hearing subjects matched for handedness, sex and age) were involved in the study. CI users (6 male; mean age: 46 years; range: 22-65 years) had lost their hearing for a period of 13 to 53 years (see table III.i). The groups were comparable in regards to their educational background and occupational status. All CI users suffered from profound bilateral hearing loss (pure tone detection thresholds at 80 dB HL or greater at octave frequencies ranging from 0.5 to 8 KHz). The principal method of communication for all CI users was oral/lip-reading. Pure-tone detection thresholds were within normal limits (30 dB HL or less) at frequencies ranging from 250 to 6000 Hz for all CI users and control group participants. CI users were separated in two groups according to the length of experience with the implant. In accordance to previous assessments of perceptional performance and duration of implant use (Allen et al., 1998; Damen et al., 2007), duration of CI use for those individuals with less than 6 years of experience was classified as "short-term" (n=11) and those with more than 6 years were classified as having "long-term" experience (n=8). The Research Ethics Board of the Université de Montréal approved the study and all the participants provided written informed consent.

III.iii.ii Materials and procedures

Prior to testing, tactile and auditory capabilities were evaluated to further ensure unisensory homogeneity for both groups. A static two-point discrimination evaluation was performed for each participant to ensure normal to fair innervation. Five one-point and five two-point contacts at a set distance were presented in random order on the right index finger. Participants were required to correctly identify the number of points for seven of ten applications. All eligible participants were confirmed to possess normal to fair (two-point distances between 6-10 mm) right index finger innervation density (Warwick et al., 2009). Tactile sensitivity thresholds were tested for all participants using Semmes-Weinstein monofilaments (Bell-Krotoski and Tomancik, 1987). All participants were able to detect a pressure of 2.83 g/mm2 on their right index fingers and deemed to have normal tactile sensitivity thresholds. Two additional tactile evaluations were conducted. Right index tactile resolution was tested using a grating orientation task in which domes of varying grating widths were presented at random orientations (Van Boven and Johnson, 1994). Participants were asked to assess the dome's orientation as either parallel or perpendicular using only tactile cues. The grating width at which participants would correctly identify the orientation for 75% of presentations was then calculated. Vibrotactile discrimination thresholds were calculated using a 2-down 1-up staircase method. Participants were presented two consecutive vibrotactile stimuli to their right index fingers and asked if they were identical or different (Alary et al., 2009). Results from the staircase method were used to calculate mean vibrotactile discrimination thresholds. A 3X2 ANOVA with group (control; short-term CI users; long-term CI users) as a between-subjects factor and conditions (grating orientation task; vibrotactile discrimination task) as a within-subjects factor was conducted. As expected, there was no main effect for groups ($F(2, 35) = 2.454$, $p = 0.101$, $\square_p^2 = .123$) and the interaction between factors was not significant ($F(2, 35) = 2.147$, $p = 0.132$, $\square_p^2 = .109$).

For the main task, participants sat in a comfortable chair in a sound-attenuated booth. They were asked to rub the palms of their hands together back and forth four times at approximately 2 cycles per second in front of a microphone. In accordance with the methods of Jousmäki and Hari (1998), the sounds produced by the rubbing of their hands were played back to them in real time through attenuating circumaural headphones (10 S/DC, David Clark, Worcester, MA, USA) at a self-adjusted comfortable hearing level (between 50-60 dB HL) for all participants. For CI users, the headphones were positioned in a normal fashion with the speaker over the CI's microphone located behind the helix of the pinna. During the experiment, three different auditory conditions were used (for an explicit detailing of the experimental procedure, see Champoux et al., 2011). In the first experimental condition, the auditory stimulus was the unaltered recorded sound. In the second and third conditions, the sounds were modified with an equalizer (Realistic, model 31-2018A) and a mixer (Yamaha, MG10/2 mixing console). In the second condition, the audio feedback was accentuated by 20 dB and the frequencies above 2 kHz were increased by an additional 12 dB. In the third condition, audio feedback was reduced by 20 dB and frequencies above 2 kHz were attenuated by an additional 12 dB. According to Jousmäki and Hari (1998), the second and third conditions induce the perception of drier and moister palmar skin, respectively. The three experimental conditions were each repeated ten times in a pseudorandom order.

