UNIVERSIDADE FEDERAL DE MINAS GERAIS

PROGRAMA DE PÓS-GRADUAÇÃO EM NEUROCIÊNCIAS

Marília Nunes Silva

Investigações sobre a modularidade do processamento cognitivo musical

Belo Horizonte

2014

UNIVERSIDADE FEDERAL DE MINAS GERAIS

PROGRAMA DE PÓS-GRADUAÇÃO EM NEUROCIÊNCIAS

Marília Nunes Silva

Investigações sobre a modularidade do processamento cognitivo musical

Tese apresentada ao Programa de Pós-graduação em Neurociências da Universidade Federal de Minas Gerais como requisito parcial para obtenção do título de doutor em Neurociências, sob orientação do Prof. Dr. Vitor Geraldi Haase.

Área de Concentração: Neurociência clínica.

Belo Horizonte

2014

A todos aqueles que seguem seu caminho,
mantendo vivos os sonhos dentro de
si mesmos e vislumbrando um
horizonte de possibilidades.

AGRADECIMENTOS

Por mais que a jornada seja individual nós nunca caminhamos sozinhos. Tudo o que produzimos só é possível graças à colaboração de muitas pessoas. Portanto, minha conquista, não só minha, mas sim de todos. É por isso que penso que a parte dos agradecimentos é uma das mais importantes. Sei que posso não contemplar a todos, então incluirei as pessoas que considero chave em minha formação e conclusão do doutorado.

Agradeço primeiramente ao meu professor, orientador e grande mestre Vitor Geraldi Haase. Nesses anos de convivência pude aprender muito com ele. Com certeza minha carreira terá muito dele. De sua postura ética, seu comprometimento e dedicação ao trabalho. Ele nos orienta não somente na pesquisa, mas também em nosso futuro profissional. Se pude estudar o que eu estudo hoje foi graças a ele, que me deu todas as ferramentas para que eu pudesse desenvolver este caminho.

Agradeço à professora Isabelle Peretz, que me deu a oportunidade de trabalhar durante um ano no *International Laboratory for Brain, Music, and Sound Research* (BRAMS). Lá tive acesso ao que tem de mais avançado no estudo de música e neurociências. Aprendi bastante e também pude trocar informações com muitos pesquisadores da área vindos de diversas partes do mundo. Sou grata a Isabelle por ter me aberto esse novo horizonte que foi transformador para mim tanto profissional quanto pessoalmente. Agradeço também à Mihaela e a todos que trabalham no suporte técnico do BRAMS e que não mediram esforços em me auxiliar.

Agradeço à minha família, principalmente aos meus pais, Raimundo e Regina, e aos meus irmãos, Thiago e Gustavo, que sempre estiveram comigo, me apoiando nos momentos mais difíceis e que toleraram minha ausência nestes anos dedicados ao trabalho de pesquisa. Família significa pra mim, um cuidar do outro. Eles que estão mais próximos a mim, que conhecem meus defeitos e qualidades e que sei que estarão comigo mesmo quando ninguém mais estiver. Agradeço de coração por tudo.

Agradeço aos amigos que me proporcionaram momentos de alegria, que me permitiram relaxar em momentos mais difíceis, que me fizeram vislumbrar soluções aonde antes havia problemas. Agradeço aos amigos do kung fu, em especial Bárbara, Igor, Fábio, Karina, Renato e Júlio e aos amigos da música, em especial, Graciela, Natália, Aline, Augusto, Alice, Ernane e Ana Roberta. Agradeço aos amigos do LND, em especial Ricardo Moura, Pedro Pinheiro e Flávia Almeida. Agradeço aos novos amigos que tive o prazer de conhecer no Canadá, em especial, Benjamin Zendel e Dominique Vuvan com os quais aprendi muito, não somente sobre pesquisa mas também sobre o Canadá e a vida.

Agradeço em especial ao Pedro Henrique Santos, Leonardo Araújo e Ana Lana que sempre estiveram ao meu lado na pesquisa em música e neurociências. Trabalhamos muito desde sempre com um interesse comum na área. Organizamos cursos, palestras, eventos culturais, além de poder contar com eles para o desenvolvimento deste trabalho.

Agradeço à Bianca e Marina, da iniciação científica, e à Juliana Bruckner pelo auxílio imprescindível na coleta de dados. Agradeço também à todos os que participaram voluntariamente da pesquisa pela cordialidade e cooperação. Agradeço às coordenadoras das escolas que sempre foram muito solícitas conosco.

Agradeço à Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), por ter me concedido uma bolsa de doutorado durante os três anos de estudo no Brasil, e ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), por ter me contemplado com uma bolsa de doutorado sanduiche, durante o período de um ano em que estive no Canadá. Sem estes subsídios não seria possível realizar a pesquisa.

Agradeço a Deus e à natureza pela vida que, apesar dos desafios e obstáculos, me tem sido muito generosa.

RESUMO

A modularidade é uma das principais questões abordadas dentro da ciência cognitiva. A música, por ser uma função cognitiva complexa, se constitui em um modelo para investigação da hipótese da organização modular do cérebro. As evidências a favor da modularidade do processamento cognitivo musical indicam que as funções musicais fazem parte de um módulo mental distinto, com seu próprio sistema de processamento de informações e substrato neural específico. A presente tese teve por objetivo investigar a hipótese da modularidade do processamento cognitivo musical a partir de uma estratégia multi-método e multi-amostra. Para o desenvolvimento das questões de pesquisa, a tese foi dividida em cinco artigos científicos. O primeiro artigo teve por objetivo investigar as evidências relacionadas à modularidade do processamento musical a partir de uma revisão integrativa. O segundo artigo teve por objetivo verificar as características psicométricas da versão traduzida e adaptada da Montréal Battery of Evaluation of Amusia (MBEA) para o Brasil. O terceiro artigo consiste em uma metanálise com o objetivo investigar a natureza do déficit da amusia congênita, relacionado à codificação musical da frequência de altura a partir do tamanho do efeito da diferença de desempenho entre amúsicos e controles nas tarefas de discriminação de frequência. O quarto artigo teve por objetivo investigar se há associação entre dificuldades do processamento de magnitudes numéricas e de frequência de altura em amúsicos congênitos. O quinto artigo investigou a relação entre o processamento musical e numérico em crianças e adolescentes com Síndrome de Williams (SW). A partir dos estudos realizados pôde-se observar que os resultados encontrados para os amúsicos congênitos de que o déficit de discriminação de frequência de altura se relaciona a déficit acústico geral e de que há associação entre percepção musical e dificuldades em comparação de magnitudes simbólica, bem como a associação encontrada entre senso numérico e percepção musical nas crianças e adolescentes avaliados se constituem em evidências a favor da existência de mecanismos compartilhados ou amodais para o processamento cognitivo musical. Em contrapartida, a dupla dissociação encontrada entre o processamento acústico e o módulo de codificação tonal, e a dissociação entre o processamento de magnitudes nos domínios musical e numérico encontrada nos amúsicos congênitos, bem como o padrão de percepção musical relativamente preservada e senso numérico comprometido em indivíduos com SW fornecem evidências a favor da hipótese da modularidade do processamento cognitivo musical. Mesmo que possa haver processos de modularização para o sistema de processamento musical durante o período de desenvolvimento estes processos poderiam ser moldados pela seleção natural de modo a produzir resultados funcionalmente organizados e com função evolutiva específica.

Palavras-chave: Modularidade, Amusias, MBEA, Processamento musical, Processamento numérico, Síndrome de Williams.

ABSTRACT

Modularity is one of the main issues in cognitive science. Because music is a complex cognitive function, it constitutes in a model for investigating the hypothesis of brain modular organization. Evidence in favor of modularity of musical cognitive processing indicate that musical functions are part of a distinct mental module with its own information processing system and specific neural substrate. This thesis aimed to investigate the hypothesis of modularity of musical cognitive processing from a multi-method and multi-sample strategy. For the development of research questions, this thesis was divided into five scientific papers. The first paper aimed to investigate the evidence related to the modularity of musical processing from an integrative review. The second paper aimed to verify the psychometric properties of the translated and adapted version of MBEA to Brazil. The third paper consists in a meta-analysis that aimed to investigate the nature of the deficit in congenital amusia, related to the musical encoding of pitch, from the effect size of the difference in performance between amusics and controls in pitch discrimination tasks. The fourth paper aimed to investigate whether there is an association between difficulties in processing numerical and pitch magnitudes in congenital amusics. The fifth paper investigated the relationship between musical and numerical processing in children and adolescents with Williams syndrome (WS). The fifth paper investigated the relationship between musical and numerical processing in children and adolescents with Williams syndrome (WS). From studies conducted, constitute evidence for the existence of shared or amodal mechanisms for cognitive music processing: 1) the relation of pitch discrimination deficit with a general acoustical deficit in congenital amusics; 2) the association observed between music perception and difficulties in symbolic magnitudes comparison in congenital amusics and; 3) the association observed between number sense and music perception in children and adolescents. In contrast, constitute evidence for the hypothesis of the modularity of musical cognitive processing: 1) the double dissociation found between the acoustic processing and tonal encoding module in congenital amusics; 2) the dissociation found in the magnitude processing between numerical and musical domains in congenital amusics and; 3) the pattern of musical perception relatively preserved and compromised number sense in individuals with WS. Even though there may be processes of modularization for music cognitive system during the development, these processes could be shaped by natural selection to produce functionally organized results with particular evolutionary function.

Key words: Modularity, Amusias, MBEA, Musical processing, Numerical processing, Williams Syndrome.

CENTROS DE PESQUISA

O trabalho foi realizado em dois diferentes centros de pesquisa listados a seguir:

1) Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, Minas Gerais, Brasil: a) Programa de Pós-Graduação em Neurociências, Instituto de Ciências Biológicas e, b) Laboratório de Neuropsicologia do Desenvolvimento (LND), Departamento de Psicologia. Trabalho realizado sob orientação do professor Dr. Vitor Geraldi Haase e com bolsa de doutorado CAPES-REUNI, subsidiada pela Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) dentro do Programa de Apoio a Planos de Reestruturação e Expansão das Universidades Federais (REUNI).

2) Université de Montréal, Montréal (UdeM), Quebéc, Canadá: Département de psychologie, International Laboratory for Brain, Music and Sound Research (BRAMS). Trabalho realizado sob orientação do professor Dr. Vitor Geraldi Haase e supervisão da professora PhD. Isabelle Peretz e com bolsa de doutorado sanduiche financiada pelo Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

LISTA DE ILUSTRAÇÕES

LISTA DE TABELAS

5. ESTUDO V: Investigação da relação entre o processamento musical e o processamento numérico na Síndrome de Williams.

LISTA DE GRÁFICOS

LISTA DE ABREVIATURAS E SIGLAS

9-HTP	*Nine Hole Peg Test*
ABSW	Associação Brasileira de Síndrome de Williams
ANOVA	*Analysis of variance*
ANS	*Approximate number system*
ATOM	*A Theory of Magnitude*
BRAMS	*International Laboratory for Brain, Music and Sound Research*
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
CNPq	Conselho Nacional de Desenvolvimento Científico e Tecnológico
DP	Desvio padrão
DTI	*Diffusion tensor imaging*
EFA	*Exploratory factor analysis*
e.g	*exempli gratia*, por exemplo
FA	*False alarm*
fMRI	*Functional magnetic resonance imaging*
GH	Giro de Heschl
HIPS	Segmento horizontal do sulco intraparietal
i.e.	*id* est, isto é
IC	Idade cronológica
IM	Idade mental
IPS	*Intraparietal sulcus*, sulco intraparietal
JND	*Just noticeable difference*
K-R20	*Kuder-Richardson Formula 20*
KMO	*Kaiser-Meyer-Olkin test*
LILACS	Literatura Latino-Americana e do Caribe em Ciências da Saúde
LND	Laboratório de Neuropsicologia do Desenvolvimento
M	Média
MBEA	*Montréal Battery of Evaluation of Amusia*
MBEMA	*Montréal Battery of Evaluation of Musical Abilities*
MD	Mão dominante
ML	*Maximum-likelihood*
MMN	*Mismatch Negativity*

MND	Mão não dominante
MRI	*Magnetic resonance imaging*
ms.	*Millisecond*
PASW	*Predictive Analytics SoftWare*
PCD	*Pitch change detection task*
QI	Quociente de inteligência
RAN	*Rapid automatized naming*
REML	*Restricted maximum-likelihood*
RT	*Reaction time*
SciELO	*A Scientific Electronic Library Online*
SD	*Standard Deviation*
SE	*Standard error*
SMARC	*Spatial-Musical Association of Response Codes*
SNARC	*Spatial-Numerical Association of Response Codes*
SW	Síndrome de Williams
TDE	Teste de desempenho escolar
TNVA	Transtorno não-verbal de aprendizagem
UdeM	Université de Montréal
UFMG	Universidade Federal de Minas Gerais
VBM	*voxel-based morphometry*
vs.	*versus*, contra
w	*Weber`s fraction*
WAIS-III	Escala de inteligência Wechsler para adultos
WISC-III	Escala de inteligência Wechsler para crianças

SUMÁRIO

1. INTRODUÇÃO

O estudo da música a partir de uma perspectiva neurocientífica tem recebido cada vez mais atenção por parte de pesquisadores de diferentes áreas, tais como a psicologia, a música e a biologia (Levitin & Tirovola, 2009). Dentro deste contexto a música não é considerada somente uma atividade artística e social, mas também uma função cognitiva complexa. Nos últimos anos, os estudos sobre o processamento cognitivo musical e suas bases neuroanatômicas tiveram consideráveis avanços que permitiram a evolução de seu conhecimento teórico e dos construtos a ele relacionados (Stewart, Kriegstein, Warren, & Griffiths, 2006). A percepção e a execução musical têm fundamentos biológicos (Peretz, 2006) e há evidências de que o processamento musical se constitua em um domínio cognitivo específico, com redes neurais especializadas (Zatorre, 2001; Peretz, 2003; Peretz & Coltheart, 2003). Por se tratar de uma função cognitiva complexa, o estudo do processamento musical pode fornecer insights também para a compreensão de outras funções cognitivas e das redes neurais envolvidas no funcionamento cerebral de alta ordem.

Estudos utilizando técnicas de neuroimagem e estudos sobre indivíduos com déficits seletivos de habilidades musicais contribuíram para a compreensão dos mecanismos subjacentes ao processamento musical evidenciando sua complexidade e levantando a hipótese da organização modular da música no cérebro. De acordo com Peretz e Coltheart (2003), nesta perspectiva, as habilidades musicais fazem parte de um módulo mental distinto composto por subsistemas de processamento, cujos domínios são restritos a aspectos particulares da música. Sendo assim, uma anomalia neurológica pode tanto danificar um ou mais componentes de processamento musical quanto interferir na passagem de informações entre eles.

Os déficits seletivos de habilidades musicais são agrupados sob o termo amusias e podem afetar tanto o reconhecimento quanto a reprodução das melodias ou de seus componentes (altura, intensidade, timbre, duração e harmonia). As amusias podem ser de dois tipos: a amusia adquirida, como consequência de doenças ou lesões cerebrais; e a amusia congênita, presente desde o nascimento e que pode ocorrer devido a fatores hereditários (Hyde & Peretz, 2004; Peretz, Cummings, & Dubé, 2007). Os estudos realizados com indivíduos amúsicos favoreceram a construção de modelos úteis para a compreensão e avaliação dos componentes envolvidos no processamento musical, tais como o que será abordado no primeiro artigo desta tese, o qual foi desenvolvido por Isabelle Peretz (Peretz & Coltheart, 2003) e especifica a arquitetura do sistema de processamento musical.

Outros modelos cognitivos foram propostos para elucidar os componentes do processamento musical não somente em indivíduos que sofreram lesões cerebrais como também em indivíduos sem alterações neurológicas. Warren (2008), por exemplo, propôs um esquema de organização do cérebro musical, ou seja, das áreas e mecanismos envolvidos na percepção e compreensão da música pelo ouvinte típico que sugere como os componentes do processamento musical se relacionam tanto funcionalmente quanto anatomicamente. Neste esquema, indicado na Figura 1, a música, enquanto um estímulo auditivo complexo, segue uma organização hierárquica anatômica e funcional com componentes acústicos mais básicos (frequência fundamental, sons harmônicos, duração e intensidade) sendo codificados primeiro, passando por estágios sucessivos de processamento das características perceptuais, acessando o conhecimento e memória musical armazenado, importando informações de outros domínios e, por fm, elaborando a resposta comportamental. A música é processada inicialmente nas vias auditivas ascendentes, nas quais são codificadas as estruturas acústicas elementares como, por exemplo, no caso da altura, a energia de uma onda de frequência específica. Já a altura, considerada enquanto percepto e resultante dos padrões totais do sinal acústico, é processada em regiões corticais.

De acordo com Warren (2008), os padrões perceptuais são inicialmente processados no córtex auditivo primário localizado na parte medial do giro de Heschl (GH), na porção superior do lobo temporal dentro da fissura lateral. Em torno do GH estão redes de áreas corticais de alta hierarquia que processam propriedades específicas dos sons complexos, representadas pelos lobos temporal, frontal e parietal. O *planum temporale* fica localizado posteriormente em relação ao GH, sendo uma área de associação auditiva implicada na análise de atributos como localização espacial, características identificáveis tais como sílabas e timbres de vozes e instrumentos. O giro temporal superior é anterior ao GH e participa da análise de fluxos de informação auditiva (fala e melodia). A identificação de melodias familiares envolve a ínsula e áreas adjacentes à porção anterior do lobo temporal. Os lobos parietal e temporal fazem a associação entre a informação auditiva e de outras modalidades sensoriais, principalmente a visão. Já a memória de trabalho para música e respostas ao som são mediadas por circuitos dos lobos frontal e parietal. Portanto, várias regiões cerebrais, que se relacionam em uma hierarquia funcional, estão envolvidas no processamento dos componentes musicais.

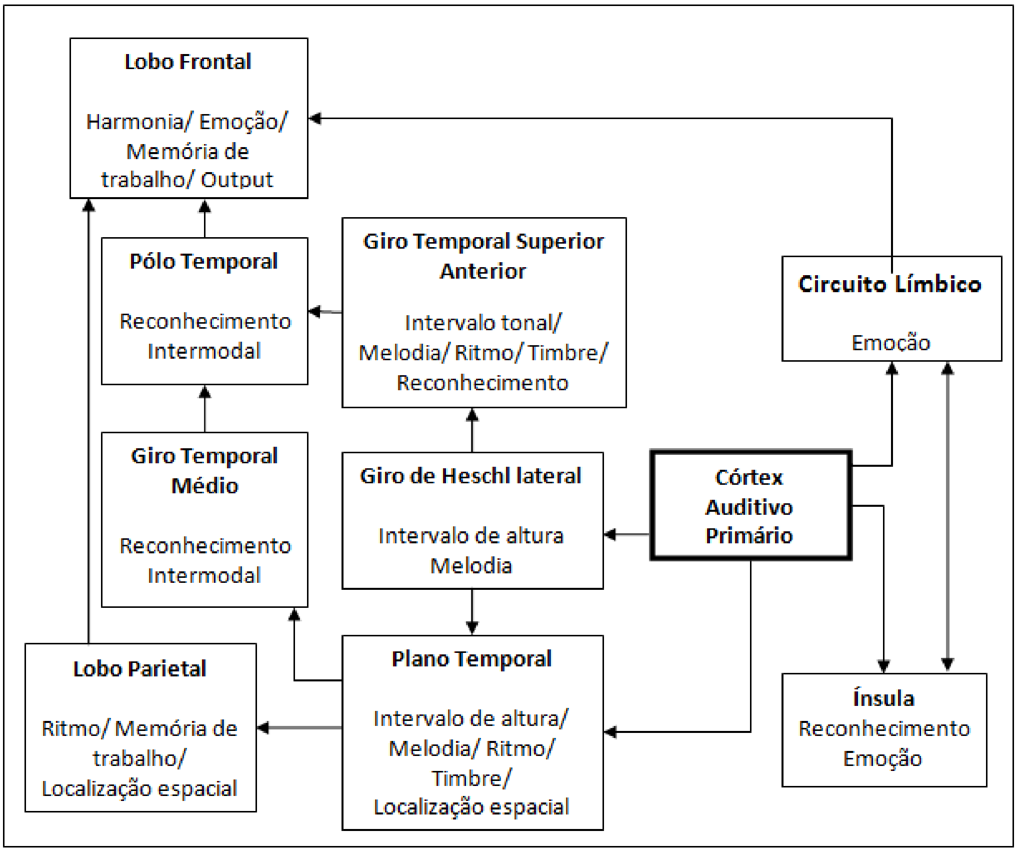

FIGURA 1. Esquema relacionando as áreas e mecanismos envolvidos na percepção e compreensão musical (adaptado de Warren, 2008).

Evidências recentes de estudos voltados para a especialização cerebral em música advêm também de pesquisas realizadas com distúrbios congênitos de habilidades musicais (Peretz, 2003). A amusia congênita, só tem sido sistematicamente investigada recentemente (Ayotte, Peretz, & Hyde, 2002) e é definida como uma incapacidade vitalícia para o processamento musical, a despeito de habilidades normais de inteligência, memória e linguagem (Hyde e Peretz, 2004). Estudos recentes sobre a amusia congênita mostram evidências de alterações estruturais e funcionais do giro temporal superior e da porção inferior do córtex frontal, que indicam a ocorrência de conectividade anormal entre essas áreas (Peretz, Brattico, & Tervaniemi, 2005; Hyde, Zatorre, Griffiths, Lerch, & Peretz, 2006; Hyde, Lerch, Zatorre, Griffiths, Evans, & Peretz, 2007; Mandell, Schulze, & Schlaug, 2007). Estudos utilizando potencial evocado de longa latência relacionado a evento também evidenciam que a atividade elétrica do córtex auditivo de amúsicos é intacta e que os padrões de alterações eletrofisiológicas encontrados se localizam provavelmente ao longo de vias fora do mesmo, indicando que os amúsicos apresentam capacidade quase normal de detectar desvios tonais sem, no entanto, estarem conscientes disso (Peretz *et al*., 2005; Peretz, Brattico, Järvenpää, & Tervaniemi, 2009). Loui, Alsop e Schlaug (2009) identificaram, a partir de um estudo de neuroimagem utilizando tractografia de difusão, anormalidades da substância branca no cérebro de amúsicos com redução no volume e alterações na estrutura do fascículo arqueado (trato de fibras que liga o córtex temporal ao córtex frontal inferior), principalmente no hemisfério direito. A redução de volume correlacionou-se com maior grau de incompatibilidade (*mismatch*) entre a percepção e produção do som musical, medida através de testes psicofísicos de discriminação da altura (Loui *et al.,* 2009).

Em um estudo utilizando estimulação direta transcraniana (*transcranial direct current stimulation* – TDCS), uma técnica de intervenção ativa e não-invasiva de estimulação cerebral, Loui, Hohmann, & Schlaug (2010) observaram redução na acurácia da percepção da altura do som após a estimulação das áreas frontal inferior e temporal superior em indivíduos normais, demonstrando que a função e conectividade intactas entre estas duas áreas são necessárias para a percepção das alterações melódicas. Hyde, Zatorre e Peretz (2011), por sua vez, utilizando imagem de ressonância magnética (IRM) em tarefas de audição de sequências melódicas montadas com tons puros, nas quais a distância entre tons consecutivos variava parametricamente, mostraram que a atividade cerebral aumentava com a distância entre os tons no córtex auditivo direito e esquerdo de amúsicos e controles. Em contraste, o giro frontal inferior direito mostrou baixa atividade e evidência de redução da conectividade com o córtex auditivo nos amúsicos, em comparação com os controles. Todos estes estudos têm levantado evidências para sustentar a hipótese de que a amusia congênita constitui-se em uma síndrome de desconexão entre o córtex auditivo direito e o giro frontal inferior direito.

As amusias podem ser avaliadas a partir de baterias de testes como a *Montreal Battery of Evaluation of Amusia* (MBEA) e através de testes psicofísicos de discriminação da altura com limiar superior a meio semitom (Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Loui, Guenther, Mathys, & Schlaug, 2008). A MBEA é uma bateria de testes que avalia habilidades musicais referentes a seis componentes do processamento musical (contorno, escala, intervalo, ritmo, métrica e memória musical) e permite o diagnóstico de diferentes amusias. O desenvolvimento da MBEA foi norteado pelo modelo cognitivo-neuropsicológico do processamento musical proposto por Isabelle Peretz (Peretz, Champod, & Hyde, 2003). A MBEA foi traduzida e adaptada para a população brasileira a partir de um estudo realizado com adolescentes de 14 a 18 anos da cidade de Belo Horizonte do estado de Minas Gerais (Nunes, C. Loureiro, M. Loureiro & Haase, 2010).

De acordo com Sloboda, Wise e Peretz (2005), a amusia congênita se revela como um transtorno de aprendizagem musical, sem nenhuma dificuldade neurológica ou cognitiva associada, que aparece precocemente e persiste até a idade adulta. Apesar disto, quase não há estudos sistemáticos sobre a amusia em crianças. Um estudo sistemático foi realizado por Lebrun, Moreau, McNally-Gagnon, Goulet e Peretz (2012), no qual é descrito um caso documentado de amusia congênita na infância em uma menina de 10 anos (AS). AS apresentou um perfil semelhante ao de adultos com amusia congênita, obtendo resultados baixos para memória e percepção melódica e rítmica em uma versão para crianças da MBEA, a despeito de prática musical regular e resultados normais de audiometria, inteligência, linguagem e atenção. Ao contrário de amúsicos adultos, AS apresentou alterações na resposta cerebral elétrica para pequenas mudanças de frequência (25 cents, que corresponde a um quarto de semitom), apontadas pelo *Mismatch Negativity* (MMN), o que pode indicar, segundo os autores, que há um atraso de maturação do córtex auditivo, sugerindo que há diferença entre o perfil do amúsico em desenvolvimento e o fenótipo estável do amúsico adulto. A amusia congênita pode se figurar, portanto, como um transtorno de aprendizagem específico para a música.

Estudos realizados tanto com indivíduos normais, músicos e não músicos, quanto com indivíduos amúsicos também permitem uma maior compreensão, não somente das bases neuroanatômicas do processamento musical, como também de sua especificidade ou, em contrapartida, dos mecanismos compartilhados com outras funções cognitivas. Pesquisas utilizando neuroimagem indicam que há diferenças entre o cérebro do músico e do não músico, em relação à lateralização (músicos têm maior ativação do hemisfério esquerdo) e diferenças em regiões cerebelares e calosas e em áreas somatosensoriais, motoras e auditivas (Gaser & Schlaug, 2003; Amunts, et al., 1997; Schlaug, Jancke, Huang, Staiger, & Steinmetz, 1995; Schneider, Scherg, Dosch, Specht, Gutschalk, & Rupp, 2002; Hutchinson, Lee, Gaab, & Schlaug, 2003). Estudos demonstram que músicos podem apresentar desempenho superior a não músicos em tarefas de memória verbal, tarefas visuoespaciais, de atenção, além de produção mais rápida de movimentos sacádicos (Brochard, Dufour, & Despres, 2004; Sluming, Howard, Downes, & Roberts, 2007; Brandler & Rammsayer, 2003). Além da investigação das diferenças funcionais, estruturais e comportamentais entre músicos e não-músicos a relação entre música e outras funções cognitivas têm sido investigada também por estudos que relacionam o treinamento musical com o desenvolvimento de outras habilidades cognitivas, tais como verbais, visuoespaciais, consciência fonológica, leitura, inteligência e habilidades matemáticas (Hetland, 2000; Vaughn, 2000; Anvari, Trainor, Woodside, & Levy, 2002; Ho, Cheung, & Chan, 2003; Schellenberg, 2006). Estes estudos também contribuem para compreensão de quais mecanismos do processamento musical são específicos e quais são compartilhados.

Especificamente considerando a relação entre música e matemática, os estudos são escassos e geralmente visam testar a hipótese de que o treinamento musical pode melhorar o desempenho em tarefas matemáticas (Vaughn, 2000). Em uma busca realizada em março de 2013 nos bancos de dados da *PubMed*, com os termos "music" ou "amusia" e "arithmetic" ou "dyscalculia" ou "mathematical learning disability", não foram encontrados estudos que tivessem como objetivo investigar se há alguma relação entre os déficits de cada um destes domínios, a partir da avaliação do processamento musical em indivíduos com transtorno de aprendizagem na matemática, ou, em outra via, da avaliação do processamento numérico de indivíduos amúsicos.

O transtorno de aprendizagem da matemática, também denominado discalculia, é um transtorno específico deste domínio, de provável etiologia neurogenética, que ocorre a despeito de nível de inteligência normal e oportunidade de aprendizagem escolar adequada (Butterworth, 2005; Geary, 2011). Em relação aos mecanismos cognitivos propostos para caracterizar a discalculia e déficits associados, há duas abordagens principais (Mazzocco, Feigenson, & Halberda, 2011). A primeira é a de domínio geral, que defende que os déficits subjacentes não são especificamente relacionados à aprendizagem matemática, mas sim resultantes de disfunções de sistemas cognitivos gerais, tais como memória de trabalho, memória de longo prazo e processamento visuoespacial (Geary, 2011). A segunda é a abordagem de domínio específico, cujos déficits são associados a disfunções do processamento numérico ou do senso numérico, que é a capacidade de perceber e se adaptar à quantidade de objetos de um determinado conjunto e está associado a um substrato neural específico (Dehaene, Piazza, Pinel, & Cohen, 2003; Butterworth, 2005; Wilson & Dehaene, 2007).

De acordo com Wilson e Dehaene (2007), os déficits da discalculia do senso numérico, relacionados à representação analógica de magnitudes, são associados a prejuízos funcionais e estruturais do segmento horizontal do sulco intraparietal (HIPS). Estudos evidenciam também o envolvimento do sulco intraparietal (IPS) em diferentes tarefas relacionadas ao processamento de magnitudes numéricas (Dehaene, Piazza, Pinel, & Cohen, 2003; Hubbard, Piazza, Pinel, & Dehaene, 2005). Porém, o IPS pode estar relacionado não somente a magnitudes numéricas. Dados de neuroimagem mostrando padrões de ativação compartilhados para diferentes magnitudes fornecem evidências convergentes para a existência de um mecanismo geral para o processamento de magnitudes no sulco intraparietal (Fias et al. 2003, Kadosh et al., 2005). Walsh (2003) também argumenta a favor da existência de um mecanismo comum para o processamento de magnitudes e propõem a teoria da magnitude (ATOM), na qual espaço, tempo e quantidade fazem parte de um sistema de magnitude generalizado. De acordo com estes pressupostos, tarefas que envolvem um componente de discriminação de magnitudes, independente da modalidade sensorial, ativariam o sulco intraparietal, o qual poderia ser considerado como uma região cerebral especializada no processamento amodal de magnitudes.

Estudos utilizando estímulos musicais, principalmente altura (*pitch*), têm mostrado que o IPS pode desempenhar um papel importante no processamento de magnitudes e manipulação das informações relacionadas a estes estímulos (Schwenzer e Mathiak, 2011; Foster e Zatorre, 2010), sugerindo que o processamento de identificação de alturas no domínio auditivo possa estar relacionado ao processamento de numerosidade no domínio visual. Estudos comportamentais também evidenciam efeitos similares aos dos estímulos numéricos para os estímulos musicais. São observados muitos paralelos entre os desempenhos comportamentais em tarefas de discriminação envolvendo magnitudes numéricas, não-numéricas e percepção de altura (Rusconi et al., 2006; Cohen Kadosh, Lammertyn, & Izard, 2008; Cohen Kadosh, Brodsky, Levin & Henik, 2008; Bonn & Cantlon, 2012).

A despeito de evidências que sugerem haver uma relação entre o processamento de magnitudes numéricas e de magnitudes de altura, uma dissociação entre os domínios de processamento musical e de processamento numérico parece ocorrer na Síndrome de Williams (SW). A SW é um transtorno genético do desenvolvimento caracterizada por retardo mental leve a moderado, dismorfias faciais, anormalidades nos sistemas cardiovascular, musculoesquelético e gastrointestinal e um perfil cognitivo constituído de habilidades sociais, musicais, verbais e de reconhecimento de faces relativamente preservadas, e de habilidades visuoespaciais e numéricas comprometidas (Levitin & Bellugi, 1998; Mervis *et al.*, 2000; Paterson & Schultz, 2007). Indivíduos com SW apresentam déficits na representação de magnitudes numéricas (Paterson, Girelli, Butterworth & Karmiloff-Smith, 2006, Ansari, Donlan & Karmiloff-Smith, 2007), mas por outro lado, parecem apresentar habilidades musicais preservadas (Levitin & Bellugi, 1998, Levitin *et al.*, 2004, Levitin, 2005). Isto indica que pode haver, em determinado nível, uma dissociação entre os domínios de processamento musical e de processamento numérico na SW.

Dentro deste contexto, a presente tese teve por objetivo investigar a hipótese da modularidade e especificidade do processamento cognitivo musical, abordando as bases teóricas da modularidade do processamento cognitivo musical, a avaliação das habilidades e déficits do processamento musical e a relação entre a cognição musical e outros domínios cognitivos, tais como o processamento acústico e a cognição numérica. O presente trabalho constitui-se em uma tese de doutorado elaborada dentro do Programa de Pós-graduação em Neurociências da Universidade Federal de Minas Gerais (UFMG). Espera-se que os resultados obtidos nesse trabalho sirvam para as seguintes finalidades: 1) contribuir para a maior compreensão do processamento cognitivo musical em geral, das características de seu desenvolvimento e dos déficits de habilidades musicais; 2) fornecer instrumentos validados para a avaliação da percepção musical e diagnóstico dos déficits relacionados ao processamento musical; 3) possibilitar uma maior compreensão da natureza do déficit na amusia congênita; 4) contribuir para elucidação da relação entre funções musicais e outras funções cognitivas, no caso a cognição numérica; 5) auxiliar na caracterização do perfil neuropsicológico musical de crianças e adolescentes com SW; 6) contribuir para o aperfeiçoamento de medidas terapêuticas coadjuvantes que utilizam a música, tais como a musicoterapia 7) fornecer subsídios teórico-metodológicos para a educação musical e medidas educacionais que se utilizem da música para treinamento de habilidades matemáticas.

1.1. Questões de pesquisa

A modularidade mental refere-se à noção de que a mente é composta por múltiplos processos distintos e não de somente um processo geral e indiferenciado. A modularidade é uma das principais questões abordadas dentro da ciência cognitiva sendo alvo de intensos debates nas últimas décadas (Barrett & Kurzban, 2006). O conceito de modularidade em ciência cognitiva remonta à publicação do livro *The Modularity of Mind* escrito por Fodor (1983), que propõe, a partir de uma perspectiva inatista, uma alternativa à visão interacionista da arquitetura cognitiva, que era dominante na época. Fodor (1983) introduz o conceito de processos psicológicos verticais e modulares, diferenciando-os dos processos horizontais (i.e. memória, julgamento), e questionando a ideia de continuidade entre percepção e cognição proposta pelos cognitivistas da época, que pressupõe que toda a informação prévia está disponível para a execução da integração perceptual. Para Fodor, a tese principal da modularidade é a de que a integração perceptual é realizada por sistemas computacionais informacionalmente encapsulados. Isto quer dizer que o sistema modular não tem completo acesso às expectativas, crenças, suposições e desejos do indivíduo, pois deve garantir a velocidade de processamento da informação e a automação. Portanto, de acordo com Fodor (1983), para um sistema ser considerado modular, as seguintes características devem ser observadas: 1) especificidade de domínio, na qual as operações mentais não atravessam outros domínios de conteúdo; 2) inatismo, que corresponde à extensão em que a estrutura pode ser considerada inata ou é desenvolvida a partir da aprendizagem; 3) não são montados (*not assembled*), ou seja, não são resultado da agregação de subprocessos mais elementares; 4) são pré-programados (*hardwired*), ou seja desenvolvidos para trabalhar de maneira especializada e relacionados a uma rede neural específica, localizada e estruturada; 5) são autônomos, ou seja, não compartilham recursos, tais como memória e atenção, com outros sistemas cognitivos.

A análise sobre a modularidade cognitiva proposta por Fodor (1983) teve uma grande influência sobre os trabalhos posteriores em ciência cognitiva, mas também foi alvo de mal-entendidos, principalmente em relação às características principais propostas por Fodor para os sistemas modulares. Apesar da observação das características principais propostas por Fodor ser importante para se considerar um sistema como modular, muitos subtendidos ocorreram ao se tomar todas estas características como condições necessárias para a modularidade do sistema. Ponderando sobre estes mal-entendidos, Coltheart (1999) propõem, a partir do trabalho de Fodor, uma definição reformulada do conceito de modularidade no contexto da neuropsicologia cognitiva, e argumenta que a principal característica e condição necessária para um sistema ser modular é a especificidade de domínio, na qual o sistema só responde a um determinado tipo de *input*. Coltheart evidencia que as outras características propostas por Fodor não são absolutamente necessárias para definir o termo modular, sendo que o sistema, por exemplo, pode ser modular mas não inato, tal como o sistema de leitura. O autor sugere que as características propostas deveriam ser consideradas como questões empíricas a serem consideradas para cada módulo. Além disso, Coltheart argumenta que a presença de *top-down feedback* nos módulos não violaria a característica de encapsulação de informação, uma vez que não interfere em sua implicação principal que é a de permitir aos módulos processarem rapidamente os *inputs* recebidos. Adicionalmente, o tipo de informação a que o módulo não teria acesso seriam as crenças, desejos e suposições do indivíduo. O autor também indica que a característica do módulo de não ser agregado não foi totalmente desenvolvida por Fodor. De acordo com Coltheart, a ideia geral de que os módulos poderiam ter subníveis de representação que comunicam entre si não violaria o princípio de encapsulação da informação, assim como

Fodor (1983) já havia sugerido ao identificar dentro dos módulos, níveis distintos de processamento que comunicam entre si. Deste modo, dentro do contexto da neuropsicologia cognitiva, o conceito de modularidade foi adotado como base para a construção de modelos cognitivos-neuropsicológicos que buscam compreender o processamento cognitivo de indivíduos com desenvolvimento típico e dos padrões de déficits congênitos e adquiridos de vários domínios cognitivos. As características propostas por Fodor são consideradas como questões empíricas a serem testadas para cada módulo, e este pode conter subníveis de representação que comunicam entre si.

A abordagem inatista da modularidade dos sistemas cognitivos, portanto, busca identificar os comprometimentos de módulos específicos e estuda as duplas-dissociações observadas a partir dos padrões de habilidades comprometidas e preservadas. Como consequência, esta abordagem inatista da modularidade acaba por subestimar o papel dos processos de desenvolvimento na formação da arquitetura cerebral. Esta crítica é evidenciada principalmente por Karmiloff-Smith (1995), que adota uma visão neoconstrutivista da modularidade, mas levando-se em conta as predisposições inatas do indivíduo. A autora considera o desenvolvimento como uma construção ativa a partir da interação entre genes, cérebro, comportamento e ambiente. Nesta visão, o desenvolvimento da mente não partiria de módulos pré-especificados, mas envolveria um processo gradual de modularização. Karmiloff-Smith (1998) argumenta que a especificidade de domínio inata seria uma característica chave do desenvolvimento humano. Porém esta característica seria apenas um ponto de partida para o módulo e poderia ser considerada inicialmente como domínio-relevante, somente tornando-se domínio-específico a partir dos processos de desenvolvimento e de determinadas interações ambientais, sendo resultado do processamento de diferentes tipos de *inputs*.

Thomas e Karmiloff-Smith (2002) ressaltam que o conceito de modularidade ainda é controverso, havendo divergências sobre o que seria a propriedade principal do módulo. Além disso, afirmam que a utilização de modelos cognitivos explicativos dos déficits adquiridos em adultos com desenvolvimento típico para avaliar e identificar componentes preservados ou comprometidos em indivíduos com transtornos do desenvolvimento não levaria em conta os processos ocorridos durante um desenvolvimento atípico e as diferenças entre os dois tipos de sistemas, uma vez que pressupõe que os módulos são pré-determinados. Como os transtornos do desenvolvimento envolvem um dano anterior à aprendizagem, Thomas e Karmiloff-Smith consideram que os processos do desenvolvimento seriam o componente chave para explicar o estado final do desenvolvimento nestes transtornos e que os esquemas conexionistas seriam uma ferramenta mais útil para modelar o desenvolvimento humano e seus transtornos, uma vez que, ao contrário dos déficits adquiridos que ocorrem por lesões no sistema maduro, aparecem durante problemas no desenvolvimento. Karmiloff-Smith (1998) argumenta que, nestes casos, as causas dos comprometimentos comportamentais seriam provavelmente encontradas em propriedades computacionais de baixo nível, e que os genes não codificariam diretamente os módulos de alto-nível. Sendo assim, o desenvolvimento atípico da estrutura modular emergente não seria o mesmo de um caso adulto típico. Mesmo que um dano precoce seja limitado a um componente específico, se a estrutura modular é dependente dos processos de desenvolvimento, compensações podem ocorrer no sistema, alterando a função de componentes previamente intactos. Portanto, o desenvolvimento por ele mesmo, desempenharia um papel crucial nos resultados fenotípicos observados nos transtornos do desenvolvimento. Como os módulos aparecem tarde no desenvolvimento seria esperado que fossem encontrados déficits de desempenho que não são ligados à um domínio em particular, mas que são preferencialmente espalhados por toda uma gama de diferentes tipos de prejuízos no desempenho.

Outros autores também levam em conta a relação entre a limitação genética e os padrões emergentes da experiência ao longo do desenvolvimento na organização cerebral e funções cognitiva mas situam a modularidade dentro do contexto evolucionário. Geary & Huffman (2002), por exemplo, a partir de uma revisão teórica de estudos genéticos e neurobiológicos sobre a arquitetura cerebral e considerando os níveis neural, perceptual, cognitivo e funcional, argumentam que os graus de limitação e de abertura à modificação pela experiência são o resultado evolutivo dos padrões de informação invariantes (informações confiáveis e consistentes sobre as condições da espécie e do ambiente, com grau de continuidade entre diferentes espécies) e variantes (informações inconstantes, que podem mudar durante o tempo de vida e entre diferentes gerações) respectivamente, que covariaram com a sobrevivência ou reprodução durante a história evolutiva das espécies. Portanto, a evolução dos sistemas cognitivos modulares limitados geneticamente é favorecida pelos benefícios de um processamento rápido e eficiente dos padrões de informação invariantes e o custo potencial de não atender a estes padrões ou não diferenciá-los de padrões irrelevantes. Ao contrário, uma organização aberta à modificação pela experiência implicaria em uma alta habilidade para adaptar a mudanças nos padrões de informação (Geary & Huffman, 2002). Além disso, os autores propõem tipos de modularidade suave (*soft modularity*), nos quais a plasticidade cerebral e cognitiva seria uma adaptação específica da espécie com função de acomodar a variabilidade das condições sociais e ecológicas, porém dentro das restrições dos sistemas prévios e comuns entre diferentes espécies.

Por sua vez, Barrette e Kurzban (2006) também consideram a compatibilidade entre as visões evolucionária e modularista e, além disso, defendem a tese da modularidade maciça, na qual considera-se, contrariamente à visão de Fodor (1983) de que só os sistemas periféricos poderiam ser considerados modulares, que os processos centrais, tais como os sistemas subjacentes ao raciocínio, julgamento e tomada de decisão, também poderiam ser considerados modulares. A modularidade maciça argumenta que a cognição opera a partir de módulos, não havendo um processador central geral. Os autores se propõe a avançar o debate sobre a visão moderna de modularidade analisando suas críticas e elucidando os pontos principais para debates futuros. Para os autores, o conceito de modularidade deve ser fundamentado na noção de especialização funcional, no sentido de que, para realizar suas funções especializadas, os módulos operariam em apenas determinados tipos de *inputs* ou *inputs* privilegiados relevantes para essa função. A especificidade de domínio seria uma consequência necessária desta especialização funcional e os domínios seriam individualizados pelas propriedades formais da representação. Isso implica em que, mesmo sendo modular, um sistema pode receber mais de um tipo de *input*, e que até mesmo os sistemas não periféricos, como a memória de trabalho por exemplo, poderiam ser considerados modulares. Portanto, os autores abordam a modularidade tendo por foco o *input* e a função e consideram principalmente as operações específicas desempenhadas pelos módulos sobre as informações recebidas.

Para Barrette e Kurzban (2006), os módulos evoluem a partir de um processo de descendência com modificação, sendo que os sistemas de desenvolvimento também são incluídos dentro da perspectiva evolucionária. Neste contexto, os sistemas de desenvolvimento, incluindo processos interativos e dinâmicos que ocorrem neste período, são moldados pela seleção natural de modo a produzir resultados funcionalmente organizados, da mesma maneira que promoveram a sobrevivência e a reprodução no ambiente natural associados a problemas adaptativos enfrentados por nossos ancestrais. Para os autores, os sistemas modulares também lidam com estímulos novos e permitem que estes estímulos sejam agregados e combinados de novas maneiras. Consequentemente, as arquiteturas modulares de nível mais alto, tais como a leitura, seriam provavelmente representações dos processos de desenvolvimento geradores de módulos destinados inicialmente para outras funções. Sendo assim, Barrette e Kurzban contrapõem o argumento de Karmiloff-Smith (1998) de que o desenvolvimento por si só contribuiria para a constituição dos módulos, e afirmam que todos os módulos teriam uma origem evolutiva. O papel da seleção natural seria moldar o critério de *input* de modo que o módulo processe *inputs* de determinados domínios de uma maneira confiável, sistemática e especializada. Qualquer estímulo que preenchesse o critério do *input*, mesmo que não estivesse presente no ambiente natural, poderia ser processado pelo sistema modular. Portanto, os autores consideram que a modularidade providencia esquemas úteis para direcionar pesquisas e debates sobre os sistemas cognitivos individuais e sobre a evolução da cognição humana.

Apesar do debate constante, há ainda muitas questões em aberto sobre o estudo da modularidade mental. Entre inatistas e interacionistas há controvérsias sobre o que poderia ser considerado de domínio geral e o que seria de domínio específico. Mesmo entre os inatistas há discussões sobre o grau de modularidade, variando-se de poucos módulos mais generalistas até muitos módulos altamente especializados. Dentro deste contexto, a música, por ser uma habilidade cognitiva complexa com função específica, se constitui em um excelente modelo para investigação da hipótese da organização modular do cérebro. As evidências sobre a modularidade e especificidade do processamento cognitivo musical indicam que as habilidades musicais fazem parte de um módulo mental distinto, com seu próprio sistema de processamento de informações e substrato neural específico (Zatorre, 2001; Peretz, 2003; Peretz, & Coltheart, 2003; Peretz, 2006). Peretz e Coltheart (2003) afirmam que a hipótese da modularidade é compatível com o conhecimento atual acerca de como a mente processa a música. Para os autores, ao se considerar a existência de um módulo de processamento musical deve-se pressupor que há um sistema de processamento de informação cujas operações são específicas para o processamento da música. Contestando a ideia de que as habilidades musicais poderiam ser produto de uma arquitetura cognitiva de propósito geral, Peretz e Coltheart propõem uma arquitetura funcional para o processamento musical que apreende as propriedades típicas da organização modular e que compreende um grupo de componentes de processamento isoláveis neurologicamente (ou subsistemas de processamento) cada um sendo potencialmente especializado para o processamento musical. Os autores baseiam-se principalmente em evidências de casos de indivíduos com déficits seletivos de habilidades musicais para identificar a especialização neuronal, ou separabilidade neuroanatômica de outros domínios cognitivos. Há evidências para a diferenciação entre música, linguagem e sons ambientais (Besson, Faïta, Peretz, Bonnel, & Requin, 1998; Marin & Perry, 1999; Peretz, Belleville, & Fontaine, 1997; Peretz, et al., 1994; Piccirilli, Sciarma, & Luzzi, 2000; Warren, Warren, Fox, & Warrington, 2003); entre duas rotas paralelas e dissociadas para o *input* musical: a rota temporal e melódica (Ayotte et al., 2000; Peretz, 1990; Peretz & Kolinsky, 1993; Piccirilli et al., 2000; Vignolo, 2003); para a existência de dois mecanismos distintos dentro da dimensão melódica: contorno e intervalo melódico (Ayotte et al., 2000; Peretz, 1990); e dentro da dimensão temporal: ritmo e métrica (Liegeois-Chauvel, Peretz, Babai, Laguitton, & Chauvel, 1998; Peretz, 1990).

Peretz (2006), a partir de uma revisão de literatura, salienta que os estudos sobre a especificidade de domínio da música, inatismo e localização cerebral que buscam entender a música a partir de suas bases biológicas, e não a partir de uma abordagem cultural, contribuem para sustentar a hipótese da organização modular da música no cérebro. A autora aponta que a música é distribuída universalmente entre culturas e possui universalidades cognitivas. Características musicais comuns podem ser encontradas em diferentes culturas, tais como a produção de melodias, percepção de intervalos consonantes e dissonantes, organização de notas em escalas e organização temporal. Além disso, destaca que o comportamento musical não é recente na evolução humana e se constitui em uma habilidade ontogeneticamente precoce, sendo que a percepção musical de bebês possui características similares a de adultos (Trehub, 2003). Adicionalmente, os mecanismos para percepção musical poderiam ser filogeneticamente antigos e, adotando-se uma perspectiva evolucionária, terem evoluído a partir de seleção natural por melhorar a capacidade reprodutiva no ambiente ancestral fortalecendo relações interpessoais e grupais (Hauser & McDermott, 2003; McDermott & Hauser, 2005). Evidências recentes de estudos voltados para a especialização cerebral em música advêm também de pesquisas realizadas com distúrbios congênitos de habilidades musicais (Ayotte, Peretz, & Hyde, 2002; Peretz, 2003; Hyde & Peretz, 2004). As amusias congênitas são concebidas como presente desde o nascimento, podem ocorrer devido a influências genéticas (Hyde & Peretz, 2004; Peretz et al., 2007), e se apresentam como um transtorno específico do processamento musical (Hyde & Peretz, 2004).