Participants were informed to focus on tactile perception and to report any perceived changes relating to palmar skin sensation on a scale of /+5/ to /-5/, where /+5/ represented dryness and /-5/ represented moistness. Before the start of the experiment, participants rubbed their palms together with the instruction to remember their sensation as "a normal palmar skin perception" (i.e. number /0/ on our scale). They were specifically instructed to report changes in tactile sensation and not auditory perception. Participants reported their responses verbally to the experimenter. The number /0/ referred to a normal degree of moisture-dryness of the palmar skin, /-5/ suggested that palmar skin felt moister whereas /+5/ suggested that palmar skin felt drier. In their original experiment of the parchment-skin illusion, Jousmäki and Hari (1998) used a similar scale to assess a range of rough/moist to smooth/dry values. However, a multi-dimensional scale such as that used by Jousmaki and Hari (1998) may generate confusion in the response (Guest et al., 2002).

Furthermore, the rough-smooth scale has been evaluated independently and has proved to be more difficult to interpret than the dry-moist scale (Guest et al., 2002). As such, the present study made use of a uni-dimensional scale (dry-moist) to minimize any potential ambiguities in qualifying palmar skin changes. As in previous investigation using the exact same procedure (see Champoux et al., 2011), non-parametric statistics were used, as it is designated for datasets without a uniform response criterion and when using scale ratings (in this case, /-5/ to /+5/).

III.iv Results

All participants were able to accurately identify the condition referred to as "a normal palmar skin perception". In this condition without auditory modification, the reported perception was continuously very close to /0/ and only had small variations in the responses (see Figure III.i A). The results show that a parchment-skin illusion was clearly perceived by each group. Indeed, all individuals consistently reported a clear change in palmar skin perception whenever the high frequencies were increased or decreased (Figure III.i A). As expected, palmar skin was reported to be dryer in the second condition and moister in the third. The performance in the "long-term" CI users group, however, appeared greater in theses conditions compared to the performance of the control and the "short-term" CI users group.

We first conducted a Mann-Whitney test in order to reveal any difference between the control group and CI users, without distinction to the duration of CI use, for the experimental conditions. When all CI users were confounded, there was a significant different between tactile sensations when high frequencies were attenuated (U = 107.0; p = 0.030). No significant differences were found between groups when auditory stimuli were not modified (U = 164.5; p = 0.638) or when high frequencies were amplified (U = 158.0; p = 0.511). Then, as in previous research using the same experimental technique (see Champoux et al., 2011), we performed a Kruskal-Wallis ANOVA between groups (control; “long-term CI users; “short-term CI users) for the three experimental conditions (no alteration; high-frequency boost; high-frequency cut). There was a significant difference between the changes in tactile sensation, both when high frequencies were amplified ($c^2(2) = 9.52$; $p = 0.009$) or attenuated ($c^2(2) = 11.67$; $p = 0.003$). As expected, there was no significant difference between groups when the auditory stimuli were not modified (c2(2) = 2.68; $p = 0.262$). Post-hoc Mann-Whitney tests revealed that the perceived changes in palmar skin for the “long-term” CI users groups were significantly different from those of the control and the “short-term” CI users groups. Significant differences were found between “long-term” CI users and control individuals, whether higher frequencies were amplified ($U = 14.5$; $p = 0.022$) or reduced ($U = 33.0$; $p = 0.001$). The same was also observed between “long-term” CI users and “short-term” CI users whether the higher frequencies were amplified ($U = 5.5$; $p = 0.001$) or reduced ($U = 12.0$; $p = 0.008$). There was no significant difference in palmar skin perception between control and “short-term” CI users whether the higher frequencies were amplified ($U = 84.0$; $p = 0.377$) or reduced ($U = 92.5$; $p = 0.599$). After correcting for multiples comparisons (corrected p-value = 0.0125), we predictably found a significant relation between the length of experience with the implant and the reported change in the tactile perception (Figure III.i B) whether higher frequencies were amplified ($r = 0.585$; $p = 0.009$) or reduced ($r = -0.702$; $p = 0.001$). We were unable to find any other significant relationships between performance in audiotactile conditions and the characteristics of hearing loss (i.e. age at the onset of deafness, deafness duration and speech recognition score with the CI).