Porém, há algumas controvérsias em relação à especificidade do processamento musical, como por exemplo, na diferenciação entre o processamento musical e o processamento de linguagem (Patel, Peretz, Tramo, & Labreque, 1998; Nicholson, Baum, Kilgour, Koh, Munhall, & Cuddya, 2003). Considerando a percepção melódica musical, por exemplo, os mecanismos envolvidos na percepção do contorno melódico são compartilhados com o domínio do processamento da linguagem (Peretz & Coltheart, 2003). Domínios temporais musicais como ritmo e métrica e o componente emocional da música também podem não ser de domínio específico (Peretz & Coltheart, 2003). Além disso, Trehub e Hannon (2006), a partir de uma revisão de estudos sobre a percepção musical na infância, comparando com a percepção musical de adultos e de não humanos, consideram que apesar de haver semelhanças no processamento musical, em relação a diferentes idades e espécies, os paralelos entre a percepção musical de adultos e crianças poderia ser atribuído a limitações biológicas sobre o processamento de informação, o qual operaria em consonância com vieses específicos da espécie e com a aprendizagem. Os autores consideram que isto não iria contra a importância biológica da música, e ressaltam que a manutenção do comportamento musical nas sociedades humanas poderia dever-se a mecanismos motivacionais. Apesar de concluírem que as habilidades musicais são produto de mecanismos perceptuais gerais que não são específicos nem da música nem da espécie humana, Trehub e Hannon consideram que o processamento musical pode se tornar modular ou automatizado, com o módulo sendo o resultado do desenvolvimento ou treinamento, tal como sugerido por Karmiloff-Smith (1998). Adicionalmente, estudos que investigam a relação entre as habilidades musicais e outras funções cognitivas tem encontrado que as amusias podem apresentar-se associadas a déficits gerais tais como na memória de trabalho, flexibilidade mental, cognição visuoespacial e funções executivas (Douglas e Bilkey, 2007; Särkämö et al., 2009). Há estudos que relacionam o treinamento musical com o desenvolvimento de outras habilidades cognitivas, tais como verbais, visuoespaciais, consciência fonológica, leitura, inteligência e habilidades matemáticas, também em crianças (Rauscher & Zupan, 2000; Hetland, 2000; Vaughn, 2000; Anvari, Trainor, Woodside, & Levy, 2002; Ho, Cheung, & Chan, 2003; Schellenberg, 2006).

Considerando o debate existente na literatura, o presente trabalho teve por objetivo investigar a hipótese de que a música é organizada modularmente no cérebro. As evidências indicam que o processamento musical é constituído de um módulo mental de processamento de informação cujas operações são específicas para este tipo de *input*, com subníveis de processamento para diferentes aspectos da música (Zatorre, 2001; Peretz, 2003; Peretz & Coltheart, 2003). Porém, questões relacionadas à diferenciação dos componentes específicos e compartilhados da cognição musical ainda não foram respondidas e requerem mais estudos e discussões. Portanto, as principais questões deste trabalho referem-se ao que pode ser considerado como domínio específico do processamento musical e o que pode ser compartilhado com outros domínios.

Para investigar a hipótese da modularidade do processamento cognitivo musical foi adotada uma estratégia de pesquisa multi-método e multi-amostra. A tese foi dividida em cinco estudos apresentados em forma de artigos científicos. No primeiro artigo são evidenciadas as questões teóricas relacionadas à hipótese da modularidade do processamento cognitivo musical e a um modelo cognitivo que permite testar essa hipótese. O segundo estudo traz para o contexto brasileiro um instrumento validado para avaliação das habilidades e déficits do processamento musical. O terceiro artigo levanta a questão sobre o que pode ser considerado de domínio específico e o que é compartilhado em relação à percepção de altura nos domínios acústicos e musicais. O quarto artigo investiga a hipótese da modularidade a partir da relação entre a cognição musical e a cognição numérica em amúsicos congênitos. O quinto artigo também investiga a relação entre a cognição musical e a cognição numérica, porém em indivíduos com Síndrome de Williams (SW). Os artigos são apresentados a seguir juntamente com as hipóteses a serem testadas:

1) O primeiro artigo, intitulado “Amusias and modularity of musical cognitive processing”, consiste em uma revisão integrativa, com o objetivo de investigar as evidências relacionadas à modularidade do processamento musical. Para isto são abordados os estudos sobre o processamento cognitivo musical e seus déficits adquiridos e congênitos, os quais forneceram evidências para a concepção da música enquanto um domínio específico com redes neurais especializadas. Estes estudos permitiram a construção de modelos cognitivos importantes para a compreensão e avaliação dos componentes envolvidos na percepção e memória musical, que por sua vez, permitem testar as hipóteses relacionadas à modularidade do processamento cognitivo musical. A revisão foi publicada em 2013 na revista *Psychology and Neuroscience, 6(1),* 45-56.

2) Elucidados os componentes do processamento musical e seus déficits, o segundo artigo, intitulado “Montreal Battery of Evaluation of Amusia: Validity evidence and norms for adolescentes in Belo Horizonte, Minas Gerais, Brazil”, teve por objetivo verificar as características psicométricas da versão traduzida e adaptada da MBEA para o Brasil (Nunes, C. Loureiro, M. Loureiro & Haase, 2010), em uma amostra de 150 adolescentes de 14 a 18 anos da cidade de Belo Horizonte, além de desenvolver normas específicas para esta população. O estudo traz para o contexto brasileiro um instrumento para avaliação da percepção e memória musical e diagnóstico de diferentes tipos de amusias e propõe, baseado na análise de seus itens, uma versão reduzida da MBEA. Em relação à questão da modularidade, o estudo contribui para identificar quais domínios musicais estão comprometidos e preservados nos indivíduos avaliados, além de permitir comparações interculturais sobre a percepção musical, identificando universalidades e diferenças culturais. O artigo foi publicado em Dezembro de 2012 na revista *Dementia and Neuropsychologia*, *6(4)*, 244-252.

3) A partir disto, o terceiro artigo, intitulado “Modularity of Pitch Processing in Congenital Amusia: A Meta-Analysis” é concernente à investigação de questões relacionadas à etiologia dos déficits congênitos de funções musicais, as amusias congênitas ou do desenvolvimento, e lança luz sobre o que pode ser considerado de domínio específico e o que é compartilhado em relação à percepção de altura (*pitch*) nos domínios acústicos e musicais. O objetivo da metanálise foi investigar a natureza do déficit na codificação musical da altura. A hipótese testada foi a de que o déficit encontrado na amusia congênita é devido à uma desordem mais ampla no processamento acústico da altura. A hipótese alternativa é de que o déficit de discriminação de altura na amusia congênita é específico de um módulo de processamento musical da altura, relacionado à codificação tonal deste estímulo. O estudo foi realizado no *International Laboratory for Brain, Music and Sound Research* (BRAMS), Université de Montréal, sob supervisão da professora Isabelle Peretz. Este artigo, do qual sou segunda autora, foi submetido para publicação na revista *Cortex* em Fevereiro de 2014 e está processo de revisão. Todos os autores concordaram com a apresentação deste estudo no presente trabalho.

4) Além de buscar compreender os componentes do processamento musical e seus déficits, procurou-se verificar os estudos sobre a relação entre processamento musical e o processamento numérico, com o objetivo de lançar luz na compreensão dos componentes do processamento musical que poderiam ser específicos ou compartilhados nestes dois sistemas distintos de aprendizagem. Focando a atenção na relação entre a cognição musical e cognição numérica, foram realizados dois estudos experimentais sobre esta possível associação, que correspondem ao quarto e ao quinto artigos desta tese. O quarto estudo foi realizado no BRAMS (Université de Montréal), sob supervisão da professora Isabelle Peretz e é apresentado em forma do artigo intitulado “Magnitude Processing in Numerical and Musical Domains” que teve por objetivo investigar se há associação entre dificuldades do processamento de magnitudes numéricas e de magnitudes de altura em indivíduos com amusia congênita. Partindo-se do pressuposto de que há um mecanismo amodal de processamento de magnitudes, localizado no sulco intraparietal, implicado tanto no processamento de frequências de altura quanto numérico, pode-se supor que os déficits de processamento de magnitudes numéricas serão acompanhados de déficits no processamento de magnitudes de altura. Sendo assim, pode-se predizer que indivíduos que apresentem baixo desempenho em tarefas que avaliam a magnitude de altura apresentarão também um baixo desempenho em tarefas de magnitudes numéricas. Supõe-se também que estes déficits são específicos para o processamento de magnitudes, ou seja, são

independentes da inteligência, memória de trabalho, funções executivas, processamento fonológico e processamento visuoespacial. Sendo assim, dentro deste contexto, a hipótese a ser testada neste estudo é a de que amúsicos congênitos que apresentam baixo desempenho em tarefas que avaliam a percepção de altura, apresentarão também um baixo desempenho em tarefas de magnitudes numéricas. Além disso, pode-se predizer que controles apresentarão desempenho normal tanto nas tarefas que avaliam a magnitude de altura musical quanto em tarefas de magnitude numérica. Para estas hipóteses temos, então, como variável dependente o desempenho nas tarefas que avaliam a percepção musical, medida pela tarefa de identificação de altura (*pitch change detection*) e pela MBEA e como variável independente o desempenho nas tarefas que avaliam o senso numérico, medido pelas tarefas de comparação de magnitudes não-simbólica. O artigo será submetido para a publicação em periódico internacional no segundo semestre de 2014.

5) O quinto estudo foi realizado no Brasil e investigou a relação entre o processamento musical e numérico em uma síndrome neuropsicológica específica, a síndrome de Williams-Beuren ou Síndrome de Williams (SW). A SW foi escolhida pois nesta síndrome parece haver uma dissociação entre os domínios musical e numérico com preservação de habilidades musicais (Levitin & Bellugi, 1998, Levitin *et al.*, 2004, Levitin, 2005) e comprometimento do senso numérico (Paterson *et al.*, 2006). O estudo, apresentado em formato de artigo científico e intitulado “Investigação da relação entre o processamento musical e o processamento numérico na Síndrome de Williams”, se constitui em um estudo analítico de comparação de grupos que teve por objetivo investigar a relação entre processamento numérico e musical em crianças e adolescentes com SW e controles com desenvolvimento típico. O estudo testa a hipótese de que indivíduos com SW que apresentam baixo desempenho em tarefas numéricas, também apresentarão baixo desempenho em tarefas musicais. As medidas utilizadas foram tarefas que avaliam a percepção musical (MBEA), e tarefas que avaliam o senso numérico (comparação de magnitudes não simbólica). O artigo será submetido para publicação em periódico internacional no segundo semestre de 2014.

1.2 Referências

Amunts, K., Schlaug, G., Jancke, L., Steinmetz, H., Schleicher, A., Dabringhaus, A., et al. (1997). Motor cortex and hand motor skills: structural compliance in the human brain. *Human Brain Mapping, 5*, 206–215.

Ansari, D., Donlan, C., & Karmiloff-Smith, A. (2007). Atypical and typical development of visual estimation abilities. *Cortex: Special Issues on Selective Developmental Disorders, 6*, 758–768.

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology, 83*, 111-130.

Ayotte, J., Peretz, I., & Hyde, K. (2002). Congenital amusia: a group study of adults afflicted with a music-specific disorder. *Brain*, *125*, 238-251.

Ayotte, J., Peretz, I., Rousseau, I., Bard, C., & Bojanowski, M. (2000). Patterns of music agnosia associated with middle cerebral artery infarcts. *Brain*, *123*, 1926-1938.

Barrett, H. C., & Kurzban, R. (2006). Modularity in cognition: framing the debate. *Psychological review, 113(3)*, 628.

Besson, M., Faïta, F., Peretz, I., Bonnel, A.M., & Requin, J. (1998). Singing in the brain: independence of lyrics and tunes. *Psychological Science*, *9(6)*, 494-498.

Bonn, C. D. & Cantlon, J. F. (2012): The origins and structure of quantitative concepts, *Cognitive Neuropsychology, 29:1-2*, 149-173.

Brandler, S., & Rammsayer, T. H. (2003). Differences in mental abilities between musicians and non-musicians. *Psychology of Music, 31 (2)*, 123-138.

Brochard, R., Dufour, A., & Despres, O. (2004). Effect of musical expertise on visuospatial abilities: Evidence from reaction times and mental imagery. *Brain & Cognition, 54 (2)*, 103–109.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46 (1)*, pp. 3-18.

Cohen Kadosh, R.C., Brodsky, W., Levin, M., Henik, A., (2008). Mental representation: what can pitch tell us about the distance effect? *Cortex, 44(4)*, 470-477.

Cohen Kadosh, R., Henik, A., Rubinsten, O., Mohr, H., Dori, H., Van de Ven, V., Zorzi, M., Hendler, T., Goebel, R. & Linden, D. E. J. (2005) Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia 43*, 1238-1248.

Cohen Kadosh, R. C., Lammertyn, J. Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology, 84*, 132–147.

Coltheart, M. (1999). Modularity and cognition. *Trends in Cognitive Sciences*, *3*(3), 115-120.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive neuropsychology, 20 (3)*, 487-506.

Douglas, K. M., & Bilkey, D. K. (2007). Amusia is associated with deficits in spatial processing. *Nature Neuroscience, 10 (7),* 915-921.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., Orban, G. A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. *Journal of Cognitive Neuroscience, 15,* 1-11.

Fodor, J.A. (1983). *The modularity of mind: an essay on faculty psychology*. Cambridge, MA: MIT Press.

Foster, N.E.V. & Zatorre, R.J. (2010). A Role for the Intraparietal Sulcus in Transforming Musical Pitch Information. *Cerebral Cortex 20 (6),* 1350-1359.

Foxton, J. M., Dean, J. L., Gee, R., Peretz, I., & Griffiths, T. D. (2004). Characterization of deficits in pitch perception underlying ‘tone deafness’. *Brain, 127(4),* 801-810.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and nonmusicians. *Journal of Neuroscience, 23 (27),* 9240–9245.

Geary, D. C. (2011). Consequences, Characteristics, and Causes of Mathematical Learning Disabilities and Persistent Low Achievement in Mathematics. *Journal of Developmental & Behavioral Pediatrics, 32 (3),* 1-14.

Geary, D. C., & Huffman, K. J. (2002). Brain and cognitive evolution: forms of modularity and functions of mind. *Psychological Bulletin, 128 (5),* 667-698.

Hauser, M. D., & McDermott, J. (2003). The evolution of the music faculty: A comparative perspective. *Nature neuroscience, 6(7),* 663-668.

Hetland, L. (2000). Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education, 34,* 179-238.

Ho, Y., Cheung, M., & Chan, A. (2003). Music training improves verbal but not visual memory: cross sectional and longitudinal explorations in children. *Neuropsychology, 17,* 439-450.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature reviews, 6,* 435-448.

Hutchinson, S., Lee, L. H., Gaab, N., & Schlaug, G. (2003). Cerebellar volume of musicians. *Cerebral Cortex, 13,* 943–949.

Hyde, K., Lerch, J., Zatorre, R., Griffiths, T.D., Evans, A., & Peretz, I. (2007). Cortical thickness in congenital amusia: when less is better than more. *Journal of Neuroscience, 47,* 13028-13032.

Hyde, K., & Peretz, I. (2004). Brains that are out of tune but in time. *Psychological Science,* *15*(5), 356-360.

Hyde, K.L., Zatorre, R.J., Griffiths, T.D., Lerch, J.P., & Peretz, I. (2006). Morphometry of the amusic brain: a two-site study. *Brain*, *129*, 2562-2570.

Hyde, K., Zatorre, R.J., & Peretz, I. (2011). Functional MRI evidence of an abnormal neural network for pitch processing in congenital amusia. *Cerebral Cortex*, *21*(2), 292-299.

Karmiloff-Smith, A. (1995). *Beyond modularity: A developmental perspective on Cognitive Science*. Cambridge, MA: MIT press.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in cognitive sciences, 2(10)*, 389-398.

Lebrun, M.-A., Moreau, P., McNally-Gagnon, A., Mignault Goulet, G., & Peretz, I. (2012). Congenital amusia in childhood: a case study. *Cortex, 48(6)*, 683-688.

Levitin, D.J. & Bellugi, U. (1998). Musical abilities in individuals with Williams Syndrome. *Music Perception*, *15(4),* 357-389.

Levitin, D.J., Cole, K., Chiles, M., Lai, Z., Lincoln, A., & Bellugi, U. (2004). Characterizing the musical phenotype in individuals with Williams syndrome. *Child Neuropsychology, 10*, 223–247.

Levitin, D. J. (2005). Musical behavior in a neurogenetic developmental disorder: Evidence from Williams syndrome. *Annals of the New York Academy of Sciences, 1060*, 325–334.

Levitin, D. J., & Tirovolas, A. K. (2009). Current advances in the cognitive neuroscience of music. *Annals of the New York Academy of Sciences, 1156(1)*, 211-231.

Liégeois-Chauvel, C., Peretz, I., Babaï, M., Laguitton, V., & Chauvel, P. (1998). Contribution of different cortical areas in the temporal lobes to music processing. *Brain, 121(10)*, 1853-1867.

Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: a new disconnection syndrome? *Journal of Neuroscience, 29(33)*, 10215-10220.

Loui, P., Guenther, F. H., Mathys, C., & Schlaug, G. (2008). Action–perception mismatch in tone-deafness. *Current Biology, 18(8*), R331-R332.

Loui, P., Hohmann, A., & Schlaug, G. (2010). Inducing disorders in pitch perception and production: a reverse-engineering approach. *Proceedings of Meetings in Acoustics*, *9*, 050002.

Mandell, J., Schulze, K., & Schlaug, G. (2007). Congenital amusia: an auditory-motor feedback disorder? *Restorative Neurology and Neuroscience*, *25*, 323-334.

Marin, O., & Perry, D. (1999). Neurological aspects of music perception and performance. In

D. Deutsch (Ed.), *The psychology of music* (pp. 653-712). San Diego: Academic Press.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Impaired Acuity of the Approximate Number System Underlies Mathematical Learning Disability (Dyscalculia). *Child Development, 82 (4)*, 1224–1237.

McDermott, J., & Hauser, M. (2005). The origins of music: Innateness, uniqueness, and evolution. *Music Perception, 23 (1)*, 29-59.

Mervis C.B., Robinson, B.F., Bertrand J, Morris, C.A., Klein-Tasman, B.P., Armstrong, S.C. (2000). The Williams syndrome cognitive profile. *Brain and Cognition, 44*, 604– 628.

Nicholson, K.G., Baum, S., Kilgour, A., Koh, C.K., Munhall, K.G., & Cuddya, L.L. (2003). Impaired processing of prosodic and musical patterns after right hemisphere damage. *Brain and Cognition, 52*, 382-389.

Nunes, M., Loureiro, C.M.V., Loureiro, M.A., & Haase, V.G. (2010). Tradução e validação de conteúdo de uma bateria de testes para avaliação de Amusia. *Avaliação Psicológica, 9(2)*, 211-232.

Patel, A.D., Peretz, I., Tramo, M., & Labreque, M. (1998). Processing prosodic and musical patterns: a neuropsychological investigation. *Brain and Language, 61*, 123-144.

Paterson, S., Girelli, L., Butterworth, B., Karmiloff-Smith, A. (2006). Are numerical difficulties syndrome specific? Evidence from Williams syndrome and Down’s syndrome. *Journal of Child Psychologic Psychiatry, 47,* 190– 204.

Paterson, S.J. & Schultz, R.T. (2007). Neurodevelopmental and Behavioral Issues in Williams Syndrome. *Current Psychiatry Reports, 9,* 165-171.

Peretz, I. (1990). Processing of local and global musical information in unilateral brain-damaged patients Brain. *Brain, 113*, 1185-1205.

Peretz, I. (2003). Brain specialization for music: new evidence from congenital amusia. In I. Peretz, & R.J. Zatorre (Eds.), *The cognitive neuroscience of music* (pp. 192-203). Oxford: Oxford University Press.

Peretz, I. (2006). The nature of music from a biological perspective. *Cognition, 100*, 1-32.

Peretz, I., Belleville, S., & Fontaine, F.S. (1997). Dissociations entre musique et langage après atteinte cérébrale: un nouveau cas d'amusie sans aphasie. *Revue Canadienne de Psychologie Expérimentale, 51*(4), 354-367.

Peretz, I., Brattico, E., Järvenpää, M., & Tervaniemi, M. (2009). The amusic brain: in tune, out of key and unaware. *Brain, 132*, 1277-1286.

Peretz, I., Brattico, E., & Tervaniemi, M. (2005). Abnormal electrical brain responses to pitch in congenital amusia. *Ann Neurol*, *58*, 478-482.

Peretz, I., Champod, A.S., & Hyde, K. (2003). Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. *Annals of the New York Academy of Sciences*, *999*, 58-75.

Peretz, I., & Coltheart, M. (2003). Modularity of music processing. *Nature Neuroscience, 6(7)*, 688-690.

Peretz, I., Cummings, S., & Dubé, M.P. (2007). The genetics of congenital amusia (tone deafness): a family-aggregation study. American Journal of Human Genetics, 81, 582-588.

Peretz, I., & Kolinsky, R. (1993). Boundaries of separability between melody and rhythm in music discrimination: A neuropsychological perspective. *Quarterly Journal of Experimental Psychology, 46A*, 301-325.

Peretz, I., Kolinsky, R., Tramo, M., Labrecque, R., Hublet, C., Demeurisse, G., & Belleville, S. (1994). Functional dissociations following bilateral lesions of auditory cortex. *Brain*, *117*, 1283-1302.

Piccirilli, M., Sciarma, T., & Luzzi, S. (2000). Modularity of music: evidence from a case of pure Amusia. *Neurol Neurosurgery Psychiatry, 69*, 541–545.

Rauscher, F. H., & Zupan, M. (2000). Classroom keyboard instruction improves kindergarten children's spatial-temporal performance: A field experiment. *Early Childhood Research Quarterly, 15 (2)*, 215-228.

Rusconi, E., Kwan, B., Giordano, B.L., Umilta, C., Butterworth, B. (2006). Spatial representation of pitch height: the SMARC effect. *Cognition, 99*, 113–129.

Särkämö, T., Tervaniemi, M., Soinila, S., & Autti, T. (2009). Cognitive deficits associated with acquired amusia after stroke: A neuropsyhological follow-up study. *Neuropsychologia*, *47(12)*, 2642-2651.

Schellenberg, E. G. (2006). Long-Term positive associations between music lessons and IQ. *Journal of Educational Psychology, 98 (2)*, 457–468.

Schlaug, G., Jancke, L., Huang, Y., Staiger, J. F., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, 33, 1047–1055.

Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., & Rupp, A. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. Nature Neuroscience, 5, 688–694.

Schwenzer, M., Mathiak, K. (2011). Numeric aspects in pitch identification: an fMRI study. *Neuroscience, 12:*26.

Sloboda, J., Wise, K., & Peretz, I. (2005). Quantifying tone deafness in the general population. *Annals of New York Academy of Science, 1060*, 255-261.

Sluming, V. B., Howard, M., Downes, J. J., & Roberts, N. (2007). Broca's area supports enhanced visuospatial cognition in orchestral musicians. Journal of Neuroscience, 27 (14), 3799–3806.

Stewart, L., von Kriegstein, K., Warren, J.D., & Griffiths, T.D. (2006). Music and the brain: disorders of musical listening. *Brain, 129,* 2533-2553.

Stromme P., Bjornstad P. G. & Ramstad K. (2002) Prevalence estimation of Williams syndrome. *Journal of Child Neurology, 17,* 269–271.

Thomas, M., & Karmiloff-Smith, A. (2002). Are developmental disorders like cases of adult brain damage? Implications from connectionist modelling. *Behavioral and Brain Sciences, 25*, 727-788.

Trehub, S. E. (2003). The developmental origins of musicality. Nature neuroscience, 6(7), 669-673.

Trehub, S.E. & Hannon, E.E. (2006). Infant music perception: Domain-general or domain-specific mechanisms? *Cognition, 100,* 73-99.

Vaughn, K. (2000). Music and mathematics: modest support for the oft-claimed relationship. *Journal of Aesthetic Education, 34*, 149-166.

Vignolo, L.A. (2003). Music agnosia and auditory agnosia: dissociations in stroke patients. *Annals of the New York Academy of Sciences, 999,* 50-57.

Zatorre, R. (2001). Neural specializations for tonal processing. *Annals of the New York Academy of Sciences, 930,* 193-210.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7(11*), 483-488.

Warren, J. (2008). How does the brain process music? *Clinical Medicine, 8 (1)*, 32-36.

Warren, J., Warren, J., Fox, N., & Warrington, E. (2003). Nothing to Say, Something to Sing: Primary Progressive Dynamic Aphasia. *Neurocase, 9(2),* 140–155.

Wilson, A. J., & Dehaene, S. (2007). Number sense and developmental dyscalculia. In: D. Coch, G. Dawson, & K. Fischer, *Human behavior, learning, and the developing brain: atypical development* (pp. 212–238). New York: Guilford.

PSYCHOLOGY & NEUROSCIENCE

Psychology & Neuroscience, 2013, 6, 1, 45-56
DOI: 10.3922/j.psns.2013.1.08

Amusias and modularity of musical cognitive processing

Marília Nunes Silva and Vitor Geraldi Haase

Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil

Abstract

In the past few years the study of music from a neuroscientific perspective has considerably improved, allowing the evolution of both theoretical knowledge and constructs related to cognitive musical processing. Both neuroimaging studies and studies of individuals who suffer from selective deficits of musical abilities have favored the construction of useful models to understand the mechanisms of musical processing, thus revealing its complexity and eliciting the hypothesis of the modular organization of music in the brain. This article reviews studies of cognitive musical processing with a focus on deficits in musical abilities and the neuropsychological model of cognitive musical processing developed by Isabelle Peretz. This model is an important contribution to neuroscientific studies of music because it furthers the understanding of selective deficits in different components of musical processing that occur in both individuals who incur brain damage and those with congenital amusia. The model also serves as theoretical support for diagnosing different types of amusia.
Keywords: amusia, music cognition, music perception, modularity.

Received 25 October 2012; received in revised form 07 February 2013; accepted 11 February 2013. Available online 27 June 2013.

Introduction

Music is not only a social and artistic activity that has been present in all epochs and civilizations but is also a complex cognitive ability. Theoretical, methodological, and empirical contributions from neurology, cognitive psychology, neuropsychology, developmental psychology, and neuroimaging have had a profound impact on music research since the second half of the 20th century, laying the foundation for a neuroanatomical perspective of musical processing. This was made possible because of improved knowledge of the effects of brain damage on musical functioning, the brain mechanisms involved in perception, memory, attention, and musical production, and the areas of the brain that are involved in the processing of different aspects of musical structure (Critchley & Henson, 1977; Brust, 2001; Peretz & Zatorre, 2005).

One trend in studies of musical cognitive neuroscience is to explore the neural substrates involved in music perception and performance to understand the biological and functional bases of music (Peretz, 2006). Research shows that musical processing constitutes itself in a specific cognitive domain within specialized neural networks (Zatorre, 2001; Peretz, 2003; Peretz & Coltheart, 2003).

Marília Nunes Silva and Vitor Geraldi Haase, Departamento de Psicologia da Universidade Federal de Minas Gerais, Brazil. Correspondence regarding this article should be directed to: Marília Nunes-Silva, Av. Antônio Carlos 6627, FAFICH-UFMG, Sala 2016, Belo Horizonte, MG, CEP 31270-901, Brazil. Phone: +55 (31) 3409-6295, +55 (31) 9209-2826. E-mail: musicainfinita@ig.com.br

In this context, the ability to acquire musical skills with regard to music perception and performance may be seen as an evolutionary adaptation based on natural selection influenced by specific genes. Recent neuropsychological studies directed toward brain specialization in music have investigated congenital disorders in the ability to acquire musical skills (Peretz, 2003). Research on congenital amusia has increased in the last decade and shed new light on the evaluation of musical abilities with regard to education and clinical diagnosis (Peretz, Champod, & Hyde, 2003).

This article reviews studies of musical ability deficits and both traditional and novel studies of cognitive musical processing that allowed improvements in theoretical constructs and the development of useful models to understand the underlying mechanisms. The cognitive neuropsychological model of musical processing developed by Isabelle Peretz (Peretz et al., 2003) is also presented together with evidence that supports it and reveals its limitations, highlighting the complexity of cognitive musical processing and the modular organization of music in the brain.

Amusias

Since the last half of the 20th century, neurologists have analyzed disorders in musical function in patients with brain illness in an attempt to associate such lesions with specific brain deficits. Such deficits have been grouped under the term *amusia*, which was coined by Steinhal in 1871 to generically describe the inability to perceive music (Steinhal, 1871; Wertheim, 1969; Warren, 2004; García-Casares, Torres, Walsh, & González-Santos, 2011). Amusia was introduced as a medical concept that corresponds to musical aphasia by the German physician and anatomist August Knoblauch in 1888 to describe a specific disorder in detecting tones that result from lesions of the motor center (Knoblauch, 1890). Knoblauch (1890) distinguished disorders of music production and comprehension using the terms "amusia" for motor disorders and "tone deafness" and "noteblindness" for sensory disorders. Since then, the concept of amusia was utilized by subsequent authors in a more general sense and has been accepted as indicative of lesions of the right temporal lobe (Henson, 1977). The earliest cognitive model of music with a classification of amusias was also proposed by Knoblauch (1890). Knoblauch proposed a detailed cognitive model of musical processing based on clinical observations of patients and suggested that amusias were a complex and heterogeneous group of disorders of music processing, with possibly nine separate types that reflect impaired music perception and performance (Knoblauch, 1890; Johnson & Graziano, 2003).

According to Henson (1977), most authors emphasized clinical case studies of amusic individuals, seeking to determine the loci of musical function or studying the relationship between amusia and aphasia rather than classifying amusias. Henson (1977) mentioned important studies that were performed with composers who had brain damage. One of the most famous studies was conducted by Alajouanine (1948) where he evaluated the composer Maurice Ravel, who manifested progressive aphasia associated with a loss of the ability to compose music because of impairment in processing compositional rules. In turn, Luria, Tsvetkova, & Futer (1965) studied the composer Vissarion Shebalin who had aphasia without amusia caused by stroke.

Benton (1977) established a classification of musical deficits based on clinical observations instead of theoretical principles, combining both local and classificatory perspectives. He recognized the difficulties in understanding the broad spectrum of deficits related to musical processing. Benton (1977) defined amusia as the loss or impairment of musical capacity that results from brain disease. According to the Bentonian proposal, the associated disability could be manifested in several ways: (*i*) receptive amusia (i.e., the difficulty discriminating melodic patterns, timbres, pitches, and tunes), (*ii*) musical alexia (i.e., the loss of the ability to read musical notation), (*iii*) musical amnesia (i.e., failure to recognize tunes that were once familiar to the individual), (*iv*) rhythm disorders (i.e., difficulty discriminating rhythmic patterns or performing them), (*v*) vocal or oral-expressive amusia (i.e., loss of the ability to sing, whistle, or hum a tune), (*vi*) instrumental amnesia or musical apraxia (i.e., loss of the ability to play an instrument without having an associated motor deficit), and (*vii*) music agraphia (i.e., loss of the ability to copy scores or write down a tune that one has heard).

Most of the classes of amusia proposed by Benton (1977) concerned trained musicians who suffered the loss of ability because of brain damage or disorders. At the time, studies with listeners without specialized musical formation were very difficult because of the lack of appropriate investigational methodology. Although Benton (1977) identified the heterogeneity of musical disorders and sought to relate them to specific loci in the brain, he did not develop a valid or reliable classification because he did not have at his disposal information processing paradigms or advanced techniques for the study of brain function.

Despite the considerable amount of clinical observations made in the 19th century, systematic and methodologically improved analyses have been used only recently in studies of brain damage that causes specific musical deficits. The subtlest observations of these deficits were only made possible because of considerable improvements in the study of music from a neurocognitive perspective in the last 30 years.

Stewart, von Kriegstein, Warren, & Griffiths (2006) highlighted the following significant improvements: (*i*) the evolution of theoretical knowledge and constructs that allowed the development of instruments for the systematic evaluation of music disorders, (*ii*) greater precision in the examination of brain changes that underlie musical performance disorders, which was made possible by the evolution of neuroimaging techniques that permit the identification of more subtle anatomical changes, and (*iii*) better knowledge of brain function in typical listeners, mainly from studies that use functional neuroimaging techniques.

Studies of patients with brain damage laid the foundation for a neuroanatomical perspective of musical processing. According to Brust (2001), cases of dissociation in which musical ability is compromised without impairments in language are normally associated with damage in the right hemisphere of the brain. These cases present impaired recognition of sounds as music and a monophonic perception of musical features as meter, tempo, and key, not only in music but also in speech.

Severe deficits in melodic processing with the preservation of verbal ability are usually associated with damage in the auditory area of the temporal lobes, mainly the right superior temporal gyrus (Ayotte, Peretz, Rousseau, Bard, & Bojanowski, 2000). Lesions of the right frontal lobe do not affect elementary tonal perception but induce similar deficits in pitch discrimination that result from damage to the right superior temporal gyrus. However, difficulties that result from frontal damage are characterized by tonal memory disorder and not perceptual difficulty (Zatorre, 2001). The processing of pitch patterns appears to require an interaction between frontal and temporal areas, especially in the right hemisphere.

Although many studies of these musical deficits have been conducted, the term *amusia* is still very generic. According to Marin & Perry (1999), this makes comprehension of the brain mechanisms involved in musical processing a difficult task. Moreover, no consensus has been reached about the classification of the many forms and definitions of this syndrome. Amusia has also been referred to as *note deafness*, *tone deafness*, *tune deafness*, and *dysmelodia* (Peretz, Cummings, & Dubé, 2007). Marin & Perry (1999) defined amusia as an acquired clinical disorder in the areas of reading, writing, perception, and musical performance caused by brain damage that is not the result of other more basic sensorial, motor, or cognitive deficits. They also considered the existence of specifically perceptual amusias as those that involve symbolic systems of reading and writing (based on prior knowledge) and others related to vocal performance or motor activities. The traditional neuropsychological classifications (Benton, 1977; Marin & Perry, 1999) do not have within their definitions congenital or developmental amusia, which shall be discussed later. Amusias may be distinguished as acquired or congenital according to their etiology. Acquired amusias result from disease or brain damage caused by accidents and can impair musical function in many ways, depending on the affected brain area. Congenital amusias, in contrast, are present from birth and may occur as a result of genetic influences (Peretz et al., 2007). Congenital amusias are often associated with impaired tonal processing, and most individuals with congenital amusia are capable of detecting variations in temporal structure (Ayotte, Peretz, & Hyde, 2002).

In addition to studies of amusic individuals with brain damage that permit the identification of brain areas that are critically involved in the processing of a specific function, structural and functional neuroimaging studies are important for understanding the anatomical and functional correlates of amusias (Tramo, Shah, & Braida, 2002, Wilson, Pressing, & Wales, 2002). Neuroimaging studies have revealed which brain areas are potentially recruited for psychological processing in a more general manner and are an important resource for the initial discovery of the relationship between cognitive and neural processes.

Although differences exist between methodological anatomical–clinical correlation paradigms and neuroimaging techniques, results generated by these methods have been consistent and convergent, suggesting the occurrence of selective deficits of components related to musical abilities. Therefore, amusias constitute a complex and heterogeneous group of musical processing disorders, and data simply from anatomical–clinical correlations are insufficient to establish a valid and reliable classification for different types of amusia. In this context, the introduction of the information processing paradigm may complement and structure the knowledge obtained from studies of musical abilities. The model of information processing permits functional interpretations of clinical findings and their neuronal correlates to allow the operationalization of deficits based on neural correlates. The construction of an information processing model for musical stimuli would allow refinement of the classification of different types of amusia and measures of specific components of musical processing.

Cognitive–neuropsychological model of musical perception and memory

Improvements in the study of music from a cognitive perspective have combined the evolution of theoretical knowledge and constructs related to cognitive musical processing. Studies performed with individuals who present selective deficits in musical abilities caused by brain damage (e.g., Peretz et al., 2003) allowed the construction of useful models to understand amusia and the components involved in musical processing.

According to Peretz et al. (2003), musical memory and perception are basic functions that can be observed and evaluated in all normal listeners, both in musicians and non-musicians. Music perception and musical memory depend on the proper functioning of multiple components and have been investigated in both the cognitive and neuropsychological domains. To evaluate these functions, Peretz et al. (2003) suggested a model that specifies the architecture of the musical system, its components, and its possible interactions or processes. In the cognitive–neuropsychological model of musical processing (Figure 1), damage can impair a processing component (boxes) and interfere with information flux among components (arrows). The model proposes different modules of musical processing, each conceived as an operation of processing particular information that contributes to the entire system (Peretz & Coltheart, 2003).

In the cognitive–neuropsychological model, the auditory input, which consists of any acoustic stimuli, first passes through an acoustic analysis module in which sound mixtures from different sound sources are segregated. The auditory input relies both on aspects that elicit the language processing action system and aspects that activate the musical processing system, insofar as both systems parallel each other (Peretz et al., 2003). The activation of musical or language processing is determined by aspects of the input to which the module is tuned, although the information proceeds to both domains, but these only respond to information that they were programmed to answer. Song lyrics, therefore, are processed in the language system, represented on the right in the model. The auditory musical input is then analyzed by two parallel and independent systems with specific functions: (*i*) one system for the melodic dimension (defined by sequential variation in the sound frequency), represented by the contour (i.e., the direction of pitch), scale (i.e., related to tonal functions), and interval (i.e., the size of the frequency interval between tones) and (*ii*) one system for the temporal dimension (defined by sequential variation in the sound duration), represented by rhythm (i.e., the grouping of events according to temporal proximity) and metric organization (i.e., basic temporal regularity or pulsation). The metric analysis corresponds to spontaneous foot tapping and thus has a direct connection in the model with this output (Peretz & Coltheart, 2003).

Both pathways and dimensions, melodic and temporal, define the components of musical analysis, sending its respective outputs or a combination of both

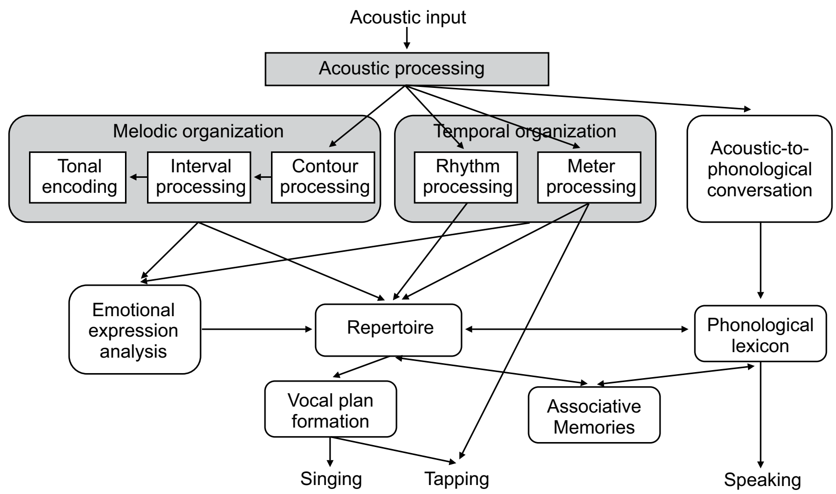

Figure 1. Cognitive–neuropsychological model of music processing, sketching the components and processes involved in music recognition (adapted with permission from Macmillan Publishers Ltd: [Nature Neuroscience] (Peretz, I. & Coltheart, M. Modularity of music processing. *Nature Neuroscience*, *6*(7), 688-691), copyright (2003).

to a *repertoire* or component analysis of emotional expression. The *repertoire* is conceived as a perceptual representation system that contains all representations of musical phrases to which a subject has been exposed during his/her lifetime. The output of the *repertoire* can activate representations stored in other systems such as lexical representation (in the case of recognizing lyrics) or associative memory (for retrieving and pronouncing the title), leading to music identification. If an individual sings a song, then the corresponding melody represented in the musical lexicon is paired with the associated lyrics that are stored in the phonological lexicon and integrated and planned in such a way that is adequate for vocal performance. It may also activate non-musical information such as an episode related to that song. Successful activation of the *repertoire* evokes a feeling of familiarity that leads to recognition, even if naming one part of the music is not possible. Therefore, this component appears to be involved in the processing of both familiar music and novel music (Peretz et al., 2003; Peretz & Coltheart, 2003).

Finally, the emotional component in the model refers to affective information provided by the musical input and depends on two structures: the mode, which is the character of one scale that varies according to the position of tones and semi-tones and its relationship to the tonic, and the tempo, which refers to the music speed (Peretz & Coltheart, 2003).

The neuropsychological model of cognitive musical processing led to the development of the Montreal Battery of Evaluation of Amusia (MBEA). The MBEA evaluates musical abilities in six components of musical processing: contour, scale, interval, rhythm, meter, and musical memory. It allows the diagnosis of different types of amusia. The MBEA, however, does not evaluate the emotional component present in the model. Therefore, Peretz et al. (2003) suggested the development of tests that evaluate this component so that they may be additionally used in the battery.

Validity of the model

The components involved in musical processing that are considered in the cognitive–neuropsychological model have been isolated in studies of patients with brain damage who presented deficits in musical abilities. Two parallel and dissociated routes for musical input have been distinguished: temporal and melodic (Peretz, 1990; Peretz & Kolinsky, 1993; Ayotte et al., 2000; Piccirilli, Sciarma, & Luzzi, 2000; Vignolo, 2003). When one of these pathways is damaged, the other may be preserved and *vice versa*, providing evidence of a double dissociation. Peretz & Zatorre (2005) considered the fact that although the dependence of rhythm and melodic processing is questionable, neuropsychological studies have indicated that melodic and temporal structures are processed independently. Thus, brain damage can produce a selective loss of perception in both the temporal and melodic dimensions.

Other studies highlighted the existence of distinct mechanisms within the melodic dimension: the contour and interval (Peretz, 1990; Ayotte et al., 2000). Damage in the left hemisphere was shown to impair interval processing, without affecting the ability to represent melodies relative to their contour. Damage in the right hemisphere interfered with both processes. Peretz et al. (2003) suggested that damage in the right hemisphere affects the processes necessary for contour representation, depriving intact structures in the left hemisphere of the information required to process interval information.

Peretz & Zatorre (2005) stated that tonal aspects of melodic processing have been little studied using neuropsychological methods. Nevertheless, evidence suggests that a specialized neural network processes tonal structure (i.e., scales) in melodies. Peretz (1993), for example, analyzed one case of a patient who, after brain damage, acquired a specific deficit in melodic tonal interpretation, although temporal structure and the ability to codify music in terms of melodic contour and interval size were preserved.

Dissociations between mechanisms of temporal organization—rhythm and meter—have been investigated in few studies (Peretz, 1990; Liégeois-Chauvel, Peretz, Babaï, Laguitton, & Chauvel, 1998). These studies showed that meter may be preserved with selective dysfunction of rhythmic structure processing and *vice versa*. Although more studies are needed, neuropsychological evidence suggests a double association between rhythm and meter. Table 1 presents some studies published from 1990 to 2003 that provided evidence of the modularity of cognitive musical processing.

Considering the emotional component, Peretz & Gagnon (1999) studied a patient with amusia caused by brain damage who was able to use the mode and tempo of music to make emotional judgments (i.e., determine whether a melody was happy or sad), although the patient could not recognize or process melodic musical information. Peretz & Gagnon (1999) found that the determinant structure of emotions (e.g., mode and tempo) utilizes pathways that are different from those involved in music recognition.

With regard to music and language, many questions are still unanswered. Based on statements from patients with amusia and without aphasia and *vice versa*, Peretz et al. (2003) argued for a double-dissociation between musical and language processing. To assess these patients, Peretz et al. (2003) relied on a review developed by Marin & Perry (1999) in which some cases were grouped. Patel (2003) provided evidence that most of the cases were from the end of the 19th century and beginning of the 20th century and usually involved professional musicians, thus not necessarily providing conclusions that could be extended to the general population. Patel (2003) also stated that case studies of aphasia without amusia, even today, lack systematic tests that evaluate syntactic musical processing with regard to harmonic processing. This author proposed a specific point of contact between syntactic processing in music and language based on neuroimaging data and aspects of cognitive theory.

More recent and systematic studies have been conducted with cases of aphasia without amusia (Warren, Warren, Fox, & Warrington, 2003) and amusia without impairment of speech and environmental sounds (Peretz et al., 1994; Peretz, Belleville, & Fontaine, 1997; Piccirilli et al., 2000). Notably, the cases cited by Marin & Perry (1999) all referred to acquired amusias because the congenital condition has only recently received more attention. Cases of congenital amusia support the differentiation between the cognitive domains of music and language. These individuals present severe musical deficits but maintain their linguistic abilities (Ayotte et al., 2002).

Even if music and language constitute different domains, some similarities exist among some of their perceptual characteristics. In addition to syntactic processing, a likely similarity exists between the processing of melodic contour and speech contour (i.e., prosody). Amusias may be followed by perception deficits with regard to speech intonation, suggesting linkages between rhythmic and melodic patterns in speech and music, and prosody and pitch discrimination may share neural networks (Nicholson, Baum, Kilgour, Koh, Munhall, & Cuddya, 2003; Patel, Peretz, Tramo, & Labreque, 1998). Bautista & Ciampetti (2003) argued that aprosodia, such as amusia, is frequently associated with damage in the right hemisphere. To support this, they presented a case of a woman with expressive amusia and aprosodia who was unable to sing and whose speech sounded monophonic.

Patel, Wong, Foxton, Lochy, & Peretz (2008) considered amusia to be associated with deficits in prosody. They analyzed two groups in which ~30% of congenital amusic individuals had difficulties in prosody when discriminating pitch changes that occurred at the end of sentences, implying changes in intention. Such a deficit may be associated with difficulty discriminating pitch directions with regard to speech, although they found movement among sounds. According to the authors, the fact that perception deficits in pitch direction extensively impact speech perception indicates the need to incorporate prosody perception tests in the diagnosis of amusia to dissociate cases that have purely musical deficits and cases that have both impaired language and musical abilities. They also indicate the need for studies that systematically manipulate stimuli with regard to the distance between sound intervals to compare the discrimination of linguistic pitch direction between amusic individuals and controls.

Peretz (2009) discussed the notion of the modularity of vocal production and provided evidence of modularity in speaking and singing by examining the extent to which vocal production in music and language share processing components. According to Peretz (2009), a double-dissociation exists between singing and speaking. Therefore, domain-specificity must be extended to music and language production tasks, and musical abilities may partially depend on modular processes. Moreover, evidence of pitch-related processes argue against the view that music is anchored in speech module mechanisms.

Considering the above discussion, we argue that musical lyrics are processed in parallel to musical melodies. This hypothesis is supported by Besson, Faïta, Peretz, Bonnel, & Requin (1998). Amusic individuals can recognize a melody from its lyrics. However, when the lyrics are absent, amusic individuals are unable to identify it. Therefore, in the model proposed by Peretz et al. (2003), lyrics are processed in a parallel manner in a different system (i.e., the language processing system).

Importantly, the model proposed by Peretz et al. (2003) was developed based on patterns of double-dissociations observed in studies of patients with brain damage. The findings that indicate double-dissociations and their implications for the organization of musical function in the brain should be carefully considered.

Table 1. Case studies of acquired amusias published from 1990 to 2003 showing selective deficits in musical processing

			Melodic organization			Temporal organization		
Study	**Cases**	**Lesions**	**Scale**	**Contour**	**Interval**	**Rhythm**	**Meter**	**Memory**
Peretz (1990)	V.G	RH	NA	-	-	+	+	+
	V.C.	RH	NA	-	-	+	+	+
	L.N.	LH	NA	+	+	-	+	+
	C.V.	LH	NA	+	+	-	+	+
	5 cases	RH	NA	-	-	-	+	+
	5 cases	LH	NA	+	-	-	+	+
Peretz (1993)	G.L.	Bilateral	-	+	+	+	+	-
Peretz & Kolinsky (1993)	C.N.	Bilateral	-	-	-	+	+	NA
Ayotte et al. (2000)	LBS1	LH	+	-	+	+	+	-
	LBS4	LH	+	+	+	-	-	-
	RBS9	RH	-	-	+	+	+	-
	RBS11 RBS12	RH	+	-	-	+	+	+
	BBS20	Bilateral	-	-	-	+	+	-
	N.R.	RH	-	-	-	-	+	-
	R.C.	Bilateral	-	-	-	+	-	-
Liégeois-Chauvel et al. (1998)	Case 19	LH T1p	-	-	-	+	-	+
	Case 16	LH T1p	+	-	-	+	+	-
	Case 17	LH T1p	+	+	-	+	+	-
	Case 44	RH T1p	-	-	-	-	+	-
	Case 50	RH T1p	-	-	-	-	-	-
	Case 47	RH T1p	+	+	+	+	+	+
	Case 46	RH T1p	-	-	-	-	-	+
	Case 54	RH T1p	-	+	-	-	+	-
Peretz & Gagnon (1999)	I.R.	Bilateral	-	-	-	-	+	-
Piccirilli et al. (2000)	1 case	LH (STG)	-	-	-	+	NA	-
Vignolo (2003)	8 cases	RH	+	+	+	+	+	NA
	2 cases	RH	-	-	-	+	+	NA
	3 cases	LH	+	+	+	-	-	NA
	6 cases	LH	+	+	+	-	-	NA

RH, right hemisphere; LH, left hemisphere; T1p, posterior part of superior temporal gyrus; STG, superior temporal gyrus; NA, not assessed.

Van Orden, Pennington, & Stone (2001) suggested that double-dissociations relate functional behavior to brain lesions and are reference points to identify causal chains in the brain. However, the patterns of dissociation have no meaning if they are outside theoretical guidelines. Modules are *a priori* assumptions that do not necessarily follow from a double-dissociation. According to Van Orden et al. (2001), the theoretical implications of double-dissociations rely on the validity of modularity. The utility and practicability of assuming that certain modularities are true is questionable. The authors argued that in some cases (e.g., reading modules), modularity fails to converge on a fixed set of exclusionary criteria that define pure case dissociations. Consequently, competing modular theories force continuous pursuits of pure cases, thus increasing the list of exclusionary criteria. This problem partially leads to failures in limiting the potential set of pure case dissociations, which perpetuates further fractionation into more modules. Thus, in addition to questions posed by individual differences, reorganization of functions induced by lesions and resource devices must consider the circularity involved in operational definitions of tasks of cognitive components and the subtractive logic implied by pure case dissociations.

Despite this, recent neuroimaging studies have contributed to the validation of double-dissociation findings (Groussard et al., 2010; Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011). Amusia cases are heterogeneous, affecting either one or more components of cognitive musical processing. Identifying the brain correlates involved in musical processing is difficult. Stewart et al. (2006) reviewed published clinical cases of amusic individuals and functional neuroimaging studies with typical listeners and identified some basic principles that can be used to organize musical processing deficits after brain damage. Despite the fact that the brain damage that caused these deficits was widespread, prevalent damage was found in the right hemisphere. The results suggested some necessary structures for musical processing such as the right superior temporal cortex and other areas such as the insula and frontal lobe. Stewart et al. (2006) considered, however, that the predominance of the right hemisphere in amusias may be attributable to sample bias in which patients with linguistic disorders, usually associated with the left hemisphere, were excluded. Because most cases are the result of stroke, a purely amusia case is rarely found in which musical deficits are followed by other auditory disorders. Nonetheless, Stewart et al. (2006) argued for the possibility of identifying, through dissociations, a few main components of music processing that can be selectively damaged such as pitch, interval, contour, tonal structure, rhythm, meter, timbre, musical memory, and emotion recognition. These components, with the exception of timbre, are included in the model proposed by Peretz et al. (2003). However, the specificity of a brain substrate identified as critical for musical function must still be considered hypothetical. Neuroimaging techniques allow the observation of variations in neural processes that are useful for elucidating neural systems but not yet sufficient to determine the domain of cognitive processing. Using these techniques in an isolated manner is not advisable because they are unable to trace the neural networks that are sufficient to perform a particular cognitive operation. Functional neuroimaging methods and studies of brain-damaged patients may be considered complementary (Price, 2000) and contribute to the identification of brain correlates involved in musical processing.

Importantly, the model proposed by Peretz et al. (2003) refers to the perception of monophonic melodies (i.e., one single voice) and mostly to music perception rather than production. Musical processing has many components and involves the activation of widespread brain areas. Other schemes and models have been proposed based on neuroimaging findings that consider other components such as symbolic system processing, harmony, and timbre (Koelsch & Siebel, 2005; Warren, 2008; Koelsch, 2011), computational models of music perception and cognition (reviewed by Purwins, Herrera, Grachten, Hazan, Marxer, & Serra 2008a; Purwins, Herrera, Grachten, Hazan, Marxer, & Serra, 2008b), and neuroscientific investigations that focus on music production (Bangert & Altenmüller, 2003; Herrojo-Ruiz, Strübing, Jabusch, & Altenmüller, 2010; Maidhof, Vavatzanidis, Prinz, Rieger, & Koelsch, 2010). Nevertheless, the model proposed by Peretz et al. (2003) is a theoretically oriented model with well-established operational definitions that allow the evaluation of musical deficits. Cultural studies that have evaluated amusia using the MBEA indicate that it is a valid and reliable tool in other Western cultures to evaluate musical function (Nunes, Loureiro, Loureiro, & Haase, 2010; Nunes-Silva & Haase, 2012). In Eastern cultures that have different rhythm and melody scales, the MBEA stimulus should be adapted according to the specific cultural background for a more sensitive evaluation (Paraskevopoulos, Tsapkini, & Peretz, 2010). Despite differences in the test stimuli, data obtained by Paraskevopulos et al. (2010) indicated that the cognitive organization of music perception is similar in Greek (i.e., Eastern) and Western cultures. Future studies should identify which cultural aspects are involved in differences in musical perception. In addition to offering support for the assessment of different types of amusia from the MBEA, the model proposed by Peretz et al. (2003), similar to the other proposed models, should advance toward integrating the various aspects of musical production, perception, and cognition into a single framework with well-established neural substrates and considering aspects such as the active nature of perception and developmental and genetic aspects of musical processing.

Congenital Amusia

According to Hyde & Peretz (2004), congenital amusia, also known as *tone-deafness*, is a lifelong inability to process music, despite normal intelligence, memory, and language skills. Individuals with congenital amusia do not develop basic musical abilities, presenting severe deficiencies in tonal processing and difficulties recognizing and distinguishing familiar tunes, distinguishing one tune from another, singing a song, or performing rhythmic patterns. Despite this, these individuals do not present any anomaly or brain damage, and they possess normal levels of education and adequate exposure to musical stimuli throughout life. Baeck (2002) argues that congenital amusic individuals can also recognize prosody, environmental tunes, and human voices, thus characterizing it as a specific musical domain disorder.

The first anecdotal evidence of congenital amusia is attributed to a case described by Charles Grant-Allen (1878), which was interestingly followed in the next number of the same journal by a publication of a self-report of the early feminist writer Edith Simcox where she self-declared having the condition previously described as well as another similar condition (but not identical) to a case related by Grant-Allen (Simcox & Grant-Allen, 1878). Despite this, congenital amusia has only recently been systematically evaluated and studied. Ayotte et al. (2002) made one of the first attempts to detail behavioral manifestations in individuals with congenital amusia. They showed that this disorder is part of an entirely new class of learning disabilities that affect musical abilities. Eleven adults participated in the study, which required the self-report of a musical handicap since birth despite much effort to learn music. Self-reports of these individuals were confirmed by a detailed interview and formal testing. These individuals also possessed high levels of education and had no neurological or psychiatric history. The participants were evaluated using a series of three groups of tests: memory recognition tests with musical stimuli, musical pitch perception tests, and musical performance tasks. Most of the tests were originally elaborated for examining the presence of musical deficits in brain-damaged patients. Individuals who declared themselves to be amusic were severely impaired in their musical recognition and discrimination abilities compared with controls who were matched with regard to sex, age, level of education, and previous music experience. The amusic participants, for example, could not recognize tunes without help from its lyrics. They were also insensitive to dissonances and could not discriminate differences in pitch. Although these individuals presented such difficulties, most were able to detect variations in temporal structure (Ayotte et al., 2002). Notably, this research focused on the fact that congenital amusia may be related to a deficiency in the processing of variations in pitch frequency. A basic perceptual flaw that compromises pitch frequency in congenital amusia was revealed by Peretz et al. (2002) and confirmed by Hyde & Peretz (2004). In this research, isotonic and monotonic sequences of five consecutive sounds were presented to amusic individuals and the control group. All amusic individuals had difficulty detecting changes in pitch that were lower than two semi-tones, with normal acuity being approximately a half semi-tone. The affected individuals did not present performance improvement with practice. Conversely, changes in time were detected by the amusic participants the same way as controls, and improved performance was observed with practice.

Many recent studies of congenital amusia have been performed, allowing a better comprehension of these deficits. For example, Hyde, Zatorre, Griffiths, Lerch, & Peretz (2006) performed a study that compared independent groups (amusic individuals and non-amusic individuals) using magnetic resonance imaging (MRI) data from two different research centers (i.e., Montreal Neurological Institute, McGill University, Montreal, Quebec, Canada and Newcastle University Medical School, Newcastle upon Tyne, UK). They investigated the neural correlates of congenital amusia and hypothesized that there are volumetric differences in both white and gray matter between individuals with and without amusia. The analyses were performed using voxel-based morphometry (VBM), which is a method that allows the investigation of focal differences in brain volume. Hyde et al. (2006) observed a reduction of white matter in the inferior frontal gyrus in amusic individuals compared with non-amusic controls, which was positively correlated with performance on musical tasks based on musical pitch perception but not rhythm perception. The study had one limitation, however, in which VBM only detects macroscopic brain abnormalities, making the detection of subtle brain anomalies impossible. Hyde et al. (2006) expected to find volumetric alterations in the auditory cortex, but such a result was not found. A later MRI study by Hyde, Lerch, Zatorre, Griffiths, Evans, & Peretz (2007) with the same patients showed that the structural alterations observed with VBM (i.e., a decrease in white matter and increase in gray matter at the level of the inferior right frontal gyrus in amusic individuals) actually reflected an increase in the thickness of the auditory cortex and inferior right frontal gyrus.

Peretz et al. (2007) performed a study of familial aggregation in which they compared families with individuals who suffered from congenital amusia and families with individuals who were all non-amusic. The findings suggested that congenital amusia has a hereditary component that is equivalent to the order of magnitude of heredity found in linguistic impairment. The relative risk for the amusic individuals' siblings and offspring were the following, respectively: λ = 10.8, 95% confidence interval, 8–13.5, and λ = 2.3, 95% confidence interval, 0–5. Importantly, Peretz et al. (2007) found differences in the results obtained between the generations (i.e., siblings and offspring). The relative risk for the children of amusic individuals was lower than the relative risk for the siblings. Peretz et al. (2007) suggested that the difference in the relative risk between generations reflected a cohort effect in which congenital amusia could be less penetrating in the children's generation because of a more enriching musical environment. Environmental influences, therefore, contributed to the reduction of the prevalence of congenital amusia in the most recent generation. The authors argued that the importance of environmental factors is paramount and concluded that congenital amusia is likely more influenced by interactions between many genes and the environment, hence favoring the general susceptibility to deficits. Peretz et al. (2007) suggested that congenital amusia is a complex disorder with likely multiple causes that develops epigenetically through interactions between genetic susceptibility factors and variations in individual experiences.

More recent studies of congenital amusia provided evidence of structural and functional alterations in hierarchical processes in the superior temporal area and inferior frontal cortex, with the presence of abnormal connectivity among these areas, indicating that congenital amusia could be a connectivity disorder

(Hyde et al., 2006; Hyde et al., 2007; Mandell, Schulze, & Schlaug, 2007). Studies that used event-related potentials supported this hypothesis (Peretz, Brattico, & Tervaniemi, 2005; Peretz, Brattico, Järvenpää, & Tervaniemi, 2009). These studies showed that amusic individuals presented an almost normal ability to detect tonal deviances without being conscious of it. Electrical activity in the auditory cortex in amusic individuals was intact, and the electrophysiological alterations that were found were likely located in pathways outside the auditory cortex. The findings suggested that the neural representation of pitch in the brains of amusic individuals is not capable of establishing contact with the knowledge of tonal pitch through the neural frontal auditory pathway.

Other studies that used different evaluation methods reinforce the concept of congenital amusia as a connectivity disorder. Loui & Schlaug (2009) used diffusion tensor tractography and found white matter abnormalities in the brains of amusic individuals. The amusic individuals presented volume reductions and changes in the structure of the arcuate fasciculus (i.e., the fiber tract that connects the temporal cortex to the inferior frontal cortex), primarily in the right hemisphere. Additionally, Loui, Alsop, & Schlaug (2009) showed that amusic individuals who presented reductions of arcuate fasciculus volume had impaired performance, with mismatches in music perception and production, assessed by psychophysical tests. Subsequently, Loui, Hohmann, & Schlaug (2010) used transcranial direct current stimulation and observed a reduction of the accuracy of pitch perception after stimulation of the inferior frontal area and temporal superior area in normal individuals, demonstrating that the intact function and connectivity of the network that connects these two areas are necessary for the efficient neural manipulation of musical stimuli (Loui et al., 2010). Finally, Hyde, Zatorre, & Peretz (2011) used functional MRI to evaluate participants who listened to melodic sequences of pure tones in which the distance between consecutive tones varied parametrically. They showed that brain activity increased as the distance between the tones increased, even with fine changes, in the right and left auditory cortices of amusic individuals and controls. In contrast, the right inferior frontal gyrus exhibited low activity and evidence of reduced connectivity in the auditory cortex in amusic individuals compared with controls (Hyde et al., 2011). The findings of these studies suggest that preserved bilateral frontotemporal networks are needed for accurate pitch perception and production.

Congenital amusia has generally been associated with pitch deficits. Nonetheless, similar to acquired amusia, congenital amusia can also impair other components of musical processing. Phillips-Silver et al. (2011) recently identified a new case of congenital amusia (Mathieu) related to the ability to perceive the pulsation of music despite normal intelligence and motor and auditory systems. Mathieu was unable to synchronize the movement of his body with music and unable to detect when the movements of a dancer were discordant with the music, although he was able to synchronize with a monometer at a close-to-normal level. Mathieu also presented a score that was under the mean only in the metrics task of the MBEA, indicating selective impairment in this task with preservation of rhythm perception and the perception of pitch frequency patterns. These findings suggested a specific beat deficit in the musical context and that time may have a neurobiological origin distinct from pitch in musical processing.

Studies of congenital amusia have contributed not only to a better understanding of such a disorder but also to a better understanding of musical processing. According to Peretz (2003), studies of congenital amusia may also provide neuropsychological evidence of brain specialization for music, suggesting that the development of neural networks that are dedicated to music occur very early in life and are essential to normal development of musical functions. In congenital amusia, these essential neural elements may be damaged, despite the preservation of other cognitive skills. Further studies are necessary to investigate its etiology and the influence of early musical stimuli on congenital amusia, which may help understand the heritable traits of the disorder and the abilities related to components of cognitive musical processing. The studies of congenital amusia provide evidence that music is a specific domain with specialized neural networks (Peretz, 2006) and suggest the possibility of a very specific type of impairment in the perception of pitch frequency with the preservation of abilities related to temporal structures, consistent with the neuropsychological model of cognitive musical processing.

Conclusion

Well-documented evidence indicates that musical processing appears to depend on a complex and specific cognitive structure for music according to the hypothesis of the modular organization of music in the brain. According to Fodor (1983), for a system to be considered modular, the following traits must be observed: (*i*) domain specificity, in which the operations do not cross other domains of content, (*ii*) innatism (i.e., the extent to which a structure is innate or formed by learning processes, (*iii*) not assembled (i.e., not formed by collections of more elementary subprocesses, no aggregation), (*iv*) hardwired (i.e., related to neural specificity, associated with specific, local, and structured neural networks), and (*v*) autonomous (i.e., not sharing horizontal resources, such as memory and attention, with other cognitive systems). The modular systems must guarantee information speed and automation. According to Fodor, one main trait is informational encapsulation, which indicates that the system does not have complete access to the expectations, beliefs, suppositions, and desires of the individual. Coltheart (1999) suggested that these traits are not absolutely necessary to define the term *modular* in which one system may be modular but not innate, such as the case of the reading system. Coltheart (1999) also indicated that the no-aggregation trait was not well-developed by Fodor and thus inconsistent with his consideration of the presence of top-down processing in the modules. His general idea was that the modules could have sub-levels of representation that communicate among themselves and whose existence, according to Fodor (1983), does not violate the principle of informational encapsulation.

Peretz & Coltheart (2003) stated that the main trait of a modular system would be the specific domain in which a system only responds to inputs from a particular class. In the case of music, the evidence presented herein indicates that music is constituted in a module of mental information processing whose operations are specific to this type of input, with smaller modules that process domains that are restricted to particular aspects of music. According to Peretz & Coltheart (2003), musical abilities should not be studied as a general product of cognitive architecture but as a distinct mental module with its own base of knowledge and procedures associated with specific neural substrates. Peretz (2006) stated that studies of the domain specificity of music, innatism, and brain location seek to understand music's functional and biological bases and support the hypothesis of the modular organization of music in the brain. Thus, a neurological anomaly may damage one or more components in processing just as it may interfere with the passage of information among components.

The cognitive–neuropsychological model of musical processing presented by Peretz et al. (2003) may contribute to a better understanding of the selective impairments of different components of musical processing that occur in individuals who suffer brain damage and have congenital amusia. In the clinical classification of amusias presented by Benton (1977), amusias can affect different kinds of musical abilities. The model of musical processing elaborated by Peretz can shed light on the classification proposed by Benton and theoretically support some of these types of amusias including musical amnesia (related to melody recognition), rhythmical disorder (related to the rhythmical component), and receptive amusia (related to the pathway of melodic organization).

Most individuals affected by congenital amusia present deficits in melodic discrimination, despite the preservation of rhythm (Hyde & Peretz, 2004). The musical processing model addresses differences in the results of melodic structure tasks and temporal structure tasks in congenital amusia and considers the hypothesis of dissociations between the processing of rhythm and melody.

With regard to the diagnoses of different types of amusia, the model offers support for developing evaluation instruments such as the MBEA, which allows a more precise diagnosis of deficits in musical abilities (Peretz et al., 2003). A more complete neuropsychological exam should include evaluations of the components of musical processing considered in the model, not only to identify deficits in musical abilities but also to determine whether interventions based on elements of music can contribute to the treatment of such disorders.

The various manifestations of amusia can be better understood and investigated based on this model. For example, it deals with selective deficits in rhythm, meter, contour, interval, tonal structure, and musical memory and is in accordance with recent neuroscientific knowledge about cognition and music perception. It also provides relevant insights for better understanding of the relationships between music domains and other domains such as emotion and language.

Importantly, according to the model presented by Peretz & Coltheart (2003), some of its subdomains such as rhythm, meter, tapping, and the emotional component may not be domain-specific. Some questions related to the differentiation of specific components of music and language are still unanswered and require further studies.

Furthermore, the model mostly refers to music perception, the pathways for music production, and the deficits with which they are associated, including vocal production and motor activities, all of which require further research. Because the model focuses on the music perception of normal listeners, without music formation, it fails to consider amusias based on prior knowledge that involves symbolic systems of reading and writing or playing a musical instrument. The issue of the pattern of connectivity between the superior temporal cortex and inferior frontal cortex in the brains of amusic individuals is also not considered.

Studies of music from a neuroscientific perspective are still too recent. Nonetheless, despite its novelty, much progress has been made. The cognitive–neuropsychological model of musical processing has provided several benefits to this field of knowledge, but it can still be enhanced and extended to other types of amusia.

References

Alajouanine, T. (1948). Aphasia and artistic realization. *Brain*, *71*, 229-241.

Ayotte, J., Peretz, I., & Hyde, K. (2002). Congenital amusia: A group study of adults afflicted with a music-specific disorder. *Brain*, *125*, 238-251.

Ayotte, J., Peretz, I., Rousseau, I., Bard, C., & Bojanowski, M. (2000). Patterns of music agnosia associated with middle cerebral artery infarcts. *Brain*, *123*, 1926-1938.

Baeck, E. (2002). The neural networks of music. *European Journal of Neurology*, *9*, 449-456.

Bangert, M., & Altenmüller, E. O. (2003). Mapping perception to action in piano practice: A longitudinal DC-EEG study. *BMC Neuroscience*, *4*, 26.

Bautista, R. E. D., & Ciampetti, M. Z. (2003). Expressive aprosody and amusia as a manifestation of right hemisphere seizures. *Epilepsia*, *44*(3), 466-467.

Benton, A. L. (1977). The amusias. In M. Critchley, & R. A. Henson (Eds.), *Music and the brain: Studies in the neurology of music* (pp. 378-397). London: Heinemann Medical.

Besson, M., Faïta, F., Peretz, I., Bonnel, A. M., & Requin, J. (1998). Singing in the brain: Independence of lyrics and tunes. *Psychological Science*, *9*(6), 494-498.

Brust, J. C. M. (2001). Music and neurologist: A historical perspective. *Annals of the New York Academy of Sciences*, *930*, 143-152.

Critchley, M., & Henson, R. A. (1977). *Music and the brain: Studies in the neurology of music*. London: Heinemann Medical.

Coltheart, M. (1999). Modularity and cognition. *Trends in Cognitive Sciences*, *3*(3), 115-120.

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, MA: MIT Press.

García-Casares, N., Torres, M. L. B., Walsh, S. F., & González-Santos, M. L. (2011). Modelo de cognición musical y amusia. *Neurología*, *28*, 179-186.

Grant-Allen, C. (1878). Note-deafness. *Mind*, 3(10), 157-167.

Groussard, M., Viader, F., Hubert, V., Landeau, B., Abbas, A., Desgranges, B., … Platel, H. (2010). Musical and verbal semantic memory: Two distinct neural networks? *Neuroimage*, *49*, 2764-2773.

Henson, R. A. (1977). Neurological aspects of musical experience. In M. Critchley, & R. A. Henson (Eds.). *Music and the brain: Studies in the neurology of music* (pp. 3-21). London: Heinemann Medical.

Herrojo-Ruiz, M., Strübing, F., Jabusch, H. C., and Altenmüller, E. (2010). EEG oscillatory patterns are associated with error prediction during music performance and are altered in musician's dystonia. *Neuroimage*, *55*(4), 1791-1803.

Hyde, K., Lerch, J., Zatorre, R., Griffiths, T. D., Evans, A., & Peretz, I. (2007). Cortical thickness in congenital amusia: When less is better than more. *Journal of Neuroscience*, *47*, 13028-13032.

Hyde, K., & Peretz, I. (2004). Brains that are out of tune but in time. *Psychological Science*, *15*(5), 356-360.

Hyde, K. L., Zatorre, R. J., Griffiths, T. D., Lerch, J. P., & Peretz, I. (2006). Morphometry of the amusic brain: A two-site study. *Brain*, *129*, 2562-2570.

Hyde, K., Zatorre, R. J., & Peretz, I. (2011). Functional MRI evidence of an abnormal neural network for pitch processing in congenital amusia. *Cerebral Cortex*, *21*(2), 292-299.

Johnson, J. K., & Graziano, A. B. (2003). August Knoblauch and amusia: A nineteenth-century cognitive model of music. *Brain and Cognition*, *51*, 102-114.

Knoblauch, A. (1890). On disorders of the musical capacity from cerebral disease. *Brain*, *13*, 317-340.

Koelsch, S. (2011). Toward a neural basis of music perception: A review and updated model. *Frontiers in Auditory Cognitive Neuroscience*, *2*, 110.

Koelsch, S., & Siebel, W. A. (2005). Towards a neural basis of music perception. *Trends in Cognitive Sciences*, 9, 578-584.

Liégeois-Chauvel, C., Peretz, I., Babaï, M., Laguitton, V., & Chauvel, P. (1998). Contribution of different cortical areas in the temporal lobes to music processing. *Brain*, *121*, 1853-1867.

Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: A new disconnection syndrome? *Journal of Neuroscience*, *29*(33), 10215-10220.

Loui, P., & Schlaug, G. (2009). Investigating musical disorders with diffusion tensor imaging: A comparison of imaging parameters. *Annals of the New York Academy of Sciences*, *1169*, 121-125.

Loui, P., Hohmann, A., & Schlaug, G. (2010). Inducing disorders in pitch perception and production: A reverse-engineering approach. *Proceedings of Meetings in Acoustics, 9*, 050002.

Luria, A. R., Tsvetkova, L. S., & Futer, D. S. (1965). Aphasia in a composer (V. G. Shebalin). *Journal of Neurological Science*, *2*, 288-292.

Maidhof, C., Vavatzanidis, N., Prinz, W., Rieger, M., & Koelsch, S. (2010). Processing expectancy violations during music performance and perception: An ERP study. *Journal of Cognitive Neuroscience*, *22*(10), 2401-2413.

Mandell, J., Schulze, K., & Schlaug, G. (2007). Congenital amusia: An auditory-motor feedback disorder? *Restorative Neurology and Neuroscience*, *25*, 323-334.

Marin, O., & Perry, D. (1999). Neurological aspects of music perception and performance. In D. Deutsch (Ed.), *The psychology of music* (pp. 653-712). San Diego: Academic Press.

Nicholson, K. G., Baum, S., Kilgour, A., Koh, C. K., Munhall, K. G., & Cuddya, L. L. (2003). Impaired processing of prosodic and musical patterns after right hemisphere damage. *Brain and Cognition*, *52*, 382-389.

Nunes-Silva, M., & Haase, V. G. (2012). Montreal Battery of Evaluation of Amusia: Validity evidence and norms for adolescents in Belo Horizonte, Minas Gerais, Brazil. *Dementia & Neuropsychology*, *6*(4), 244-252.

Nunes, M., Loureiro, C. M. V., Loureiro, M. A., & Haase, V. G. (2009). Tradução e validação de conteúdo de uma bateria de testes para avaliação de Amusia. *Avaliação Psicológica*, *9*(2), 211-232.

Paraskevopoulos, E., Tsapkini, K., & Peretz, I. (2010). Cultural aspects of music perception: Validation of a Greek version of the Montreal Battery of Evaluation of Amusias. *Journal of the International Neuropsychological Society*, *16*, 695-704.

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience*, *6*(7), 674-681.

Patel, A. D., Peretz, I., Tramo, M., & Labreque, M. (1998). Processing prosodic and musical patterns: A neuropsychological investigation. *Brain and Language*, *61*, 123-144.

Patel, A., Wong, M., Foxton, J., Lochy, A., & Peretz, I. (2008). Speech intonation perception deficits in musical tone deafness (congenital amusia). *Music Perception*, *25*, 357-368.

Peretz, I. (1990). Processing of local and global musical information in unilateral brain-damaged patients. *Brain*, *113*, 1185-1205.

Peretz, I. (1993). Auditory atonalia for melodies. *Cognitive Neuropsychology*, *10*(1), 21-56.

Peretz, I. (2003). Brain specialization for music: New evidence from congenital amusia. In I. Peretz, & R. J. Zatorre (Eds.), *The cognitive neuroscience of music* (pp. 192-203). Oxford: Oxford University Press.

Peretz, I. (2006). The nature of music from a biological perspective. *Cognition*, *100*, 1-32.

Peretz, I. (2009). Music, language and modularity framed in action. *Psychologica Belgica*, *49*(2-3), 157-175.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., & Jutras, B. (2002). Congenital amusia: A disorder of fine-grained pitch discrimination. *Neuron*, *33*, 185-191.

Peretz, I., Belleville, S., & Fontaine, F. S. (1997). Dissociations entre musique et langage après atteinte cérébrale: Un nouveau cas d'amusie sans aphasie. *Revue Canadienne de Psychologie Expérimentale*, *51*(4), 354-367.

Peretz, I., Brattico, E., Järvenpää, M., & Tervaniemi, M. (2009). The amusic brain: In tune, out of key, and unaware. *Brain*, *132*, 1277-1286.

Peretz, I., Brattico, E., & Tervaniemi, M. (2005) Abnormal electrical brain responses to pitch in congenital amusia. *Annals of Neurology*, *58*, 478-482.

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. *Annals of the New York Academy of Sciences*, *999*, 58-75.

Peretz, I., & Coltheart, M. (2003). Modularity of music processing. *Nature Neuroscience*, *6*(7), 688-690.

Peretz, I., Cummings, S., & Dubé, M. P. (2007). The genetics of congenital amusia (tone deafness): A family-aggregation study. *American Journal of Human Genetics*, *81*, 582-588.

Peretz, I., & Gagnon, L. (1999). Dissociation between recognition and emotional judgment for melodies. *Neurocase*, *5*, 21-30.

Peretz, I., & Kolinsky, R. (1993). Boundaries of separability between melody and rhythm in music discrimination: A neuropsychological perspective. *Quarterly Journal of Experimental Psychology*, *46*, 301-325.

Peretz, I., Kolinsky, R., Tramo, M., Labrecque, R., Hublet, C., Demeurisse, G., & Belleville, S. (1994). Functional dissociations following bilateral lesions of auditory cortex. *Brain*, *117*, 1283-1302.

Peretz, I., & Zatorre, R. J. (2005). Brain organization for music processing. *Annual Review of Psychology*, *56*, 89-114.

Phillips-Silver, J., Toiviainenc, P., Gosselina, N., Pichéa, O., Nozaradana, S., Palmera, C., & Peretz, I. (2011). Born to dance but beat deaf: A new form of congenital amusia. *Neuropsychologia*, *49*, 961-969.

Piccirilli, M., Sciarma, T., & Luzzi, S. (2000). Modularity of music: Evidence from a case of pure amusia. *Neurology, Neurosurgery, and Psychiatry*, *69*, 541-545.

Price, C. J. (2000). The anatomy of language: Contributions from functional neuroimaging. *Journal of Anatomy*, *197*, 335-359.

Purwins, H., Herrera, P., Grachten, M., Hazan, A., Marxer, R., & Serra, X. (2008a). Computational models of music perception and cognition: I. The perceptual and cognitive processing chain. *Physics of Life Reviews*, *5*, 151-168.

Purwins, H., Herrera, P., Grachten, M., Hazan, A., Marxer, R., & Serra, X. (2008b). Computational models of music perception and cognition. II. Domain-specific music processing. *Physics of Life Reviews*, *5*, 169-182.

Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nature Neuroscience*, *14*(2), 257-262.

Simcox, E. & Grant-Allen, C. (1878). Note-Deafness. *Mind*, 3 (11), 401-404.

Steinthal, H. (1871). Einleitung in die Psychologie und Sprachwissenschaft. *Abriss der sprachwissenschaft*. Berlin: Dümmlers.

Stewart, L., von Kriegstein, K., Warren, J. D., & Griffiths, T. D. (2006). Music and the brain: Disorders of musical listening. *Brain*, *129*, 2533-2553.

Tramo, M. J., Shah, G. D., & Braida, L. D. (2002). Functional role of auditory cortex in frequency processing and pitch perception. *Journal of Neurophysiology*, *87*, 122-139.

Van Orden, G. C., Pennington, B. F., & Stone, G. O. (2001). What do double dissociations prove? *Cognitive Science*, *25*, 111-172.

Vignolo, L. A. (2003). Music agnosia and auditory agnosia: Dissociations in stroke patients. *Annals of the New York Academy of Sciences*, *999*, 50-57.

Warren, J. (2004). The amusias. In: F. C. Rose (Ed.), *Neurology of the arts: Painting, music, and literature* (pp. 275-305). London: Imperial College Press.

Warren, J. (2008). How does the brain process music? *Clinical Medicine*, *8*(1), 32-36.

Warren, J. D., Warren, J. E., Fox, N. C., & Warrington, E. K. (2003). Nothing to say, something to sing: Primary progressive dynamic aphasia. *Neurocase*, *9*(2), 140-155.

Wertheim, N. (1969). The amusias. In P. J. Vinken, & G. W. Bruyn (Eds.), *Disorders of speech, perception and symbolic behaviour* (series title: *Handbook of clinical neurology*, vol. 4) (pp. 195-206). Amsterdam: New Holland.

Wilson, S. J., Pressing, J. L., & Wales, R. J. (2002). Modelling rhythmic function in a musician post-stroke. *Neuropsychologia*, *40*, 494-505.

Zatorre, R. J. (2001). Neural specializations for tonal processing. *Annals of the New York Academy of Sciences*, *930*, 193-210.

Montreal Battery of Evaluation of *Amusia*

Validity evidence and norms for adolescents in Belo Horizonte, Minas Gerais, Brazil

Marília Nunes-Silva[1], Vitor Geraldi Haase[2]

ABSTRACT. The Montreal Battery of Evaluation of Amusia (MBEA) is a battery of tests that assesses six music processing components: scale, contour, interval, rhythm, metric, and music memory. The present study sought to verify the psychometric characteristics of the MBEA in a sample of 150 adolescents aged 14-18 years in the city of Belo Horizonte, Minas Gerais, Brazil, and to develop specific norms for this population. We used statistical procedures that explored the dimensional structure of the MBEA and its items, evaluating their adequacy from empirical data, verifying their reliability, and providing evidence of validity. The results for the difficult levels for each test indicated a trend toward higher scores, corroborating previous studies. From the analysis of the criterion groups, almost all of the items were considered discriminatory. The global score of the MBEA was shown to be valid and reliable ($r_{K\text{-}R20}$=0.896) for assessing the musical ability of normal teenagers. Based on the analysis of the items, we proposed a short version of the MBEA. Further studies with larger samples and amusic individuals are necessary to provide evidence of the validity of the MBEA in the Brazilian milieu. The present study brings to the Brazilian context a tool for diagnosing deficits in musical skills and will serve as a basis for comparisons with single case studies and studies of populations with specific neuropsychological syndromes.

Key words: music, cognition, neuropsychological tests, validation studies, Montreal battery.

BATERIA MONTREAL DE AVALIAÇÃO DE AMUSIA: EVIDÊNCIAS DE VALIDADE E NORMAS PARA ADOLESCENTES DE BELO HORIZONTE

RESUMO. A Montreal Battery of Evaluation of Amusia (MBEA) é uma bateria de testes que avalia funções musicais referentes a seis componentes do processamento musical: escala, contorno, intervalo, ritmo, métrica e memória musical. O presente estudo objetivou verificar as características psicométricas da MBEA em uma amostra de 150 adolescentes de 14 a 18 anos da cidade de Belo Horizonte e compor normas específicas para essa população. Foram utilizados procedimentos estatísticos que permitiram explorar a estrutura dimensional da MBEA e dos itens componentes, avaliar a adequação dos itens a partir de dados empíricos, verificar a confiabilidade e levantar evidências de validade a partir da análise fatorial. A análise de grupos-critério indicou que quase todos os itens podem ser considerados discriminativos. O índice global da MBEA se mostrou válido e fidedigno ($r_{K\text{-}R20}$=0,896) para avaliar as habilidade musicais de adolescentes normais. A partir da análise dos itens foi proposta uma versão reduzida da MBEA. O presente estudo, além de trazer para o contexto brasileiro um instrumento para o diagnóstico de déficits de funções musicais, poderá servir como base de comparação para estudos de caso simples e estudos posteriores em populações com síndromes neuropsicológicas específicas.

Palavras-chave: música, cognição, testes neuropsicológicos, estudos de validação, bateria Montreal.

INTRODUCTION

Music is a complex cognitive ability that requires efficient brain mechanisms to be processed. Failure of these mechanisms can result in different types of clinical musical deficits. Neurologists have analyzed disorders of musical functioning in patients with brain illness since the latter half of the 20th century in an attempt to associate brain lesions with specific brain deficits. Deficits in musical processing are grouped under the term *amusia*, which was first introduced by the German

[1]Doctoral student in the Neuroscience Program at the Universidade Federal de Minas Gerais (UFMG), Belo Horizonte MG, Brazil. Master's degree in developmental Psychology at UFMG. Graduated in Psychology at UFMG and in Music at Universidade do Estado de Minas Gerais (UEMG). [2]Full Professor in the Psychology Department at UFMG. Graduated in Medicine at the Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre RS, Brazil. Master's Degree in Applied Linguistics at the Pontifícia Universidade Católica do Rio Grande do Sul (PUCRS), Porto Algre RS, Brazil. Ph.D. in Medical Psychology at the Ludwig-Maximilians-Universität in München.

Marília Nunes-Silva. Avenida Antônio Carlos 6627 - FAFICH-UFMG / Sala 2016 – 31270-901 Belo Horizonte MG – Brazil. E-mail: musicainfinita@ig.com.br.

Disclosure: The authors report no conflicts of interest. Received August 29, 2012. Accepted in final form November 3, 2012.

doctor and anatomist August Knoblauch in 1888 to describe a specific disorder that results from lesions to the motor center for tones.[1]

The term *amusia* is still controversial, with no consensus on the classification of the many forms and definitions of this syndrome, despite many studies of these musical deficits.[2] Amusia has also been described under the terms *note deafness*, *tone deafness*, *tune deafness*, and *dysmelodia*.[3] Many classifications have been proposed for the different kinds of amusias. According to Johnson and Graziano (2003),[1] for example, Knoblauch proposed a detailed cognitive model for music processing, suggesting nine different types of amusias from clinical observations of patients. Benton (1977)[4] also classified musical deficits based on clinical observations, observing that amusias could manifest in several ways. Benton (1977)[4] classified amusias as receptive amusia, musical alexia, musical amnesia, rhythm disorders, vocal or oral-expressive amusia, instrumental amnesia or musical apraxia, and music agraphia. Marin and Perry (1999)[5] defined amusias as acquired clinical disorders attributable to brain damage in the fields of reading, writing, and musical perception and performance and proposed a classification of amusias according to a hierarchical order of processing. The authors considered the existence of specifically perceptual amusias, amusias that involve symbolic systems of reading and writing (based on previous knowledge), and other amusias related to vocal performance or motor activities. Levitin (1999)[2] also proposed a taxonomic system for classifying the various forms of amusias (i.e. tone-deafness), grouping them according to four different deficits: production deficits, perceptual deficits, memory deficits, and symbolic manipulation deficits (either music reading or writing). All of these classifications consider amusias as a complex and heterogeneous group of disorders of music processing that affect either one or more components of musical cognitive processing. Therefore, amusias can affect the performance and perception of melodies or their components (pitch, loudness, timbre, duration, and harmony) as well as symbolic systems of musical reading and writing.

Amusias can be categorized into two types: acquired amusias, resulting from disease or brain damage caused by accidental injury, and congenital amusias that are present since birth and may be due to hereditary factors.[3,6] Congenital amusia has been systematically investigated only recently.[7] Hyde and Peretz (2004)[6] defined congenital amusia as a lifelong inability to process musical skills, despite normal intelligence, memory, and language. Individuals with congenital amusia do not develop basic musical abilities, presenting deficits in tonal processing, exhibiting difficulty recognizing familiar sounds, distinguishing one tune from another, and singing tunes or producing rhythmic patterns.

According to Peretz, Champod, and Hyde (2003),[8] musical abilities may be compromised in a very selective way in both acquired and congenital amusias. Brain damage or deficits may interfere with musical function, whereas other domains, such as intelligence and language, remain intact. Moreover, not all musical abilities are equally affected. The processing of music relies on a complex and specific cognitive structure based on the modular organization of music in the brain. According to Peretz and Coltheart (2003),[9] musical functions are part of a distinct mental module with its own system of information processing and specific neural substrates. This module consists of processing subsystems, whose domains are restricted to particular aspects of music. Thus, neurological abnormalities can either damage one or more of the processing components or interfere with the passage of information between components. This perspective and studies of individuals who suffer selective deficits in musical abilities because of brain injuries, allowed the development of models to understand the components involved in the processing of music perception, such as the model described by Peretz and Coltheart (2003).[9] This neuropsychological model of musical cognitive processing, which specifies the components involved in perception and musical memory and their possible interactions, is depicted in Figure 1.

In this model, the auditory input has some aspects that elicit the action of the language processing system and other aspects that trigger the musical processing system. The lyric component of song is processed in the language processing system in parallel with the musical processing system.[9] The musical auditory input is analyzed by two independent and parallel systems with specific functions: one for the melodic dimension (related to variations in sound frequency), represented by the contour (direction of pitch sequences in a melody), scale (related to tonal functions), and interval (range size between two different pitches), and one for the temporal dimension (related to variations in the duration of sounds), represented by the rhythm (grouping of events according to temporal proximity) and metric organization (basic temporal regularity or pulse).

The outputs of melodic and temporal dimensions are sent to the *repertoire*, which is conceived as a perceptual representation system that contains all of the representations of musical phrases to which the subject was exposed throughout their life. In this model, the emo-

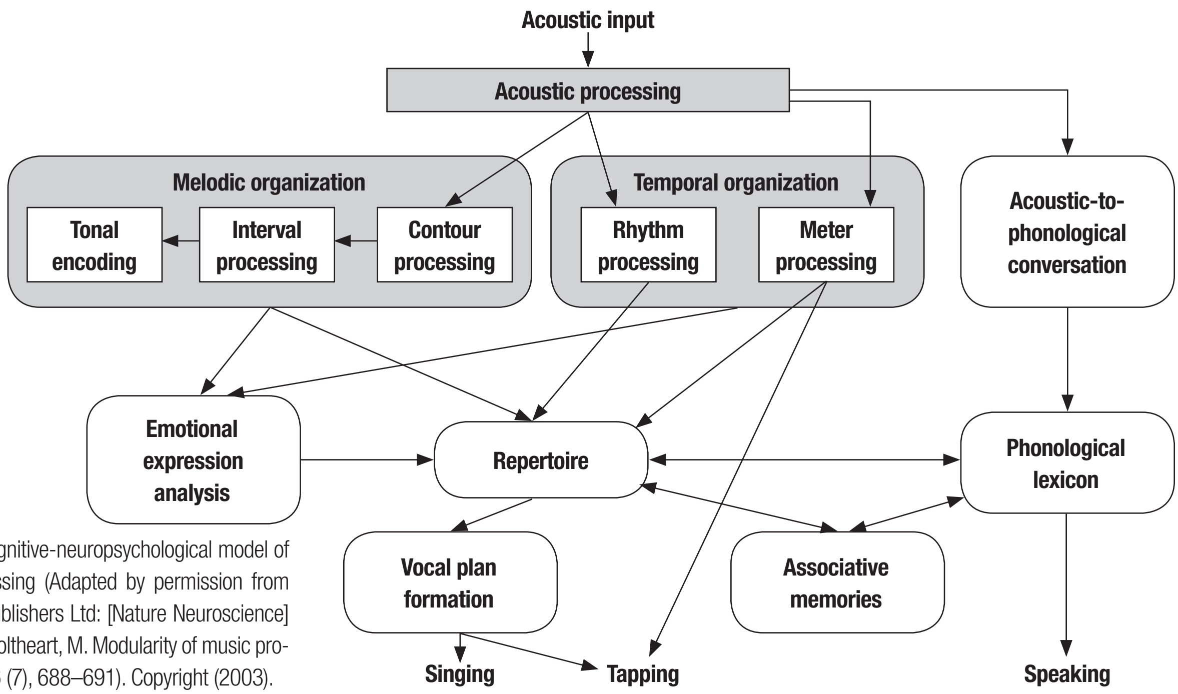

Figure 1. Cognitive-neuropsychological model of music processing (Adapted by permission from Macmillan Publishers Ltd: [Nature Neuroscience] (Peretz, I. & Coltheart, M. Modularity of music processing, Vol 6 (7), 688–691). Copyright (2003).

tional component refers to affective information provided by musical input and depends on two structures: the mode (i.e., the character of a scale that varies with the position of tones and semitones and their relationship to the tonic) and the tempo (i.e., the speed or pace of a piece).[8,9]

The neuropsychological cognitive model of musical processing was constructed from double dissociations observed in different studies of amusic individuals following brain injury. In acoustic processing, these studies allowed the differentiation of separate modules for processing music, language, and other environmental sounds.[5,10-14] With regard to music perception, these studies support the existence of two dissociated and parallel routes for musical input: temporal and melodic.[13,15-18] The melodic route is divided into three distinct modules: tonal encoding, contour, and interval.[15,16] The temporal dimension has two distinct modules: rhythm and meter.[16.19] According to Peretz et al. (2003),[8] this model led to the development of the Montreal Battery of Evaluation of Amusia (MBEA), providing theoretical support for the battery as a tool for neuropsychological assessment.

The MBEA is a battery of tests that assesses musical abilities that has been developed and revised since 1987.[8] The MBEA allows the diagnosis of different types of amusia by assessing musical abilities related to six components of musical processing presented in the neuropsychological model of musical cognitive processing, namely: Contour, Scale, Interval, Rhythm, Meter, and Musical Memory. The Contour test assesses the perception of a global form of a melody created from sequences of pitch direction (ascendant and descendant) of the melody. The Scale test assesses the tonal encoding of a melody that is related to tonal functions and harmonic structures. The Interval test evaluates the perception of distances between two successive pitches and is related to the analytical processing of the melodic domain. The Rhythm test assesses the perception of the grouping of events related to the temporal dimension of a melody with regard to the temporal proximity of consecutive sounds without considering its periodicity. The Meter test evaluates the global perception of the temporal music domain with regard to the temporal regularity or pulse of a melody. The Memory test assesses the recognition of musical phrases after implicit storage.[8]

The MBEA has been used in studies of populations of individuals with brain injuries with different etiologies to assess various types of amusia and was shown to be useful for this purpose.[10,15,16] Studies have used the MBEA to validate the battery.[7,8,20,21] Satisfactory results were obtained from a psychometric perspective. Peretz et al. (2003)[8] estimated that, although the data obtained for each test were asymmetric (i.e., tending toward higher scores), the overall index (i.e., the average scores on the six tasks of the MBEA) followed a normal distribution and thus constituted a good index of perception and musical memory that can be used to distinguish between normal and deficient performance in the general population.

Peretz et al. (2003)[8] reported that the concurrent validity of the MBEA was derived from Gordon's Musical Aptitude Profile tests. The study included a group of 68 firemen in training who obtained similar and positively correlated scores (r=0.53, p<0.001) on both tests. According to Peretz et al.,[8] the MBEA also has test-retest reliability (r=0.75, p<0.01). With regard to the diagnostic value of the MBEA for detecting amusia in the general population, Peretz et al.[8] conducted a study to determine whether 27 healthy individuals who declared themselves amusical truly had a deficit in their skills of musical perception. The results showed that, as a group, their performance was lower than the control group for each MBEA test, thereby confirming their subjective experience. This outcome indicates that the MBEA can serve as a useful tool for diagnosing amusia not only in patients with brain injuries but also in the general population.

In Brazil, research in music and cognitive neuropsychology is incipient, with a lack of studies on deficits in musical processing. Nevertheless, some research efforts have been undertaken,[22-26] mainly in musical education. Despite these efforts, we found no validated instruments in the Literatura Latino Americana em Ciências da Saúde (LILACS) or Scientific Electronic Library Online (SciELO) databases, evaluating musical deficits in the Brazilian context. The diagnosis of amusia is reached based on clinical observations of patients with brain damage, with no specific criteria to distinguish neurological conditions of musical deficits from other causes of musical deficiencies in the musical education context, especially with regard to cases of congenital amusia.

Studies conducted by the authors of the present work[27] to adapt the MBEA for use in the Brazilian context permitted verification of the relevance of its items and adequacy of its constructs to allow its use in adolescents in the city of Belo Horizonte. The evaluation of the relevance and adequacy of means, and the layout of the questions and instructions in the test setting, mode of application, and method of categorization were also satisfactory for the use of the MBEA in the Brazilian context. Following this first study, the present investigation sought to assess the psychometric characteristics of the MBEA and develop norms for the adapted version of the MBEA[27] based on a sample of Brazilian adolescents from the city of Belo Horizonte.

METHODS

Participants. The psychometric parameters of the MBEA were investigated in a convenience sample of 150 individuals who had no formal musical education, aged between 14 and 18 years. The sample was stratified according to 1-year age groups. In each age stratum, 30 individuals were equally divided between both sexes. The participants were secondary school students in Belo Horizonte, Minas Gerais, Brazil. The sample was also equally subdivided by type of educational institution (i.e., state-run, city-run, and private).

Materials. Adapted version of the Montreal Battery of Evaluation of Amusia (MBEA): The MBEA was adapted for use with adolescents aged 14 to 18 years in Belo Horizonte after a study that examined the adequacy of its constructs, items, and application procedures.[27] The MBEA assesses six components of music processing: Contour, Interval, Scale, Rhythm, Meter, and Musical Memory. The MBEA stimuli consist of 30 original musical phrases for each test, which were composed according to the Western tonal system comprising a total of 180 items. For the evaluation of Contour, the items are identical melodies presented in pairs. Half of the items have one note altered in the second melody according to the direction of pitch (ascendant to descendant and vice-versa), while the other half of the pairs remains unchanged. The interval and scale of the melodies remains unaltered. Modified and non-modified phrases are pseudorandomly dispersed among a total of 30 items. The subject's task is to identify whether one of the phrases is modified or not. The Interval test is similar to the Contour test, but the note is altered in the modified items according to the extent of the pitch in relation to a previous note (in terms of semi-tone distance), keeping the original scale and contour. In the Scale test, the manipulations of the modified items consist of modifying the pitch to be out of scale, maintaining the original melodic contour. In the Rhythm test, groupings by temporal proximity are manipulated by changing the durations of two adjacent tones while the same meter and total number of sounds were maintained. For these first four tests, an additional item, the catch trial, consists of strategic trials that had to be answered correctly for responses to be considered. This item contains pairs of melodies that are clearly different to determine whether the individual remains attentive throughout the test session. In the Meter test, half of the 30 phrases were composed in a duple meter, and the other half were composed of a triple meter. The subjects are required to categorize the melodies as a waltz or march. Finally, in the Memory Recognition test, the participants are required to recognize 15 of the previously presented phrases pseudorandomly interspersed with 15 novel melodies. The MBEA is individually applied, and has a duration of approximately 90 min.[8,27] Examples of the musical stimuli and test construction are outlined in detail in Peretz et al. (2003).[8]

Procedures. The project was approved by the review board of the Federal University of Minas Gerais (ETIC no. 318/08). After obtaining permission from the school principals, the research project was presented in the classrooms. The parents or guardians of the interested students received an invitation letter and provided informed consent. The inclusion criterion was absence of formal musical education. All 150 participants were individually subjected to the MBEA in adequate and properly prepared rooms provided by the schools. Testing was conducted by a team of undergraduate psychology students with training in psychometrics, which was led by the first author of this article.

Statistical analyses. Item dimensionality and homogeneity were analyzed using exploratory factor analysis (EFA). Item difficulty was estimated by percent accuracy (i.e., the number of individuals who correctly answered an item divided by the total number of participants who responded to the item), with higher difficulty indices indicating easier items. Discrimination indices were calculated based on criterion groups in the higher and lower quartiles using both the *D* index and *t*-test. The internal consistency of the items was assessed using the Kuder-Richardson (K-R20) formula. Norms for statistical analyses of single case studies were built, estimating mean scores and standard deviations for each gender and age stratum according to the method proposed by Crawford and Howell (1998).[28] Percentile norms were also estimated because this scale directly expresses the rarity of scores.