III.v Discussion

In the present study, we examined spectral audiotactile integration capabilities of CI users. Consistent with previous results, these data confirm that a prolonged period of deafness followed by cochlear implantation can lead to abnormal audiotactile interactions (Landry et al. 2013). Moreover, our results suggest that length of CI use might be an important factor related to audiotactile performance. This is consistent with the general assumption that longer periods of experience with a CI might lead to restored sensory functions (e.g. Allen et al., 1998; O'Donoghue et al., 1998; Nicholas and Geers, 2006; Pantev et al., 2006; Damen et al., 2007). The results are also in agreement with data suggesting important tactile-to-auditory changes following deafness and that auditory experience plays an important role in efficient cross-modal processing. Indeed, evidence of altered susceptibility to auditory-tactile illusions suggests two important facets of multisensory integration in relation to temporary deafness. First, constant auditory input is necessary from birth for the proper development of normal-like audiotactile interactions. Second, auditory and tactile information is seemingly processed differently in CI users.

Despite the apparent similarities between results from both audiotacile integration studies conducted in our laboratory, some important distinctions must be emphasized. Our previous investigation suggests that CI users are able to easily ignore auditory stimuli in a temporal cross-modal segregation task compared to controls, regardless of the duration of CI use (Landry et al., 2013). Contrarily, the results of the present study suggest that as they become more experienced, CI users are increasingly influenced by auditory stimuli in a spectral cross-modal fusion task. Taken together, these results support the notion that CI users have abnormal overall multisensory interactions. However, these combined data underline why a general statement as to whether CI users are better or worse multisensory integrator will most probably never be entirely valid. It
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appears that the directionality of the results obtained is dependent on a variety of factors, such as the examined sensory modalities, task directives, CI proficiency, and the characteristics related to hearing loss. Hence, multisensory data for CI users needs to be considered in the context of the specificity of the task along with the modalities examined.

A number of human and non-human primate studies have investigated cortical regions involved in the convergence of auditory and somatosensory processing (e.g. Caetano and Jousmäki, 2006; Foxe et al., 2000; 2002; Fu et al., 2003; Hackett et al., 2007; Lakatos et al., 2007; Murray et al., 2005; Schürmann et al., 2006). These studies suggest an interactions of auditory and tactile inputs in cortical areas such as primary and associative auditory regions which were traditionally assumed to be unimodal. After auditory deprivation, the brain can reorganize so that the deprived sensory cortex increasingly processes tactile stimuli. Indeed, imaging data suggests that vibrotactile stimuli can activate auditory regions in the deaf (Levänen et al., 1998; Schurmann et al., 2006; Sharma et al., 2007) and cortical over-representation of somatosensory evoked potentials in the left temporal region was found in deaf children using a CI (Charroó-Ruíz et al., 2013). Several data demonstrate that brain reorganization induced by deafness leads to behavioral changes for numerous perceptual tasks (Bavelier et al., 2000; 2001; 2006; Bosworth and Dobkins, 2002; Hanson, 1982; Heming and Brown, 2005; Loke and Song, 1991; Neville and Lawson, 1987; Turgeon et al., 2012), although it is unsure whether behaviorally advantageous (e.g. Bolignini et al., 2012). The effect of cross-modal reorganization raises important questions on the importance of hearing experience in shaping perceptual processing, but also in regards to cochlear implantation. It is now generally accepted that brain reorganization is likely a factor restricting access to auditory stimulation in long-term deafened individuals following cochlear implantation (p. ex.; Doucet et al., 2006; Giraud et al., 2001; Green et al., 2005; Lee et al., 2001; Naito et al., 1997). In light of the possibility that visual and tactile input may be redirected to auditory cortical areas, the question of how these modalities interact during tasks that require multisensory processing following cochlear implantation is of great interest.

Research on multisensory integration has suggested ease for CI users when using congruent cues (Geers, 2004; Giraud et al., 2001; Kaiser et al., 2003; Moody-Antonio et al., 2005; Tyler et al., 1997). Some researchers have even gone as far as to suggest that CI users could be better than hearing individuals at integrating audiovisual information (e.g. Rouger et al., 2007). However, given the apparent invasion of the auditory cortex by visual or tactile information, it could be hypothesized that visual or tactile information might interferes with auditory treatment when stimuli from these modalities are incongruent. The ability to fuse incongruent audiovisual information has been studied by Schorr and his colleagues (2005). They used McGurk-like stimuli (see McGurk and McDonald, 1976) to investigate the ability to integrate incongruent multisensory cues in children with CI as a function of experience with spoken language. The authors found normal-like results for the audiovisual task in children aged two and a half years or younger. Conversely, the fusion capability in children implanted later in life was reduced. This is consistent with the notion that duration of deafness influences cortical reorganization and has an impact on CI proficiency. The ability of CI users to fuse and segregate conflicting auditory and visual information has been investigated with speech and non-speech tasks (e.g. Champoux et al., 2009; Landry et al., 2012; Tremblay et al., 2010). It is essential to consider this potential difficulty for CI users to interpret audiovisual information in conjunction with investigations of other cross-modal interactions, such as audiotactile, to form a complete view of multisensory interactions in CI users. The data from the examination of audiotactile cross-modal segregation capabilities in CI users (Landry et al., 2013) and the one conducted in the present studies using a cross-modal fusion task are in complete agreement with the outcomes from studies in the audiovisual domain. Indeed, these data suggest that while non-auditory signals can facilitate auditory perception in some multisensory conditions (i.e. in cross-modal fusion tasks), they may hinder discrimination performance for some CI users when multisensory inputs require segregation. The aforementioned investigations highlight the potential changes to tactile-to-auditory interactions following profound deafness. These observed change in cross-modal performance require interpretation in relation to factors related to deafness as factors of hearing loss seem to play a considerable role in the extensive cross-modal changes

Several deafness and implantation factors have been shown to influence CI performance (see Collignon et al., 2011). Our data suggest that of these factors, spectral audiotactile interaction might be influenced more significantly by duration of CI use. This lends credence to the notion that a greater span of experience with the implant might help re-establish sensory functions after a prolonged deprivation (e.g. Nicholas and Geers, 2006; Pantev et al., 2006). However, we found no relationship between any other of the characteristics of the hearing loss and the examined multisensory performance. Thus, the data suggest that neither age at the onset of deafness, the duration of auditory deprivation, or CI proficiency had an impact on spectral audiotactile integration. However, the composition of the group regarding the many characteristics of the hearing loss and CI use may explain why no significant differences were found for these factors. First, all participant had more than a decade of auditory deprivation and were implanted at least at 15 years of age. Second, although some participants were congenitally deaf, all participants continuously used hearing devices before cochlear implantation, possibly preserving a minimal degree of auditory inputs during this period. Finally, CI speech perception proficiency was almost identical between groups, with the exception of two participants. These limitations could explain why no significant relationship was found between the results and performance with the CI or characteristics of hearing loss.

CI user results for the parchment skin illusion are constant with the notion that continuous auditory input from birth seems to be necessary for the maintenance of normal auditory interactions. Moreover, the conjunction of deafferentation and reafferentation can result in extensive cross-modal changes. The results presented in this study contribute to the burgeoning literature regarding the effects of a temporary auditory deprivation on the emergence, development, and maintenance of normal-like multisensory processes. However, further experiments comprising groups of deaf individuals with more homogeneous characteristic of hearing loss and CI use will be needed in order to support the implication of each feature of hearing loss in multisensory processing. The functional implications for the alterations observed in this study also merit further investigations; as such abnormal interactions could prove to be either beneficial or detrimental depending of perceptual situations.