RESULTS

Item dimensionality. According to the pre-specified MBEA model, each domain should be unidimensional.[8,9] The EFA conducted for the 30 items in each of the six MBEA components using the principal component analysis method revealed that only the results for the Meter test were adequate according to the Kaiser-Meyer-Olkin test (KMO=0.659). Twenty-six of the 30 Meter items loaded on the same factor but explained only 15.95% of its variance.

Item difficulty. The difficulty indices for the several MBEA domains varied between 44.7% and 100%, with 84.44% above 70%. Item 1 from Recognition Memory was the only item with a difficulty index of 100%, indicating that it was extremely easy.

Item discrimination. Criterion groups were established according to performance. Individuals with performance above the 73rd percentile were allocated to the high performance group. The group of participants whose performance was below the 27th percentile was designated as the low performance group. The D index results for each test are shown in Table 1.

Table 1. D indexes for MBEA Tests.

Items	Scale	Contour	Interval	Rhythm	Meter	Memory
Item 1	18.2	43.0	21.7	17.0	42.6	**0.0**
Item 2	44.0	23.7	39.3	12.0	31.3	**3.7**
Item 3	28.0	**14.7**	21.4	44.0	31.0	**6.0**
Item 4	20.6	20.7	16.6	39.2	27.2	**3.7**
Item 5	**6.7***	31.3	20.8	6.7	5.6	7.4
Item 6	21.2	31.0	34.6	6.5	40.4	55.9
Item 7	-----**	29.3	16.5	8.0	36.6	17.4
Item 8	42.5	27.7	21.2	34.7	34.7	31.3
Item 9	62.2	36.0	23.9	18.5	29.0	16.1
Item 10	15.4	30.7	28.3	16.0	38.9	**1.9**
Item 11	27.6	**16.0**	38.7	10.0	22.1	17.1
Item 12	28.4	36.3	14.3	26.2	23.8	17.4
Item 13	24.8	**9.0**	37.4	14.7	16.7	24.3
Item 14	32.6	16.3	32.2	------	9.0	**7.8**
Item 15	18.0	**11.3**	11.8	24.2	24.1	18.9
Item 16	30.5	**11.0**	29.3	18.0	50.0	**14.3**
Item 17	21.2	22.3	21.3	18.7	44.4	9.3
Item 18	**1.4**	38.7	16.8	29.2	38.6	11.1
Item 19	21.1	**–0.7**	23.2	17.7	24.1	28.6
Item 20	11.3	**15.3**	**8.3**	12.0	33.0	**1.9**
Item 21	15.4	-----	38.0	23.2	13.0	9.3
Item 22	20.8	**12.3**	24.8	18.7	25.8	37.4
Item 23	11.5	40.7	14.9	22.0	14.8	7.4
Item 24	23.1	21.7	35.2	6.0	20.4	16.7
Item 25	16.8	44.7	25.0	10.2	22.1	**4.6**
Item 26	34.4	35.0	39.4	20.0	22.2	18.8
Item 27	48.5	**7.0**	**8.0**	8.5	29.6	13.0
Item 28	64.1	27.3	------	30.2	34.7	13.4
Item 29	30.9	**4.3**	15.2	18.2	36.8	16.7
Item 30	29.8	**5.3**	49.8	20.2	22.2	**5.6**
Item 31	40.1	40.0	42.4	22.0		

*In bold, items not discriminative also by t Test (p>0.05); **Catch Trials.

Reliability. The K-R20 coefficient for the entire sample of items was 0.896. Internal consistency was also high when considering each of the main component subgroups, with the exception of Recognition Memory. The K-R20 was estimated to be 0.848 for Melodic Organization, 0.775 for Temporal Organization, and 0.582 for Recognition Memory. Meter was the only isolated music component for which the K-R20 coefficient was higher than 0.70.

Factor validity. An EFA analysis was conducted using the average of raw scores over all of the subtests. The KMO test resulted in a value of 0.858, indicating the adequacy of the sample. The Bartlett test of sphericity yielded p<0.0001, indicating that the correlation matrix was different from the identity matrix.[29] Using the principal component extraction method, observing one factor that could explain 56.58% of the variance was possible. The factor loadings are shown in Table 2.

Participant performance profile on the MBEA. The data obtained from the adolescents indicated that the results on the temporal tests (Rhythm, M=26.3, SD=2.7; Meter, M=24.7, SD=4.1; Recognition Memory, M=26.8, SD=2.4) were greater than the results on the melodic tests (Scale, M=23.2, SD=3.6; Contour, M=23.9, SD=3.3; Interval, M=22.8, SD=3.7). Perfect scores were obtained for all of the tests, with the exception of the Contour test. However, no perfect score was obtained for the overall index (M=24.6, SD=2.5). Although the data for each test were skewed toward higher scores, the average score over the six tests used to generate the overall index followed a normal distribution (Figure 2).

Considering the overall index, at the lower extreme, we found that five individuals (approximately 3% of the sample) obtained scores that were two standard deviations less than the mean. These results are considered to indicate abnormal performance, and these individuals may likely be considered amusic.

Establishment of norms for the MBEA. To establish norms that can serve as basis for single case studies, the data given in Table 3 contain the means and standard deviations for each sex (male and female) for each age of the sample (14, 15, 16, 17, and 18 years).

Preliminary norms for adolescents aged 14 to 18 years were also established by converting the raw scores into percentiles (Table 4).

Proposal for a short version of the MBEA. Based on the analysis of the items, we proposed a short version of the MBEA by considering: [1] items with higher D indexes that could better discriminate the different levels of musical abilities in the general population, [2] items with lower levels of difficulty to allow greater variability in the results, [3] items with satisfactory factor loading, and [4] items with adequate item-total correlation coefficients. Importantly, the Musical Memory test depends on items from other tests because it requires the participants to recognize the melodies that they heard in previous tests. Moreover, the tunes should be equal for all of the tests. Therefore, to compose a short version of the MBEA, equal melodies were verified for all of the tests of the battery that showed the best psychometric results throughout the battery while maintaining the equal proportion between items with same and different answers (Table 5).

Table 2. Principal component analysis of MBEA.

MBEA tests	Factor loading	h^2
Scale	0.818	0.669
Contour	0.871	0.759
Interval	0.821	0.675
Rhythm	0.647	0.419
Meter	0.580	0.337
Musical Memory	0.732	0.536

h^2: Communalities (proportion of variance that can be explained by the factor).

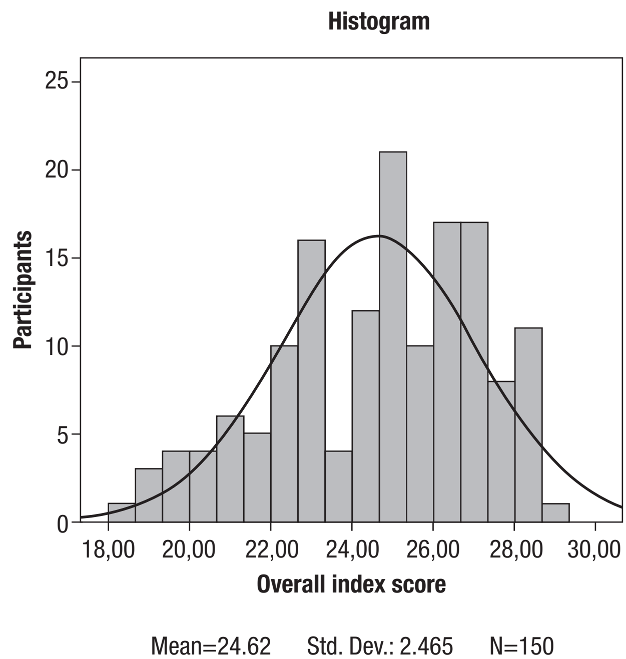

Figure 2. Distribution of global composite scores obtained on the MBEA for 150 normal adolescents. The mean corresponds to a score of 24.6 and the standard deviation to 2.5.

Table 3. Norms of MBEA for single case studies (Belo Horizonte-MG).

		Scale		Contour		Interval		Rhythm		Meter		Memory		Average	
Gender	**Age**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Female	14	23.67	3.48	23.40	3.46	23.53	3.04	24.87	4.21	25.13	2.90	26.87	2.26	24.58	2.48
	15	22.33	4.30	23.73	3.75	22.33	4.30	25.80	3.05	23.47	3.98	26.00	2.62	23.94	2.91
	16	21.93	2.60	23.53	2.33	21.80	2.98	27.07	2.28	25.40	3.11	27.07	2.40	24.47	1.43
	17	22.27	3.69	23.40	4.00	21.73	4.03	25.93	2.31	24.60	4.53	26.33	2.89	24.04	2.79
	18	23.20	3.34	23.73	3.33	23.13	3.72	26.73	1.75	24.73	3.79	26.93	2.05	24.74	2.19
Male	14	22.87	3.14	23.13	2.95	22.00	2.85	26.27	2.74	23.40	4.07	27.47	1.88	24.19	2.16
	15	24.73	2.94	23.60	3.68	23.53	3.50	25.73	2.58	25.93	3.75	26.80	2.31	25.06	2.32
	16	23.00	4.88	25.00	3.68	23.40	4.24	26.53	2.92	25.27	4.85	27.33	2.13	25.09	2.94
	17	24.13	3.09	24.73	3.10	23.87	3.98	27.20	2.27	25.27	3.45	26.73	2.25	25.32	2.32
	18	23.73	4.04	24.67	2.87	23.13	4.41	26.47	2.50	24.07	5.64	26.80	2.93	24.81	3.03

n=15 for each age and gender. M: mean; SD: standard deviation.

Table 4. Norms of MBEA for adolescents aged 14 to 18 years (Belo Horizonte-MG).

Percentile	Scale	Contour	Interval	Rhythm	Meter	Musical memory	Average*
10	18.10	19.10	17.00	22.00	19.00	23.00	21.00
20	20.00	21.00	20.00	24.00	22.00	25.00	22.50
30	21.00	22.00	21.00	25.00	23.00	26.00	23.17
40	22.40	23.00	22.00	26.00	24.00	27.00	24.33
50	23.00	25.00	23.00	27.00	25.00	27.00	25.00
60	24.00	25.60	25.00	27.00	27.00	28.00	25.67
70	26.00	26.00	25.00	28.00	28.00	28.00	26.33
80	27.00	27.00	26.00	29.00	28.00	29.00	26.67
90	28.00	28.00	27.00	29.00	29.00	29.00	27.67

n=150. *Average corresponds to the overall index over the six tests of battery.

The melodies composed for all of the tests were identified during the entire battery. We identified 26 main melodies present in all of the tests, with the exception of the Musical Memory test, for which 15 additional melodies were composed. For the short version, we excluded items with poor psychometric results and repeated items, leaving only 14 tunes comprising the entire battery. The identified melodies in the table chosen to compose the short version of the MBEA were 1, 2, 5, 6, 7, 8, 9, 12, 13, 19, 21, 22, 23, and 26. We suggest [1] replacing ex. 1 of the Scale test with melody 24, corresponding to item 29 of the same test, [2] replacing ex.2 of the Interval test with melody 24, item 2, so that they are not the same as the test items, [3] replacing ex.1 of the Memory test with melody 5, item 1, because tune 4 was excluded from the short version, and [4] retaining the catch trials because they determine whether the person remains alert during testing. Thus, in the short version, the first four tests (Scale, Contour, Interval, and Rhythm) have seven trials that contain pairs of identical melodies, seven trials that include a different comparison melody and one catch trial in random order. For the Meter test, half of the trials correspond to a binary structure (march), and half correspond to a ternary structure (waltz). Finally, in the Memory test, half of the trials correspond to a melody that was previously heard, and half of the trials correspond to a novel melody.

DISCUSSION

The results of the psychometric quality analysis of the items indicated that the test was considered relatively easy, which is consistent with the findings of previous studies involving a Canadian sample.[8] With regard to discrimination, although most of the items presented positive D indexes, they showed little discriminative value with regard to the criterion groups. The sample was composed of a non-clinical group, and the test itself was easy, which likely contributed to the low D indexes.

Notably, however, the *t*-test revealed that most of the items could be considered significantly discriminative for this population.

The analysis of the items' dimensionality from EFA indicated that the items in each test could not be reduced to a single dimension or variable, with the exception of the metric test. Nonetheless, the items of the metric test were responsible for a small portion of the explained variance, indicating that the items were distributed in more than one factor. This result was expected because the sample was homogeneous, consisting of healthy individuals, and the test was very easy for this population, reflected by the distribution of the data. Although the distribution of the data can be considered normal for most tests, it shows a tendency toward negative skewness.

For this reason, a one-factor model of the MBEA observed from factor validity data would most likely be confirmed. The factor analysis for a one-factor model was performed with the total scores of the battery, which showed greater variability in the sample. Moreover, as this was a study focused on a non-clinical sample, the tendency would be to find more general results as obtained in previous studies. Therefore, the obtained factorial matrix was similar to the theoretical factor concerning the musical perception global ability, indicating that the overall index of the MBEA is appropriate to measure these abilities in the adolescent population in Belo Horizonte.

The coefficient of precision was high ($r_{K\text{-}R20}$=0.896) considering all items of the battery. This result indicates adequate reliability with regard to the whole instrument for assessing musical ability and corroborates the results obtained from the EFA, indicating that the MBEA is a good instrument for assessing musical ability in the adolescent population in Belo Horizonte.

The findings of the present study are consistent with previous studies,[8] provide an empirical basis for the model of music processing developed by Isabelle Peretz,[8,9] and contribute to a better understanding of musical processing. However, some limitations should be highlighted, such as the sample size and its homogeneity, which resulted in the low variability of results on each specific test. The validity analysis did not include any other instrument adapted for Brazil to assess the constructs because no such instrument was available. Using other strategies in future studies may provide further evidence for the validity of the MBEA. Nevertheless, the lack of studies demonstrates the importance of the present study because an instrument that assesses musical ability deficits in the Brazilian context is needed.

The validation of the MBEA for the assessment of amusia, both congenital and acquired, in a Brazilian sample may allow a more accurate diagnosis of musical ability deficits and help estimate the impact of clinical interventions based on elements of music. We may then be able to identify preserved and compromised domains

Table 5. Proposal for a short version of the MBEA.

Items	Scale	Contour	Interval	Rhythm	Meter	Memory
ex1	24/29*	20	18	3	catch trial	5/1
ex2	15	4	24/2	17	4	31
ex3	*	*	*	*	15	*
ex4	*	*	*	*	27	*
1	1+	5	19	6	5	5
2	2	25	24	21	12	32
3	3	9	11	16	28	19
4	4	21	22	22	22	33
5	5	26	23	15	10	34
6	6	11	21	24	29	35
7	catch trial	12	13	13	2	14
8	7	7	7	10	14	12
9	8	13	17	1	11	36
10	9	7	9	7	8	7
11	10	19	8	18	16	37
12	11	23	7	2	19	38
13	7	13	14	12	3	39
14	12	24	26	catch trial	24	9
15	13	17	18	26	9	40
16	7	3	3	3	20	16
17	14	5	12	5	26	41
18	15	6	20	14	7	10
19	16	15	16	19	30	42
20	17	22	15	23	1	13
21	18	catch trial	4	8	13	21
22	19	1	10	22	25	22
23	20	2	25	5	21	43
24	5	14	5	25	17	44
25	21	7	7	11	6	2
26	22	8	6	20	18	24
27	23	4	5	7	23	11
28	13	20	catch trial	9	15	45
29	24	18	1	4	27	46
30	25	16	2	13	4	8
31	26	10	13	17		

+Numbers correspond to melodies composed for the tests. The items that will be kept are in grey. *24/29= melody 24, corresponding to item 29 of the same test; 24/2=melody 24, item 2; 5/1=melody 5, item 1.

of musical processing in individuals on the neuropsychological domain and consequently develop more effective rehabilitation strategies. The present study brings to the Brazilian context a tool for diagnosing musical ability deficits, serves as a basis for single case study comparisons and future studies in populations with specific neuropsychological syndromes, and may contribute to future music and cognition research in Brazil. In the musical education context, the MBEA may be able to distinguish between neurological conditions and others causes of musical deficiencies,[22] especially in cases of congenital amusia. Notably, the MBEA evaluates musical perception and does not assess musical performance skills, such as singing and playing. The MBEA also does not include all musical perception abilities. Evaluations of the emotional component of the melodies and perception of harmony, for example, must be performed using additional batteries.[30]

The item analysis allowed the selection of items to compose a short version of the MBEA based on their psychometric properties. Some barriers were found with regard to using the same melodies in different tests and the difficulty maintaining the proportion of items with equal and different answers. Nevertheless, we were able to exclude at least five of the worst items in each test and generate a version with 14 melodies that had satisfactory psychometric results throughout the battery without repetition. Administering the MBEA required approximately 90 min for each individual. The test requires sustained attention and can be very tiring for the participant. The use of a short version of the MBEA in validation studies may yield better psychometric results and enable quicker evaluation of musical abilities.

The present study provides evidence of the validity and reliability of the MBEA for the target population and demonstrates that the overall index of the MBEA is appropriate for assessing musical abilities in normal adolescents in Belo Horizonte. Future studies should provide additional psychometric data and include clinical populations with specific deficits.

Acknowledgments. This research received no specific grant from any funding agency, or commercial or not-for-profit sectors.

REFERENCES

1. Johnson JK, Graziano AB. August Knoblauch and amusia: A nineteenth-century cognitive model of music. Brain Cogn 2003;51:102-114.
2. Levitin D. Tone deafness: failures of musical anticipation and self-reference. International Journal of Computing and Anticipatory Systems. 1999;4:243-254.
3. Peretz I, Cummings S, Dubé MP. The genetics of congenital Amusia (Tone Deafness): A family-aggregation study. Am J Hum Genet. 2007; 81:582-588.
4. Benton AL. The Amusias. In. Critchley M, Henson RA, orgs. Music and the Brain. London: Heinemann; 1977:378-397.
5. Marin O, Perry D. Neurological aspects of music perception and performance. In: Deutsch D, editor. The Psychology of Music. California: Academic Press; 1999: 653-712.
6. Hyde K, Peretz I. Brains that are out of tune but in time. Psychol Sci 2004;15:356-360.
7. Ayotte J, Peretz I, Hyde K. Congenital amusia: A group study of adults afflicted with a music-specific disorder. Brain 2002;125:238-251.
8. Peretz I, Champod S, Hyde K. Varieties of Musical Disorders: The Montreal Battery of Evaluation of Amusia. Ann N Y Acad Sci 2003;999:58-75.
9. Peretz, I., & Coltheart, M. (2003). Modularity of music processing. Nat Neurosci. 2003;6:688-690.
10. Peretz I, Kolinsky R, Tramo M et al. Functional dissociations following bilateral lesions of auditory cortex. Brain 1994;117:1283-1302.
11. Besson M, Faïta F, Peretz I, Bonnel A, Requin J. Singing in the brain: Independence of lyrics and tunes. Psychol Sci 1998;9:494-498.
12. Peretz I, Belleville S, Fontaine F-S. Dissociations entre musique et langage après atteinte cérébrale: un nouveau cas d'amusie sans aphasie. Can J Exp Psychol. 1997;51:354-367.
13. Piccirilli M, Sciarma T, Luzzi S. Modularity of music: evidence from a case of pure Amusia. J Neurol Neurosurg Psychiatry 2000;69:541-545.
14. Warren J, Warren J, Fox N, Warrington E. Nothing to Say, Something to Sing: Primary Progressive Dynamic Aphasia. Neurocase 2003;9: 140-155.
15. Ayotte J, Peretz I, Rousseau I, Bard C, Bojanowski M. Patterns of music agnosia associated with middle cerebral artery infarcts. Brain. 2000; 123:1926-1938.
16. Peretz I. Processing of local and global musical information in unilateral brain-damaged patients. Brain 1990;113:1185-1205.
17. Peretz I, Kolinsky R. Boundaries of separability between melody and rhythm in music discrimination: A neuropsychological perspective. Q J Exp Psychol 1993; 46A:301-325.
18. Vignolo L. Music agnosia and auditory agnosia: dissociations in stroke patients. Ann N Y Acad Sci 2003;999:50-57.
19. Liégeois-Chauvel C, Peretz I, Babaï M, Laguitton V, Chauvel P. Contribution of different cortical areas in the temporal lobes to music processing. Brain 1998;121:1853-1867.
20. Peretz, I. Brain specialization for music: New evidence from congenital amusia. In: Peretz I, Zatorre R. editors. The Cognitive Neuroscience of Music. Oxford: Oxford University Press; 2003:192-203.
21. Peretz I, Ayotte J, Zatorre R, et al. Congenital Amusia: A Disorder of Fine-Grained Pitch Discrimination. Neuron 2002;33:185-191.
22. Sobreira S. Afinação e desafinação: Parâmetros para a avaliação vocal. Augustus. 2002;7:58-72.
23. Sobreira S. Desafinação Vocal. Rio de Janeiro: MusiMed; 2003.
24. Oliveira JZ, Ranvaud R, Tiedemann K. Assimetria funcional dos hemisférios cerebrais na percepção de timbre, intensidade ou altura, em contexto musical. In: Anais do Simpósio Internacional de Cognição e Artes Musicais. Curitiba: Deartes 2005:91-98.
25. Aguiar FN, Branco C. Amusia e a questão da inclusão no ensino de música. Cadernos do Colóquio. 2009;10:90-101.
26. Souza AR. A percepção musical da fala e o problema do alinhamento da curva de freqüência fundamental. Anais do Colóquio Brasileiro de Prosódia da Fala 2011;1:82-85.
27. Nunes M, Loureiro CMV, Loureiro MA, Haase VG. Tradução e validação de conteúdo de uma bateria de testes para avaliação de Amusia. Aval Psicol 2010;9:211-232.
28. Crawford JR, Howell DC. Comparing an individual's test score against norms derivedfrom small samples. Clin Neuropsychol 1998;4:482-486.
29. Hair JF, Anderson RE, Tatham RL, Black WC. Multivariate Data Analysis. New Jersey: Prentice Hall Press; 2005.
30. Sloboda JA, Wise KJ, Peretz I. Quantifying Tone Deafness in the General Population. Ann. N.Y. Acad. Sci 2005;1060:255-261.

4. ESTUDO III

Modularity of Pitch Processing in Congenital Amusia: A Meta-Analysis

Authors: Dominique T. Vuvan[1], Marilia Nunes-Silva[2,3], Isabelle Peretz[1]

[1] International Laboratory for Brain, Music, and Sound Research (BRAMS), Department of Psychology, Université de Montréal.
[2] Laboratório de Neuropsicologia do desenvolvimento, Departamento de Psicologia, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil.
[3] Programa de Pós-graduação em Neurociências, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil.

Abstract

One of the major themes driving research in congenital amusia is related to the modularity of the musical disorder, with researchers disagreeing with regard to the source of the amusic pitch perception deficit. Some scholars argue that the amusic deficit is due to a broad disorder of acoustic pitch processing that has the effect of disrupting downstream musical pitch processing, whereas others maintain that amusia is specific to a musical pitch processing module. In order to interrogate these hypotheses, we have performed a meta-analysis on two types of effect sizes in the amusia literature: the performance gap between amusics and controls on pitch discrimination tasks, and the correlation between acoustic pitch perception and musical pitch perception. To augment the correlation database, we have also calculated this correlation using data from 106 participants tested by our own research group. We found strong evidence for the acoustic account of amusia. The magnitude of the performance gap was moderated by the size of pitch change, but it was not affected by whether the stimuli were composed of tones or speech. Furthermore, there was a significant correlation between an individual's acoustic and musical pitch perception. However, individual cases show a double dissociation between acoustic and musical processing, which suggests that although most amusic cases are probably explainable by an acoustic deficit, there is heterogeneity within the disorder. Finally, we found that tonal language fluency is associated with a smaller control – amusic performance gap, and that there was no evidence that amusics fare worse with pitch direction tasks than pitch

discrimination tasks. These results constitute a quantitative review of the current literature of congenital amusia, and suggest several new directions for research.

4.1 Introduction

Congenital amusia is defined as a lifelong deficit in melody perception and production that cannot be explained by hearing loss, brain damage, intellectual deficiencies, or lack of music exposure (Peretz, 2001). Its first description was made possible by the use of a standardized tool, the Montreal Battery for the Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003) which provided the music neuroscience community with an objective, empirically-derived method by which congenital amusia (henceforth referred to simply as “amusia”) could be diagnosed. In the decade since, this area of research has proliferated, with nearly 300 published studies citing the MBEA.

One of the major themes driving research on amusia is related to the specificity of the musical disorder. Peretz and Coltheart (2003) proposed a modular model of music processing (Figure 1), which describes three pitch organization (tonal encoding, interval analysis, and contour analysis) and two temporal organization (rhythm analysis and meter analysis) components essential to the processing of music. In this model, tonal encoding of pitch is conceived as the core processing component that is specific to music and hence, modular (Peretz, 2006). The MBEA scale test probes participants’ tonal (musical) encoding of pitch. Most amusics tested fail to obtain normal scores on this test, and thus the scale test is often used as a key diagnostic criterion for amusia (e.g., Hyde & Peretz, 2004; Liu, Jiang, et al., 2012; Loui & Schlaug, 2012).

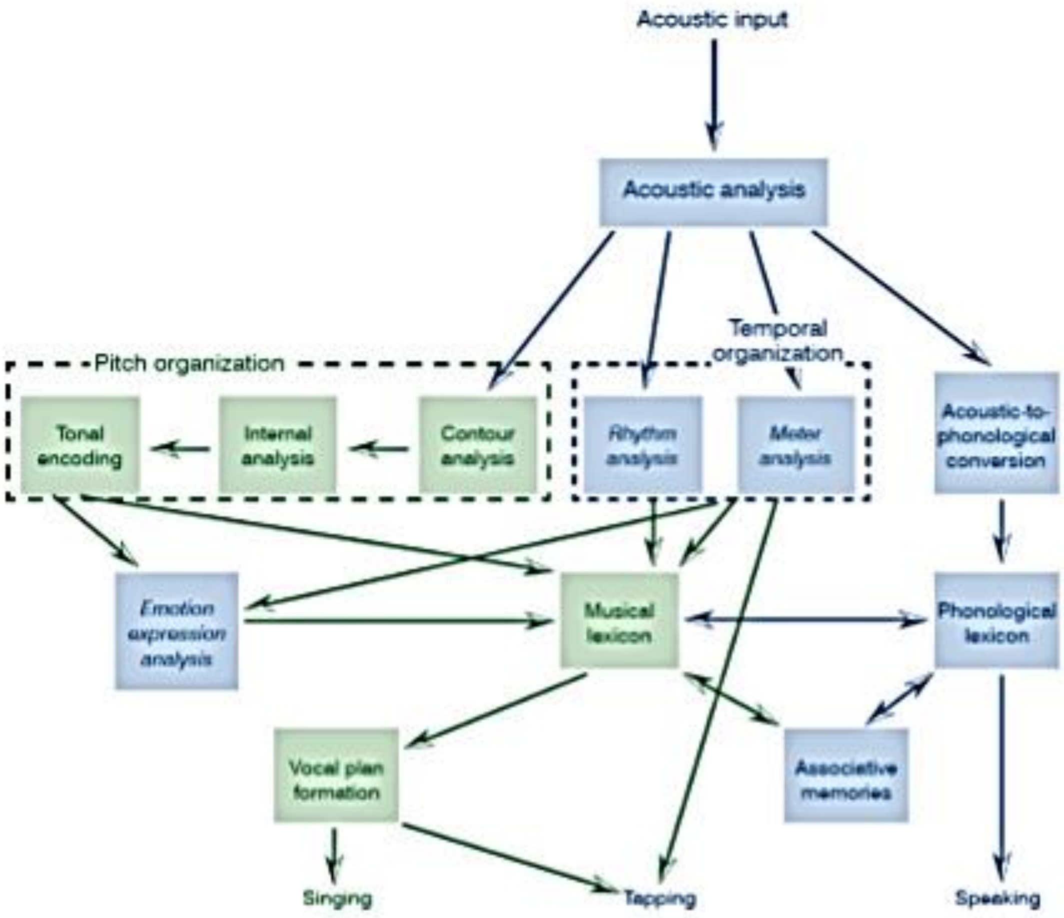

Figure 1. A modular model of music processing, reproduced with permission from Peretz & Coltheart (2003). What appears in green was considered music-specific.

However, the origin of the deficit in musical encoding of pitch seems to arise from a non-modular, lower level of pitch processing. Specifically, the musical deficit is associated to an acoustical deficit in fine-grained pitch discrimination (see Peretz et al., 2002 for an initial report). In other words, the amusic deficit has been proposed to lie in the acoustic analysis of sounds, and since music processing lies downstream from acoustic processing, amusics manifest a musical impairment. The literature has since reached the consensus that amusics display significantly worse pitch discrimination performance as compared to controls, which bears out Peretz et al.'s (2002) hypothesis. Indeed, in addition to poor performance on the MBEA, a pitch discrimination deficit has become a diagnostic benchmark for the identification of new amusic cases.

Interestingly, there is evidence for the music specificity, and hence modularity of the disorder. For instance, amusics seem to perceive speech normally. They can recognize and sing songs through lyrics but not the tune (Ayotte, Peretz, & Hyde, 2002; Dalla Bella, Giguère, & Peretz, 2009; Tremblay-Champoux, Dalla Bella, Phillips-Silver, Lebrun, & Peretz, 2010). Amusics do show an impairment of pitch perception in speech (Hutchins, Gosselin, & Peretz, 2010; Liu, Patel, Fourcin, & Stewart, 2010; Patel, Wong, Foxton, Lochy, & Peretz, 2008; Tillmann, Rusconi, et al., 2011), but as Peretz (2013) notes, this deficit is mild relative to their impairment with musical materials. Assuming modular separation between music and speech, one could argue that, because of their musical pitch deficit, amusics use speech mechanisms to process music, but incur a cost, since these mechanisms are not adapted to musical input (Tillmann, Rusconi, et al., 2011). Thus, amusia is a musical disorder that results from a pitch deficit that may (or may not) be acoustic in origin.

One useful way to adjudicate these competing accounts would be to take advantage of the large number of studies that have been carried out on amusics over the last decade. As discussed above, many researchers have included behavioral measures of pitch discrimination in their studies as an ancillary diagnostic (to the MBEA) for amusic cases. We can thus use a meta-analytic approach to the amusia literature as a whole to determine whether the data favour an acoustic or tonal locus for the amusic pitch deficit.

Several aspects of the literature can be assessed for evidence for and against pitch modularity in amusia: (1) Whether or not the difference in performance between amusics and controls, henceforth referred to as the "performance gap", is moderated by variations in acoustic difficulty; (2) Whether the performance gap depends on the stimuli being composed of tones versus speech; (3) Whether an individual's acoustic pitch performance is correlated with their musical pitch performance; and (4) Whether acoustic and musical deficits are doubly dissociated in the population.

If the amusic deficit is acoustic in origin, variations in the difficulty of the acoustic task across studies should moderate the performance gap. For instance, Hyde and Peretz (2004) found that amusics had trouble distinguishing pitch changes of 100 cents, whereas controls performed close to ceiling down to changes of 25 cents. Accordingly, the acoustic account suggests that across studies we should observe that small pitch changes are associated with larger performance gaps between amusics and controls. Furthermore, the severity of the acoustic deficit should be correlated with the severity of the resultant musical deficit, because of the putative causal link from acoustic to musical pitch processing. Finally, if the origin of the amusic deficit is truly acoustic, scrutiny of individual data should reveal that every amusic case (i.e., individual with low MBEA scale test score), also performs poorly in an acoustical perception task.

The alternative hypothesis is that the amusic pitch deficit is specific to the tonal encoding module (Peretz & Coltheart, 2003), and thus to music. According to this modular account, the size of the performance gap should be larger for tones than speech. Moreover, acoustic pitch discrimination should be dissociable from musical pitch discrimination. Thus, we should observe no correlation between acoustic and musical pitch performance, and consequently, we should be able to identify individuals who have poor acoustical pitch perception but who are not amusic, and conversely, amusic individuals who demonstrate normal pitch discrimination abilities.

In order to test these hypotheses, we investigated patterns of effect sizes across studies in two different ways. For the first analysis, we performed a meta-analytic review of the literature on amusia, following the guidelines of Johnson and Eagly (2000), Rosenthal, and DiMatteo (2001). Here, we considered as effect sizes the amusic-control performance gap on tests of pitch discrimination. For the second analysis, we considered as effect sizes the correlations between performance on acoustical tests of pitch processing and scores on another task of interest, namely the MBEA scale test. Since the individual data required for this latter type of analysis is less commonly reported in the literature, we also included data from the large database (the "Montreal database") of amusic and control performance collected by our research group over the last decade.

In order to assess the modularity of the amusic pitch deficit, we coded the size of pitch change used in the task and whether the stimuli were composed of tones or speech for each effect size in the meta-analytic database. In addition to these factors, we also assessed some further features of these studies. Specifically, we coded the various studies according to age, the duration of the pitch target, whether the experimental task required the simple detection of a pitch change or the identification of the direction of a change, and whether study participants spoke a tonal language.

Age was of interest because pitch discrimination abilities change over the lifespan, due to changes in both peripheral and central mechanisms of hearing (Gordon-Salant, Frisina, Popper, & Fay, 2010). This phenomenon should lead to a higher prevalence of acoustical pitch disorders with no associated musical disorder in older participants, in support of the modularity hypothesis. Furthermore, musical experience is known to alter the developmental trajectory of acoustical abilities (e.g., Parbery-Clark, Anderson, Hittner, & Kraus, 2012; Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011; Zendel & Alain, 2012). Given the altered musical experience of amusics, it is possible that the pitch systems of amusics and controls develop differently throughout the lifespan. In this case, the size of the pitch discrimination performance gap may change depending upon participant age.

Target duration was of interest because some researchers have argued that the pitch deficit found in amusia is a failure of pitch memory rather than a failure of perception (Albouy, Mattout, et al., 2013; Albouy, Schulze, Caclin, & Tillmann, 2013; Tillmann, Schulze, & Foxton, 2009; Williamson, McDonald, Deutsch, Griffiths, & Stewart, 2010; Williamson & Stewart, 2010). If the amusic pitch deficit is due in part to a failure to adequately form pitch traces in memory, then stimuli with longer targets will support better pitch encoding than stimuli with shorter targets. Thus, we would predict that the performance gap would be smaller when target duration is longer, because longer targets compensate for the amusics' poor pitch memory.

Pitch change vs. direction was of interest because some authors have made the claim that amusics suffer from a deficit in perceiving pitch direction rather than small pitch changes (e.g., Liu et al., 2010). This meta-analysis is thus a good opportunity to assess the validity of this claim over many studies.

Lastly, whether participants spoke a tonal language is of interest because tonal languages use pitch contrasts to convey meaning. Therefore, if the disorder is not music-specific, we should observe a lower prevalence of amusia among tonal language speakers. Furthermore, amusic tonal language speakers might have difficulties with speech comprehension, although these difficulties could be mitigated by syntactic and semantic cues. On the contrary, if amusia is specific to music, the prevalence of amusia should be similar between tonal language speakers and non-speakers. Furthermore, the comparison of tonal language speakers and non-speakers impinges upon the question of whether amusics can improve through training, either indirect (such as through tonal language learning) or direct. For instance, an ongoing study in our lab seeks to train amusic teenagers to better discriminate pitch through guitar lessons (Mignault Goulet et al., in preparation).

4.2 Methods

4.2.1 Search Procedure

The literature was searched through November 2013. Google Scholar was used exclusively as a search database, following recent research that demonstrated that the search results for previously published systematic reviews (which used GS, in addition to PubMed, Cochrane, Dissertation Abstracts International, and a variety of other sources), were 100% covered by Google Scholar (Gehanno, Rollin, & Darmoni, 2013). Searches were executed using the following terms: amusia, auditory agnosia, dysmelodia, melody deafness, note blindness, pitch deafness, poor pitch singing, and tone deafness.

4.2.2 Inclusion and Exclusion Criteria for Database

In advance of the development of the MBEA, formal assessments of musical ability existed. However, these tests were either not informed by recent empirical neuropsychological work (e.g., Seashore Measures of Musical Talent; Seashore, 1939) or contaminated by prior knowledge of the test material (e.g., Distorted Tunes Test; Kalmus & Fry, 1980). Thus, the first inclusion criterion was the use of the MBEA for diagnosis of amusic subjects. Application of this criterion formed an initial database of 117 unique articles. Furthermore, studies were required to: (a) study congenital, not acquired, amusia; (b) be published in English; (c) contain data for a sample of amusics and a sample of controls, the performance for which can be compared via the performance gap (i.e., no case studies); (d) report behavioural measures of pitch discrimination, broadly defined.

This last criterion requires some further discussion. The net for pitch discrimination was cast fairly wide, in order to capture a wide array of different methodologies and domains. As long as pitch was the critical dimension serving as a cue for task performance, the study was included in our sample. Thus, our final meta-analytic database included studies using psychoacoustic, musical, and speech materials put to use in pitch matching, memory, comparison, and identification tasks; these tasks are listed in Table 1. The application of all selection criteria resulted in the inclusion of 43 unique articles.

Table 1: Pitch discrimination tasks included in meta-analytic database.

Task	Description	Example	Number of Effect Sizes
Pitch matching	Use a dial to match a tone to a target	Anderson et al. (2012)	1
Pure tone pitch change detection	Determine whether one tone in a set differs from the others	Hyde & Peretz (2004)	10
Pure tone pitch change identification	Determine which of the tones is different from the others	Liu et al. (2010)	17
Pure tone pitch change discrimination	Determine whether two sets of tones are the same or different	Gosselin et al. (2009)	11
Pure tone pitch direction identification	Determine whether the pitch change is up or down	Loui et al. (2008)	16
Pure tone pitch direction discrimination	Determine whether the first two or the last two tone pairs have the same direction of pitch change	Jiang et al. (2013)	1
Melodic pitch judgment	Determine whether the melody contained a bad note	Peretz et al. (2008)	6
Speech intonation (or complex tone analogue) identification	Determine whether the sentence is a statement or a question	Liu et al. (2010)	10
Speech intonation (or complex tone analogue) discrimination	Determine whether the the intonation of the second sentence is the same as the first	Patel et al. (2008)	16
Effect size is a combination of more than one pitch discrimination task		Foxton et al. (2004)	2

<u>*4.2.3 Performance Gap Analysis*</u>

4.2.3.1 Quantifying the effect sizes. For the performance gap analysis, the effect size was a quantification of the differential performance of amusics and controls on the pitch discrimination task of interest. For each result in each study, the effect size was extracted (*t*, *F*, *or z*), and then converted to the r metric for its ease of interpretation (Rosenthal & DiMatteo, 2001). These *r* values were then adjusted for bias using the approximation of the population effect size G (Johnson & Eagly, 2000), and coded as positive if amusics performed worse, and negative if amusics performed better than controls on the task. Our performance gap database comprised 90 effect sizes contained within 43 studies.

4.2.3.2 Coding of Moderators. The coding of potential moderators was performed by the first two authors. Reliabilities were then established on 35% of the dataset; the intercoder reliability for each moderator is reported below. Moderators were coded for each effect size rather than each study; therefore, studies that included multiple effect sizes received a distinct code for each moderator, for each effect size. Descriptive statistics for these moderators are shown in Tables 2 and 3 (continuous and dichotomous moderators, respectively).

Table 2. Continuous moderators of the control-amusic performance gap.

Moderator	Mean	SD	Median	Range
Size of pitch change (cents)	566	503	400	[25, 1970]
Participant age (years)	42	15	48	[12, 66]
Target duration (ms)	377	204	350	[100, 850]

Table 3. Dichotomous moderators of the control-amusic performance gap.

Moderator	Coding Scheme	Number “0”	Number “1”
Tone vs. speech	0 = tone; 1 = speech	68	17
Pitch change vs. direction	0 = change; 1 = direction	63	25
Participant language	0 = non-tonal; 1 = tonal	63	27

Size of pitch change was a continuous variable coded in cents (percentage of a semitone, the smallest pitch change employed in music). Cents are logarithmically related to physical frequency (e.g., Hertz), and highly correlated with the human perception of pitch height. For studies that supplied only the range of pitch changes (i.e., minimum and maximum), the centre of the range was calculated. For instances where multiple pitch change sizes were collapsed into one result, the average was calculated. Notably, size of pitch change was only meaningful for tasks in which the pitch changes were fixed, i.e., the same pitch changes were administered to every participant, amusic or control (58 effect sizes). For a significant proportion of results, adaptive tasks were used to identify and individual pitch change detection threshold for each participant (32 effect sizes). In these latter cases, the performance gap would be measured by the difference in threshold between controls and amusics, and thus is confounded with the size of the pitch change employed for each participant in the study. Thus, fixed and adaptive pitch change studies were considered separately in the latter part of the moderator analysis (see below). The intercoder reliability for this variable was 93%.

Tone vs. speech was a dichotomous variable, with effect sizes being coded according to whether the stimulus was comprised of tones or speech. In certain studies where results were collapsed across speech and tone stimuli, the stimulus timbre was not given a value. The intercoder reliability for this variable was 100%.

Participant age was a continuous variable coded in years. This was calculated, where possible, as the weighted mean of the average ages of the amusic and control subjects. If a range was provided rather than means, the centre of the range was taken. Finally, in one study (Hutchins, Zarate, Zatorre, Peretz, 2010), where only data for the amusics was provided (but controls were matched for age), the mean of the amusics' ages was used. The intercoder reliability for this variable was 100%.

Target duration was a continuous variable coded in milliseconds (ms). "Target" refers to the critical tone or syllable within a stimulus that contains the pitch change. In studies where target duration was not explicitly given (i.e., many studies using speech), target duration was estimated from the average number of syllables within a stimulus and the average sentence length. The intercoder reliability for target duration was 85%.

Pitch change vs. direction was a dichotomous variable, with effect sizes being coded according to whether the task required the discrimination of a change, irrespective of its direction, or whether direction was key to a correct judgment. The intercoder reliability for this variable was 100%.

Participant language was also a dichotomous variable, with effect sizes being coded according to whether participants in that study spoke a tonal language or not. The intercoder reliability for this variable was 100%.

4.2.3.3 Assessing hierarchical dependencies. Before building a meta-analytic model for the data, a methodological decision had to be made concerning the appropriate unit of analysis. There are a small number of research groups producing the majority of the studies in this domain, and often multiple effect sizes are reported within the same study. Thus, there seem to be hierarchical dependencies built into these data (effect sizes nested within studies, studies nested within research groups). In order to determine whether this hierarchy should be modeled in our meta-analysis, it was important to assess the quantitative reality of these dependencies. To this end, each effect size was coded according to two variables: the study in which the result was reported, and the research group that published the study. The following steps were executed for both the performance gap and correlation data.

A study was defined as an experiment or series of experiments that was run on a single set of participants. In nearly all cases, this corresponded to one study per published article. In the one exception (Patel et al., 2008), the authors reported two studies. With regard to the "research group" variable, all authors of the 43 studies included in our database could be reduced into five research groups, associated with C. Jiang, I. Peretz, G. Schlaug, L. Stewart, and B. Tillmann.

Thus, any study with one of these individuals as authors was coded as coming from that research group. In the event that more than one of these individuals appeared as authors on a single paper, the paper was attributed to the research group whose lab tested the participants. For example, Tillmann, Rusconi, et al. (2011) was coded as coming from the Peretz group, and Liu, Jiang, et al. (2012) was coded as coming from the Jiang group. As with the moderators, reliabilities were then established on 35% of the dataset. Intercoder reliability was 100% for both study and research group variables.

For each performance gap analysis reported in the results section, a baseline (no predictors) hierarchical linear model (effect sizes nested within studies nested within research groups) was considered. Within these nested models, the variance for each effect size was weighted by the inverse of the corresponding sample size (1/N; Johnson & Eagly, 2000). Interestingly, the intraclass correlations obtained for these hierarchical models were uniformly low (< .10) and the likelihood ratio test comparing the hierarchical model to the non-nested model (in which each effect size was treated as an independent observation) was non-significant ($p > .05$) for all analyses. Our effect sizes could thus be considered statistically independent from one another, and were modeled as such for all performance gap analyses.

4.2.3.4 Analysis procedure. We performed a two-stage analysis of the performance gap effect sizes (Johnson & Eagly, 2000), starting with the summary of the effect sizes at the study level (i.e., multiple effect sizes within each study were collapsed), and then subsequently considered these effect sizes as independent for the analysis of the potential moderators. All meta-analytic models were fitted using the metafor package (Viechtbauer, 2010) in R (R Core Team, 2013).

4.2.3.5 Overall effect size. This analysis was performed at the level of the study. To combine multiple results in the case that a study reported more than one effect size, the corrected *r* values were transformed to Fisher's *z* scores, a mean was calculated, and then this mean was converted back to an *r* value. Central tendency was estimated using several measures, including unweighted mean *r*, median *r*, and weighted mean *r* (by sample size). In order to estimate the weighted mean *r* and its associated significance level and confidence interval, all *r* values were entered into a random effects model using the rma function with restricted maximum-likelihood (REML) estimation of residual heterogeneity from the metafor package. In order to assess the possibility that any of the study effect sizes acted as influential outliers in this analysis, Cook's distances were calculated for each study using the influence function of the metafor package (with a threshold of d > 1).

4.2.3.6 Moderators. These analyses were performed at the level of the individual effect sizes. First, a baseline random effects model (no moderators) was fitted using the rma function with REML estimation, and Cook's distances were calculated to eliminate outliers. This function also estimates $\tau^{\wedge}$ and I^2, which refer to the amount of residual heterogeneity and the percentage of that heterogeneity not due to sampling error, respectively. These statistics, in combination with the *ι* significance test for heterogeneity, can be used to infer the usefulness of moderator analyses, since a significant amount of variability in effect sizes can indicate the explanatory usefulness of moderating factors.

Second, to get a general idea for the predictive value of each moderator in the absence of the others, we fitted simple regressions for each moderator. To do this, we built a mixed effects model using *rma* and REML estimation. In addition to the significance level of the moderator, comparing the heterogeneity statistics from these simple moderator models with the baseline model enabled us to assess each moderator's contribution to effect size.

Third, to get an idea of how the moderators might relate to one another, we used backwards elimination stepwise regression to build a mixed effects model that predicted all corrected *r* values from a combination of the moderators that were significantly predictive in the simple models. Models were estimated separately for effect sizes resulting from fixed and adaptive pitch change methods, since neither size of pitch change nor stimulus timbre could be used as moderators for adaptive pitch studies (for adaptive studies the size of pitch change was not fixed, and the stimuli were always composed of tones).

We first fitted the full model containing all significant moderators, using *rma* and maximum-likelihood (ML) estimation. Next, we removed the moderator with the lowest *t* value, and compared this model to the previous one with a likelihood ratio test. Note that for the stepwise regression, the ML estimation was used because REML estimation does not allow for a meaningful likelihood ratio test. If there was no significant difference between the two models, testing stopped and the model was kept as is, before the removal of the current moderator. If there was a significant difference, the current moderator was dropped, and the process was iterated for each moderator until no significance was found between two subsequent models. Once the final model was specified, like for the overall effect size analysis, the *rma* function was re-run with REML estimation (Viechtbauer, 2010), and provided estimates of moderator significance, confidence intervals, and residual heterogeneity ($\tau^{\wedge}$, I^2, Q) in the effect sizes following the fitting of moderator variables.

4.2.4 Correlation Analysis

4.2.4.1 Quantifying the effect sizes. For the correlation analyses, the effect size of interest was the Pearson *r* calculated by relating participants' MBEA scale score and acoustic (not musical, or speech) pitch discrimination performance. Therefore, only the first six pitch discrimination tasks from Table 1 were considered. Where possible, *r* was taken directly from the article. When raw participant data was provided, *r* was calculated from these data. These *r* values were then adjusted for bias with G, as above. When pitch discrimination was measured via a threshold, thus giving *r* a negative sign if there was a positive correlation between pitch discrimination performance and the MBEA scale score, the *r* was re-coded with the opposite sign for consistency with other values. Our correlation database was comprised of seven effect sizes contained within four studies.

To augment the small meta-analytic database, the participant scores from the Montreal database (compiled from our research group's data) were used to calculate a similar correlation. Here, pitch discrimination performance was measured via the task used by Hyde and Peretz (2004), consisting of trials containing a sequence of five pure tones. The fourth tone was either identical to the other tones or deviated from the other tones (by 25-200 cents); participants were required to judge whether the fourth tone was the same or different from the other tones. We considered the Montreal data separately from the meta-analytic database because there is partial overlap between the data herein and data presented in some of the published studies from our research group.

4.2.4.2 Assessing hierarchical dependencies. Just as we assessed the performance gap database for hierarchical dependencies, so too did we assess the correlation database. Each effect size was coded according to study and research group (intercoder reliability = 100%), and then a baseline hierarchical linear model was calculated, weighted for each sample size. Like for the performance gap data, the intraclass correlations for this model was low ($< .10$) and the likelihood ratio test was not significant ($p > .05$). We thus considered these effect sizes to be statistically independent and modeled them as such.

4.2.4.3 Analysis procedure. Meta-analysis of the correlations between pitch discrimination and MBEA scale test scores from the literature followed the methods described above for the calculation of overall effect size for the performance gap data. Specifically, central tendency was estimated by unweighted mean *r*, median *r*, and weighted mean *r* (by sample size). In order to estimate the weighted mean *r* and its associated significance level and confidence interval, all *r* values were entered into a random effects model using the *rma* function with restricted maximum-likelihood (REML) estimation of residual heterogeneity from the metafor package. In order to assess the possibility that any of the study effect sizes acted as *influential* outliers in this analysis, Cook's distances were calculated for each study using the influence function of the metafor package (with a threshold of $d > 1$).

4.3 Results

4.3.1 Performance Gap: Overall Effect Size

At the level of the study, the mean weighted effect size was $r(38) = 0.61$ ($SE = 0.03$), $p < .0001$. This is a fairly strong effect, with low variability, indicating that controls consistently outperform amusics on pitch-based musical tasks. The unweighted mean and median (0.56 and 0.52, respectively) were slightly lower than the weighted mean, indicating that studies with larger participant samples tended to report higher effect sizes. Figure 2 shows a forest plot of the effect sizes (*r*) by study. The calculation of Cook's distances indicated that no outlying effect sizes significantly influenced the model estimate (all D < 4N; Bollen & Jackman, 1985).

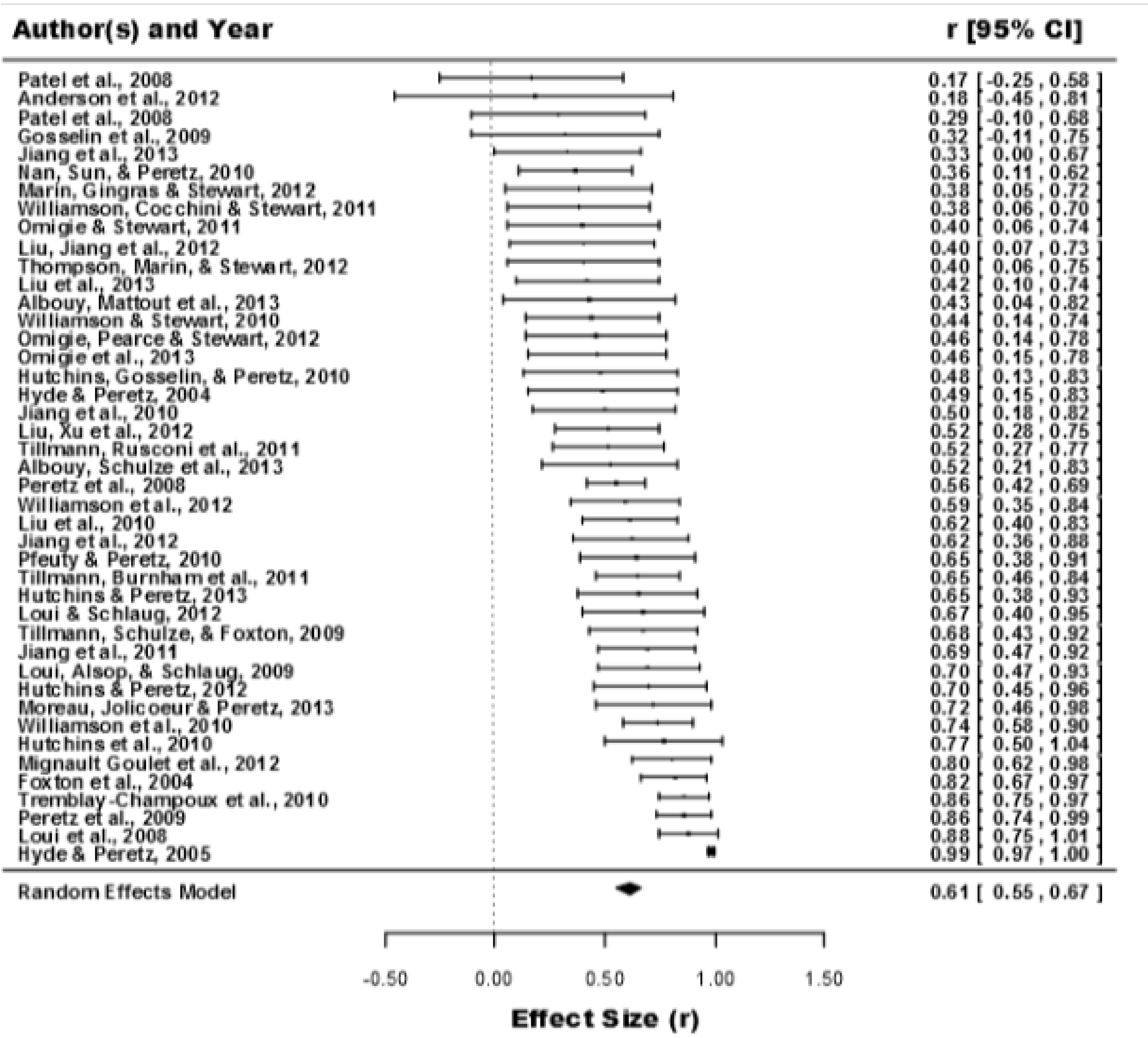

Figure 2. Forest plot showing performance gap effect sizes (*r*) by study.

4.3.2 Performance Gap: Moderator Analysis

4.3.2.1 Baseline model. At the level of the effect sizes, the mean weighted effect size was $r(88) = 0.55$ ($SE = 0.03$), $p < .0001$. Confirming the overall effect size analysis, the mean effect is quite high, with low variability, with controls consistently outperforming amusics. The unweighted mean and median (0.51 and 0.53, respectively) were slightly lower than the weighted mean, again consistent with the previous analysis. Figure 3 shows a forest plot of all effect sizes. The calculation of Cook's distances indicated that one effect size from Jiang, Lim, Wang, and Hamm (2013), with a value of $r(26) = -0.57$, exceeded Bollen and Jackman's (1985) criterion. Thus, this effect size was excluded from further analysis.

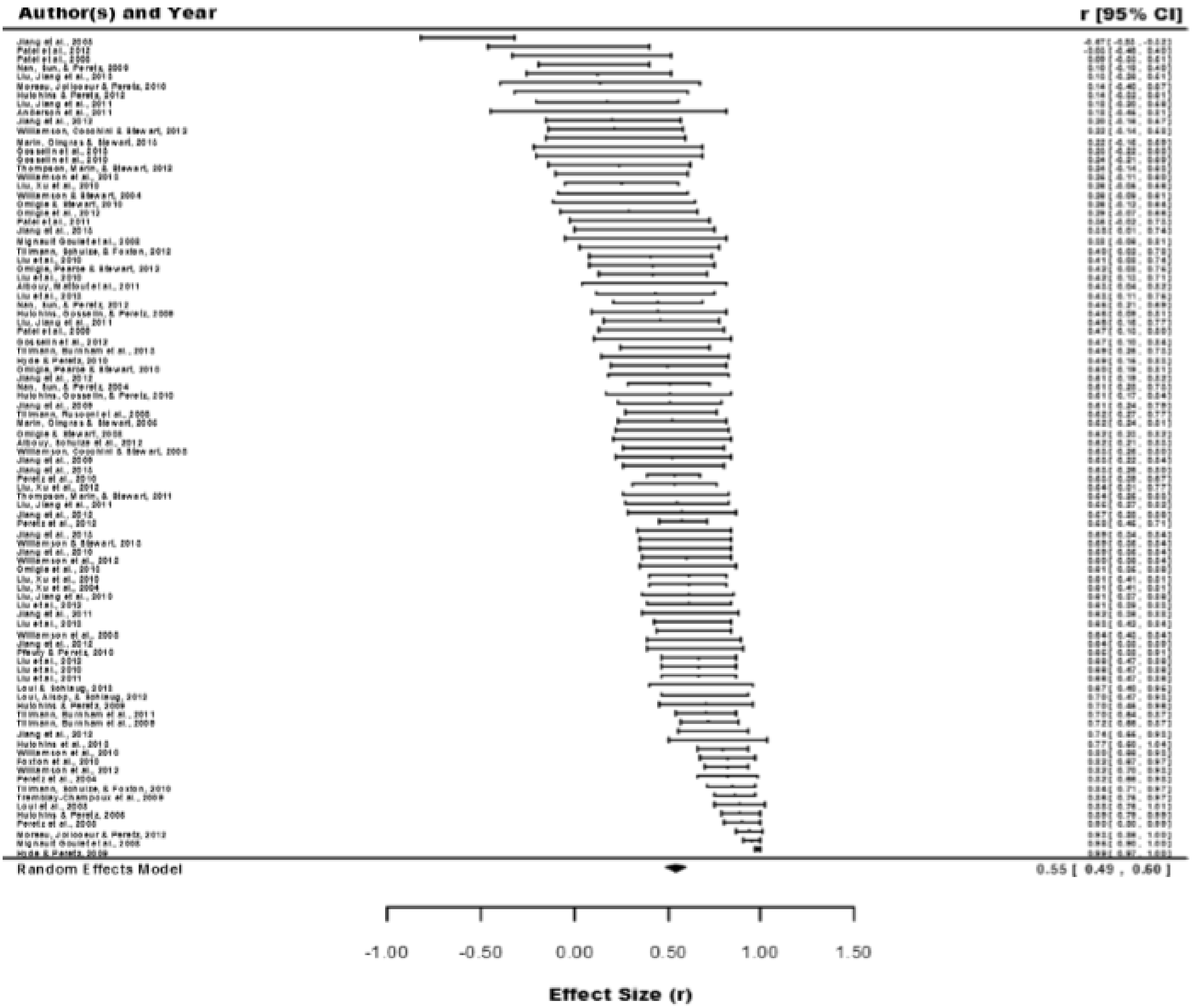

Figure 3. Forest plot showing all performance gap effect sizes (*r*).

The estimates of heterogeneity for the random-effects model revealed that the overall amount of heterogeneity was fairly low, $\tau^{\wedge 2}$ = 0.05, confirming the small estimate of standard error of the weighted mean effect size (0.03). Despite the small variability in effect size, a large proportion of that variability could potentially be accounted for by our hypothesized moderators, I^2 = 0.89, $Q(89)$ = 960.27, $p < .0001$. Thus, the next analysis was aimed at determining which of these moderators were significant predictors of the variability in effect sizes.

4.3.2.2 Simple regressions. We used simple regression models to predict effect size from each moderator alone. These analyses revealed mixed- three moderators of interest. Size of pitch change had a significant impact on effect size, b = -0.0002, SE = 0.0001, $p < .0001$, with larger pitch changes corresponding to a smaller performance gap between controls and amusics (Figure 4).

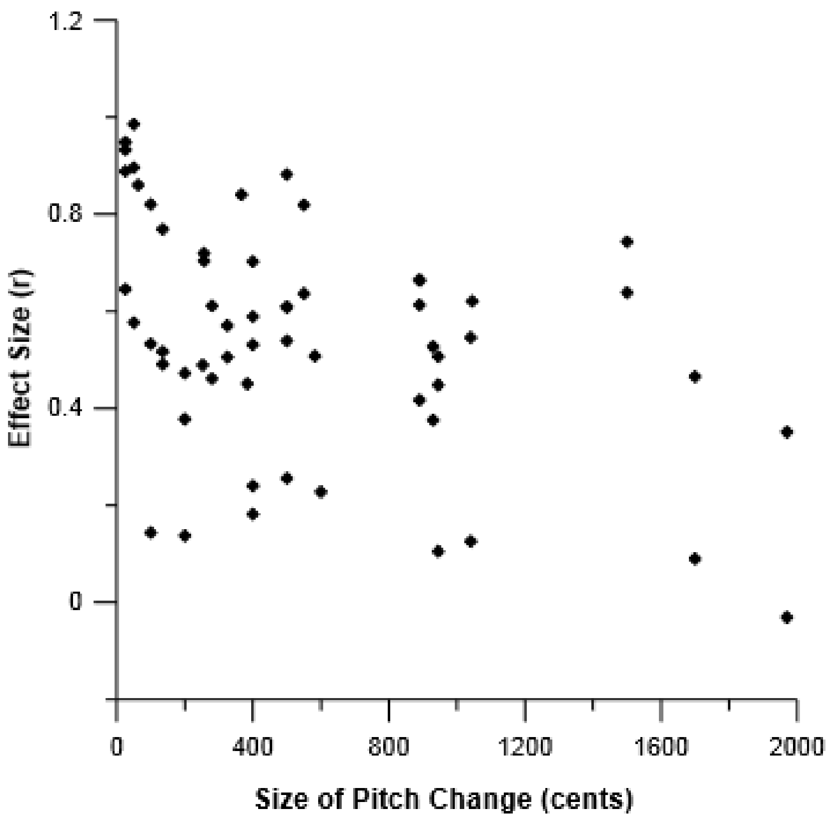

Figure 4. The effect of size of pitch change on the performance gap between controls and amusics.

Whether or not the participant spoke a tonal language also had a significant effect on the effect size, *b* = -0.12, *SE* = 0.05, *p* = .02, with smaller performance gaps between controls and amusics for studies of tonal language speakers (27 effect sizes, mean *r* = 0.43, *SD* = 0.26) than studies of non-tonal language speakers (63 effect sizes, mean *r* = 0.54, *SD* = 0.24).

Finally, participant age had a marginally significant impact on effect size, *b* = -0.003, *SE* = 0.002, *p* = .07, with studies using older participants reporting larger performance differences between controls and amusics (Figure 5). Scrutiny of this figure reveals that study participants tend to be quite young (20-30) or old (50-60). Thus, the effect of age is driven by the tendency for studies using younger participants to have slightly lower effect sizes than studies using older participants. Recall that the hierarchical dependence analyses described in the methods section showed that there is no systematic effect of research group on effect size. Thus, this marginal effect seems to be truly driven by age.

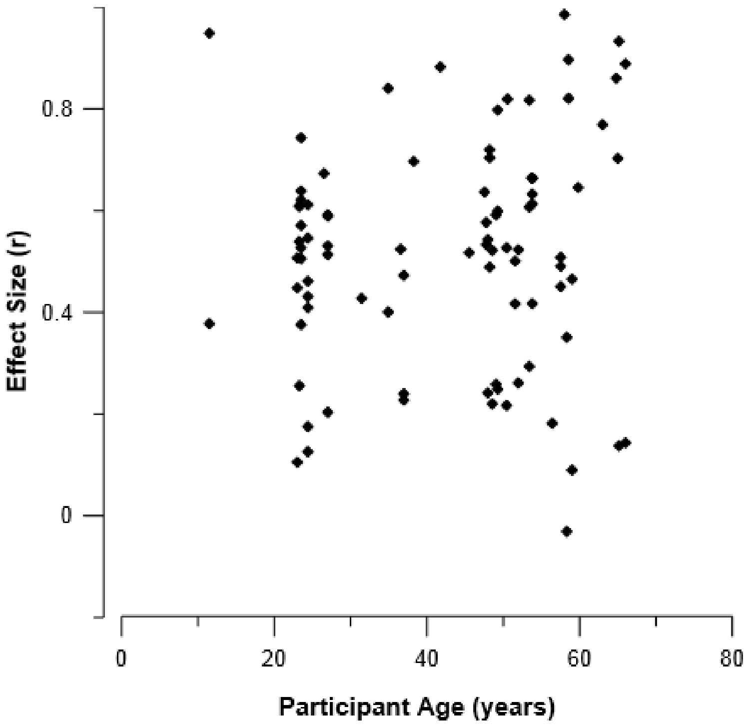

Figure 5. The effect of participant age on the performance gap between controls and amusics.

None of the other hypothesized moderators (target duration, tone vs. speech, or pitch change vs. direction) were significantly predictive of effect size in these simple models, all *p* > .18. Particularly of interest is the lack of effect for tone vs. speech, indicating that the average performance gap in studies employing tone stimuli is the same as that in studies employing speech stimuli (mean for tones $r(66) = 0.51$, $SD = 0.27$; mean for speech $r(15) = 0.50$, $SD = 0.16$). This is a key contrast relative to the assessment of the modularity of congenital amusia, and this result supports the idea that the locus of the amusic disorder is in acoustic processes, which affect pitch processing in music and speech equally.

4.3.2.3 Stepwise regression for fixed pitch studies. Stepwise regression for the fixed pitch studies resulted in a final mixed-effects model that included size of pitch change, participant age, and participant language as moderators. With all three moderators entered into the model, only the size of pitch change remained a significant predictor of the performance gap between controls and amusics, $b = -0.0002$, $SE = 0.0001$, $p = .0009$. This result confirms that studies using larger pitch changes tended to report smaller performance gaps, and suggests that the other variables entered into the model (participant age and language) might be confounded with size of pitch change across studies. In particular, studies of tonal language speakers tended to employ larger pitch changes, $t(56) = 1.96$, $p = .05$. The correlation between size of pitch change and participant age is not significant, $p > .05$.

4.3.2.4 Stepwise regression for adaptive pitch studies. Stepwise regression for the adaptive pitch studies resulted in a final mixed-effects model that included participant age and language as moderators. With both moderators entered into the model, neither moderator remained a significant predictor of the performance gap between controls and amusics, all p values > .40. This is likely because participants in studies of tonal language speakers tended to be significantly younger than participants in studies of non-tonal languages speakers, $t(88) = 11.73$, $p < .001$.

<u>*4.3.3 Correlations: Meta-analytic Database*</u>

The mean weighted effect size for the correlation between the MBEA scale score and the pitch discrimination measure in the study was $r(5) = 0.46$ ($SE = 0.09$), $p < .0001$. This result indicates that acoustic pitch performance significantly predicts musical pitch performance. Interestingly, the weighted mean is a bit higher than the unweighted mean and median (0.42 and 0.35, respectively), indicating possible outliers. Figure 6 shows a forest plot of the effect sizes. The calculation of Cook's distances indicated that one effect size from Tillmann et al. (2009), with a value of $r(18) = 0.81$, exceeded Bollen and Jackman's (1985) criterion. The recalculation of the mean weighted effect size, omitting this effect size, yielded a value of $r(5) = 0.39$ ($SE = 0.07$), $p < .0001$.

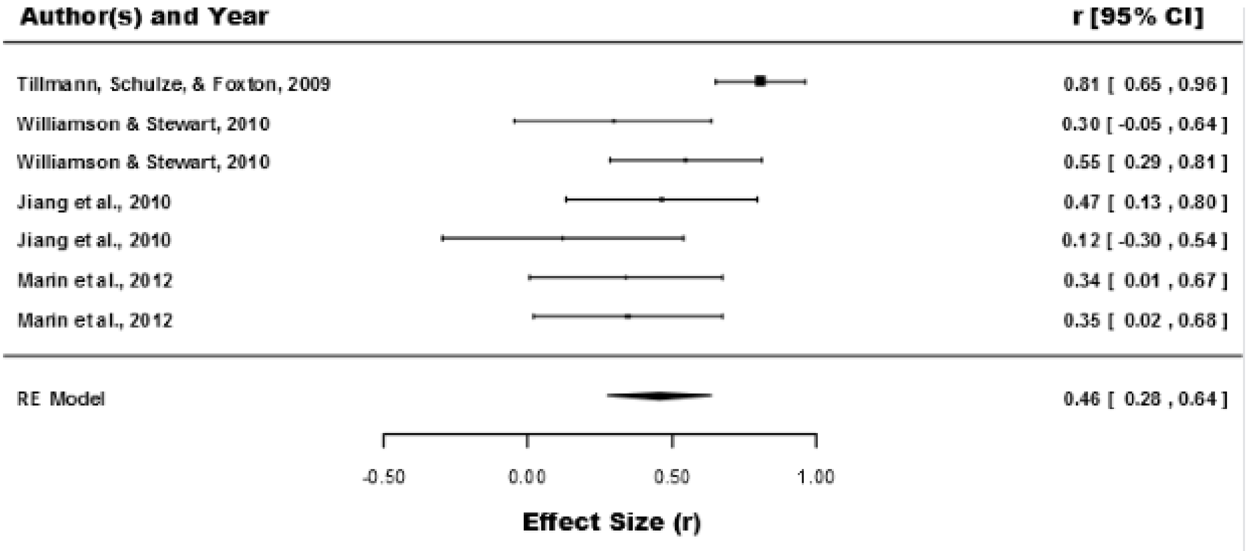

Figure 6. Forest plot of effect sizes for the correlation data.

4.3.4 Correlations: Montreal Database

We analyzed our database for the relation between musical pitch (MBEA scale score) and acoustic pitch discrimination. For the latter, we considered the hit rate – false alarm rate of a 25 cents change in a five repeating tone sequence; this was the smallest pitch change employed in this task, and therefore most difficult to detect (Hyde & Peretz, 2004). These data include 106 participants, 61 amusics and 44 controls matched in age, education and musical background. In our pool, we also found a correlation between the musical pitch and acoustical pitch score with $r(104) = 0.58$, $p = <.0001$. The correlation was still significant when considering amusics only, $r(59) = 0.34$, $p = 0.007$. These data confirmed the results from the meta-analytic database, indicating that musical pitch abilities are significantly associated with acoustic pitch abilities in the population.

As can be seen in Figure 7, there are cases showing dissociation between musical and acoustic pitch performance. We defined the cutoff for poor MBEA scale performance at 22.73 (two SD below the mean of the controls), and the cutoff for poor pitch change detection performance was set at hit rate – false alarm rate = 57.84 (two SD below the mean of controls in our data). Using these cutoffs, we found 17 cases who were normal at processing musical pitch despite having a deficit in acoustical pitch perception (top left quadrant of Figure 7). Thus, a deficit in acoustic pitch perception does not necessarily lead to a musical disorder. Conversely, there were nine amusic cases who had normal pitch perception (bottom right quadrant, Figure 7), indicating that amusia may occur without an associated pitch deficit. Importantly, it is unlikely that the dissociations we have observed here are due to hearing problems. For the subset of these participants (7 of the 17 participants with an acoustic deficit, 6 of the 9 participants with a musical deficit) who had undergone audiometric testing, all had normal pure tone thresholds, standardized for their age (ISO1999 standard, 2013).

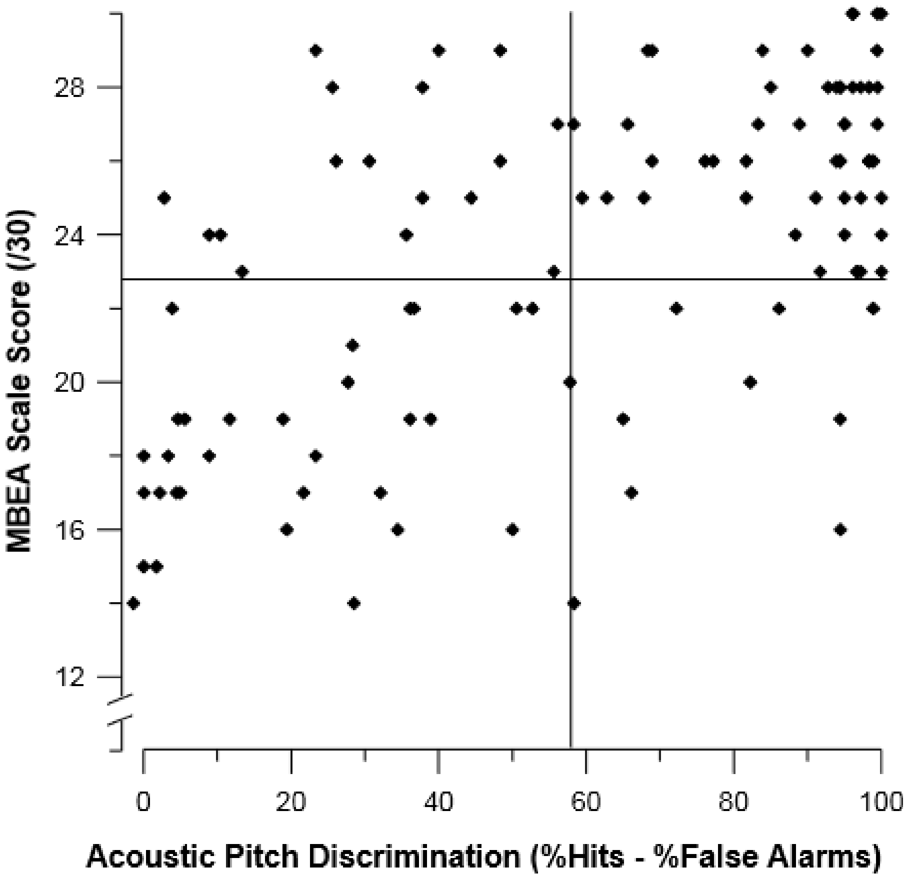

Figure 7. Montreal database acoustic pitch discrimination plotted against MBEA scale scores. The cutoff for poor acoustic performance is 57.84 (vertical line); the cutoff for poor musical performance is 22.73 (horizontal line).

4.4 Discussion

This quantitative review has demonstrated the reality of the amusic pitch discrimination deficit. The size of this effect, as quantified by the performance gap between amusics and controls, is robust, large, and significant. Additionally, our analyses enabled us to assess the extent to which amusia is specific to the processing of musical pitch, or affects the more general processing of acoustic pitch.

Recall that we investigated four different sources of evidence to determine the cognitive mechanism underlying the pitch discrimination deficit observed in amusia. The first three sources of evidence found in favour of the long-hypothesized model, wherein an acoustic deficit leads to the downstream malfunction of tonal pitch processing (Peretz & Coltheart, 2003).

Specifically, we found that the size of the pitch change employed in a study, which is importantly an acoustic variable, moderated the effect size. Furthermore, we found no significant moderating effect of tone vs. speech stimuli, which indicates that the amusic deficit is something that affects the processing of pitch in both tones and speech, i.e., acoustic processing. Third, we observed a significant correlation between measurements of acoustic functioning (i.e., pitch discrimination) and measurements of musical functioning (i.e., MBEA scale subtest). This is evidence that the extent to which an individual's acoustic pitch processing is compromised is related to the extent to which that individual's musical pitch processing is also compromised, indicating a link between acoustic and tonal processing in amusia. Thus, the pitch discrimination deficit observed in amusia is located at both acoustic and musical levels. This is evidence against the modularity of the disorder and suggests that the acoustic account, whereby a general acoustic pitch deficit is responsible for the musical pitch deficit in amusia, is correct.

However, one source of evidence does speak against the conclusion that the amusic deficit is acoustic in nature. Namely, scrutiny of individual cases in our database revealed a double dissociation between the functioning of acoustic processing and that of the tonal encoding module. We observed 9 cases with poor musical performance alongside normal acoustic performance, and 17 cases with normal musical performance alongside poor acoustic performance out of our database of 106 participants.

The former nine cases suggest that it is possible for an individual to demonstrate the amusic deficit without an acoustic deficit. However, the relation between acoustic and musical pitch abilities in these cases may have changed over the lifespan, particularly because amusia is a developmental disorder. Specifically, it is possible that an acoustic deficit in infancy was the origin of the musical disorder in these participants, but that acoustic pitch discrimination abilities have improved over the lifetime due to prolonged experience with pitch in other domains, such as speech. At the very least, these cases argue for the existence of heterogeneous phenotypes in the amusic population. It is likely that the majority of amusic cases present an acoustic deficit, but there clearly exist cases who present musical difficulties in the absence of acoustic problems.

Additionally, the latter 14 cases indicate that it is possible to have an acoustic deficit without a resulting musical deficit, in participants who do not present with hearing problems as measured by pure tone audiometry. There is a possibility that this is the result of the effects of aging on hearing abilities; the average age of these 17 cases is 58.6 (*SD* = 12.4), with only two of these cases below the age of 50. Although the participants who underwent audiometric testing all had normal pure tone thresholds, these thresholds do not account for all the processing, both peripheral and central, that is undertaken during the acoustic pitch discrimination task. Thus, as acoustic abilities degrade with age (Gordon-Salant et al., 2010), musical perception could ostensibly remain, aided by top-down processing of extra-acoustic cues. However, the dissociation between acoustic and musical processing in amusia presents a parsimonious explanation for these cases.

Regardless, our results call attention to the need for the direct experimental study of the relation between music and acoustic processing in congenital amusia. One potentially fruitful approach would be to target acoustic pitch processing with transcranial magnetic stimulation in order to simulate the amusic deficit in non-amusic participants. The observation of a musical pitch deficit in participants whose acoustic processing has been disrupted would provide compelling evidence that this type of disruption is responsible for the amusic disorder.

In addition to the analysis targeting questions of modularity in amusia, we also assessed the moderating influence of some additional variables of interest on the performance gap. This analysis indicated a role for participant language, with studies of tonal language speakers reporting a smaller performance gap between amusics and controls. Although amusia has been shown to be highly heritable and therefore dependent upon genetics (Peretz, Cummings, & Dubé, 2007), this result speaks to the possible effect of experience on the severity of this disorder. Tonal language speakers receive lifelong implicit pitch discrimination training in a speech context, and this may alleviate the impact of the amusic disorder. The effect of participant language thus advocates for the importance of studies directed at pitch acuity training in amusic participants, with the possibility that the pitch deficit in amusia could be improved through training. Indeed, we are aware of a few studies of this nature that are in progress (Florin, Vuvan, Baillet, & Peretz, in preparation; Mignault-Goulet et al., in preparation; Vuvan, Zendel, & Peretz, in preparation). Interestingly, in one study, Peretz, Nguyen, and Cummings (2011) tested young, non-amusic participants and found that tonal language speakers were impaired as compared to non-tonal language speakers in the discrimination of falling pitches in tone sequences, despite being matched for MBEA scores. However, our meta-analysis indicates that, at least in the context of amusia, tonal language fluency seems to help, rather than hinder pitch discrimination.

One caveat of our results regarding tonal language is that this variable was correlated with age, such that studies of tonal language speakers tested participants who were on average younger than studies of non-tonal language speakers. Indeed, age had a marginal influence on the performance gap, with studies of older participants reporting a larger gap between amusics and controls. In fact, the effect of age on the performance gap, along with the Montreal database cases in which poor acoustic perception in older participants did not lead to amusia, hints at differential developmental trajectories in amusics and controls for pitch change perception across the lifespan. Congenital amusia in childhood seems to have a very similar profile to that which is observed in adults (Lebrun, Moreau, McNally-Gagnon, Mignault Goulet, & Peretz, 2012; Mignault Goulet, Moreau, Robitaille, & Peretz, 2012), but this issue requires further systematic study to better understand the relation between acoustic and musical pitch processing throughout development.

Lastly, we found that target duration did not have a significant impact upon the control-amusic performance gap, nor did pitch change vs. direction. Turning first to target duration, our meta-analytic database contained durations with a mean of 377 ms and a range from 100 to 850 ms. Intriguingly, this range overlaps considerably with the profile of pitch durations used in music (280 ± 291 ms; Patel, 2013). However, there is a large amount of variation in terms of duration in our database, and notably, some studies used very long durations (850 ms) that are unlikely to be found in musical melodies. As previously discussed, some theorists have argued that amusia might be explained by a deficit of memory encoding, rather than of discrimination (Albouy, Mattout, et al., 2013; Albouy, Schulze, et al., 2013; Tillmann et al., 2009; Williamson et al., 2010; Williamson & Stewart, 2010). If amusia can be explained by a memory deficit, then amusics should perform better given memory enhancing contexts, such as long (i.e., 850 ms) targets that are more easily encoded. Therefore, the lack of a significant effect for duration presents evidence contrary to the memory account of amusia.

The lack of effect for pitch change vs. direction is interesting, as some individual studies have reported that amusics perform significantly worse on direction tasks than on change detection tasks (Omigie & Stewart, 2011; Patel, Foxton, & Griffiths, 2005; Williamson, Cocchini, & Stewart, 2011). One intriguing reason that direction is might be found to be more difficult for amusic participants might be that the detection of the direction of a pitch change is more explicit a task than the simply noticing that there was a change. Given that amusia has been characterized as a deficit of awareness (Peretz, Brattico, Järvenpää, & Tervaniemi, 2009), as have other neurodevelopmental disorders such as dyslexia (Bruck, 1992) and prosopagnosia (Tranel & Damasio, 1985), the level of explicit awareness of pitch information required for the task may play an important role. That said, other studies have shown mixed results (Liu et al., 2013; Liu, Jiang, et al., 2012; Liu et al., 2010; Williamson, Liu, Peryer, Grierson, & Stewart, 2012), and the weight of the evidence here indicates that amusics have equal difficulty with change detection and direction tasks. Additionally, all the tasks assessed by our meta-analysis were explicit ones, and it may be that a small difference in degree of explicitness is not enough to elicit effect size differences between change detection and direction tasks across studies. Interestingly, Patel's (2010) melodic contour deafness hypothesis draws on evidence that amusics perform more poorly on direction than change detection tasks to argue that contour is not processed in separate modules for music and speech, but rather that there is a common contour processor across music and speech. In this view, the fact that amusics show direction deficits with both music and speech materials is evidence for the lack of contour modularity. However, our meta-analysis results advocate against this evidence regarding pitch direction, and therefore this view regarding the modularity of contour processing for music.

In summary, this quantitative review has confirmed the reality of the amusic pitch discrimination deficit, confirmed the acoustic locus of the amusic deficit (albeit with a caveat concerning heterogeneity in the amusic population), and suggested some fascinating avenues for future research. It is likely that this area of study will continue to be productive, as congenital amusia constitutes an advantageous natural experiment that offers a window to the many important questions of cognitive neuropsychology, which include the investigation of processing modularity between music and speech, a focus of this study (see also Mantell & Pfordresher, 2013 for a recent discussion), and the search for etiological similarities between amusia and other neurodevelopmental disorders such as dyslexia, which like amusia, may result from a low-level sensory deficit (Ramus, 2003).

4.5 Acknowledgments

This research was supported by grant from the Natural Sciences and Engineering Research Council of Canada to the third author and a grant from the Conselho Nacional de Desenvolvimento Científico e Tecnológico of Brazil to the second author. The authors would like to thank Stefano DiDomenico, Elizabeth Page-Gould, Marion Cousineau, and Benjamin Zendel for their statistical guidance and insightful comments.

4.6 References

Albouy, P., Mattout, J., Bouet, R., Maby, E., Sanchez, G., Aguera, P.-E., Caclin, A. (2013). Impaired pitch perception and memory in congenital amusia: the deficit starts in the auditory cortex. *Brain, 136(5),* 1639-1661.

Albouy, P., Schulze, K., Caclin, A., & Tillmann, B. (2013). Does tonality boost short-term memory in congenital amusia? *Brain Research, 1537(6)*, 224-232.

Anderson, S., Himonides, E., Wise, K., Welch, G., & Stewart, L. (2012). Is there potential for learning in amusia? A study of the effect of singing intervention in congenital amusia. *Annals of the New York Academy of Sciences, 1252(1),* 345-353.

Ayotte, J., Peretz, I., & Hyde, K. (2002). Congenital amusia: A group study of adults afflicted with a music-specific disorder. *Brain, 125,* 238-251.

Bollen, K. A., & Jackman, R. W. (1985). Regression diagnostics an expository treatment of outliers and influential cases. *Sociological Methods & Research, 13(4),* 510-542.

Bruck, M. (1992). Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology, 28(5),* 874.

Dalla Bella, S., Giguère, J.-F., & Peretz, I. (2009). Singing in congenital amusia. *The Journal of the Acoustical Society of America, 126(1),* 414-424.

Foxton, J. M., Dean, J. L., Gee, R., Peretz, I., & Griffiths, T. D. (2004). Characterization of deficits in pitch perception underlying 'tone deafness'. *Brain, 127(4),* 801-810.

Gehanno, J.-F., Rollin, L., & Darmoni, S. (2013). Is the coverage of Google Scholar enough to be used alone for systematic reviews. *BMC Medical Informatics and Decision Making,* *13(1*), 7.

Gordon-Salant, S., Frisina, R. D., Popper, A. N., & Fay, R. R. (2010). *The aging auditory system*. New York: Springer.

Gosselin, N., Jolicœur, P., & Peretz, I. (2009). Impaired memory for pitch in congenital amusia. *Annals of the New York Academy of Sciences, 1169(1)*, 270-272.

Hutchins, S., Gosselin, N., & Peretz, I. (2010). Identification of changes along a continuum of speech intonation is impaired in congenital amusia. *Frontiers in Psychology*, 1, 236.

Hutchins, S., & Peretz, I. (2012). Amusics can imitate what they cannot discriminate. *Brain and language, 123(3)*, 234-239.

Hutchins, S., & Peretz, I. (2013). Vocal pitch shift in congenital amusia (pitch deafness). *Brain and language, 125(1*), 106-117.

Hutchins, S., Zarate, J. M., Zatorre, R. J., & Peretz, I. (2010). An acoustical study of vocal pitch matching in congenital amusia. *The Journal of the Acoustical Society of America, 127(1)*, 504-512.

Hyde, K. L., & Peretz, I. (2004). Brains that are out of tune but in time. *Psychological Science, 15(5),* 356-360.

Hyde, K. L., & Peretz, I. (2005). Congenital amusia: Impaired musical pitch but intact musical time. In J. Syka & M. M. Merzenich (Eds.), *Plasticity and signal representation in the auditory system*. New York: Springer.

Jiang, C., Hamm, J. P., Lim, V. K., Kirk, I. J., Chen, X., & Yang, Y. (2012). Amusia results in abnormal brain activity following inappropriate intonation during speech comprehension. *PLoS ONE, 7(7),* e41411.

Jiang, C., Hamm, J. P., Lim, V. K., Kirk, I. J., & Yang, Y. (2010). Processing melodic contour and speech intonation in congenital amusics with Mandarin Chinese. *Neuropsychologia, 48(9),* 2630-2639.

Jiang, C., Hamm, J. P., Lim, V. K., Kirk, I. J., & Yang, Y. (2011). Fine-grained pitch discrimination in congenital amusics with Mandarin Chinese. *Music Perception, 28(5),* 519-526.

Jiang, C., Lim, V. K., Wang, H., & Hamm, J. P. (2013). Difficulties with pitch discrimination influences pitch memory performance: Evidence from congenital amusia. *PLoS ONE, 8(10*), e79216.

Johnson, B. T., & Eagly, A. H. (2000). Quantitative synthesis of social psychological research, *CHIP Documents (Paper 13).*

Kalmus, H., & Fry, D. (1980). On tune deafness (dysmelodia): frequency, development, genetics and musical background. *Annals of human genetics, 43(4)*, 369-382.

Lebrun, M.-A., Moreau, P., McNally-Gagnon, A., Mignault Goulet, G., & Peretz, I. (2012). Congenital amusia in childhood: a case study. *Cortex, 48(6)*, 683-688.

Liu, F., Jiang, C., Pfordresher, P. Q., Mantell, J. T., Xu, Y., Yang, Y., & Stewart, L. (2013). Individuals with congenital amusia imitate pitches more accurately in singing than in speaking: Implications for music and language processing. *Attention, Perception, & Psychophysics, 75(8)*, 1783-1798.

Liu, F., Jiang, C., Thompson, W. F., Xu, Y., Yang, Y., & Stewart, L. (2012). The mechanism of speech processing in congenital amusia: Evidence from Mandarin speakers. *PLoS ONE, 7(2)*, e30374.

Liu, F., Patel, A. D., Fourcin, A., & Stewart, L. (2010). Intonation processing in congenital amusia: Discrimination, identification and imitation. *Brain, 133(6)*, 1682-1693.

Liu, F., Xu, Y., Patel, A. D., Francart, T., & Jiang, C. (2012). Differential recognition of pitch patterns in discrete and gliding stimuli in congenital amusia: Evidence from Mandarin speakers. *Brain and Cognition, 79(3*), 209-215.

Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: A new disconnection syndrome? *The Journal of Neuroscience, 29(33*), 10215-10220.

Loui, P., Guenther, F. H., Mathys, C., & Schlaug, G. (2008). Action–perception mismatch in tone-deafness. *Current Biology, 18(8*), R331-R332.

Loui, P., & Schlaug, G. (2012). Impaired learning of event frequencies in tone deafness. *Annals of the New York Academy of Sciences, 1252(1)*, 354-360.

Mantell, J. T., & Pfordresher, P. Q. (2013). Vocal imitation of song and speech. *Cognition, 127(2)*, 177-202.

Marin, M. M., Gingras, B., & Stewart, L. (2012). Perception of musical timbre in congenital amusia: Categorization, discrimination and short-term memory. *Neuropsychologia, 50(3)*, 367-378.

Mignault Goulet, G., Moreau, P., Robitaille, N., & Peretz, I. (2012). Congenital amusia persists in the developing brain after daily music listening. *PLoS ONE, 7(5)*, e36860.

Moreau, P., Jolicoeur, P., & Peretz, I. (2009). Automatic brain responses to pitch changes in congenital amusia. *Annals of the New York Academy of Sciences, 1169*, 191-194.

Nan, Y., Sun, Y., & Peretz, I. (2010). Congenital amusia in speakers of a tone language: association with lexical tone agnosia. *Brain, 133(9*), 2635-2642.

Omigie, D., Pearce, M. T., & Stewart, L. (2012). Tracking of pitch probabilities in congenital amusia. *Neuropsychologia, 50(7)*, 1483-1493.

Omigie, D., Pearce, M. T., Williamson, V. J., & Stewart, L. (2013). Electrophysiological correlates of melodic processing in congenital amusia. *Neuropsychologia, 51(9)*, 1749-1762.

Omigie, D., & Stewart, L. (2011). Preserved statistical learning of tonal and linguistic material in congenital amusia. *Frontiers in Psychology*, *2*, 1-11.

Parbery-Clark, A., Anderson, S., Hittner, E., & Kraus, N. (2012). Musical experience offsets age-related delays in neural timing. *Neurobiology of aging, 33(7*), 1483.e1481-1483.e1484.

Parbery-Clark, A., Strait, D. L., Anderson, S., Hittner, E., & Kraus, N. (2011). Musical experience and the aging auditory system: implications for cognitive abilities and hearing speech in noise. *PLoS ONE, 6(5),* e18082.

Patel, A. D. (2010). *Music, language, and the brain*. New York: Oxford University Press.

Patel, A. D. (2013). Can nonlinguistic musical training change the way the brain processes speech? The expanded opera hypothesis. Hearing Research, 308, 98-108.

Patel, A. D., Foxton, J. M., & Griffiths, T. D. (2005). Musically tone-deaf individuals have difficulty discriminating intonation contours extracted from speech. *Brain and Cognition*, *59(3*), 310-313.

Patel, A. D., Wong, M., Foxton, J., Lochy, A., & Peretz, I. (2008). Speech intonation perception deficits in musical tone deafness (congenital amusia). *Music Perception, 25(4),* 357-368.

Peretz, I. (2001). Brain specialization for music. *Annals of the New York Academy of Sciences, 930(1)*, 153-165.

Peretz, I. (2006). The nature of music from a biological perspective. *Cognition, 100(1),* 1-32.

Peretz, I. (2013). The biological foundations of music: Insights from congenital amusia. In D. Deutsch (Ed.). *The Psychology of Music*. London, UK: Academic Press.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., & Jutras, B. (2002). Congenital amusia: A disorder of fine-grained pitch discrimination. *Neuron, 33*, 185-191.

Peretz, I., Brattico, E., Järvenpää, M., & Tervaniemi, M. (2009). The amusic brain: In tune, out of key, and unaware. *Brain, 132*, 1277-1286.

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders. *Annals of the*

New York Academy of Sciences, *999(1*), 58-75.

Peretz, I., & Coltheart, M. (2003). Modularity of music processing. Nature *Neuroscience, 6(7*), 688-691.

Peretz, I., Cummings, S., & Dubé, M.-P. (2007). The genetics of congenital amusia (tone deafness): a family-aggregation study. *The American Journal of Human Genetics, 81(3)*, 582-588.

Peretz, I., Gosselin, N., Tillmann, B., Cuddy, L. L., Gagnon, B., Trimmer, C. G., Bouchard, B. (2008). On-line identification of congenital amusia. Music Perception: An *Interdisciplinary Journal*, *25(4)*, 331-343.

Peretz, I., Nguyen, S., & Cummings, S. (2011). Tone language fluency impairs pitch discrimination. *The relationship between music and language*, 84.

Pfeuty, M., & Peretz, I. (2010). Abnormal pitch—time interference in congenital amusia: Evidence from an implicit test. *Attention, Perception, & Psychophysics, 72(3)*, 763-774.

R Core Team. (2013). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org.

Ramus, F. (2003). Developmental dyslexia: specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology, 13(2)*, 212-218.

Rosenthal, R., & DiMatteo, M. R. (2001). Meta-analysis: Recent developments in quantitative methods for literature reviews. *Annual Review of Psychology*, *52*, 59-82.

Seashore, C. E. (1939). Psychology of Music. XXI. Revision of the Seashore measures of musical talent. *Music Educators Journal*.

Thompson, W. F., Marin, M. M., & Stewart, L. (2012). Reduced sensitivity to emotional prosody in congenital amusia rekindles the musical protolanguage hypothesis. *Proceedings of the National Academy of Sciences, 109(46)*, 19027-19032.

Tillmann, B., Burnham, D., Nguyen, S., Grimault, N., Gosselin, N., & Peretz, I. (2011). Congenital amusia (or tone-deafness) interferes with pitch processing in tone languages. *Frontiers in Psychology*, 2.

Tillmann, B., Rusconi, E., Traube, C., Butterworth, B., Umiltà, C., & Peretz, I. (2011). Fine-grained pitch processing of music and speech in congenital amusia. The *Journal of the Acoustical Society of America, 130(6)*, 4089-4096.

Tillmann, B., Schulze, K., & Foxton, J. M. (2009). Congenital amusia: A short-term memory deficit for non-verbal, but not verbal sounds. *Brain and Cognition, 71(3)*, 259-264.

Tranel, D., & Damasio, A. R. (1985). Knowledge without awareness: An autonomic index of facial recognition by prosopagnosics. *Science, 228(4706)*, 1453-1454.

Tremblay-Champoux, A., Dalla Bella, S., Phillips-Silver, J., Lebrun, M.-A., & Peretz, I. (2010). Singing proficiency in congenital amusia: Imitation helps. *Cognitive Neuropsychology, 27(6)*, 463-476.

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software, 36(3)*, 1-48.

Williamson, V. J., Cocchini, G., & Stewart, L. (2011). The relationship between pitch and space in congenital amusia. *Brain and Cognition, 76(1)*, 70-76.

Williamson, V. J., Liu, F., Peryer, G., Grierson, M., & Stewart, L. (2012). Perception and action-de-coupling in congenital amusia: Sensitivity to task demands. *Neuropsychologia, 50(1)*, 172-180.

Williamson, V. J., McDonald, C., Deutsch, D., Griffiths, T. D., & Stewart, L. (2010). Faster decline of pitch memory over time in congenital amusia. *Advances in Cognitive Psychology, 6(1)*, 15-22.

Williamson, V. J., & Stewart, L. (2010). Memory for pitch in congenital amusia: Beyond a fine-grained, pitch discrimination problem. *Memory, 18(6)*, 657-669.

Zendel, B. R., & Alain, C. (2012). Musicians experience less age-related decline in central auditory processing. *Psychology and Aging, 27(2)*, 410-417.

5. ESTUDO IV

Magnitude Processing in Numerical and Musical Domains.

Autores: Marilia Nunes-Silva[1,2], Ricardo José de Moura[1,2], Júlia Beatriz Lopes-Silva[1,3], & Vitor Geraldi Haase[1,2]

[1] Laboratório de Neuropsicologia do desenvolvimento, Departamento de Psicologia, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil.
[2] Programa de Pós-graduação em Neurociências, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil.
[3]Programa de Pós-graduação em Saúde da Criança e do Adolescente, Faculdade de Medicina, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil.

Resumo

A relação entre as habilidades musicais e outras funções cognitivas auxilia na identificação de quais domínios são específicos do processamento musical, contribuindo para levantar evidências quanto à hipótese da modularidade e especificidade do processamento musical. Dentro deste contexto a relação entre música e matemática, apesar de muito debatida no âmbito pedagógico, tem sido pouco investigada do ponto de vista neurocientífico. Estudos sobre a relação entre processamento musical e numérico geralmente visam testar a hipótese de que o treinamento musical pode melhorar o desempenho em tarefas matemáticas. Porém, também se pode investigar esta relação a partir de estudos que avaliem se há associação entre seus déficits. O objetivo principal do presente estudo foi investigar se há uma associação entre dificuldades no processamento de magnitudes numéricas e de processamento de magnitudes de altura em indivíduos com amusia congênita e controles com desenvolvimento típico. Participaram um grupo de 11 indivíduos com amusia congênita e um grupo controle constituído de 6 indivíduos com desenvolvimento típico, pareados por idade, sexo e escolaridade com o grupo de amúsicos. Os participantes realizaram sessões de avaliações utilizando tarefas específicas para avaliação da cognição numérica e da cognição musical. A partir dos dados obtidos pode-se observar, como esperado, os efeitos de distância sobre o desempenho de todos os participantes nas tarefas numéricas. Os resultados obtidos indicaram que, em comparação com controles, os indivíduos com amusia congênita não apresentaram diferença de performance

na tarefa de linha mental numérica nem na tarefa de comparação de magnitudes não-simbólica. Apesar de estatisticamente não significativa, a diferença da média entre grupos na tarefa de comparação de magnitudes não-simbólica apresentou-se mais acentuada para razões menores. Além disso, indivíduos com amusia congênita apresentaram um pior desempenho na tarefa numérica simbólica quando comparados a controles. Portanto, observou-se que indivíduos com amusia congênita que têm desempenho comprometido em tarefas que avaliam o processamento de magnitudes de altura exibiram representação de magnitudes numéricas não simbólicas preservada, o que é indicativo de que haja um mecanismo não compartilhado de representação de magnitudes não simbólicas para processamento de cognição musical e cognição numérica. Os resultados corroboraram estudos que mostram que os amúsicos congênitos tem representações visuoespaciais e de linha mental numérica preservados, além de diferentes representações mentais para altura e números. O pior desempenho para discriminar magnitudes numéricas simbólicas indica que os amúsicos congênitos podem apresentar dificuldades de acesso simbólico a partir de representações analógicas de magnitudes, o que deve ser melhor investigado. Os resultados, portanto, não favorecem a hipótese de que há um mecanismo compartilhado para processamento de magnitudes, como proposto pela ATOM, e são compatíveis com a hipótese da modularidade e especificidade do processamento cognitivo musical.