II.viii References

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Table III.i

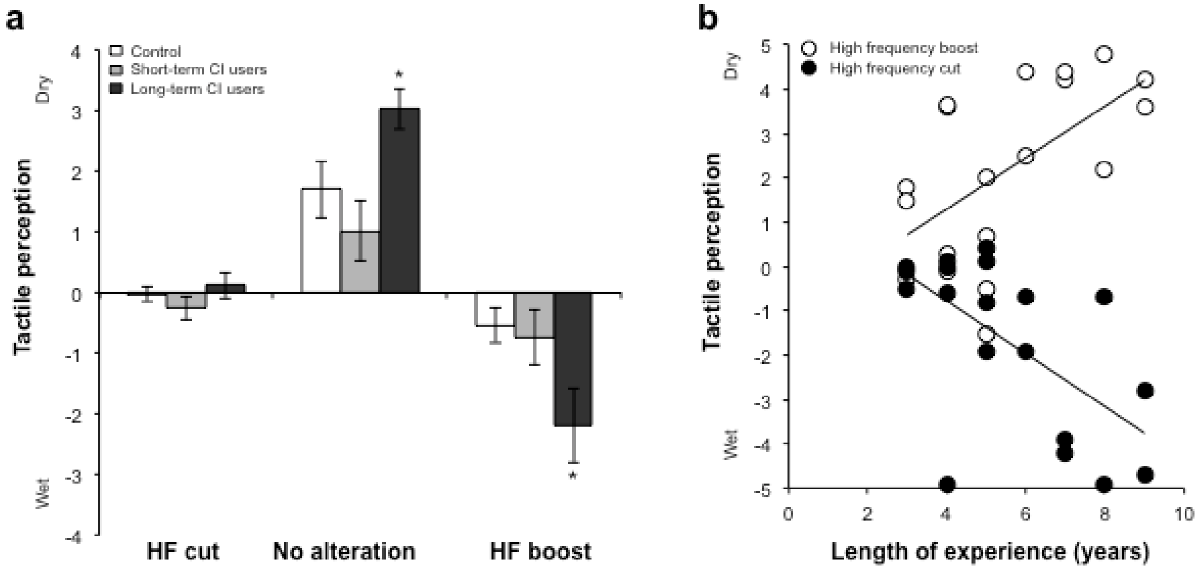
Clinical profile of cochlear implant users

Participants	Sex	Age	Age at onset of deafness (years)	Cause of deafness	Deafness duration (years)	Speech recognition (%)	Duration with the implant (years)
S1	F	46	0 (sudden)	Hereditary	43	0	3
S2	F	65	16-62 (progressive)	Hereditary	46	76	3
S3	M	40	7-35 (progressive)	Unknown	30	90	3
S4	F	49	17-38 (progressive)	Hereditary	21	76	3
S5	M	22	0 (sudden)	Unknown	18	80	4
S6	F	35	0 (sudden)	Hereditary	31	82	4
S7	F	32	0-14 (progressive)	Hereditary	14	84	4
S8	F	56	16-50 (progressive)	Hereditary	34	92	5
S9	F	58	0 (sudden)	Hereditary	53	20	5
S10	F	43	14-33 (progressive)	Ototoxic	24	78	5
S11	F	57	0-52 (progressive)	Hereditary	52	72	5
L1	M	58	10-33 (progressive)	Ototoxic	42	84	6
L2	F	44	0 (sudden)	Hereditary	38	56	6
L3	M	48	0-39 (progressive)	Hereditary	41	80	7
L4	M	65	14 (sudden)	Infectious	42	66	8
L5	F	63	7-11 (progressive)	Hereditary	25	54	8
L6	F	38	0 (sudden)	Unknown	30	20	8
L7	F	36	12-26 (progressive)	Unknown	14	78	9
L8	M	24	0 (sudden)	Hereditary	13	2	9

S=short-term experience (group 1); L=long-term experience (group 2)

Figure III.i

(A) Changes in palmar skin perception during the parchment-skin illusory task in the control, short-term and long-term CI users without modification of the auditory signal (no alteration), with accentuated high frequencies (HF boost) or with attenuated high frequencies (HF cut). (B) Individual results of CI users in the two experimental conditions (HF boost and HF cut). The data reveals that CI users with less experience with the implant perceive significantly less change in tactile sensation compared to individuals with more experience.