Abstract

The relationship between musical abilities and other cognitive functions helps to identify domains that are specific to musical processing, contributing to gather evidence about the hypothesis of modularity and specificity of musical processing. Within this context the relationship between music and mathematics, although highly debated in the educational context has been poorly investigated from the neuroscience point of view. Studies on the relationship between musical and numerical processing are generally designed to test the hypothesis that musical training can improve performance on mathematical tasks. However, one can also investigate this relationship from studies evaluating if there are associations between deficits in both domains. This study aims at investigating whether there is an association between difficulties in numerical magnitude processing and pitch magnitude processing in individuals with congenital amusia and typically developing controls. The amusic group constituted of 11 individuals with congenital amusia and the control group comprised 6

typically developing individuals matched for age, sex and education level. Participants were assessed with specific tasks of numerical and musical cognition. We could observe, as expected, the distance effect on the performance of all participants in numerical tasks. The results indicated that, compared with controls, individuals with congenital amusia showed no difference in performance in both mental number line and non-symbolic magnitudes comparison tasks, although the RT mean difference between groups was greater for smaller ratios in the non-symbolic magnitudes comparison tasks. Nevertheless, individuals with congenital amusia showed a worse performance in the symbolic numerical comparison task. Therefore, we could observe that individuals with congenital amusia, who have impaired performance on tasks that evaluate pitch magnitude processing, showed preserved non-symbolic numerical magnitude representation. This suggests that there is a non-shared mechanism for processing non-symbolic magnitude representation considering both musical and numerical domains. The results corroborate studies showing that congenital amusics have preserved visuospatial and mental number line representations, and differences in pitch and numbers mental representations. The lower performance in discriminating symbolic numerical magnitudes indicates that congenital amusics may present difficulties in accessing the symbolic representation from the analog magnitude representation, which should be further investigated. These results, therefore, do not support the hypothesis that there is a shared mechanism for processing magnitudes, as proposed by ATOM, and they are compatible with the hypothesis of modularity and specificity of musical cognitive processing.

5.1 Introduction

Studies that investigate the relationship between music and other cognitive functions may contribute in identifying domains that are specific to musical processing (Hetland, 2000; Anvari, Trainor, Woodside, & Levy, 2002; Brandler & Rammsayer, 2003; Gaser & Schlaug, 2003; Brochard, Dufour, & Despres, 2004; Sluming, Howard, Downes, & Roberts, 2007; Ho, Cheung, & Chan, 2003; Schellenberg, 2006). Musical structures are based on mathematical principles and the association between music theory and mathematical concepts is used in educational context (Upson, 2002; Guia & França, 2005; Bamberger & diSessa, 2003; Martinez, et al, 2008). Despite this, Vaughn (2000) reported in a meta-analysis, that there are few studies that investigate whether musical training improves performance in math and the findings are still controversial.

Regardless this lack of systematic studies about the relationship between musical and numerical processing, Schmithorst and Holland (2004), in a preliminary study of functional magnetic resonance imaging (fMRI), have sought to investigate the effect of musical training on the neural correlates that are associated with math processing. The authors evaluated 15 normal adults, from which seven had formal music training since childhood and eight were untrained, while they performed tasks of fractions addition and subtraction. The musical training level was associated with increased activation of the left prefrontal cortex and left fusiform gyrus and lower activation in visual association areas and the left inferior parietal lobule. The authors argue that the increased activation in the left prefrontal cortex suggests that the link between musical training and improved math performance may be associated with improved performance of semantic working memory in musicians, related to a better conflict resolution among right and wrong answers in an equation. Moreover, the authors highlight that the left fusiform gyrus activation, which is involved in a more abstract level of visual form processing, indicates that better math performance in musicians could be associated with an improved abstract representation of numerical quantities.

Studies about music and math are generally designed to test the hypothesis that musical training can improve performance on mathematical tasks. However, we can also investigate the relationship between musical processing and numerical processing from studies evaluating if there are associations among their deficits. Selective deficits of musical abilities are classified as amusias and can affect both recognition and reproduction of melodies or their components. The amusias can be of two types: acquired amusia, because of disease or brain injury; and congenital amusia, present from birth, which may occur due to hereditary factors (Hyde & Peretz, 2004; Peretz, Cummings, & Dubé, 2007).

Hyde and Peretz (2004) define congenital amusia as a life-long disability for musical processing despite normal intelligence, memory, language and adequate exposure to music during the developmental period. Congenital amusia is therefore a developmental disorder and it is associated with an acoustic deficit in fine-grained pitch discrimination (Ayotte, Peretz & Hyde, 2002). Studies show that congenital amusics present impaired performance in both pitch change discrimination tasks (pitch change detection), in which individuals are required to identify whether there is or not a difference (equal vs. different), and for tasks of pitch change direction identification, that is a forced choice task in which the individual must indicate whether a tone was higher or lower than the previous one (higher vs. lower pitch) (Peretz et al, 2002; Peretz & Hyde, 2003; Hyde & Peretz, 2004; Liu et al, 2010). Congenital amusics have mainly impairment in melodic perception and inaccurate pitch production and, less commonly, inaccurate temporal perception, showing mismatches between capacities of musical perception and production, which indicates an impairment of neural networks involved in the perception-action process (Peretz et al, 2002; Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Loui, Guenther, Mathys, & Schlaug, 2008). Moreover, some studies suggest that congenital amusia constitutes a disconnection syndrome between the right auditory cortex and the right inferior frontal gyrus (Loui, Alsop & Schlaug, 2009; Loui, Schlaug and Hohmann, 2010; Hyde, Zatorre & Peretz, 2011).

Mathematics learning disability, also known as dyscalculia, is characterized by persistent problems in the acquisition of basic numerical principles and arithmetic concepts, with difficulty in memorizing and recalling arithmetic facts and in performing calculation operations, which ultimately lead to lifelong negative psychosocial impact (Butterworth, 2005; Geary, 2011). Individuals with dyscalculia show a variety of numerical processing deficits, including basic skills. Wilson and Dehaene (2007) consider the existence of four main subtypes of dyscalculia: 1) Pure dyscalculia, related to deficits in number sense and which includes difficulty in understanding the concept of numbers and quantities as well as in estimating quantities; 2) Verbal dyscalculia, involves deficits in the verbal symbolic numerical representation; 3) Spatial dyscalculia, associated with visuospatial deficits that result in difficulties in "subtizing" (ability to recognize and identify small amounts of objects automatically) and arrangements of numbers for mathematical operations; 4) Dyscalculia due to deficits in executive functions, associated with frontal lobe dysfunctions.

Pure dyscalculia is related to a deficit in the number processing system associated to the analogical representation of numerosities. Numerosities refer to the cardinal property of sets. Each numerosity is internally represented by a noisy distribution of activation on an internal continuum or mental number line (Dehaene, 2003). The cognitive system of approximate number representations that estimates and combines the numbers of objects in sets with ratio-limited precision is called approximate number system (ANS). The amount of noise in an individual's ANS is indexed as a Weber fraction (w), that can be calculated by asking an individual to evaluate which of two arrays of objects is more numerous (Halberda, Mazzoco & Feigenson, 2008). As the ratio between two arrays approaches the result "1" (meaning two identical numerosities), individuals make more errors judging which of the two is more numerous. According to Mazzocco, Feigenson and Halberda (2011a), the ANS is activated during both nonsymbolic approximations (e.g., judging which array of items is more numerous, irrespective of item size) and symbolic number tasks (e.g., judging whether a series of Arabic numerals refers to increasing or decreasing quantities). Studies have shown that interindividual variability in the acuity of the ANS correlates with mathematical achievement (Halberda et al., 2008; Gilmore et al., 2010; Mazzocco et al., 2011b).

According to Wilson and Dehaene (2007), deficits on number sense are associated with functional and structural damage of the horizontal segment of the intraparietal sulcus (hIPS). Studies also indicate the involvement of the intraparietal sulcus (IPS) in different tasks related to the processing of numerical magnitude (Dehaene, Piazza, Pinel, & Cohen, 2003; Hubbard, Piazza, Pinel, & Dehaene, 2005). However, the IPS may be related not only to numerical magnitudes, and neuroimaging studies provide converging evidence that IPS may constitute in a neuroanatomical basis for a general and amodal magnitude processing mechanism (Fias et al., 2003, Walsh, 2003; Cohen Kadosh et al., 2005; Cohen Kadosh, Lammertyn & Izard, 2008). In this sense, Walsh (2003) proposed A Theory of Magnitude (ATOM), in which it is assumed that time, space and quantity are part of a generalized magnitude system. Walsh suggests that there are neurological and behavioral similarities between time, space and quantity that reflect a common processing mechanism, linked to our need to process information about the spatiotemporal structure of the external world. ATOM also states that the arrangement of the inferior parietal cortex reflect the common need of the information about space, time and quantity in being used for sensorimotor transformations, which is the main goal of these cortical areas. An ATOM presupposition is that there should be a monotonic mapping of quantities: bigger, faster, brighter and farther in a domain should correlate with bigger, faster, brighter and farther in a different domain (Walsh, 2003). Therefore, magnitude refers to the quantitative information in different dimensions and psychophysical sensorial modalities.

Some authors claim that pitch can also be considered as a magnitude domain (Cohen Kadosh, Lammertyn, & Izard, 2008; Cohen Kadosh, Brodsky, Henik & Levin, 2008; Bonn & Cantlon, 2012). Pitch is a sound attribute that can be ordered on a scale from lowest to the highest frequency. Bonn and Cantlon (2012) argue that pitch could also be considered as a quantitative dimension, since changes in its stimuli may be readily interpreted in terms of quantity, and there are cognitive and neural parallels between the pitch magnitude processing and other numerical and non-numerical magnitudes. As stated by Stevens (1975), adults can easily transform continuous dimensions in digital numbers. Accordingly, we can assume that if pitch can be considered along a frequency continuum, then pitch judgments could be made in a quantitative form (higher vs. lower pitch), in addition to their quality form (i.e. considering tonal structure, octaves, etc.). The pitch estimation could thus be considered as a form of magnitude estimation.

Many parallels are observed between the behavioral performances in pitch perception tasks and discrimination tasks involving numerical and other non-numerical magnitudes (Rusconi, Kwana, Giordano, Umilta, & Butterworth, 2006; Cohen Kadosh, Lammertyn, & Izard, 2008; Cohen Kadosh, Brodsky, Levin & Henik, 2008; Bonn & Cantlon, 2012). One of the behavioral evidence shared between pitch and other magnitude domains is the psychophysical performance. In the same way as in other domains, pitch can be depicted on a logarithmic scale and is in accordance with the Weber's law. According to Weber's law, the increase in stimulus intensity required to produce a difference that is noticeable by humans, or just noticeable difference (JND), is a constant function of intensity of this stimulus. The discrimination of a stimulus along a given continuum depends on its ratio and not on its absolute values, and the relationship between the physical stimulus and its perception is depicted on a logarithmic scale (Stevens, 1975). According to Roederer (2008), considering the ability of an individual to establish a relative order of pitch when two pure tones are presented alternately to be discriminated against, there is a perceptual threshold of this ability. The individual cannot notice the difference between two pitches frequencies if this difference is below a certain value and he will consider the two frequencies as being the same. Therefore, as well as other psychophysical magnitudes, there is a differential threshold or JND for pitches.

There is also evidence of interaction between pitch and other magnitudes, such as time and luminance, in studies of categorization of stimuli and studies that use tasks, which elicit representations in two dimensions simultaneously. The high frequencies sounds (higher pitches) are classified as faster and brighter and the low frequency sounds are classified as slower and darker (Collier & Hubbard, 1998; Collier & Hubbard, 2004). Furthermore, experiments show interactions between frequency (lower vs. higher pitches) and luminance (darker vs brighter), in which individuals respond faster when the stimuli are congruent (lower-darker, higher-brighter) than when they are incongruent (Mark, 1987; Ludwig, Adachid & Matsuzawa, 2011). There is also interference between pitch and time when the durations of the high pitched tones is underestimated and the low tones is overestimated, (i.e., higher frequencies are judged as faster and lower frequencies are judged as slower) (Lake & LaBar, 2014).

According to Cohen Kadosh, Lammertyn and Izard (2008), behavioral studies regarding musical stimuli also show similar effects to those of numerical stimuli, suggesting that the mechanisms for processing numerical magnitudes and pitch can be shared. One of these effects is evidenced in studies using Spatial-Musical Association of Response Codes (SMARC) tasks, which are correlated to Spatial-Numerical Association of Response Codes (SNARC) tasks, but regarding frequency comparison. Studies about the SNARC effect show, based on reaction time, that there is an association between increasing number format and spatial reference (Dehaene, Bossini, & Giraux, 1993; Fias and Fischer, 2004). Studies on the SMARC effect indicate, also from measurements of reaction time, that there is an association between pitch (lower and higher) and spatial reference. Responding to lower pitches is faster using a left or lower key than using a right or higher key, and the opposite occurs for higher pitches (Rusconi *et al.*, 2006; Lidji, Kolinsky, Lochy, & Morais, 2007). These tasks suggest that both mathematical and musical cognition elements are mapped onto a mental spatial representation that can interfere with performance.

Mapping pitch frequency onto a vertical high-low line is not arbitrary. Instead, the auditory scene statistics show a clear mapping between the pitch frequency and the elevation in space, suggesting that the sound localization behavior and the hearing anatomy are adjusted for the statistics of natural auditory scenes (Parise, Knorre, & Ernst, 2014). Moreover, this mapping seems to occur early in human development, with 3-4 months babies having visual preference for congruent stimuli (high frequency with high visual stimulus in space; lower frequency with low visual stimulus in space; displacement from low to high frequencies with ascending shapes; displacement from high to low frequencies with descending shapes) connecting pitch frequency to visual shape and visuospatial height (Walker *et al*, 2009).

Another effect that occurs with both numerical and pitch comparison is the distance effect. The distance effect for numerical stimuli refers to a negative correlation between the numerical distance and response time, since quantitatively farther numbers are easier to be compared than closer numbers. The distance effect depends only on the numerical proximity rather than the shape of digits or the word corresponding to the number. It is a semantic effect based on an abstract parameter, the numerical visual shapes, which are quickly converted by individuals in an amodal representation of the quantity and on its numerical proximity from other numbers. Therefore, the distance effect is considered as an indicative of the consolidation of the mental number line knowledge (Dehaene *et al.*, 1993; Pinel et al, 2001; Fias et al, 2003).

The distance effect is also demonstrated in pitch comparison tasks, resulting in a reaction time profile that is identical to the one obtained from comparing other types of magnitudes. It is also possible to observe that the greater the quantitative difference between the pitches, the lower is the reaction time. Despite pitch representation being more complex than that of other stimuli, because it is two-dimensional and helicoidal (height and chroma dimensions), considering comparison tasks, the distance effect is identical to other kinds of magnitudes. This indicates that the distance effect may be more related to a common mechanism affected by the salience of the stimulus that is required for sensorimotor transformations, than to the mental representation of the stimulus itself (Rusconi et al, 2006; Cohen Kadosh, Brodsky, Henik & Levin, 2008).

Additionally, neuroimaging studies using musical stimuli, mainly related to height, have shown that the intraparietal sulcus may also play a role in magnitude processing and in manipulating information related to these musical stimuli, suggesting that pitch identification processing in the auditory domain may be related to the processing of numerosity in visual domain (Foster & Zatorre, 2010; Schwenzer & Mathiak, 2011). Schwenzer and Mathiak (2011) have demonstrated that pitch identification tasks, which involves alternatives processing, differ from pitch discrimination tasks, regarding the activation of the intraparietal sulcus. Moreover, pitch identification was positively correlated with the activation of the left IPS. Thus, the authors suggest that the IPS activity during this task could be the auditory correlate of the numerosity processing in the visual domain. Foster and Zatorre (2010), in turn, from a study of functional magnetic resonance imaging, found that activity in the right intraparietal sulcus predicts the performance on melodic comparison tasks, both in musicians and in non-musicians, especially in the transposed melody condition. As transposed melody requires auditory patterns encoding and comparison with different tonal reference points, the results point to the role of the IPS in transforming high-level auditory information, suggesting that this area may be related to general ability in transforming and comparing systematically related to stimulus attributes.

In this context, the main objective of this study was to investigate whether there is an association between difficulties in numerical magnitude processing and pitch magnitude processing in individuals with congenital amusia. Starting from the presupposition that there is an amodal mechanism for processing magnitudes, located in the IPS, involved in both numerical and pitch magnitude processing, we can assume that deficits in numerical magnitudes processing would be accompanied by deficits in pitch magnitude processing. If magnitudes are amodaly processed, then the performance on different magnitudes discrimination tasks, regardless of the sensory modality, would be positively correlated. Accordingly, one may predict that amusic individuals who have a poor performance in tasks assessing tonal magnitude would also show low performance on tasks assessing numerical magnitudes and that the control group would show normal performance on both types of tasks. Moreover, the performance in both numerical and pitch magnitude tasks could be positively correlated.

5.2 Method

5.2.1 Participants

The study was conducted with two groups of participants: an amusic group and a control group. The amusic group sample consisted of 11 Canadian individuals with congenital amusia who were confirmed as amusic on the basis of the aforementioned behavioural testing using Montréal Battery of Evaluation of Amusia (MBEA). The control group sample consisted of 6 subjects with no musical impairment confirmed by a normal score obtained in MBEA and Pitch Change Detection (PCD) task (Peretz, Champod, & Hyde, 2003; Hyde & Peretz, 2004). The two groups were matched on gender, age, years of formal education, and musical training background. A summary of these variables is presented in Table 1.

Table 1. Characteristics of the participants and their mean percentage of correct answers on musical tests.

Group	N	Gender	Age	General Education	Music Education	MBEA Global	PCD % (Hits-FA)
Amusics	11	9F	65.27 (5.6)	17.5 (3.4)	1.1 (1.1)	0.65 (0.07)	22.4 (18.23)
Controls	6	5F	62.17 (3.5)	14.8 (2.9)	1.5 (1.8)	0.89 (0.04)	94.4 (5.1)
t Test		n.s.	n.s.	n.s	n.s.	*t*(17)= -8.06, *p*<.001	*t*(17)= -9.35, *p*<.001

n.s. non-significant.

5.2.2 Material

Amusic and control individuals were assessed with the following instruments for investigating musical and numerical cognition:

1) Montreal Battery of Evaluation of Amusia (MBEA)*:* MBEA assesses six components of music processing: Contour, Interval, Scale, Rhythm, Meter, and Musical Memory. Stimuli consist of 30 original musical phrases, which were composed according to the Western tonal system. Each melody is presented in pairs, being one of the melodies manipulated. In the first

four subtests, subject's task is to identify if the melodies differ from each other. For the Meter subtest, subject should identify if the melody presented is a waltz or a march. In the Memory subtest, subject's task is to identify if the melody was heard previously during the testing or not (Peretz *et al.*, 2003).

2) Pitch Change Detection Task: Stimuli consisted of different sequences containing five successive tones. In the standard sequence, all tones were 100 ms long, played at the pitch level of C6 (1047 Hz), and synthesized with a piano timbre. The intertone interval (ITI; onset to onset) was 350 ms. In half of the sequences, the fourth tone was displaced upward or downward in pitch by one of five pitch distances. These ranged from 25 to 300 cents (where 100 cents corresponds to 1 semitone). Trials were randomized and mixed with half of the sequences containing no change (i.e., the standard sequence). Participants were informed about the position in the sequence where a change could occur. The task comprised 600 sequences (300 standards). Participants were asked to press a "yes" button whenever they detected a change and a "no" button when they were unable to detect a change (Hyde & Peretz, 2004).

3) Non-symbolic Number Magnitude Comparison Task: The subject must compare two sets of points shown on the computer screen, indicating which of the two contains more points. The task is composed of eight training trials and 64 test trials, and included eight different magnitudes (8, 10, 12, 14, 18, 20, 22, and 24) to be compared with 16 points. Results are grouped according to ratio (i.e., test/baseline number of dots). There are eight ratios evaluated in the task: 0.5, 0.625, 0.75, 0.875, 1.125, 1.25, 1.375 and 1.5. The size of dots and luminance are controlled trough the test.

4) Symbolic Number Magnitude Comparison Task: The subject must decide if a number displayed on the computer screen, ranging from 1 to 9, is smaller or higher than the number five (5). If the displayed number is higher than the number five, the subject must press a predefined key on the right side of the keyboard, and if the number displayed is smaller than the number five, he must press a predefined key on the left side of the keyboard. Participant's hands are positioned on the keys to be pressed prior to the beginning of the task. Between trials, a fixation point is displayed on the screen (a cross of the same size and color of the stimuli) in order to keep the child's attention. Numeric distances between the reference number and the

number five ranged from 1 to 4 and appeared the same number of times. The number 5 is not presented. The task contains 8 training trials and 80 experimental trials.

5) Mental Number Line Task: The Mental number line task is a paper-and-pencil task that evaluates the spatial representation of numbers. Subject has to indicate on a left-to-right oriented number line the location of specific Arabic digits presented orally. There are four scales ranging from 0 to 10, 0 to 20, 0 to 100 and 0 to 1000, respectively. All scales have 25 cm in length and only the start and end points are marked. Each individuals evaluate in a total of 50 items. There are more trials for the scale of 100 (24 trials).

5.2.3 Procedures

Participants completed the tasks, in return for a small honorarium. After the contact and consent from the subjects for their participation in the study, the groups were defined. All participants had completed the MBEA (Peretz et al., 2003) and PDC task (Hyde & Peretz, 2004) in previous testing. The criteria for group definition was the result obtained in MBEA and PCD task. The selected participants have performed the numerical cognition tasks in at least one testing session of about half an hour.

5.3 Results

Analyses of variance (ANOVA) with repeated measures were performed for the numerical tasks data. The original degrees of freedom for all analyses are reported throughout the article. Type I errors associated with homogeneity of variance were controlled by decreasing the degrees of freedom using the Greenhouse–Geisser epsilon, and the probability estimates are based on these reduced degrees of freedom. Pearson correlation between numerical and musical tasks were also calculated. Results are presented separately for non-symbolic and symbolic numerical magnitude comparison tasks.

5.3.1 Non-symbolic numerical magnitude comparison task

A repeated measures ANOVA including “group” (amusics and controls) as between-participants factor and within-participants factor of “ratios” (0.5, 0.625, 0.75, 0.875, 1.125, 1.25, 1.375, 1.5) was run for both reaction time (RT) and accuracy. For the RTs, we could observe a main effect of ratio (F [2,34] = 33.74, p<.001, η2= 0.69), as responses were slower in trials with ratio closer to 1. Although the difference between groups was more prominent for ratios closer to 1 (as shown in Figure 1), there was no significant difference between groups regarding RTs (F [1,15] = 1.91, p=0.187, η2= 0.11) and no interaction between group and ratios (F [2,34] = 1.45, p=0.25, η2= 0.09). Figure 1 shows the results for RT in the non-symbolic numerical comparison task.

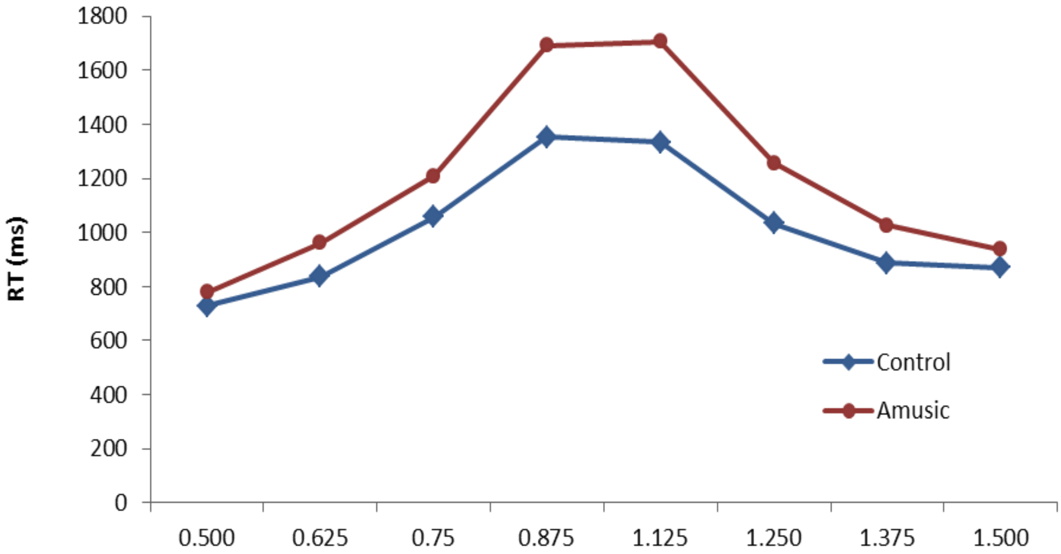

Fig. 1. Plots for means of reaction time obtained by the participants in the Non-Symbolic numerical magnitude comparison task on the eight different ratios. RTs are shown for both the amusic participants (red) and the control participants (blue).

Regarding the accuracy in the non-symbolic task, results disclosed a main effect of ratio (F [2,26] = 16.57, p < .001, η2 = 0.52), as responses were less accurate in trials with ratio closer to 1. Scores on the non-symbolic task were similar between the two groups (F [1,15] = 0.035, p = 0.855, η2 = 0.002), and no interaction involving the factor group was observed (F [2,26] = 0.081, p = 0.901, η2 = 0.005). Figure 2 shows the results for accuracy in the non-symbolic numerical comparison task.

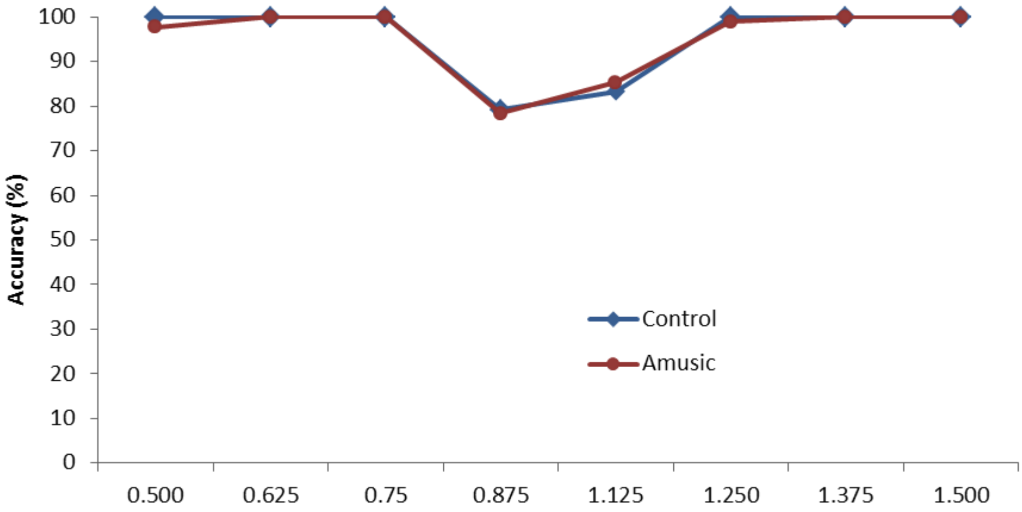

Fig. 2. Plots for mean performance (% of correct responses) obtained by the participants in the Non-Symbolic numerical magnitude comparison task on the eight different ratios. Accuracy is shown for both the amusic participants (red) and the control participants (blue).

The Weber fraction was calculated from the data obtained in the non-symbolic magnitude comparison task. The internal Weber fraction (w) evaluates the acuity of the non-symbolic representation and it is a measure that express the amount of error existing in the mental representation of any kind of magnitude. The w is calculated from the rate of correct answers and is modelated for each participant as 1 minus proportion of errors (see Piazza et al., 2004 and Dehaene, 2007 for further details). Correlations between the Weber fraction and the musical tasks (MBEA subtests and PCD) were also performed for each group separately. Results for the amusics are shown in Table 2.

Table 2. Correlation between Weber fraction and musical tasks for the amusic group.

	Weber Fraction	
	r	p
Scale	0,15	0,66
Contour	-0,12	0,73
Interval	0,19	0,58
Rhythm	0,03	0,93
Metric	-0,62*	0,04
Memory	-0,03	0,93
PCD ¼ %(Hits- FA)	-0,23	0,49

*p<0.05 (2-tailed).

As can be observed on the table above, there was a significant negative correlation in the amusic group between the Metric subtest of MBEA and *w*. Regarding control group, values are shown on the Table 3.

Table 3. Correlations between non-symbolic task and musical tasks for the control group.

	Weber Fraction	
	r	p
Scale	-0,38	0,46
Contour	-0,14	0,79
Interval	-0,59	0,21
Rhythm	-0,82*	0,05
Metric	0,15	0,77
Memory	0,68	0,14
PCD ¼ %(Hits- FA)	-0,59	0,22

*p<0.05 (2-tailed).

Concerning the control group, there was a significant negative correlation between non-symbolic magnitude comparison task and the Rhythm subtest of MBEA.

5.3.2 Symbolic numerical magnitude comparison task

For the symbolic task, a repeated measures ANOVA was run including "group" (amusics and controls) as between-participants factor and "distance" (1 to 4 from the reference number) for both RT and accuracy outcomes as within-participants factors. Concerning the RTs, we observed a main effect of distance ($F [2,35] = 19.79$, $p<.001$, $\eta 2= 0.57$), as responses were slower in trials with smaller distances. No group effect was observed ($F [1,15] = 1.5$, $p=0.239$, $\eta 2= 0.09$) as well as no interaction between group and distance ($F [2,35] = 1.37$, $p=0.269$, $\eta 2= 0.084$). Figure 3 shows the results for RT in the symbolic numerical comparison task.

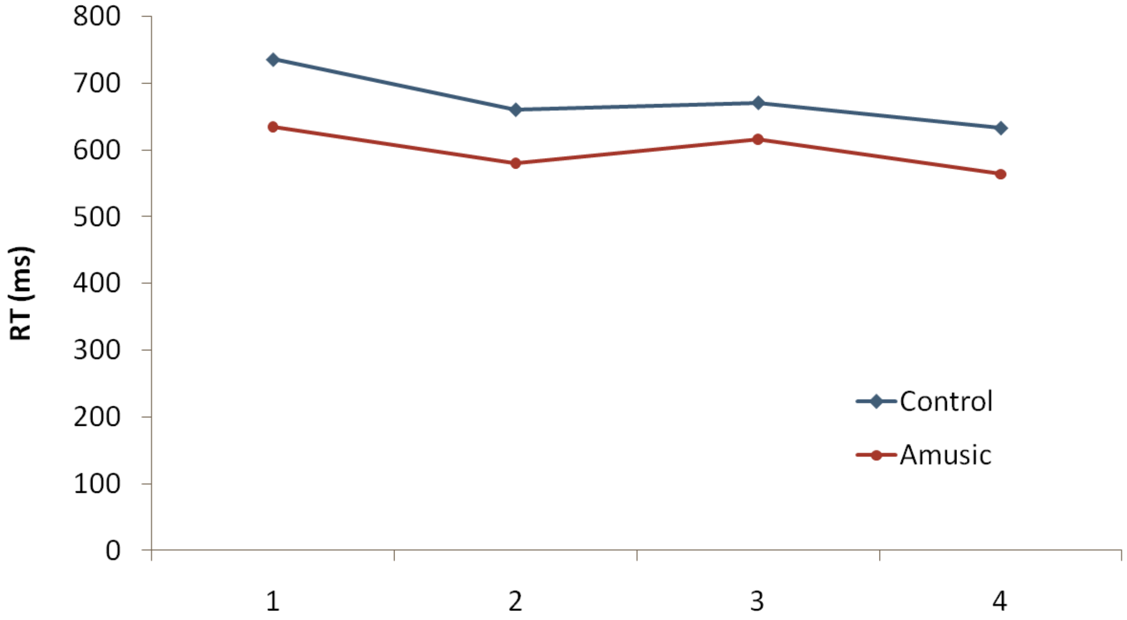

Fig. 3. Plots for means of reaction time obtained by the participants in the Symbolic numerical magnitude comparison task on the four different distances. RTs are shown for both the amusic participants (red) and the control participants (blue).

Regarding the accuracy in the symbolic task, results show a marginally significant main effect of distance (F [2,28) = 3.268, p=0.056, η2= 0.18), as performance was better in trials with bigger distances. Regarding the difference between-participants, it was observed a main effect of group (F [1,15] = 5.33, p=0.036, η2= 0.26) with controls presenting better performance on the symbolic numerical comparison task than the amusics individuals. No interaction involving the factor group was observed (F [2,28) = 0.784, p=0.458, η2= 0.05). Figure 4 shows the results for accuracy in the symbolic numerical comparison task.

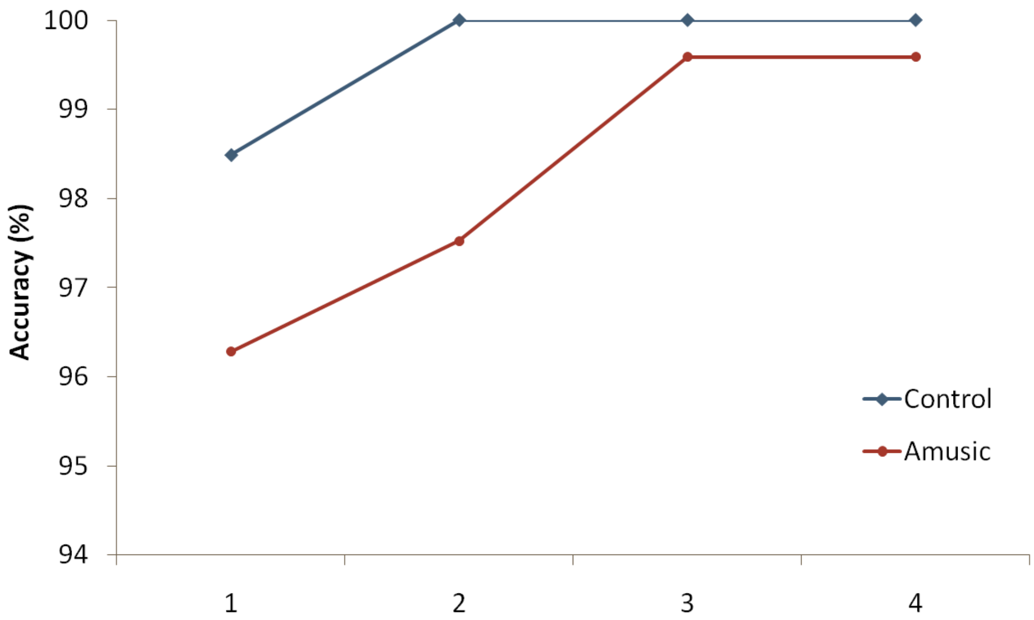

Fig. 4. Plots for mean performance (% of correct responses) obtained by the participants in the Symbolic numerical magnitude comparison task on the four different distances. Accuracy is shown for both the amusic participants (red) and the control participants (blue).

Correlations between the RTs in the Symbolic numerical magnitude comparison task (comprising the four different distances) and the musical tasks (global score on MBEA and PCD score) were also calculated separately for each group. Results are shown in Table 4.

Table 4. Correlations between symbolic task (RT) and musical tasks for both control and amusic group.

		Global_MBEA		PCD %(Hits- FA)	
Group	Distance	r	p	r	p
Amusics	1	-0.702*	0.016	-0.694*	0.018
	2	-0.731*	0.011	-0.794**	0.004
	3	-0.704*	0.016	-0.738**	0.009
	4	-0.637*	0.035	-0.716*	0.013
Controls	1	0.632	0.178	0.624	0.186
	2	0.607	0.201	0.550	0.258
	3	0.607	0.202	0.570	0.238
	4	0.543	0.266	0.588	0.220

* p<0.05

**p<0.01

As shown on Table 4, we can observe that there was a significant negative correlation between the performance on musical tasks and the RT in the symbolic numerical magnitude comparison task only for the amusic group, indicating that for amusics, higher global MBEA and PCD scores were associated with faster RTs on the symbolic task. On the control group, this correlation was not significant. Moreover, the performance on musical tasks did not correlated with accuracy in the symbolic numerical magnitude comparison task.

5.3.3 Mental Number Line task

The scores from the mental number line task were converted into a common metric for all scales. All values were converted taking into account the different scales and stipulating the gap between the estimated value and the actual value for each item of each participant [(estimated number - stimulus number) / scale)]. An average score of the difference between actual and estimated number was generated for each participant in each scale. Repeated measures ANOVA including the factors "group" (amusics and controls) and "scales" (four different scales – 10, 20, 100 and 1000) was run for both the difference between actual and estimated number and the absolute values of this difference.

For the difference value, we could observe a main effect of scale ($F [2,34] = 10,06$, $p<.001$, $\eta2= 0.40$). There were fewer differences between actual and estimated numbers for the scale of 1000 for both groups (as shown in Figure 5). It is important to note that, for this scale, amusic tended to overestimate the numbers while controls underestimated them. Despite this, there was no significant difference between groups ($F [1,15] = 5,33$, $p=.932$, $\eta2= 0.001$) and no interaction between group and scales ($F [2,34] = 1.17$, $p=0.325$, $\eta2= 0.07$). Figure 5 shows the results for the performance profile of numerical underestimation and overestimation in the mental number line task for both amusic and control groups. Negative values correspond to underestimation and positive values to overestimation of the actual numbers.

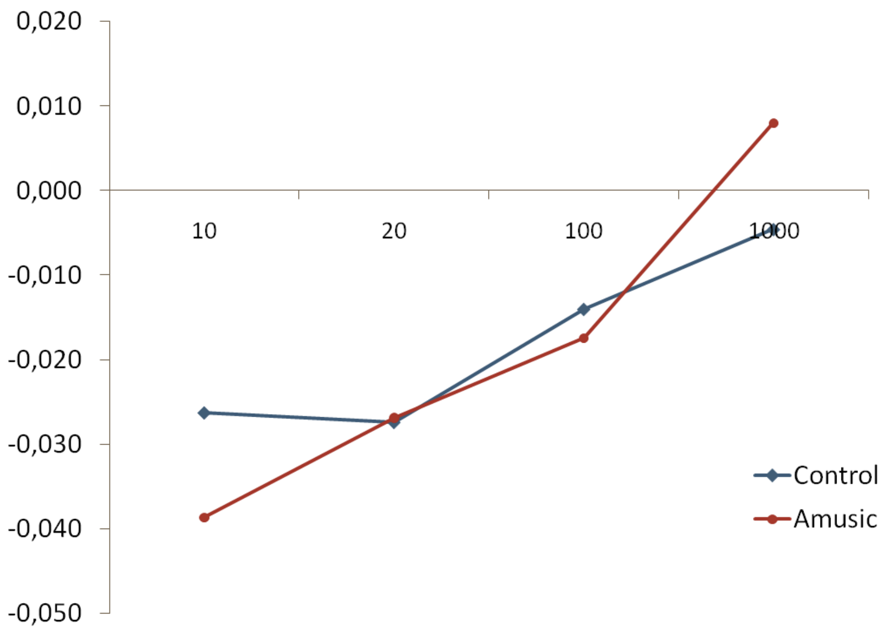

Fig. 5. Plots for the difference value obtained by the participants on the Mental Number Line task on the four different scales. Difference value is shown for both the amusic participants (red) and the control participants (blue).

Regarding the absolute values of the difference value, the main effect of scale was not observed ($F\ [2,30] = 1,02$, $p=.373$, $\eta 2= 0.06$). There was no significant difference between groups ($F\ [1,15] = 0,013$, $p=.911$, $\eta 2= 0.01$) as well. Figure 6 shows the results for the percentage of error's absolute values in mental number line task.

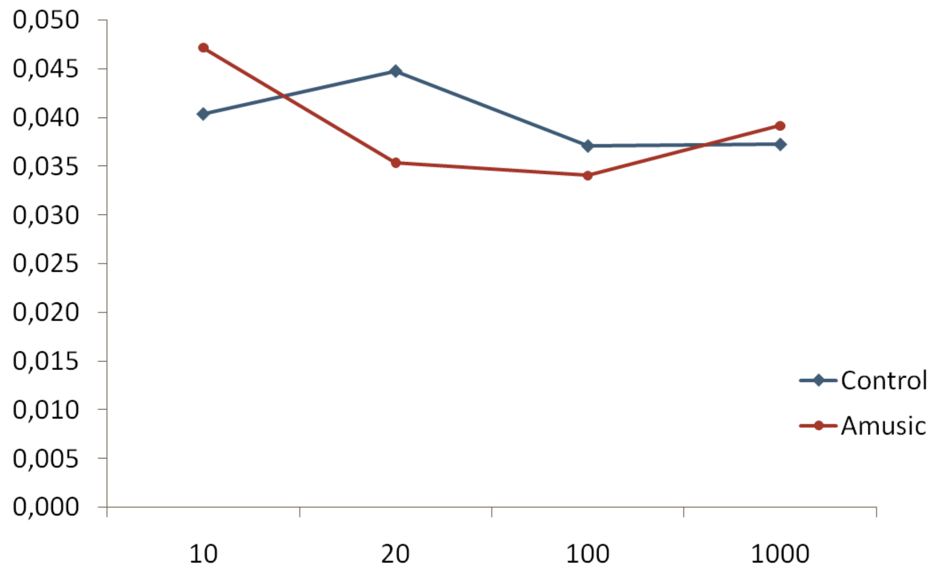

Fig. 6. Plots for difference value (absolute values) obtained by the participants on the Mental Number Line task on the four different scales. Absolute values for difference between actual and estimated number is shown for both the amusic participants (red) and the control participants (blue).

5.4 Discussion

From the results obtained, we could observe, as it was expected from previous studies (Dehaene *et al*. 1993; Pinel *et al*., 2001, Fias *et al*., 2003), the distance effects on individuals performance in the numerical tasks. Participants performed worse when the ratio was close to 1 in the non-symbolic task and for lower distances from the reference number (5) in the symbolic task.

Regarding non-symbolic magnitude representation, the results showed that participants with congenital amusia exhibited a normal performance in the non-symbolic magnitude comparison task. Despite this, it was observed a trend indicating that the mean difference between groups, regarding the RTs, was more prominent for lower ratios. This trend could indicate a difficulty in congenital amusic, compared to controls, in processing non-symbolic numerical stimuli. However, this should be carefully considered since there was no significant difference between groups in this task.

The Weber fraction represents the extent to which two numerosities can be discriminated and it is determined from the relationship among their ratio. This measure from the non-symbolic magnitude comparison task was correlated in a different way in each of the two groups considered. For the amusic group, the Weber fraction correlated negatively with the Metric subtest of MBEA, which is a more global measure of the temporal domain in the musical cognition. The results indicated that amusics individuals with a less precise magnitude representation obtained a worse performance in metric processing. Considering the control group this measure correlated negatively with the Rhythm subtest of MBEA that is a local measure of the temporal musical domain. This means that individuals with typical development that present a less precise magnitude representation obtained a worse performance in the rhythm processing which was not present on the amusic group. One can infer that there is a difference between amusics and controls regarding strategies for extraction of musical temporal information, which could be related, somehow, to a quantitative representation of this temporal information.

Concerning the symbolic numerical processing, we could observe that individuals with congenital amusia showed a worse performance in the symbolic numerical task compared to control individuals. Although there are differences between groups, it is important to note that there was a ceiling effect for the task, with a high performance for all individuals, regardless of group. Further studies using symbolic magnitude comparison tasks with a higher level of difficulty, such as tasks using fractions as a stimulus rather than Arabic numerals, would be useful to better investigate the differences found in this study. There was no different between groups regarding RTs in the symbolic task. The RTs were negatively correlated with performance in musical tasks only in the amusic group, indicating that individuals with congenital amusia that are faster in discriminating symbolic numerical magnitude also exhibit a better performance in tasks that evaluates musical perception.

Regarding the ability to map numbers onto space (number line task), congenital amusics did not present a significant different performance from control group. This result is in agreement with Tillmann et al. (2010), regarding the preserved visuo-spatial and mental number line representations in congenital amusia as well as with the evidence for differences in the mental representation for pitch and numbers (Cohen Kadosh, Brodsky, et al., 2008). Although even if the spatial representation for number and pitch are different, this does not imply that the mechanism for estimating magnitudes cannot be impaired for both domains, since comparison tasks might not reflect the mental representation of the manipulated features (Cohen Kadosh, Brodsky, et al., 2008).

Overall, we can consider that congenital amusic individuals that are impaired in the pitch magnitude processing (high vs low judgments) presented a preserved performance in the non-symbolic numerical magnitude comparison task. This result is indicative of a non-shared mechanism for non-symbolic magnitude representation in numerical and musical domains. Moreover, they showed no difference compared to the control group in the spatial representation of numbers. Importantly, it was found that congenital amusic individuals were less precise than controls in discriminating symbolic numerical magnitudes, which depends on the ability to link Arabic symbols to magnitude representations and is associated to symbolic access difficulties.

Music symbolic system as well as the numerical symbolic system is based on the spatial representation of the sensory stimulus, which is favored for its structuring in tonotopic regions and numbertopic regions, respectively (Harvey, Klein, Petridou & Dumoulin, 2013). Although they are encoded in distinct brain regions, and have apparently distinct mental representations, these two systems could present common mechanisms. These mechanisms could not be necessarily linked to the salience of the stimuli, as suggested by Cohen Kadosh, Brodsky et al. (2008), and hence to an amodal magnitude processing system, but related to a similarity in the mechanisms involved in the spatial categorization of stimulus. Thus, the mechanisms implied in this encoding process may be shared, or otherwise be independent but operate similarly. The understanding of these mechanisms has implications for the knowledge of perception and planning of multisensory training. It could also be questioned if, as well as training focused on strengthening the connection between non-symbolic numerical representation and spatial representation has proven to be effective in improving the mathematical performance in dyscalculic and typical developed children (Wilson *et al.*, 2006; Siegler & Ramani, 2009; Kucian *et al*., 2011), individuals with congenital amusia could also benefit from learning musical notation (symbolic musical system based on spatial representation) in order to improve their perceptual accuracy in processing pitch. Musical training could lead to increased precision in mapping pitch height into a mental spatial representation.

Some limitations especially regarding the difference in the number of participants by group should be noted in this study. Further studies are needed to investigate the relationship between symbolic and non-symbolic numerical representation and musical abilities. Evidences about the relationship among pitch and other magnitudes are still scarce. Studies using tasks that simultaneously elicit representations in these two dimensions could be useful to collect evidence about interactions among pitch and numerical stimuli. In the musical domain, the task that could better relate to the numerical magnitude processing is the pitch direction discrimination task (high-low judgments) using pure tones stimuli. In this sense, we should highlight that in our study we did not evaluate all components of musical processing. An association between musical and numerical domains could be found if considering another musical component that was not investigated in this study. Experiments using cross modal habituation paradigm could also contribute to the investigation of the relationship between these two domains.

Since individuals with deficits in pitch magnitude processing did not presented an impaired numerical magnitude processing, the results obtained in this study do not support the hypothesis that there is an amodal mechanism for processing magnitudes, as proposed by ATOM. Instead, the results are compatible with the hypothesis of modularity and specificity of musical cognitive processing. A dissociation seems to occur between numerical and musical domains, since congenital amusics present preserved mental number line and non-symbolic magnitudes representation despite of an impaired pitch discrimination. Nevertheless, the lower performance of congenital amusics in discriminating symbolic numerical magnitudes in relation to controls indicates that could be an association between numerical and musical domains considering the symbolic access from magnitude representation, which should be further investigated.

5.5 Acknowledgments

We are grateful to the technical support of BRAMS/CRBLM and the financial support from Natural Sciences and Engineering Research Council of Canada, the Canadian Institutes of Health Research and from a Canada Research Chair. This research was also supported by a Sandwich PhD Fellowship from *Conselho Nacional de Desnvolvimento Cientifico e Tecnológico* (CNPq) to Marília-Nunes Silva, a doctorate fellowship from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) to Ricardo Moura, and a doctorate fellowship from CAPES to Júlia Beatriz Lopes-Silva. Vitor G. Haase is supported by a CNPq fellowship (308157/2011-7).

5.6 References

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology, 83*, 111-130.

Ayotte, J., Peretz, I., & Hyde, K. (2002). Congenital amusia: A group study of adults afflicted with a music-specific disorder. Brain, 125, 238-251.

Bamberger, J., & diSessa, A. A. (2003). Music as embodied mathematics: A study of a mutually informing affinity. *International Journal of Computers for Mathematical Learning, 8(2)*, 123–160.

Brandler, S., & Rammsayer, T. H. (2003). Differences in mental abilities between musicians and non-musicians. *Psychology of Music, 31 (2)*, 123-138.

Brochard, R., Dufour, A., & Despres, O. (2004). Effect of musical expertise on visuospatial abilities: Evidence from reaction times and mental imagery. *Brain & Cognition, 54 (2)*, 103–109.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46 (1)*, 3-18.

Bonn, C. D. & Cantlon, J. F. (2012): The origins and structure of quantitative concepts, *Cognitive Neuropsychology, 29:1-2*, 149-173.

Cohen Kadosh, R.C., Brodsky, W., Levin, M., Henik, A., (2008). Mental representation: what can pitch tell us about the distance effect? *Cortex, 44(4)*, 470-477.

Cohen Kadosh, R., Henik, A., Rubinsten, O., Mohr, H., Dori, H., Van de Ven, V., Zorzi, M., Hendler, T., Goebel, R. & Linden, D. E. J. (2005) Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia 43*, 1238-1248.

Cohen Kadosh, R. C., Lammertyn, J. Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology, 84*, 132–147.