Annexe IV - Curriculum Vitae

SIMON P. LANDRY

ÉDUCATION

2012- présent	Université de Montréal - **Ph. D**. Sciences biomédicales, option audiologie *Effets d'un entrainement musical sur les interactions multisensorielles tactiles.*
2010-2012	Université du Québec à Montréal - **M.Sc**. Kinanthropologie *L'intégration audiotactile chez les porteurs de l'implant cochléaire.*
2004-2008	Bishop's University - **B.Sc**. majeur: neuroscience, mineure: entrepreneuriat

PUBLICATIONS AVEC COMITÉS DE PAIRS

Maheu, M., Sharp, A., **Landry, S. P.**, & Champoux, F. (2017). Sensory reweighting after loss of auditory cues in healthy adults. *Gait & Posture*, ePub.

Landry, S. P., & Champoux, F. (2017). Musicians react faster and are better multisensory integrators. *Brain and Cognition*, *111*, 156-162.

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

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.

Maheu, M., Fournier, P., **Landry, S. P**., Houde, M. S., Champoux, F., & Saliba, I. (2016). Structural and functional changes of cortical and subcortical structures following peripheral vestibular damage in humans. *European archives of oto-rhino-laryngology*

Houde, M. S., **Landry, S. P**., Pagé, S., Maheu, M., & Champoux, F. (2016). Body Perception and Action Following Deafness. *Neural plasticity*, *2016*.

Landry, S. P., Pagé, S., Shiller, D. M., Lepage, J. F., Théoret, H., & Champoux, F. (2015). Auditory imagery forces motor action. *NeuroReport*, *26*(3), 101-106.

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Landry, S. P., Shiller, D. M., & Champoux, F. (2013). Short-term visual deprivation improves the perception of harmonicity. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(6), 1503.

Landry, S. P., Guillemot, J. P., & Champoux, F. (2013). Temporary Deafness Can Impair Multisensory Integration A Study of Cochlear-Implant Users. *Psychological science*, *24*(7), 1260-1268.

Landry, S., Lévesque, J., & Champoux, F. (2012). Breaking News: Brain Plasticity an Obstacle for Cochlear Implant Rehabilitation. *The Hearing Journal*, *65*(8), 26-28.

Landry, S., Bacon, B. A., Leybaert, J., Gagné, J. P., & Champoux, F. (2012). Audiovisual segregation in cochlear implant users. *PloS one*, *7*(3), e33113.

PRIX ET BOURSES

2016 – Prix étudiant de rayonnement, *École d'Orthophonie et Audiologie, Université de Montréal.*

2016 – Prix de la meilleure présentation affichée*, International Multisensory Research Forum.*

2016 – Bourse de stage postdoctoral, *Fonds de Recherche du Québec – Santé.*

2015 - Bourse pour participer au « Summer Institute in Neurotechnology Innovation, Commercialization and Entrepreneurship », *Dalhousie University*.

2015 - Audiology/Hearing Science Research Travel Award, *American Speech-Language-Hearing Association*.

2015 - Bourse de déplacement, *Université de Montréal.*

2015 - Mention honorable pour présentation affichée, *Institutes de Recherche en Santé du Canada.*

2014 - Bourse d'études supérieures Frederick Banting and Charles Best, *Institutes de Recherche en Santé du Canada.*

2014 - Prix Brain Vision pour la meilleure présentation par affiche, *22nd Journée Scientifique du Centre de Recherche en Neurophysiologie et Cognition.*

2013 - Bourse de déplacement, *Centre for Research on Brain, Language and Music*

2012 - Bourse de recrutement de la faculté de médecine, *Université de Montréal.*