Collier, W. G., & Hubbard, T. L. (1998). Judgments of happiness, brightness, speed and tempo change of auditory stimuli varying in pitch and tempo. Psychomusicology: Music, Mind & Brain, 17(1), 36-55.

Collier, W. G., & Hubbard, T. L. (2004). Musical scales and brightness evaluations: Effects of pitch, direction, and scale mode. Musicae Scientiae, 8(2), 151-173.

Dehaene, S. (2003). The neural basis of the Weber–Fechner law: a logarithmic mental number line. *Trends in cognitive sciences, 7(4)*, 145-147.

Dehaene, S. (2007). Symbols and quantities in parietal cortex: elements of a mathematical theory of number representation and manipulation. In Haggard, P., Rossetti, Y., & Kawato M. (Eds.).*Sensoriomotor Foundations of Higher Cognition - Attention and Performance XXII* (pp. 527-574). Cambridge: Harvard University Press.

Dehaene, S; Bossini, S & Giraux, P. (1993). The mental representation of parity and number magnitude. *J Exp Psychol Gen*, 122, pp. 371–396.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive neuropsychology, 20 (3)*, pp. 487-506.

Fias, W. & Fischer, M. H. (2004). Spatial representation of numbers. In: *Handbook of mathematical cognition*, ed. J. I. D. Campbell. New York, NY: Psychology Press.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., Orban, G. A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. *Journal of Cognitive Neuroscience, 15*, 1-11.

Foster, N.E.V. & Zatorre, R.J. (2010). A Role for the Intraparietal Sulcus in Transforming Musical Pitch Information. *Cerebral Cortex 20 (6)*, 1350-1359.

Foxton, J. M., Dean, J. L., Gee, R., Peretz, I., & Griffiths, T. D. (2004). Characterization of deficits in pitch perception underlying “tone deafness”. Brain, 127, 801-810.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and nonmusicians. *Journal of Neuroscience, 23 (27)*, 9240–9245.

Geary, D. C. (2011). Consequences, Characteristics, and Causes of Mathematical Learning Disabilities and Persistent Low Achievement in Mathematics. *Journal of Developmental & Behavioral Pediatrics, 32 (3)*, 1-14.

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition*, *115(3),* 394-406.

Guia, R. L., & França, C. C. (2005). Matemúsica. In: R. L. Guia, & C. C. França, *Jogos pedagógicos para educação musical* (pp. 147-181). Belo Horizonte: UFMG.

Halberda, J., Mazzocco, M. M., and Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with math achievement. *Nature, 455*, 665–668.

Harvey, B. M., Klein, B. P., Petridou, N., & Dumoulin, S. O. (2013). Topographic representation of numerosity in the human parietal cortex. Science, 341(6150), 1123-1126.

Hetland, L. (2000). Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education, 34 (4)*, pp. 179-238.

Ho, Y., Cheung, M., & Chan, A. (2003). Music training improves verbal but not visual memory: cross sectional and longitudinal explorations in children. *Neuropsychology*, *17,* pp. 439-450.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature reviews, 6*, 435-448.

Hyde, K., & Peretz, I. (2004). Brains that are out of tune but in time. *Psychological Science, 15(5),* pp. 356-360.

Hyde, K., Zatorre, R. & Peretz, I. (2011). Functional MRI Evidence of an Abnormal Neural Network for Pitch Processing in Congenital Amusia. *Cerebral Cortex*, *21,* 292-299.

Kucian, K., Grond, U., Rotzer, S., Henzi, B., Schönmann, C., Plangger, F. & von Aster, M. (2011). Mental number line training in children with developmental dyscalculia. *Neuroimage, 57(3),* 782-795.

Lake, J. I., LaBar, K. S., & Meck, W. H. (2014). Hear it playing low and slow: How pitch level differentially influences time perception. *Acta psychologica, 149,* 169-177.

Lidji, P., Kolinsky, R., Lochy, A., & Morais, J. (2007). Spatial Associations for Musical Stimuli: A Piano in the Head? *Journal of Experimental Psychology: Human Perception and Performance*, *33 (5)*, 1189–1207.

Liu, F., Patel, A. D., Fourcin, A., & Stewart, L. (2010). Intonation processing in congenital amusia: Discrimination, identification and imitation. Brain, 133(6), 1682-1693.

Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: a new disconnection syndrome? *The Journal of Neuroscience, 29(33)*, 10215-10220.

Loui, P., Guenther, F. H., Mathys, C., & Schlaug, G. (2008). Action-perception mismatch in tone-deafness. Current Biology, 18, R331-R332.

Loui, P., Hohmann, A., & Schlaug, G. I.-e. (2010). Inducing disorders in pitch perception and production: a reverse-engineering approach. *Proceedings of Meetings in Acoustics, 9,* 1-8.

Ludwig, V. U., Adachi, I., & Matsuzawa, T. (2011). Visuoauditory mappings between high luminance and high pitch are shared by chimpanzees (Pan Troglodytes) and humans. *Proceedings of the National Academy of Sciences, 108(51),* 20661-20665.

Marks, L. E. (1987). On cross-modal similarity: Auditory–visual interactions in speeded discrimination. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 384–394.

Martinez, M. E., Peterson, M., Bodner, M., Coulson, A., Vuong, S., Hu, W., et al. (2008). Music Training and Mathematics Achievement: A Multi-Year, Iterative Project Designed to Enhance Student Learning. *Paper presented at The Annual Conference of the American Psychological Association,* (pp. 1-33). Washington, DC.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011a). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child development, 82(4),* pp. 1224-1237.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011b). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PLoS one, 6(9),* e23749.

Parise, C. V., Knorre, K., & Ernst, M. O. (2014). Natural auditory scene statistics shapes human spatial hearing. Proceedings of the National Academy of Sciences, 111(16), 6104-6108.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., et al. (2002). Congenital amusia: a disorder of fine-grained pitch discrimination. *Neuron, 33*, 185–191.

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders. *Annals of New York academy of science*, *999,* 58-75.

Peretz, I., Cummings, S., & Dubé, M. (2007). The genetics of congenital Amusia (Tone Deafness): A family-aggregation study. *The American Journal of Human Genetics*, *81*, 582-588.

Peretz, I. & Hyde, K. (2003). What is specific to music processing? Insights from congenital amusia. *Trends in Cognitive Sciences, 7(8),* 362-367.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., Dehaene, S. (2004), "Tuning curves for approximate numerosity in the human intraparietal sulcus," *Neuron, 44*, 547-555.

Pinel, P., Dehaene, S., Riviere, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage, 14(5),* 1013-26.

Roederer, J. G. (2008). The physics and psychophysics of music: An introduction. Fourth Edition. New York: Springer.

Rusconi, E., Kwan, B., Giordano, B.L., Umilta, C., Butterworth, B. (2006). Spatial representation of pitch height: the SMARC effect. *Cognition, 99,* 113–129.

Schellenberg, E. G. (2006). Long-Term Positive Associations Between Music Lessons and IQ. *Journal of Educational Psychology, 98 (2),* 457–468.

Schmithorst, V. J., & Holland, S. K. (2004). The effect of musical training on the neural correlates of math processing: a functional magnetic resonance imaging study in humans. *Neuroscience Letters, 354,* 193–196.

Schwenzer, M., Mathiak, K. (2011). Numeric aspects in pitch identification: an fMRI study. *Neuroscience, 12:*26.

Siegler, R. S., & Ramani, G. B. (2009). Playing linear number board games—but not circular ones—improves low-income preschoolers' numerical understanding. *Journal of Educational Psychology, 101(3),* 545.

Sluming, V. B., Howard, M., Downes, J. J., & Roberts, N. (2007). Broca's area supports enhanced visuospatial cognition in orchestral musicians. *Journal of Neuroscience, 27 (14),* 3799–3806.

Stevens, S. S. (1975). Psychophysics: Introduction to its perceptual, neural, and social prospects. New York, NY: Wiley.

Tillmann, B., Jolicœur, P., Ishihara, M., Gosselin, N., Bertrand, O., Rossetti, Y., et al. (2010). The amusic brain: Lost in music, but not in space. *PLoS ONE, 5(4),* e10173.

Upson, R. (2002). Educational sonification exercises: Pathways for mathematics and musical achievement. *Proceedings of the 2002 International Conference on Auditory Display,* (pp. ICAD02-1-ICAD02-6). Kyoto, Japan.

Vaughn, K. (2000). Music and mathematics: modest support for the oft-claimed relationship. *Journal of Aesthetic Education, 34,* pp. 149-166.

Walker, P., Bremner, J. G., Mason, U., Spring, J., Mattock, K., Slater, A., et al. (2009). Preverbal infants' sensitivity to synaesthetic cross-modal correspondences. *Psychological Science, 21(1*), 21–25.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7(11),* 483-488.

Wilson, A. J., Revkin, S. K., Cohen, D., Cohen, L., & Dehaene, S. (2006). An open trial assessment of "The Number Race", an adaptive computer game for remediation of dyscalculia. *Behavioral and Brain Functions, 2(1),* p. 20.

Wilson, A. J., & Dehaene, S. (2007). Number sense and developmental dyscalculia. In: D. Coch, G. Dawson, & K. Fischer, *Human behavior, learning, and the developing brain: atypical development* (pp. 212–238). New York: Guilford.

6. ESTUDO V

Investigação da relação entre o processamento musical e o processamento numérico na Síndrome de Williams.

Autores: Marilia Nunes-Silva[1,2], Pedro Henrique Santos Abreu[1], Flávia Neves Almeida[1], Ana Carolina Almeida Prado[1] & Vitor Geraldi Haase[1,2]

[1] Laboratório de Neuropsicologia do desenvolvimento, Departamento de Psicologia, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brasil.
[2] Programa de Pós-graduação em Neurociências, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brasil.

Resumo

A Síndrome de Williams (SW) é um transtorno genético do desenvolvimento com perfil cognitivo constituído de algumas habilidades sociais, verbais e de reconhecimento de faces relativamente preservadas, a despeito de habilidades visuoespaciais e numéricas comprometidas. Estudos relatam que indivíduos com SW apresentam habilidades musicais preservadas. Porém, a preservação da musicalidade na SW pode não estar relacionada à habilidade analítica de percepção musical, mas sim ao engajamento em atividades musicais e à utilização da música como meio de expressão. O estudo teve por objetivo investigar a relação entre o processamento musical e o senso numérico em crianças e adolescentes com Síndrome de Williams e controles com desenvolvimento típico, observando-se principalmente quais os domínios da cognição musical estão comprometidos e quais estão preservados. Participaram do estudo 30 indivíduos divididos em três grupos de 10 participantes cada: um grupo experimental constituído por indivíduos portadores de SW, e dois grupos controle, sendo um pareado por idade mental (IM) e outro por idade cronológica (IC) com o grupo experimental. Os participantes foram testados em suas habilidades musicais e em relação ao processamento de magnitudes numéricas não simbólicas. Adicionalmente, foi realizada uma análise de série de casos com cinco dos adolescentes participantes do grupo com SW. Os resultados indicaram que quando comparado por idade mental o desempenho dos indivíduos com SW em tarefas que avaliam a percepção musical e o senso numérico é similar ao de crianças com desenvolvimento típico. Porém, considerando a idade cronológica, os indivíduos com SW apresentaram um comprometimento das funções de percepção musical e da discriminação de magnitudes numéricas não simbólicas. Além disso, considerando todos os participantes, o desempenho nas tarefas musicais teve forte correlação com o limiar para discriminação de magnitudes (r= -0,81, p<0.001). A partir da análise de série de casos foi encontrado dentre os participantes com SW, um perfil heterogêneo de habilidades musicais, sendo possível observar uma dupla dissociação entre as habilidades de senso numérico e habilidades musicais, a despeito de um resultado global de percepção musical prejudicado. Apesar de evidências sugerirem que as habilidades musicais estão relativamente preservadas na SW, os resultados obtidos a partir da comparação entre grupos apontam na direção de estudos que evidenciam que a preservação da musicalidade na SW pode não estar relacionada à habilidade analítica na discriminação de altura e ritmo. Além disso, os resultados indicaram que houve uma associação entre o senso numérico e o desempenho em tarefas de percepção musical.

Abstract

Williams Syndrome (WS) is a genetic developmental disorder with a cognitive profile consisting of relatively preserved social verbal and recognition of faces abilities, despite impaired visuospatial and numerical skills. Studies have reported that individuals with WS show preserved musical abilities. However, the preservation of musicality in WS may be due not so much to the analytical musical perception ability, but rather to engaging in musical activities and using music as a mean of expression. This study aimed to investigate the relationship between music processing and number sense in children and adolescents with WS and typically developing controls, observing which areas of music cognition are impaired and which are preserved. We evaluated 30 individuals divided into three groups of 10 participants each: an experimental group consisting of individuals with WS, and two control groups, one matched for mental age (MA) and another for chronological age (CA) with the experimental group. Participants were tested on their musical abilities and for the processing of non-symbolic numerical magnitude. Additionally, we have conducted a case series analysis of five adolescents that participated in the SW group. Results indicated that comparing by mental age the performance of individuals with WS on tasks assessing music perception and number sense is similar to that of children with typical development. However, considering the chronological age, individuals with WS showed an impairment in functions of musical perception and discrimination of non-symbolic numerical magnitude. Moreover, considering all participants, performance on musical tasks had strong correlation with the threshold for discrimination of magnitudes (r = -0.81, p <0.001). From the case series analysis we found a heterogeneous musical abilities profile among participants with SW, and we could observe a double dissociation between number sense and musical abilities, despite an impaired global result in the musical perception. Although evidence suggests that musical abilities are relatively preserved in WS, the results obtained from the comparison between groups point toward studies that show that the preservation of musicality in WS may not be related to the analytical ability in the discrimination of pitch and rhythm. Furthermore, the results showed an association between number sense and performance on music perception tasks.

6.1 Introdução

A Síndrome de Williams (SW) é um transtorno genético do desenvolvimento ocasionado pela deleção de um segmento de genes no cromossomo 7, banda 7q11.23 (Francke, 1999). A prevalência da SW é estimada entre cerca de 1 para 7.500 casos até cerca de 1 para 20.000 casos por nascimento (Stromme, Bjornstad & Ramstad, 2002). A SW é caracterizada por retardo mental leve a moderado, dismorfias faciais, anormalidades nos sistemas cardiovascular, musculoesquelético e gastrointestinal e um perfil cognitivo constituído de habilidades sociais, musicais, verbais e de reconhecimento de faces relativamente preservadas, e de habilidades visuoespaciais e numéricas comprometidas (Levitin & Bellugi, 1998; Mervis *et al*., 2000; Levitin *et al.*, 2004, Levitin, 2005; Paterson, Girelli, Butterworth & Karmiloff-Smith, 2006; Paterson & Schultz, 2007; Ansari, Donlan & Karmiloff-Smith, 2007).

A SW se constitui em um dos fenótipos cognitivos do transtorno não-verbal de aprendizagem (TNVA). De acordo com Rourke *et al*. (2002), o TNVA pode ser definido como uma síndrome caracterizada por um grupo de déficits neuropsicológicos primários, secundários e terciários que levam a dificuldades acadêmicas, sócio-emocionais e adaptativas distintas de outros subtipos de transtornos de aprendizagem. Os déficits primários ocorrem em dimensões da percepção tátil, percepção visual, habilidades psicomotoras complexas e na habilidade de lidar com circunstâncias novas. Estes conduzem a déficits secundários na atenção tátil e visual e limitações no comportamento exploratório, os quais, por sua vez, conduzem a déficits terciários. Os déficits terciários se constituem em déficits na memória tátil e visual e em funções executivas que levam, por sua vez, a dificuldades nas dimensões de conteúdo e função da linguagem. O TNVA caracteriza-se, pois, como uma entidade heterogênea, da qual fazem parte: transtornos somatosensoriais (como agnosia digital e desorientação direita-esquerda), dificuldades visuoespaciais, dificuldades na construção de inferências não-verbais e com conceitos de numerosidade e aritmética, além de déficits sócio-cognitivos.

Em relação às habilidades numéricas, estudos mostram que crianças e adultos com SW apresentam déficits na representação de magnitudes, apresentando dificuldades em tarefas de estimação e discriminação de numerosidade (Paterson *et al.*, 2006, Ansari *et al.*, 2007). Ao contrário de crianças com desenvolvimento típico, na SW a linguagem parece desempenhar um papel maior na aquisição da compreensão da numerosidade (cardinalidade) do que as habilidades visuoespaciais (Ansari *et al.*, 2003). Crianças e adultos com SW apresentam também anormalidades estruturais da substância cinzenta na região parieto-occipital esquerda que são consistentes com os déficits severos apresentados tanto no processamento visuoespacial quanto na cognição numérica (Boddaert *et al*., 2006).

Por outro lado, há estudos que relatam que indivíduos com SW apresentam habilidades musicais preservadas. Indivíduos portadores de SW têm desempenho similar a controles em tarefas percepção musical rítmica e melódica e tendem a se envolver mais em atividades musicais do que indivíduos dos grupos de controle e portadores de autismo ou de Síndrome de Down (Levitin & Bellugi, 1998, Levitin *et al.*, 2004, Levitin, 2005). Isto indica que pode haver, em determinado nível, uma dissociação entre os domínios de processamento musical e de processamento numérico na SW. Porém, a despeito disto, há estudos que relatam que a preservação da musicalidade na SW pode dever-se não tanto à habilidade analítica na discriminação de altura e ritmo, mas sim ao engajamento que eles têm em atividades musicais utilizando a música como meio de expressão (Hopyan, Dennis, Weksberg, Cytrynbaum, 2001).

Em relação aos substratos neurais envolvidos no processamento musical de indivíduos com SW, Levitin et al. (2003), em um estudo pioneiro, utilizaram imagem de ressonância magnética funcional para examinar a base neural do processamento auditivo musical e de ruído em indivíduos com SW e controles pareados por idade cronológica. Os autores encontraram padrões diferentes de organização neural entre os grupos, sendo que os indivíduos com SW apresentaram, em relação aos controles, uma ativação reduzida em regiões dos lobos temporais (giro temporal superior e médio) associadas ao processamento de música e de ruído em indivíduos normais, maior ativação na amígdala direita, e uma rede de ativação cortical e subcortical amplamente distribuída durante o processamento de música, incluindo ativação do tronco cerebral. Estes padrões divergentes de ativação podem auxiliar na compreensão do comportamento atípico dos indivíduos com SW em relação ao processamento de sons.

Em um estudo mais recente Wengenroth, Blatow, Bendszus & Schneider (2010) investigaram os substratos neurais para a musicalidade característica em indivíduos com SW, estudando a relação estrutura-função do córtex auditivo a partir de imagem de ressonância magnética, magnetoencefalografia e tarefas psicoacústicas. Eles identificaram que indivíduos com SW exibem uma percepção holística do som contrapondo-se à percepção da população geral. Funcionalmente eles apresentaram, em relação aos controles, aumento de amplitude dos campos evocados auditivos esquerdos e estruturalmente um aumento de volume do córtex auditivo esquerdo comparável ao de músicos treinados, mesmo que eles não tivessem treinamento musical, o que aponta a SW como um modelo genético único para estudar as propriedades do sistema auditivo independente de treinamento. Estes estudos indicam que o perfil musical atípico dos indivíduos com SW se manifesta não somente a nível comportamental como também funcional e estrutural.

O presente estudo constitui-se, portanto, em um estudo analítico de comparação de grupos e tem por objetivo investigar a relação entre processamento musical e o senso numérico em crianças e adolescentes com Síndrome de Williams e controles com desenvolvimento típico. A investigação do perfil neuropsicológico de crianças e adolescentes com síndromes neuropsicológicas específicas pode auxiliar na compreensão dos mecanismos envolvidos na cognição musical e, ao mesmo tempo, contribuir para a melhor caracterização dos padrões de déficits de funções musicais nestas síndromes, observando-se quais os domínios da cognição musical estão comprometidos e quais estão preservados. Além disso, a investigação da relação entre a cognição musical e a cognição numérica na SW pode auxiliar na compreensão de quais mecanismos são específicos do processamento musical e quais são compartilhados.

6.2 Método

6.2.1 Participantes

Participaram do estudo um total de 30 indivíduos, divididos em três grupos de 10 participantes cada (7 rapazes por grupo): um grupo experimental constituído por indivíduos portadores de SW, e dois grupos controle constituídos por indivíduos com desenvolvimento típico, sendo um pareado por idade mental (IM) e outro por idade cronológica (IC) com o grupo experimental. Os participantes do grupo experimental foram recrutados a partir do contato com a Associação Brasileira de Síndrome de Williams (ABSW - site http//www.swbrasil.org.br), e são principalmente oriundos do Estado de Minas Gerais, onde a pesquisa foi realizada. Dentre os 30 participantes inicialmente recrutados pela equipe do Laboratório de Neuropsicologia do Desenvolvimento (LND) para avaliação neuropsicológica, somente 10 participaram da pesquisa, por terem a inteligência não tão comprometida e conseguirem realizar as tarefas propostas. Participantes com idades abaixo de 6 anos e acima de 20 anos não participaram da pesquisa em função da idade necessária à realização das tarefas e para maior homogeneidade da amostra. Participantes cujo diagnóstico genético ainda não havia sido estabelecido, também não participaram do estudo. Sendo assim, os 10 indivíduos com SW que participaram do estudo possuíam idades entre 8 e 19 anos (M=13,8, DP=3,5), e tinham diagnóstico genético para SW já estabelecido. A idade mental dos participantes, que variou entre 5 e 15 anos (M=7,7, DP=3,2), foi calculada a partir do quociente de inteligência (QI) de cada participante (M= 54,2, DP= 9,9), obtidos através do desempenho em testes de avaliação neuropsicológica (Escala de Inteligência Wechsler para Crianças - WISC-III - e Escala de Inteligência Wechsler para adultos - WAIS-III) em relação à idade cronológica (IM=QI/100*IC).

Os controles com desenvolvimento típico foram recrutados em instituições de ensino público, que não forneciam educação musical formal. Os critérios de inclusão para o grupo controle foram: 1) apresentar, caso já alfabetizado, desempenho escolar normal, mensurado pelo Teste de Desempenho Escolar (TDE); 2) apresentarem índices de inteligência normal, estabelecido pelo desempenho nas Matrizes progressivas de Raven; 3) não possuírem história pregressa de doenças neurológicas, visuais ou auditivas e; 4) não possuírem treinamento musical formal. Além disso, foram pareados com o grupo experimental por sexo e em relação à idade cronológica (M=13,8, DP=3,5) ou idade mental (M=7,9, DP=2,9), dependendo do grupo controle.

6.2.2 Instrumentos de coleta de dados

Para o presente estudo foram utilizados instrumentos que permitiram avaliar a cognição musical, cognição numérica, inteligência e linguagem dos participantes. Os testes de avaliação do desempenho escolar e da inteligência foram utilizados como medida de controle de variáveis e critérios de inclusão no grupo controle. Os instrumentos são apresentados a seguir:

1) Escala Wechsler de Inteligência: Foi utilizada a versão para Crianças (WISC-III) ou versão para adultos da escala (WAIS-III), de acordo com a idade do participante. As escalas Wechsler de Inteligência são instrumentos utilizados para avaliar a capacidade intelectual e são compostas de vários subtestes, que medem aspectos diferentes da inteligência. O WISC-III é composto de dois conjuntos de subtestes, sendo um verbal (Informação, Semelhanças, Aritmética, Vocabulário, Compreensão e Dígitos) e outro de execução ou perceptivo-motor (Completar Figuras, Código, Arranjo de Figuras, Cubos, Armar Objetos, Procurar Símbolos e Labirintos). O desempenho pode ser resumido em três medidas compostas: QI Verbal (conhecimento adquirido, raciocínio verbal e atenção para os materiais verbais), QI de Execução (raciocínio fluido, processamento espacial, atenção para detalhes e integração visuomotora) e QI Total (nível geral de funcionamento intelectual). Já o WAIS-III permite investigar diferentes aspectos da cognição de adolescentes e adultos. A escala é composta de dois conjuntos de sete subtestes, sendo um verbal (Vocabulário, Semelhanças, Aritmética, Dígitos, Informação, Compreensão e Sequência de Números e Letras) e outro de execução (Completar Figuras, Códigos, Cubos, Raciocínio Matricial, Arranjo de Figuras, Procurar Símbolos e Armar Objetos). O desempenho também pode ser resumido em três medidas compostas: QI Verbal, QI de Execução e QI Total (Figueiredo, 2002). As escalas foram utilizadas apenas no grupo experimental para obtenção das medidas de QI.

2) Teste de desempenho Escolar (TDE): O TDE foi elaborado por Stein (1994) e tem por objetivo avaliar de forma objetiva as capacidades em leitura, escrita e aritmética consideradas fundamentais para um bom desempenho escolar. O estudo para o desenvolvimento e validação do TDE foi realizado no Rio Grande do Sul, com 538 crianças de 1ª a 6ª série, oriundas de escolas públicas e privadas e com diferentes níveis socioeconômicos. O teste apresentou resultados psicométricos satisfatórios com alta consistência interna (α=0,945 para a tarefa de Escrita, α=0,932 para a de Aritmética e α=0,988 para a de Leitura).

O instrumento é composto por três subtestes: o de Escrita, que é constituído por 35 itens sob a forma de ditado de palavras isoladas; o de Aritmética, com 35 itens por escrito e três itens orais de resoluções de operações matemáticas; e o de Leitura para reconhecimento de palavras fora do contexto, que se constitui de 70 itens. A ordem dos itens é disposta de acordo com grau de dificuldade, havendo um critério de interrupção. A aplicação é individual. Os resultados brutos são transformados em percentis, fornecendo classificação de desempenho em três tipos: inferior, médio e superior. Os examinandos são avaliados de acordo com a série e as tabelas de idade estimam apenas o desempenho esperado. Resultados insatisfatórios podem indicar dificuldades de aprendizagem.

3) Teste das Matrizes progressivas de Raven: Foi utilizada a Escala Geral (a partir de 11 anos de idade) ou a Escala Colorida (crianças de 5 a 11 anos de idade), de acordo com a idade do participante. O teste de Raven é uma medida de inteligência não-verbal, que avalia mais especificamente o fator "g", proposto por Spearman, relacionando-se mais à capacidade imediata do indivíduo para observar e pensar com clareza (método de raciocínio) do que à variação do conhecimento destes indivíduos. A Escala Geral do teste contém 60 problemas divididos em 5 séries (A, B, C, D, E), as quais estão ordenadas em dificuldade crescente. Cada série apresenta um problema inicial de solução clara e problemas sucessivos que vão se complexificando. Os itens são matrizes ou desenhos nos quais falta uma parte. O indivíduo deve escolher, na parte inferior da página, dentre uma série de 6 ou 8 alternativas, aquela que completa logicamente o conjunto. A pontuação total corresponde ao número de acertos em todas as séries, sendo os escores brutos transformados em percentil para fins de comparação (Raven, 2003). A Escala Colorida é similar à Escala Geral e também apresenta uma série de matrizes ou desenhos nos quais falta uma parte com 6 ou 8 alternativas para completar logicamente o conjunto. Porém a escala colorida é composta por 36 tarefas não verbais coloridas, divididas em apenas três séries (A, Ab e B) com níveis crescentes de dificuldade.

4) Montreal Battery of Evaluation of Amusia (MBEA)*:* A MBEA é uma bateria de testes que avalia habilidades musicais referentes a seis componentes do processamento musical (contorno, escala, intervalo, ritmo, métrica e memória musical) e permite o diagnóstico de diferentes tipos de amusia (Peretz, Champod, & Hyde, 2003; Peretz, 2003; Ayotte, Peretz, & Hyde, 2002; Peretz *et al.*, 2002). Os subtestes são compostos de frases musicais inéditas compostas de acordo com o sistema tonal ocidental, sintetizadas a partir de um programa de computador utilizando o timbre de piano. Para os subtestes Escala, Contorno, Intervalo e Ritmo, o indivíduo deve comparar diversos pares de melodias, decidindo se as mesmas são iguais ou diferentes. A Métrica é avaliada pedindo-se às pessoas para classificarem 30 sequências melódicas como valsa ou marcha. Já o subtestes de Memória Musical é composto por 30 sequências melódicas. Destas, 15 já foram ouvidas nos testes anteriores e 15 correspondem a novas melodias compostas seguindo o mesmo princípio, mas diferindo em seus padrões de tempo e alturas. O participante deve dizer se já ouviu a melodia previamente ou não. A MBEA

foi adaptada e validada para a população de adolescentes de 14 a 18 anos da cidade de Belo Horizonte a partir de estudos que verificaram a adequação de seus construtos, itens e modo operacional, além de levantar evidências de validade e criar normas específicas para essa população (Nunes-Silva, C. Loureiro, M. Loureiro & Haase, 2010; Nunes-Silva & Haase, 2012). Para a avaliação de crianças de até 12 anos, foi utilizada a versão abreviada da MBEA para crianças, a *Montreal Battery of Evaluation of Musical Abilities* (MBEMA). A MBEMA foi desenvolvida para a avaliação de habilidades musicais de crianças e segue os mesmos princípios e suporte teórico da MBEA. Todos os testes da MBEMA possuem melodias compostas de acordo com o sistema tonal ocidental, que consistem em versões menores usadas na versão original da MBEA. Para a versão abreviada, os três testes melódicos de Escala, Contorno e Intervalo da MBEMA, foram unificados em um só teste melódico. A versão abreviada consiste então de três testes (melodia, ritmo e memória musical) com 20 itens cada. O participante deve julgar, para os testes de melodia e ritmo, se os pares de melodias ouvidos são iguais ou diferentes. Para o teste de memória, que é incidental, o participante deve julgar a melodia já foi ouvida anteriormente durante o teste ou não (Peretz et al., 2013).

5) Tarefa de comparação de magnitudes não simbólica: Na tarefa de comparação de magnitude não simbólica pede-se ao participante que compare dois conjuntos de pontos apresentados na tela do computador, indicando qual dos dois apresenta uma maior quantidade de pontos. Os conjuntos de pontos são apresentados no interior de um círculo, com o plano de fundo da tela do computador preto. A tarefa constitui-se de 8 ensaios de treino e 64 ensaios de teste, sendo apresentadas 8 magnitudes diferentes (8, 10, 12, 14, 18, 20, 22, 24) a serem comparadas com 16 pontos. Cada magnitude é repetida 8 vezes, em 8 configurações diferentes. O tamanho dos pontos e a luminescência dos dois conjuntos de pontos são controlados. O tempo máximo de apresentação de cada conjunto de pontos é de 4000ms, com um intervalo entre os ensaios de 700ms. É apresentado entre os ensaios um ponto de fixação na tela (uma cruz centralizada em cor branca, contendo 2cm de em cada linha) com a finalidade de manter a atenção do particippnte.

8.1.3. Procedimentos

O projeto foi aprovado pelo Comitê de Ética da Universidade Federal de Minas Gerais (Parecer nº 88.267/12, CAAE 01384212.8.0000.5149). Após a definição dos grupos, os participantes selecionados realizaram as tarefas de avaliação neuropsicológica que foram distribuídas em, no mínimo, três sessões de testagens de cerca de uma hora e quarenta minutos cada. Somente participaram do estudo as crianças e adolescentes que concordaram oralmente e cujos pais assinaram o termo de consentimento livre-esclarecido. Na primeira sessão eles realizaram as tarefas neuropsicológicas que avaliavam diferentes domínios cognitivos. No grupo controle, somente os participantes que obtiveram escores normais no TDE (de acordo com a norma por série escolar) e Raven (acima do percentil 25) foram convidados a realizarem as outras sessões. Na segunda sessão os participantes realizaram as tarefas de cognição numérica e na terceira sessão, as tarefas de cognição musical. A coleta de dados foi realizada pela autora do projeto e por estudantes de Psicologia, previamente treinados. Para obtermos informações adicionais sobre o perfil de desempenho dos participantes, principalmente em relação às habilidades musicais, foi realizada uma análise de série de casos com cinco adolescentes participantes do grupo com SW. Eles foram escolhidos em função de terem a mesma faixa etária (entre 15 e 19 anos) e por terem realizado a versão adaptada completa da MBEA, com normas específicas para adolescentes, a qual permite uma avaliação mais seletiva das habilidades musicais (Nunes-Silva & Haase, 2012). Para esta análise foram disponibilizados dados adicionais obtidos a partir da avaliação neuropsicológica destes adolescentes realizada pela equipe do LND.

6.3 Resultados

Os escores obtidos pelos participantes foram tabulados em um banco de dados que serviu de base às análises estatísticas realizadas através do pacote estatístico *PASW statistics 18*. Os resultados são apresentados a seguir.

6.3.1 Resultados obtidos no TDE e Raven

Os participantes do grupo controle realizaram o TDE e Raven como critério de inclusão de grupo. Os dados correspondentes aos escores dos participantes de cada grupo controle (IC e IM) no TDE e no Raven são apresentados na Tabela 1.

Tabela 1. Média e desvio padrão dos participantes do grupo controle no TDE e Raven.

	IM		IC	
Teste	Média	DP	Média	DP
Raven - Percentil	56,20	27,87	69,90	19,66
TDE - Escrita	16,50	8,65	32,33	1,66
TDE - Aritmética	10,38	11,20	28,11	5,06
TDE - Leitura	54,25	15,17	69,11	2,03
TDE- Total	81,13	31,85	129,56	7,38

Os participantes obtiveram escores dentro do esperado para a capacidade intelectual. Os escores obtidos pelos participantes no Raven correspondem à média da população. Para o TDE os participantes do grupo IC obtiveram maiores resultados em relação ao grupo IM, pois o TDE reflete o desempenho escolar de acordo com a série e idade. Todos os participantes obtiveram escores dentro do esperado em relação à série e idade para cada subteste do TDE.

6.3.2 Resultados obtidos nas tarefas musicais

Considerando os testes que avaliam a percepção musical, os escores obtidos na MBEA versão original e na MBEA versão infantil foram convertidos em porcentagem de acerto. Todos os participantes, exceto um (pertencente ao grupo experimental), realizaram o teste de métrica da versão original da MBEA. Como metade dos participantes realizou a versão infantil da MBEA e a outra metade a versão original, os dados foram categorizados levando-se em consideração os seguintes domínios teóricos: melodia, ritmo, métrica e memória musical. Para isto, foi computada a média dos três subtestes melódicos da MBEA versão original dos participantes, transformando-os em um escore único para melodias. Para os demais domínios musicais não houve alteração. O escore total foi gerado para cada teste e corresponde à média da pontuação em todos os subtestes da versão que o participante realizou. Os resultados obtidos pelos participantes são apresentados no Gráfico 1. É apresentada a média e desvio padrão da porcentagem de acertos para cada grupo (SW, IM e IC) em cada domínio musical investigado e para o escore total (N=10 para todos os domínios, exceto Métrica, no qual N=9).

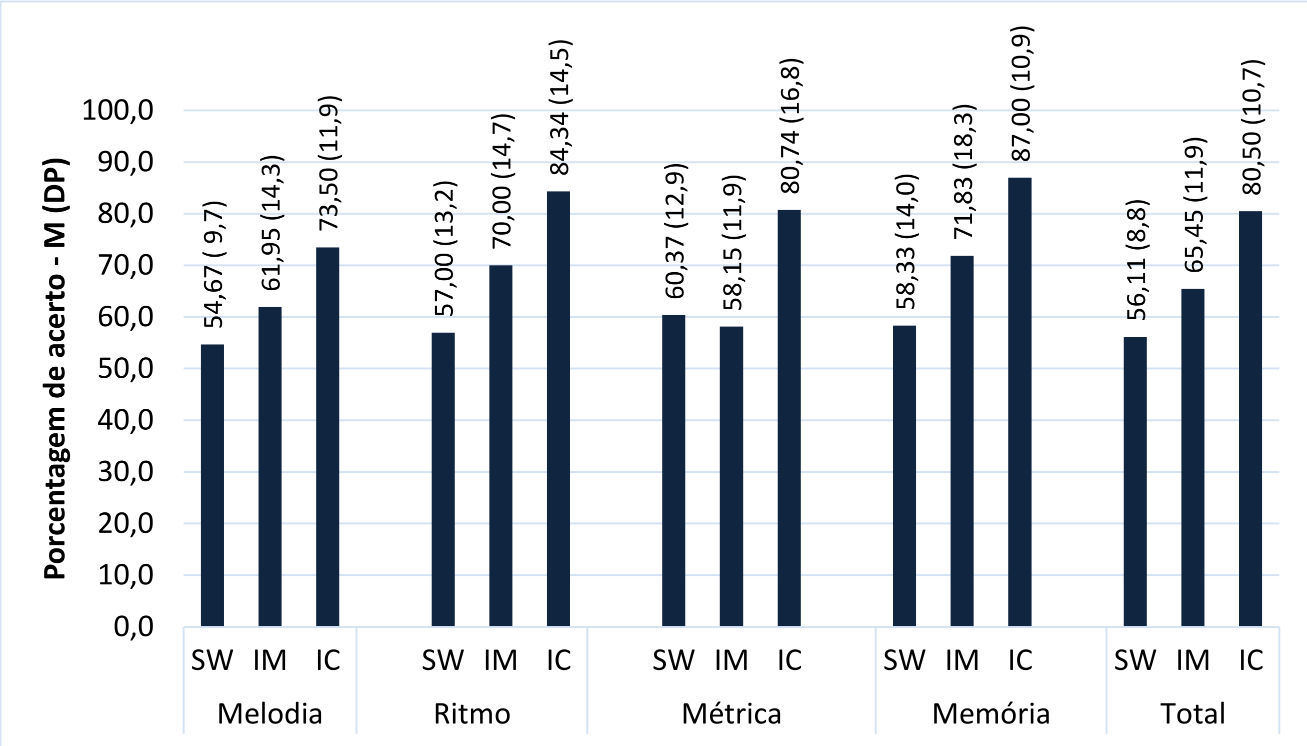

Gráfico 1. Média e desvio padrão da percentagem de acerto para cada grupo (SW, IM e IC) em cada domínio musical.

Como pode-se observar, o grupo de indivíduos com SW apresentou um desempenho inferior aos demais grupos para todos os domínios investigados, com exceção de Métrica, para o qual teve um desempenho superior ao grupo pareado por idade mental, mas inferior ao grupo pareado por idade cronológica. Para investigar se as diferenças entre o grupo SW e os grupos controles foram estatisticamente significativas foi utilizado o Teste *t de Student* para amostras independentes. O resultado para a diferença entre o grupo SW e os grupos IM e IC é apresentado na Tabela 2.

Tabela 2. Teste *t* para a diferença entre o grupo SW e os grupos controle (IM e IC).

	IM		IC	
Domínios	t	p	t	p
Melodia	-1,333	0,199	-3,882	0,001*
Ritmo	-2,080	0,052	-4,411	0,001*
Métrica	0,380	0,709	-2,888	0,011**
Memória Musical	-1,856	0,080	-5,110	0,001*
Percentual total	-2,001	0,061	-5,573	0,001*

*p < 0.01; **p < 0.05

Como pode ser observado na Tabela 2, não houve diferenças significativas entre o grupo SW e o grupo controle IM. Convém notar que para o domínio Ritmo, a diferença entre esses grupos foi marginalmente significante ($p=0.052$). Já o desempenho do grupo controle IC foi significativamente diferente do grupo SW, sendo que o grupo controle pareado por idade cronológica apresentou um desempenho superior ao dos indivíduos com SW.

6.3.3 Resultados obtidos na tarefa de avaliação do senso numérico

Em relação à avaliação do senso numérico, para análise dos dados foi feito o cálculo da fração de Weber para cada participante a partir dos resultados obtidos na tarefa de comparação de magnitudes não simbólica. A fração de Weber interna (w) avalia a acuidade das representações não-simbólicas de magnitude e é uma medida que expressa a quantidade de erro existente na representação mental de qualquer tipo de quantidade. O w é uma medida derivada da taxa de acertos na tarefa de comparação de magnitudes não-simbólicas, sendo modelada individualmente para cada participante como: 1 – proporção de erros (para mais detalhes ver Piazza et al., 2004 e Dehaene, 2007).

Dentro do grupo SW, dois indivíduos apresentaram um gradiente singular nos resultados (somente um tipo de resposta para todos os itens) da tarefa de comparação de magnitudes não simbólica, o que inviabilizou o cálculo da fração de Weber destes participantes. Os cálculos a seguir foram realizados com exclusão destes dois indivíduos e seus respectivos controles (portanto, N=8 para cada grupo). O ajuste para o modelo mostrou-se adequado para todos os casos (com r^2 em torno de 0.9). A média da fração de Weber para cada grupo é apresentada no Gráfico 2.

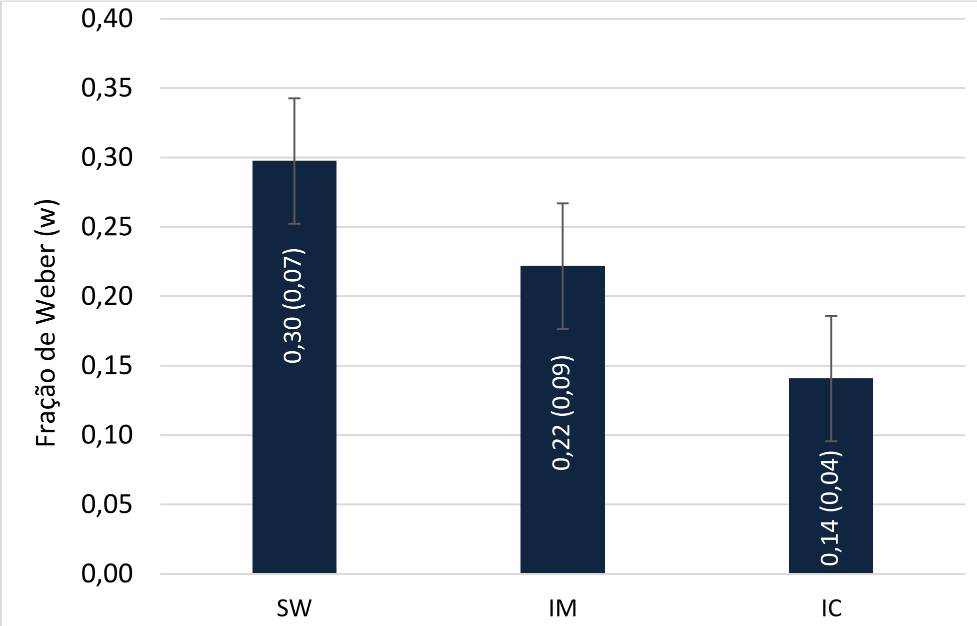

Gráfico 2. Média e desvio padrão da fração de Weber para cada grupo.

Observa-se que o grupo SW apresentou um maior limiar para discriminação de magnitudes (M=0,30, DP=0,07), seguido pelo grupo IM (M=0,22, DP=0,09) e grupo IC (M=0,14, DP=0,04), respectivamente. A partir do Teste *t* verificou-se que houve diferença entre grupos SW e IC ($t(14)= 5,15$; $p<0,001$), com menor valor w para o grupo controle. Não houve diferenças significativas entre o grupo SW e o grupo controle IM ($t(14)= 1,86$; $p=0,085$).

6.3.4 Relação entre as tarefas musicais e numéricas

Para investigar se houve relação entre os escores obtidos nos testes de percepção musical e nos testes de avaliação do senso numérico foi realizada a correlação de Pearson entre o valor de w e a percentagem de acerto correspondente ao escore total dos testes, considerando os participantes de todos os grupos. Foi obtida uma forte correlação negativa ($r= -0,81$, $p<0.001$, N=24) entre os valores de w e o escore total nas tarefas musicais. O Gráfico 3 apresenta o diagrama de dispersão da correlação entre a fração de Weber e o escore total nas tarefas musicais. Adicionalmente é fornecido o valor do ajuste para a equação linear, tendo como variável dependente o valor w ($r^2=0,654$), indicando que 65% da variação no valor de w poderia ser explicada pelo resultado total nas tarefas musicais.

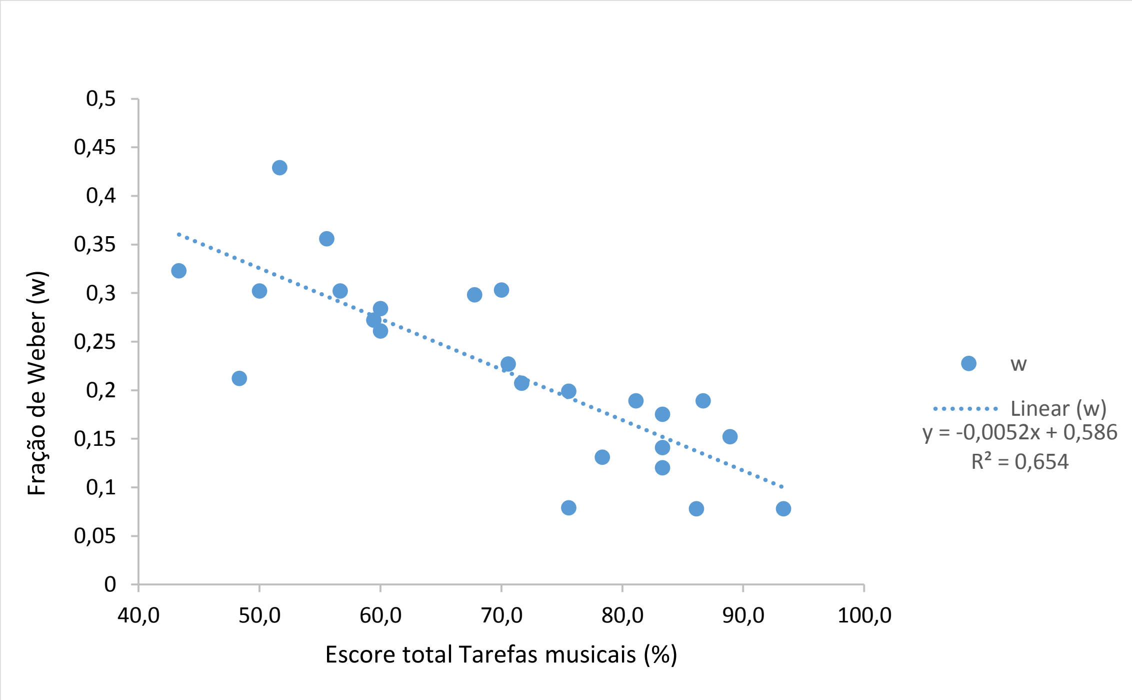

Gráfico 3. Diagrama de dispersão com ajuste linear da relação entre o valor w para a tarefa de senso numérico e o escore total nas tarefas musicais.

6.3.5 Análise de série de casos clínicos

A partir da análise de série de casos realizada com cinco adolescentes participantes do grupo SW, com idades entre 15 e 19 anos, observou-se que, em geral, os adolescentes com SW apresentaram déficit intelectual moderado, com exceção de B.A, que apresentou inteligência preservada. Com exceção de A.N., todos os adolescentes apresentaram melhor resultado nas tarefas de capacidade verbal em relação às tarefas de habilidades visuoespaciais e visoconstrutivas. Os dados são apresentados na Tabela 3.

Tabela 3. Dados demográficos e QIs dos adolescentes com SW.

Participantes	Sexo	IC	IM	QI Verbal	QI Execução	QI Total
N.C.	F	15	8	70	46	55
A.N.	M	15	9	56	68	58
A.F.	F	16	8	51	45	50
J.H.	M	18	9	62	45	50
B.A.	M	19	15	83	81	81

Em relação a habilidades cognitivas específicas, todos os adolescentes apresentaram um resultado abaixo do esperado na avaliação da coordenação motora fina (Nine Hole Peg test –

9-HPT) tanto para a mão dominante (MD) como para a mão não dominante (MND). Os adolescentes também apresentaram comprometimento das habilidades visuoespaciais (Cópia da Figura de Rey). Os adolescentes privilegiaram a percepção local ao invés da percepção global. Em relação à memória de curto prazo, em geral, os adolescentes não apresentaram dificuldades no armazenamento de curto prazo de informações de caráter fonológico e espacial (dígitos e cubos de Corsi – ordem direta). Porém, os adolescentes apresentaram dificuldades de manejo das ordens inversas de ambos os testes, o que indica dificuldades quando é preciso recorrer ao componente executivo para manipulação de informações de caráter fonológico e espacial. Os dados podem ser observados na Tabela 4. Os dados em negrito se referem aos resultados abaixo do esperado em relação à média normativa para a idade.

Tabela 4. Resultados dos adolescentes nos testes de avaliação neuropsicológica.

Participantes	Idade	9-HPT-MD	9-HPT-MND	Cópia - Figura de Rey	Dígitos Direta	Dígitos Inversa	Corsi Direta	Corsi Inversa
N.C	15	**27.9**	**23.9**	**8.5**	4	3	5	**2**
A.N.	15	**29.5**	**37.2**	**12**	4	**2**	5	**3**
A.F.	16	**29.5**	**37.2**	**3**	4	**2**	**4**	**3**
J.H.	18	**39.5**	**43.5**	**9**	4	**0**	5	**0**
B.A.	19	**20,3**	**26,2**	**8,5**	4	**3**	**4**	**3**

*Em negrito, escores abaixo da média normativa.

Considerando habilidades de linguagem, os adolescentes apresentaram boa capacidade de sustentar novas informações fonológicas na memória, durante um curto prazo de tempo (repetição de Pseudopalavras). Em relação à tarefa de velocidade de nomeação (*Rapid automatized naming* - RAN), eles apresentaram um tempo de execução maior do que o esperado para suas faixas etárias, o que pode indicar dificuldade de associação semântica e da qualidade das representações de informação na memória de curto prazo (dado faltante para B.A.). Em relação ao acesso lexical (tarefa de decisão lexical), nem todos os adolescentes apresentaram resultados dentro do esperado, o que indica, para estes casos, dificuldades em acessar as representações lexicais das palavras. Os dados são apresentados na Tabela 5.

Tabela 5. Resultados dos adolescentes nos testes de avaliação da linguagem.

Participantes	Idade	Repetição de pseudopalavras	RAN (Tempo Total - seg)	Decisão Lexical
N.C.	15	11 (73.3%)	**66**	93.3%
A.N.	15	13 (86%)	36	83%
A.F.	16	14 (93%)	**64**	**67%**
J.H.	18	10 (66.6%)	**64**	**46.6%**
B.A.	19	14 (93%)	**---**	**70%**

*Em negrito, escores abaixo da média normativa.

Em relação às habilidades do senso numérico, todos os adolescentes apresentaram uma fração de Weber (w) elevada, indicando baixa capacidade de discriminação de magnitudes numéricas não-simbólicas ou representação analógica de magnitudes. Os dados são apresentados na Tabela 6, juntamente com os dados dos percentis relacionados às tarefas musicais. Para esta tabela, os dados em negrito correspondem às habilidades preservadas.

Tabela 6. Resultados dos adolescentes nas tarefas musicais e do senso numérico.

Participantes	Idades	w	Escala	Contorno	Intervalo	Ritmo	Métrica	Memória	Índice Global
N.C.	15	0,284	10	10	20	10	10	10	10
A.N.	15	0,272	10	20	20	10	10	10	10
A.F.	16	0,298	**70***	10	10	10	**80**	10	10
J.H.	18	0,356	10	10	10	10	10	10	10
B.A.	19	0,207	10	10	**30**	**40**	10	**70**	10

*Em negrito, escores dentro da média normativa.

Em relação às funções musicais, observa-se na Tabela 6 que, no geral, os adolescentes apresentaram as funções musicais comprometidas. Porém, observou-se certa variabilidade no desempenho dos adolescentes em relação aos seis componentes musicais avaliados, sendo que dois dos adolescentes (A.F. e B.A.), apresentaram preservação de subdomínios do processamento musical. A.F apresentou Escala e Métrica preservados e Intervalo, Ritmo e Memória Musical comprometidos enquanto B.A apresentou um padrão inverso com Intervalo, Ritmo e Memória Musical preservados e Escala e Métrica comprometidos.

Em suma, os adolescentes com SW apresentaram, no geral, déficit intelectual moderado (exceto B.A.), prejuízo das habilidades visuoespaciais, numéricas, musicais gerais e de memória de trabalho, e preservação da memória de curto-prazo fonológica, aspectos da linguagem, além de variabilidade de desempenho em relação aos componentes do processamento cognitivo musical.

6.4 Discussão

Os resultados obtidos indicaram que não houve diferenças significativas entre o grupo SW e o grupo IM para todos os domínios das tarefas musicais e para a fração de Weber numérica. Porém, foram observadas diferenças significativas entre o grupo SW e o grupo IC para as mesmas tarefas. Considerando todos os participantes, foi obtida uma forte correlação negativa entre os valores de w e o escore total nas tarefas musicais. Portanto, a partir dos resultados obtidos pode-se notar que, quando comparado por idade mental, o desempenho dos indivíduos com SW em tarefas que avaliam a percepção musical é similar ao de crianças com desenvolvimento típico. Porém, considerando a idade cronológica, os indivíduos com SW apresentam um comprometimento das funções de percepção musical relacionadas à melodia, ritmo, métrica e memória musical. Dentre estes domínios, os indivíduos com SW apresentaram um melhor desempenho em Métrica em relação aos demais, observando-se o poder estatístico das diferenças entre grupos.

Apesar de algumas evidências sugerirem que as habilidades musicais estão preservadas ou relativamente preservadas na SW (Don, Schellenberg, & Rourke, 1999; Levitin & Bellugi, 1998; Levitin et al., 2004), os resultados obtidos a partir da comparação entre grupos apontam na direção de estudos que evidenciam que a preservação da musicalidade na SW pode não estar relacionada à habilidade analítica na discriminação de altura e ritmo (Don et al., 1999; Hopyan *et al.*, 2001; Deruelle, Schon, Rondan, & Mancini, 2005; Martínez-Castilla & Sotillo, 2008; Martens, Reutens & Wilson, 2010; Martínez-Castilla, Sotillo & Campos, 2011). Nestes estudos, que geralmente utilizam controles pareados por idade cronológica, as habilidades como a discriminação de altura, discriminação rítmica, cantar com precisão, memória rítmica e tonal e reprodução de ritmos e melodias, apresentaram-se comprometidos nos indivíduos com SW. Portanto, a musicalidade, concebida enquanto interesse musical, criatividade e expressividade, nos indivíduos com SW podem dever-se mais ao engajamento que eles têm em atividades musicais utilizando a música como meio de expressão do que à sua capacidade de percepção musical (Lenhoff *et al.*, 1997; Levitin & Bellugi, 1998; Levitin et al., 2004; Levitin, 2005; Levitin, Cole, Lincoln, & Bellugi, 2005; Ng, Lai, Levitin, & Bellugi, 2013). Além disso, esta musicalidade e engajamento em atividades musicais pode estar associada à maior resposta emocional apresentada por indivíduos com SW diante de um estímulo musical, possivelmente ocasionada pela maior ativação da amígdala em relação a controles quando expostos a estes estímulos (Levitin et al., 2003). Porém, é importante ressaltar que a amostra do presente estudo é pequena e heterogênea e os resultados devem ser considerados com bastante cautela. Adicionalmente, a partir da análise de casos foram encontrados dentre os participantes com SW, um perfil heterogêneo de habilidades musicais, sendo que dois deles (A.F. e B.A.) apresentaram componentes musicais preservados a despeito de um resultado global de percepção musical prejudicado e do comprometimento da habilidade de senso numérico. É interessante notar também que os desempenhos destes dois participantes se caracterizam não somente em uma dissociação entre as habilidades de senso numérico e habilidades musicais, mas também em duplas dissociações entre os componentes do processamento cognitivo musical, pois apresentam, um em relação ao outro, um perfil inverso de habilidades musicais comprometidas e preservadas. O resultado encontrado para a preservação de habilidades musicais, parece não estar associado à preservação da inteligência, pois, apesar de B.A. apresentar capacidade intelectual preservada, A.F. apresenta esta capacidade comprometida.

Em relação ao senso numérico, os indivíduos com SW apresentaram desempenho similar aos controles quando pareados por idade mental e desempenho inferior, quando comparados por idade cronológica, indicando um maior limiar de discriminação e consequentemente um comprometimento em tarefas de comparação de magnitudes não simbólica. Estes resultados corroboram estudos anteriores que mostram que crianças e adultos com SW apresentam déficits na representação de magnitudes numéricas (Paterson *et al.*, 2006, Ansari *et al.*, 2007). De acordo com Libertus et al. (2014), adolescentes com SW tem desempenho em tarefas de comparação de magnitudes não-simbólicas compatível com a de crianças de quatro anos de idade e a precisão nestas tarefas melhora com a idade apesar de não alcançarem o nível de crianças entre 6 e 9 anos com desenvolvimento típico. Em contraste, os autores encontraram um desempenho em tarefas de estimação numérica verbal similar a crianças de 6 e 9 anos, sugerindo que o sistema de aproximação numérico é de certa forma separado dos processos numéricos baseados na linguagem. Os resultados encontrados no nosso estudo vão na mesma direção dos resultados apresentados por Libertus et al. (2014) em relação ao comprometimento da fração de Weber numérica em indivíduos com SW, porém os participantes do presente estudo não apresentaram resultados significativamente diferentes de crianças do grupo controle de IM, cujas idades variaram entre 5 e 15 anos, mas com idade média entre 7 e 8 anos (M=7,9, DP=2,9). Os resultados indicaram, portanto, que os indivíduos com SW apresentaram comprometimento tanto em tarefas que avaliam a percepção musical, quanto em tarefas de avaliação do senso numérico.

Considerando o resultado de todos os participantes, o escore total das tarefas musicais apresentou forte correlação negativa com a fração de Weber (w) extraída da tarefa de comparação de magnitudes, indicando que quanto menor o limiar para discriminação de magnitudes numéricas não simbólicas, maior o escore nas tarefas musicais. Isto indica que o processamento de magnitudes numéricas pode estar associado à percepção musical em crianças e adolescentes. O resultado vai de encontro a estudos que indicam haver uma relação entre treinamento musical e aptidão matemática (Schmithorst e Holland, 2004), e poderia ser indicativo de um mecanismo compartilhado para a percepção de magnitudes nos domínios da cognição numérica e musical (Cohen Kadosh, Lammertyn, & Izard, 2008; Cohen Kadosh, Brodsky, Levin & Henik, 2008; Bonn & Cantlon, 2012). Os resultados encontrados no estudo realizado por Rousselle, Dembour e Noël (2013), indicam que os déficits do processamento de magnitudes encontrados nos indivíduos com SW se estende também ao domínio espacial, não sendo específico do processamento numérico. Os autores observaram uma menor acuidade (fração de Weber) destes indivíduos em relação a controles pareados por nível de desenvolvimento verbal tanto em tarefas de comparação de magnitude numérica não simbólica, quanto em tarefas de magnitude espacial (comprimento de linhas). Não houve diferença entre grupos para a tarefa de magnitude temporal (duração de estímulos sonoros). Além disso, Rousselle et al. relatam que tanto magnitudes numéricas quanto não numéricas se correlacionaram com aquisições mais básicas da competência numérica simbólica, indo de encontro à perspectiva de Walsh (2003) em relação à habilidade de manipulação de magnitudes não-numéricas como base para o processamento numérico e desenvolvimento de capacidade matemáticas mais complexas. Os autores também sugerem que a dificuldade básica de processamento de magnitudes numéricas pode estar relacionada ao processamento de numerosidades apresentadas no espaço visual. A associação entre a fração de Weber e as habilidades musicais encontrada no presente estudo pode indicar, portanto, que representações de magnitude de distintos domínios se diferenciem a partir de interações ambientais e aprendizado, a partir de um núcleo comum abstrato e amodal, o que vai de encontro à posição de Trehub e Hannon (2006), quanto à percepção musical como produto de mecanismos perceptuais mais gerais que poderiam se tornar modulares com o desenvolvimento, assim como proposto por Karmiloff-Smith (1998). Além disso, estudos sobre as relações entre o processamento musical e o processamento espacial (Rauscher et al., 1997; Costa-Giomi, 1999; Rauscher & Zupan, 2000; Hetland, 2000) poderiam fornecer evidências adicionais para direcionar a investigação da relação entre processamento musical e numérico.

Além disso, os resultados encontrados no presente estudo sobre a percepção musical na SW não permitem afirmar que o processamento musical se manifeste enquanto um módulo independente de funcionamento nesta síndrome. Convém ressaltar, porém, que os participantes deste estudo não possuíam qualquer treinamento musical prévio. Estudos futuros poderiam investigar se os indivíduos com SW poderiam potencialmente desenvolver suas habilidades musicais equiparando-se a controles com desenvolvimento típico de mesma idade cronológica, e com mesmo tempo de estudos musicais. Além disso, a amostra é pequena e heterogênea e considerando estudos prévios sobre a percepção musical preservada e sobre a grande incidência de habilidades musicais excepcionais em indivíduos com SW (Levitin & Bellugi, 1998; Lenhoff, 1997; Levitin *et al.*, 2004, Levitin, 2005), bem como a análise de série de casos realizada no presente estudo, pode-se considerar que há uma relativa preservação das habilidades musicais na SW. A preservação relativa das habilidades musicais e a presença do déficit no senso numérico se constituem em evidências a favor da hipótese da modularidade do processamento cognitivo musical, na qual as funções musicais fazem parte de um módulo mental distinto, com seu próprio sistema de processamento de informações e substrato neural específico (Zatorre, 2001; Peretz, 2003; Peretz, & Coltheart, 2003; Peretz, 2006). Portanto, considerando que por um lado houve preservação relativa das habilidades musicais em indivíduos com SW com comprometimento do senso numérico e, por outro lado, uma associação entre o desempenho dos participantes na fração de Weber e nas tarefas de habilidades musicais, os resultados do presente estudo são inconclusivos em relação à hipótese da modularidade do processamento musical e do processamento do senso numérico.

Por fim, mesmo considerando os casos em que os indivíduos com SW apresentam um comprometimento na percepção musical, o engajamento e a musicalidade preservada na SW podem ser utilizados em benefício da aprendizagem e facilitação dos processos sócio-afetivos. A utilização da música em propostas de intervenção na SW pode favorecer à diminuição da ansiedade, maior compreensão das emoções, e a habilidade de interagir socialmente de uma maneira apropiada, uma vez que em indivíduos com SW a expressão através da música se correlaciona com a sensibilidade e a responsividade às emoções dos outros (Järvinen-Pasley et al., 2010; Dykens, Rosner, Ly, & Sagun, 2005; Ng *et al.*, 2013). Além disso, a relação encontrada entre processamento de magnitudes numéricas e tarefas musicais pode ter implicações práticas em programas de treinamento multissensoriais tanto para aprimoramento de habilidades musicais, quanto na utilização de elementos musicais para auxiliar a aprendizagem de outros domínios cognitivo (Reis, Schader, Milne, & Stephens, 2003).

6.5 Agradecimentos

Agradecemos ao Leonardo Araújo, Marina Goulart e Bianca Ruas que nos auxiliaram na coleta de dados. Agradecemos ao suporte dado pela equipe do Laboratório de Neuropsicologia do Desenvolvimento no recrutamento e avaliação neuropsicológica dos participantes. A pesquisa recebeu apoio financeiro da Coordenação de aperfeiçoamento de Pessoal de Nível Superior (CAPES), com uma bolsa de doutorado CAPES-REUNI para Marília Nunes Silva.

6.6 Referências

Ansari, D., Donlan, C., Thomas, M. S. C., Ewing, S. A., Peen, T., & Karmiloff-Smith, A. (2003). What makes counting count? Verbal and visuo-spatial contributions to typical and atypical counting development. Journal of Experimental Child Psychology, 85, 50-62.

Ansari, D., Donlan, C., & Karmiloff-Smith, A. (2007). Atypical and typical development of visual estimation abilities. *Cortex: Special Issues on Selective Developmental Disorders, 6*, 758–768.

Ayotte, J., Peretz, I., & Hyde, K. (2002). Congenital amusia: A group study of adults afflicted with a music-specific disorder. *Brain, 125*, 238-251.

Boddaert, N., Mochel, F., Meresse, I., Seidenwurm, D., Cachia, A., Brunelle, F., Lyonnet, S. Zilbovicius, M. (2006). Parieto-occipital grey matter abnormalities in children with Williams syndrome. *NeuroImage, 30 (3)*, 721-725.

Bonn, C. D. & Cantlon, J. F. (2012): The origins and structure of quantitative concepts, *Cognitive Neuropsychology, 29:1-2*, 149-173.

Cohen Kadosh, R.C., Brodsky, W., Levin, M., Henik, A., (2008). Mental representation: what can pitch tell us about the distance effect? *Cortex, 44(4)*, 470-477.

Cohen Kadosh, R. C., Lammertyn, J. Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology, 84*, 132–147.

Costa-Giomi, E. (1999). The effects of three years of piano instruction on children's cognitive development. *Journal of Research in Music Education, 47 (3)*, 198-212.

Dehaene, S. (2007). Symbols and quantities in parietal cortex: elements of a mathematical theory of number representation and manipulation. In Haggard, P., Rossetti, Y., & Kawato M. (Eds.).Sensoriomotor Foundations of Higher Cognition - Attention and Performance XXII (pp. 527-574). Cambridge: Harvard University Press.

Deruelle, C., Schon, D., Rondan, C., & Mancini, J. (2005). Global and local music perception in children with Williams syndrome. *Neuroreport, 16*, 631–634.

Don, A.J., Schellenberg, E.G., & Rourke, B.P. (1999). Music and language skills of children with Williams syndrome. *Child Neuropsychology, 5*, 154–170.

Dykens, E.M., Rosner, B.A., Ly, T., & Sagun, J. (2005).Music and anxiety in Williams syndrome: A harmonious or discordant relationship? *American Journal on Mental Retardation, 110,* 346–358.

Figueiredo, V. L. M. (2002). WISC-III: Escala de Inteligência Wechsler para Crianças. Manual Adaptação e Padronização Brasileira. São Paulo: Casa do Psicólogo.

Francke, U. (1999). Williams-Beuren syndrome: Genes and mechanisms. Human Molecular Genetics, 8, 1947–1954.

Hetland, L. (2000). Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education, 34*, 179-238.

Hopyan T, Dennis M, Weksberg R, Cytrynbaum C. (2001). Music skills and the expressive interpretation of music in children with Williams-Beuren syndrome: pitch, rhythm, melodic imagery, phrasing, and musical affect. *Child Neuropsychology 7*(1), 42-53.

Järvinen-Pasley, A., Vines, B. W., Hill, K. J., Yam, A., Grichanik, M., Mills, D., Reiss, A.L., Korenberg, J.R., & Bellugi, U. (2010). Cross-modal influences of affect across social and non-social domains in individuals with Williams syndrome. *Neuropsychologia, 48(2),* 456-466.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in cognitive sciences, 2(10)*, 389-398.

Lenhoff, H.M., Wang, P.P., Greenberg, F., & Bellugi, U. (1997). Williams syndrome and the brain. *Scientific American, 277,* 42–47.

Levitin, D. J. (2005). Musical behavior in a neurogenetic developmental disorder: Evidence from Williams syndrome. *Annals of the New York Academy of Sciences, 1060*, 325–334.

Levitin, D.J., & Bellugi, U. (1998). Musical abilities in individuals with Williams syndrome. *Music Perception, 15*, 357–389.

Levitin, D.J., Cole, K., Chiles, M., Lai, Z., Lincoln, A., & Bellugi, U. (2004). Characterizing the musical phenotype in individuals with Williams syndrome. *Child Neuropsychology, 10*, 223–247.

Levitin, D.J., Cole, K., Lincoln, A., & Bellugi, U. (2005). Aversion, awareness, and attraction: Investigating claims of hyperacusis in the Williams syndrome phenotype. *Journal of Child Psychology and Psychiatry*, *46*, 514–523.

Levitin, D. J., Menon, V., Schmitt, J. E., Eliez, S., White, C. D., Glover, G. H., Kadis, J., Korenberg, J. R., Bellugi, U., & Reiss, A. L. (2003). Neural correlates of auditory perception in Williams syndrome: An fMRI study. *NeuroImage, 18*, 74–82

Libertus, M. E., Feigenson, L., Halberda, J., & Landau, B. (2014). Understanding the mapping between numerical approximation and number words: evidence from Williams syndrome and typical development. Developmental science. doi: 10.1111/desc.12154.

Martens, M. A., Reutens, D. C., & Wilson, S. J. (2010). Auditory cortical volumes and musical ability in Williams syndrome. *Neuropsychologia*, *48(9*), 2602-2609.

Martínez-Castilla, P., & Sotillo, M. (2008). Singing abilities in Williams syndrome. *Music Perception*, *25*, 449–469. doi:10.1525/mp.2008.25.5.449.

Martínez-Castilla, P., Sotillo, M., & Campos, R. (2011). Rhythmic abilities of adolescents and adults with Williams syndrome. *Music Perception*, *29*, 77–89.

Mervis CB, Robinson BF, Bertrand J, Morris CA, Klein-Tasman BP, Armstrong SC. (2000). The Williams Syndrome cognitive profile. *Brain and Cognition*, *44*: 604–628.

Ng, R., Lai, P., Levitin, D. J., & Bellugi, U. (2013). Musicality Correlates with Sociability and Emotionality in Williams Syndrome. *Journal of mental health research in intellectual disabilities, 6(4),* 268-279.

Nunes-Silva, M., & Haase, V. G. (2012). Montreal Battery of Evaluation of Amusia. Validity evidence and norms for adolescents in Belo Horizonte, Minas Gerais, Brazil. Dementia & neuropsychologia, 6(4), pp. 244-252.

Nunes-Silva, M.S., Loureiro, C.M.V., Loureiro, M. & Haase, V.G. (2010). Tradução e validação de conteúdo de uma bateria de testes para avaliação de amusia. *Avaliação Psicológica, 9(2)*, 211-232.

Paterson, S., Girelli, L., Butterworth, B., Karmiloff-Smith, A. (2006). Are numerical difficulties syndrome specific? Evidence from Williams syndrome and Down's syndrome. *Journal of Child Psychologic Psychiatry*, *47*, 190– 204.

Paterson, S.J. & Schultz, R.T. (2007). Neurodevelopmental and Behavioral Issues in Williams

Syndrome. *Current Psychiatry Reports, 9,* 165-171.

Peretz, I. (2003). Brain specialization for music: New evidence from congenital amusia. In: I. Peretz, & R. Zatorre, The Cognitive Neuroscience of Music (pp. 192-203). Oxford: Oxford University Press.

Peretz, I. (2006). The nature of music from a biological perspective. *Cognition, 100,* 1-32.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., et al. (2002). Congenital amusia: a disorder of fine-grained pitch discrimination. *Neuron, 33,* 185–191.

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders. *Annals of New York academy of science, 999,* 58-75.

Peretz, I., & *Coltheart, M. (2003). Modularity of music processing.* Nature Neuroscience, 6(7), 688-691.

Peretz, I., Gosselin, N., Nan, Y., Caron-Caplette, E., Trehub, S. E., & Béland, R. (2013). A novel tool for evaluating children's musical abilities across age and culture. *Frontiers in systems neuroscience, 7, 30,* 1-10.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., Dehaene, S. (2004), "Tuning curves for approximate numerosity in the human intraparietal sulcus," *Neuron 44,* 547-555.

Rauscher, F. H., Shaw, G. L., Levine, L. J., Wright, E. L., Dennis, W. R., & Newcomb, R. L. (1997). Music training causes long-term enhancement of preschool children's spatial-temporal reasoning. *Neurological Research, 19 (1),* 2-8.

Rauscher, F. H., & Zupan, M. (2000). Classroom keyboard instruction improves kindergarten children’s spatial-temporal performance: A field experiment. *Early Childhood Research Quarterly, 15 (2),* 215-228.

Raven, J.C. (2003). *Teste das matrizes Progressivas*. Escala Geral. (3ª ed). (F. Campos, tradutor). Rio de janeiro: CEPA. (trabalho original publicado em 1997).

Reis, S.M., Schader, R., Milne, H., & Stephens, R. (2003). Music and minds: Using a talent development approach for young adults with Williams syndrome. *Exceptional Children, 69,* 293–313.

Rourke, B.P.; Ahmad, S.A.; Collins, D.W.; Hayman-Abello, B.A.; Hayman-Abello, S.E. & Warriner, E.M. (2002). Child clinical/pediatric neuropsychology: Some recent advances. Annu. Rev. Psychol., 53, pp. 309-339.

Rousselle, L., Dembour, G., Noël, M. P. (2013). Magnitude representations in Williams Syndrome: differential acuity in time, space, and number processing. *PLOS One, 8 (8),* e72621.

Schmithorst, V. J., & Holland, S. K. (2004). The effect of musical training on the neural correlates of math processing: a functional magnetic resonance imaging study in humans. *Neuroscience Letters*, *354*, 193–196.

Stein L. M. (1994). *Teste de Desempenho Escolar: Manual para Aplicação e Interpretação*. São Paulo: Casa do Psicólogo.

Strømme, P., Bjørnstad, P. G., & Ramstad, K. (2002). Prevalence estimation of Williams syndrome. *Journal of Child Neurology*, *17,* 269–271.

Trehub, S.E. & Hannon, E.E. (2006). Infant music perception: Domain-general or domain-specific mechanisms? *Cognition*, *100*, 73-99.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7(11),* 483-488.

Wengenroth, M., Blatow, M., Bendszus, M., & Schneider, P. (2010). Leftward lateralization of auditory cortex underlies holistic sound perception in Williams syndrome. *Plos One, 5 (8),* e1232. doi:10.1371/journal.pone.0012326.

Zatorre, R. (2001). Neural specializations for tonal processing. *Annals of the New York Academy of Sciences, 930*, 193-210.

7. DISCUSSÃO GERAL

A música é uma função cognitiva complexa e multicomponencial, cujos componentes podem ser afetados seletivamente por lesões cerebrais, e cujos correlatos neurofuncionais ainda não estão totalmente esclarecidos. Apesar dos avanços alcançados no estudo da música a partir de uma perspectiva neurocientífica, de acordo com Levitin (2005), há questões fundamentais na pesquisa em cognição musical que permanecem não resolvidas e os resultados das investigações neuropsicológicas ainda são contraditórios. Uma das questões principais dentro da pesquisa em música e neurociências é a da modularidade do processamento cognitivo musical. A questão da modularidade em ciência cognitiva, desde a introdução e definição do conceito realizada por Fodor (1983), tem sido alvo de debates que favoreceram a evolução do conhecimento atual acerca da arquitetura cerebral e de diferentes domínios cognitivos. Apesar de inicialmente associado à perspectiva inatista, de acordo com Mandelbaum (2013), a questão da modularidade é em essência uma hipótese sobre a estrutura dos processos mentais e não demanda necessariamente uma abordagem inatista. Ao contrário, permite ser abordada a partir de outras perspectivas, tal como Karmiloff-Smith (1998) ao defender a existência de um processo de modularização a partir da aprendizagem e experiência. Dentro da psicologia evolucionista, porém, estes processos de desenvolvimento geradores de módulos são considerados a partir da perspectiva inatista (ver Barrett & Kurzban, 2006). A música, por ser uma função cognitiva complexa, foi utilizada neste estudo como base para a investigação da hipótese da organização modular do cérebro. As evidências sobre a modularidade e especificidade do processamento cognitivo musical indicam que as habilidades musicais fazem parte de um módulo mental distinto, com seu próprio sistema de processamento de informação e substrato neural específico (Zatorre, 2001; Peretz, 2003; Peretz & Coltheart, 2003). Apesar disso, estudos sobre o desenvolvimento musical podem indicar que as habilidades musicais são produto de mecanismos perceptuais gerais que não são específicos nem da música nem da espécie humana (Trehub e Hannon, 2006).

Considerando a questão da modularidade do processamento cognitivo musical, o primeiro artigo deste trabalho, a partir de uma revisão integrativa, evidenciou que os estudos sobre o processamento cognitivo musical, favoreceram a evolução teórica dos construtos a ele relacionados e a construção de modelos úteis para sua compreensão e testagem de hipóteses. O modelo cognitivo neuropsicológico elaborado por Peretz, Champod e Hyde (2003), por exemplo, foi desenvolvido a partir de padrões de duplas dissociações e permitiu identificar estruturas funcionais que constituem o sistema de processamento da música. Este modelo contribuiu, portanto, para um melhor entendimento dos diferentes componentes da percepção musical e melhor compreensão dos déficits seletivos do processamento musical e da relação entre o domínio musical e outros domínios de processamento. Porém, a especificidade dessas estruturas funcionais, ou seja, desses subsistemas de representação do processamento musical, ainda apresenta controvérsias e permite que mais investigações sejam realizadas buscando uma maior compreensão não somente do sistema de processamento musical, mas também de sua relação com outros domínios cognitivos. Além disso, a inter-relação entre estas estruturas funcionais e sua dinâmica de funcionamento ainda merece maiores esclarecimentos.

Mesmo que as evidências apontem para a existência de dois módulos distintos de processamento auditivo, sendo um para a música, e outro para a linguagem, por exemplo, estes dois domínios possuem tanto componentes específicos como compartilhados. De acordo com Peretz e Coltheart (2003), um exemplo de componente distinto e específico para a música é a codificação tonal da altura. Na música, as alturas são perceptualmente organizadas em uma estrutura escalar em torno de uma altura central e com uma ordem hierárquica de importância ou estabilidade para as outras alturas, o que permite criar as expectativas na audição musical. Esta organização hierárquica está presente em músicas de diferentes culturas e é percebida por membros imaturos da espécie (Trehub, 2003). Peretz e Coltheart (2003) também consideram componentes que não são restritos ao processamento musical, como o contorno, por exemplo, que pode estar envolvido também no processamento de entonação da fala (Patel, Wong, Foxton, Lochy, & Peretz, 2008).

Nesta perspectiva, em relação aos domínios teóricos, o presente trabalho contribui para um maior entendimento do processamento musical, na medida em que evidencia e analisa os estudos acerca do processamento cognitivo musical que permitiram seu desenvolvimento teórico-metodológico. Além disto, a partir do segundo estudo, traz para o contexto brasileiro um instrumento validado para a avaliação das habilidades musicais e para o diagnóstico de diferentes tipos de amusias, que pode ser utilizado em pesquisas sobre o processamento cognitivo musical dentro do contexto brasileiro. O estudo contribui também como base empírica para o modelo de processamento musical elaborado por Isabelle Peretz (Peretz & Coltheart, 2003), na medida em que corrobora a existência de estruturas que são específicas do processamento cognitivo musical e evidencia que o processamento de habilidades musicais básicas independe do contexto cultural ao qual o indivíduo pertence.

Ainda em relação à especificidade do processamento cognitivo musical, a investigação de questões relacionadas à etiologia das amusias congênitas, realizada no terceiro estudo desta tese colabora com a discussão sobre o que pode ser considerado de domínio específico e o que é compartilhado em relação à percepção de altura nos domínios acústico e musical. A revisão quantitativa, além de corroborar a existência do déficit de altura na amusia congênita (Peretz et al., 2002), permitiu avaliar até que ponto este déficit é específico do processamento musical de altura ou se é afetado por um mecanismo mais geral de processamento acústico. A evidência encontrada de que o déficit de discriminação de altura observado na amusia congênita é localizado tanto em nível acústico como musical vai contra a hipótese de modularidade e especificidade deste transtorno, sendo que um déficit acústico geral pode ser responsável pelo déficit musical encontrado na amusia congênita.

Porém, a dupla dissociação observada entre o funcionamento do processamento acústico e o módulo de codificação tonal apontam para um perfil heterogêneo do déficit, indicando que os casos de amusia congênita não necessariamente implicam na existência de um déficit acústico. Isto corrobora os estudos acerca da especificidade do déficit de processamento cognitivo musical. É importante ressaltar que esta relação entre a altura acústica e musical pode ser alterada ao longo do desenvolvimento, sendo que as habilidades acústicas em alguns indivíduos pode ter originado o déficit no processamento musical, mas ter melhorado ao longo de suas vidas. Portanto, mais estudos são necessários para investigar se o déficit acústico é necessário para a manifestação da amusia congênita. Adicionalmente, o estudo também fornece evidências contrárias em relação à explicação da amusia congênita enquanto um déficit de memória ao invés de associado à discriminação perceptual (Albouy, Mattout, et al., 2013; Albouy, Schulze, et al., 2013; Tillmann, Schulze, & Foxton, 2009; Williamson *et al*., 2010; Williamson & Stewart, 2010), pois não houve efeito significativo em relação à duração dos estímulos das tarefas de discriminação de frequências de altura. Isto reforça a especificidade dos déficits de percepção musical.

A investigação da relação entre a cognição musical e a cognição numérica, realizada no presente trabalho, tanto na amusia congênita quanto na SW também auxilia na compreensão de quais mecanismos são específicos do processamento musical e quais são compartilhados. Na amusia congênita parece não haver relação entre o processamento de magnitude nos domínios musical e numérico, o que aponta para um mecanismo não-compartilhado para a representação de magnitudes nestes domínios. Mas uma associação parece ocorrer considerando o acesso simbólico a partir de representações de magnitudes. Na SW, por sua vez, houve um padrão similar de desempenho tanto na tarefa de comparação de magnitudes não simbólica, quanto nas tarefas de percepção musical, sendo que indivíduos com SW apresentaram, quando comparados por idade mental, um desempenho similar ao dos controles nestes dois tipos de tarefas e um pior desempenho quando comparados por idade cronológica, indicando que apresentam comprometimento em ambos os domínios, musical e numérico. Os resultados não permitiram, portanto, afirmar que há uma dissociação no desempenho dos indivíduos com SW considerando estes dois domínios cognitivos. Porém, a análise de série de casos realizada, identificou que a despeito dos participantes com SW apresentarem desempenho musical global prejudicado, alguns deles podem evidenciar preservação de subdomínios do processamento musical com comprometimento do senso numérico. Mais estudos são necessários para avaliar quais mecanismos são específicos de cada domínio e quais são compartilhados, levando-se em conta que música e matemática são duas áreas de aprendizagem humana que, apesar de distintas, podem apresentar alguns mecanismos associados.

Em suma, os resultados encontrados para os amúsicos congênitos de que o déficit de discriminação de altura se relaciona a um déficit acústico geral e de que há associação entre percepção musical e dificuldades em comparação de magnitudes simbólica, bem como a associação encontrada entre o senso numérico e a percepção musical nas crianças e adolescentes avaliados se constituem em evidências contra a modularidade e especificidade do processamento cognitivo musical e a favor da existência de mecanismos compartilhados ou amodais para o processamento cognitivo musical (Walsh, 2003; Cohen Kadosh, Lammertyn, & Izard, 2008; Cohen Kadosh, Brodsky, Henik & Levin, 2008; Bonn & Cantlon, 2012; Patel *et al*., 2008; Trehub e Hannon, 2006). Em contrapartida, a dupla dissociação encontrada entre o funcionamento do processamento acústico e o módulo de codificação tonal, e a dissociação entre o processamento de magnitudes nos domínios musical e numérico nos amúsicos congênitos, bem como o padrão de percepção musical relativamente preservada e senso numérico comprometido em indivíduos com SW fornecem evidências a favor da hipótese da modularidade do processamento cognitivo musical (Coltheart, 1999; Zatorre, 2001; Peretz, 2003; Peretz & Coltheart, 2003. Peretz, 2006; Tillmann *et al*., 2010). Convém ressaltar que tanto as amusias congênitas, quanto a SW se constituem em transtornos do desenvolvimento e, por promoverem um desenvolvimento cerebral atípico, os processos ocorridos durante este período não podem ser ignorados (Karmiloff-Smith, 1998). Deve-se considerar também que mesmo que possa haver processos de modularização para o sistema de processamento cognitivo musical durante o período de desenvolvimento (Trehub e Hannon, 2006), estes processos poderiam ser moldados pela seleção natural de modo a produzir resultados funcionalmente organizados (Barrett & Kurzban, 2006), e com uma função evolutiva de, por exemplo, melhorar a capacidade reprodutiva no ambiente ancestral fortalecendo relações interpessoais e grupais (Hauser & McDermott, 2003; McDermott & Hauser, 2005).

Adicionalmente, o presente trabalho contribui para o melhor entendimento dos déficits encontrados tanto na amusia congênita quanto na SW. Na amusia congênita, a dificuldade de acesso simbólico observada para estímulos numéricos poderia relacionar-se ao reduzido fascículo arqueado presente em amúsicos congênitos (Hyde, Zatorre & Peretz, 2011, Loui, Alsop e Schlaug, 2009, Loui, Hohmann, & Schlaug, 2010). O fascículo arqueado, apesar de ter terminações em regiões posteriores diferentes, tem região de terminação frontal adjacente ao fascículo longitudinal superior, cuja propriedade de difusão prediz o desempenho de crianças em tarefas aritméticas (Tsang *et al.*, 2009). Mesmo que a conectividade em sua região central não se correlacione com o desempenho em tarefas matemáticas (Tsang *et al*., 2009), o fascículo arqueado inclui seções de duas projeções frontais das vias do fascículo longitudinal superior, sendo até considerado parte deste último. Além disso, foram observadas diferenças funcionais, analisadas a partir de imagem de tensor de difusão (diffusion tensor imaging- DTI), com maior assimetria esquerda relacionadas ao ouvido absoluto em músicos treinados (Oechslin *et al.*, 2010). O ouvido absoluto refere-se à habilidade de reconhecer e nomear uma altura sem que haja uma referência tonal ou de altura prévia. Questiona-se também se a aprendizagem da notação musical ou mesmo o treinamento multissensorial poderia beneficiar os indivíduos com amusia congênita e sua acurácia perceptual de altura.

Já a investigação do perfil neuropsicológico musical na SW contribui para caracterizar melhor a variabilidade de seu fenótipo, observando-se quais os domínios da cognição musical estão comprometidos e quais estão preservados nesta síndrome. As consequências práticas desta investigação estão relacionadas à reabilitação de indivíduos com SW. O presente estudo pode fornecer subsídios para as propostas de intervenções nessa população e programas de treinamento multissensoriais para aprimoramento tanto de habilidades musicais, quanto utilizando-se de elementos musicais para auxiliar a aprendizagem em outros domínios cognitivos. Como os indivíduos com SW apresentaram déficits de processamento musical, a música deve ser utilizada de forma a considerar o perfil de desempenho apresentado pelo paciente. Sendo assim, o presente estudo contribui para aumentar o corpo de conhecimento a respeito dos déficits presentes na SW e nas amusias congênitas, bem como sobre se há associação entre a cognição musical e a cognição numérica nestas condições. Mais estudos são necessários para investigar melhor as relações encontradas.

Dentro do contexto clínico, em geral, o maior entendimento dos mecanismos subjacentes ao processamento cognitivo musical, permite uma melhor avaliação do perfil de habilidades musicais dos pacientes e norteia a elaboração de estratégias de intervenção. A validação da MBEA para o contexto brasileiro permite um melhor diagnóstico das amusias, além de identificar domínios comprometidos e preservados do processamento musical. A inclusão da avaliação das habilidades musicais dentro do contexto de avaliação neuropsicológica deve ser incentivada, por fornecer mais informações sobre o fenótipo cognitivo do paciente e aumentar o leque de estratégias de reabilitação. A proposta da versão reduzida da MBEA pode ser útil para estudos experimentais e avaliação de casos mais severos de comprometimento da capacidade intelectual do paciente. O trabalho também contribui para práticas clínicas que se utilizam de elementos musicais como meio principal de intervenção. Existem muitos estudos que abordam a utilização da musicoterapia com crianças e adolescentes com síndromes neuropsicológicas, mas nem sempre é acompanhado pelo entendimento acerca dos mecanismos teórico-metodológicos subjacentes aos resultados terapêuticos observados. A avaliação das habilidades musicais pode também ajudar a estimar o impacto de intervenções clínicas baseadas em elementos musicais.

No contexto educacional, a utilização da MBEA pode auxiliar na diferenciação entre condições neurológicas e outras causas para dificuldades de aprendizagem musical, especialmente em casos de amusia congênita. Na prática coral, por exemplo, é comum os comentários por parte dos maestros e próprios coralistas sobre a existência de cantores com dificuldades de afinação. Uma avaliação da percepção musical nestes casos pode nortear as estratégias de ensino e aprendizagem. O governo brasileiro sancionou em 2008 uma lei que torna obrigatório mas não exclusivo o ensino de música na educação básica (Lei 11.769). A compreensão dos mecanismos envolvidos na percepção e performance musical também pode ser aplicada ao ensino musical em geral e contribuir para melhores propostas de projetos pedagógicos nas escolas, e mesmo para a aprendizagem musical formal.

Ainda dentro do contexto pedagógico, o trabalho pode auxiliar na melhor compreensão da associação comumente feita entre a educação musical e a educação matemática, que embora muitas vezes tenham sido utilizadas em conjunto, pouco se sabe sobre os mecanismos subjacentes a esta associação. Música e matemática são muitas vezes consideradas como linguagens universais da humanidade. Apesar da utilização da música como auxiliar na aprendizagem de matemática e vice-versa, há uma lacuna de investigações sistemáticas da relação entre o processamento musical e o processamento numérico. Estudos como este lançam luz sobre até que ponto o ensino da música pode contribuir para o aprendizado em outros domínios de conhecimento, além de contribuir para o próprio ensino musical. Compreender uma função complexa e multicomponencial como a música nos fornece *insights* não somente para este campo de conhecimento em si, como também para outras áreas do conhecimento humano. Obviamente a compreensão de uma parte da percepção musical não encerra o fenômeno enquanto um todo, mas nos permite estabelecer relações contingenciais e lidar melhor com a realidade que nos cerca.

7.1. Referências

Albouy, P., Mattout, J., Bouet, R., Maby, E., Sanchez, G., Aguera, P.-E., Caclin, A. (2013). Impaired pitch perception and memory in congenital amusia: the deficit starts in the auditory cortex. *Brain, 136(5),* 1639-1661.

Albouy, P., Schulze, K., Caclin, A., & Tillmann, B. (2013). Does tonality boost short-term memory in congenital amusia? *Brain Research, 1537(6),* 224-232.

Barrett, H. C., & Kurzban, R. (2006). Modularity in cognition: framing the debate. *Psychological review, 113(3),* 628.

Bonn, C. D. & Cantlon, J. F. (2012): The origins and structure of quantitative concepts, *Cognitive Neuropsychology, 29:1-2*, 149-173.

Cohen Kadosh, R.C., Brodsky, W., Levin, M., Henik, A., (2008). Mental representation: what can pitch tell us about the distance effect? *Cortex, 44(4),* 470-477.

Cohen Kadosh, R. C., Lammertyn, J. Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology, 84*, 132–147.

Coltheart, M. (1999). Modularity and cognition. *Trends in Cognitive Sciences*, *3*(3), 115-120.

Fodor, J.A. (1983). *The modularity of mind: an essay on faculty psychology*. Cambridge, MA: MIT Press.

Hauser, M. D., & McDermott, J. (2003). The evolution of the music faculty: A comparative perspective. *Nature neuroscience, 6(7),* 663-668.

Hyde, K., Zatorre, R. & Peretz, I. (2011). Functional MRI Evidence of an Abnormal Neural Network for Pitch Processing in Congenital Amusia. *Cerebral Cortex, 21*, 292-299.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in cognitive sciences, 2(10)*, 389-398.

Levitin, D. (2005). Musical Behavior in a Neurogenetic Developmental Disorder: Evidence from Williams Syndrome. Annals of the New York Academy of Sciences, 1060, pp. 325–334.

Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: a new disconnection syndrome? *The Journal of Neuroscience, 29(33),* 10215-10220

Loui, P., Hohmann, A., & Schlaug, G. I.-e. (2010). Inducing disorders in pitch perception and production: a reverse-engineering approach. *Proceedings of Meetings in Acoustics, 9,* 1-8.

Mandelbaum, E. (2013). Numerical architecture. Topics in Cognitive Science, 5, 367-386.

McDermott, J., & Hauser, M. (2005). The origins of music: Innateness, uniqueness, and evolution. *Music Perception, 23 (1),* 29-59.

Oechslin, M. S., Imfeld, A., Loenneker, T., Meyer, M., & Jäncke, L. (2010). The plasticity of the superior longitudinal fasciculus as a function of musical expertise: a diffusion tensor imaging study. *Frontiers in human neuroscience, 3,* 76.

Patel, A. D., Wong, M., Foxton, J., Lochy, A., & Peretz, I. (2008). Speech intonation perception deficits in musical tone deafness (congenital amusia). Music Perception, 25(4), 357-368.

Peretz, I. (2003). Brain specialization for music: New evidence from congenital amusia. In: I. Peretz, & R. Zatorre. The Cognitive Neuroscience of Music (pp. 192-203). Oxford: Oxford University Press.

Peretz, I. (2006). The nature of music from a biological perspective. *Cognition*, *100*, 1-32.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., & Jutras, B. (2002). Congenital amusia: a disorder of fine-grained pitch discrimination. *Neuron, 33(2),* 185-191.

Peretz, I., Champod, A.S., & Hyde, K. (2003). Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. *Annals of the New York Academy of Sciences, 999,* 58-75.

Peretz, I., & Coltheart, M. *(2003). Modularity of music processing. Nature Neuroscience, 6(7),* 688-691.

Tillmann, B., Jolicœur, P., Ishihara, M., Gosselin, N., Bertrand, O., Rossetti, Y., et al. (2010). The amusic brain: Lost in music, but not in space. *PLoS ONE, 5(4)*, e10173.

Tillmann, B., Schulze, K., & Foxton, J. M. (2009). Congenital amusia: A short-term memory deficit for non-verbal, but not verbal sounds. *Brain and Cognition, 71(3)*, 259-264.

Trehub, S.E. (2003). The developmental origins of musicality. *Nature Neuroscience*, *6,* 669-673.

Trehub, S.E. & Hannon, E.E. (2006). Infant music perception: Domain-general or domain-specific mechanisms? *Cognition*, *100*, 73-99.

Tsang, J. M., Dougherty, R. F., Deutsch, G. K., Wandell, B. A., & Ben-Shachar, M. (2009). Frontoparietal white matter diffusion properties predict mental arithmetic skills in children. *Proceedings of the National Academy of Sciences*, *106(52*), 22546-22551.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7(11),* 483-488.

Williamson, V. J., McDonald, C., Deutsch, D., Griffiths, T. D., & Stewart, L. (2010). Faster decline of pitch memory over time in congenital amusia. *Advances in Cognitive Psychology*, *6(1*), 15-22.

Williamson, V. J., & Stewart, L. (2010). Memory for pitch in congenital amusia: Beyond a fine-grained, pitch discrimination problem. *Memory*, *18(6)*, 657-669.

Zatorre, R.J. (2001). Neural specializations for tonal processing. *Annals of the New York Academy of Sciences*, *930*, 193-210.

UNIVERSIDADE FEDERAL DE MINAS GERAIS
COMITÊ DE ÉTICA EM PESQUISA - COEP

Parecer nº. ETIC 318/08

Interessado(a): Prof. Vitor Geraldi Haase
Departamento de Psicologia
FAFICH - UFMG

DECISÃO

O Comitê de Ética em Pesquisa da UFMG – COEP aprovou, no dia 19 de setembro de 2008, após atendidas as solicitações de diligência, o projeto de pesquisa intitulado **"Adaptação de uma bateria de testes para avaliação de amusia para uso com adolescentes no Brasil"** bem como o Termo de Consentimento Livre e Esclarecido.

O relatório final ou parcial deverá ser encaminhado ao COEP um ano após o início do projeto.

Profa. Maria Teresa Marques Amaral
Coordenadora do COEP-UFMG

Av. Pres. Antonio Carlos, 6627 – Unidade Administrativa II - 2º andar – Sala 2005 – Cep:31270-901 – BH-MG
Telefax: (031) 3409-4592 - e-mail: coep@prpq.ufmg.br

PROJETO DE PESQUISA

Título: Investigação da relação entre o processamento de magnitudes nos domínios da cognição numérica e da cognição musical

Área Temática:

Versão: 2

CAAE: 01384212.8.0000.5149

Pesquisador: Vitor Geraldi Haase

Instituição: PRO REITORIA DE PESQUISA ((UFMG))

PARECER CONSUBSTANCIADO DO CEP

Número do Parecer: 88.267

Data da Relatoria: 05/09/2012

Apresentação do Projeto:

Projeto da área de Saúde, do programa de Pós-Graduação em Neurociências do ICB/UFMG que conta além do coordenador com a participação da doutoranda Marília Nunes Silva. O projeto visa avaliar a relação entre as habilidades musicais e matemáticas em indivíduos com síndrome de Síndrome de Williams (SW). A SW é um transtorno genético do desenvolvimento caracterizada por retardo mental leve a moderado, dismorfias faciais, anormalidades nos sistemas cardiovascular, musculoesquelético e gastrointestinal e um perfil cognitivo constituído de habilidades sociais, musicais, verbais e de reconhecimento de faces
preservadas, a despeito de habilidades visuoespaciais e numéricas comprometidas.

Objetivo da Pesquisa:

O presente projeto tem por objetivo investigar a relação entre processamento de magnitudes numéricas e de magnitudes tonais em indivíduos com Síndrome de Williams (SW). Os participantes do estudo serão divididos em dois grupos, sendo um grupo experimental, constituído por indivíduos portadores de SW, e um grupo controle, constituído por indivíduos com desenvolvimento típico. Estima-se que o grupos experimental seja composto de 30 indivíduos e o grupo controle de 60 indivíduos. Os participantes do grupo experimental serão recrutados a partir da Associação Brasileira de Síndrome de Williams. O
grupo controle será recrutado em instituições de ensino de Belo Horizonte. Os participantes realizarão no mínimo três sessões de avaliações, cada qual com duração média de 1h e 30 min., utilizando testes neuropsicológicos. Os escores obtidos pelos participantes serão tabulados em um banco de dados que serviráde base às análises estatísticas. Serão utilizadas estatísticas descritivas e inferenciais para caracterização da amostra e comparação entre grupos.

Avaliação dos Riscos e Benefícios:

Os riscos para os participantes podem estar relacionados ao afastamento das
atividades escolares no período de aplicação dos testes, bem como ao desconforto e cansaço pela testagem. Os benefícios se relacionam com a eventual identificação de indivíduos que apresentem déficits nas áreas avaliadas. Os pais e responsáveis serão então chamados para uma entrevista e aconselhados quanto aos eventuais encaminhamentos que se façam
necessários para investigações clínicas mais detalhadas. Para os participantes com SW, além da avaliação neuropsicológica, será oferecida uma orientação para os seus pais ou responsáveis.

Comentários e Considerações sobre a Pesquisa:

Projeto meritório e relevante, representa uma contribuição importante para a área de interesse.

Considerações sobre os Termos de apresentação obrigatória:

Protocolo de pesquisa, folha de rosto, parecer consubstanciado com aprovação da Câmara Departamental, anuência das escolas e da Sociedade Brasileira de SW onde será realizada a pesquisa, TCLEs adequados de acordo com as faixas etárias.

Recomendações:

Não há. Foram feitas as alterações solicitadas para os TCLEs.

Conclusões ou Pendências e Lista de Inadequações:

Não há pendências.

Situação do Parecer:

Aprovado

Necessita Apreciação da CONEP:

Não

Considerações Finais a critério do CEP:

Aprovado conforme parecer.

BELO HORIZONTE, 03 de Setembro de 2012

____

Assinado por:
Maria Teresa Marques Amaral