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CENTER FOR MUSIC IN THE BRAIN

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Center for Music in the Brain
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WORDS FROM THE DIRECTOR

Since its inception, Center for Music in the Brain (MIB) has been increasingly productive, as can be seen both in its high number of interdisciplinary publications in trendsetting journals, and by the fact that these publications are cited 50 % more than the average of their respective fields. MIB is now recognised as one of the world's leading research centres in the field owing to its large, high-level international team, with complementary interdisciplinary competences, including a signature set of experimental paradigms and analysis instruments. This is reflected in the participation in four out of twelve symposia of the upcoming Neuromusic Conference, which is the most important conference in the field of neuroscience of music. As an even more encouraging fact, homebread MIB researchers, Victor Pando-Naude and David Quiroga, won two out of three Young Researcher awards at the International Conference on Music Perception and Cognition in August in Tokyo, Japan.

The MIB research is centered around the predictive coding of music (PCM) model for understanding brain processing of music in terms of active inference and minimisation of prediction error. As described in our highly-cited review in Nature Reviews Neuroscience in 2022, PCM radically changed the prevailing understanding of the relationship between music and the human brain, in that it combines a fundamental prediction-centred theory of brain processing with a mathematical and theoretical account of music to describe music perception, action, emotion and learning. On top of these basic strands of research, music interaction, is an overarching theme, which is the responsibility of all the MIB PIs - Elvira Brattico, Morten Kringelbach, Peter Keller and myself.

2023 saw the culmination of many novel lines of research in MIB. Worth mentioning is the discovery of the "bodily hierarchy" by PhD student Signe Hagner Mårup: that holding meter and rhythm simultaneously in two limbs is more difficult one way than the other. Also, the "encoding and decoding of music" paradigm developed by Leonardo Bonetti, which allows to track memory-related predictive coding across the different hierarchical levels in the brain, has been a major breakthrough both for an enhanced understanding of the brain but also clinically, where we are currently using it to investigate the aging brain. Finally, as a particularly important development, in collaboration with researchers at McMasters University in Canada we have developed a new mathematical modelling approach for the "inverted U-shape of groove": that our urge to move forms an inverted U-shaped relationship with the predictability of groovy rhythms. This approach promises to unravel the mysterious relationship between the moment-to-moment surprise in groovy

MISSION STATEMENT

The Danish National Research Foundation's Center for Music in the Brain (MIB) is an interdisciplinary research centre aiming at addressing the dual questions of how music is processed in the brain and how this can inform our understanding of fundamental principles behind brain processing in general.

With a strong foundation in music practice and theory at the highest level, and a focus on clinical application of music, MIB combines neuroscientific, musicological and psychological research in music perception, action, emotion and learning, with the potential to test the most prominent theories of brain function, and to influence the way we play, teach, use, and listen to music.

rhythms and the pleasure/urge to move to these rhythms. Based on our and others' research in groove there is now an international conference dedicated to this subject.

Increasingly important to MIB is the efforts to translate the fundamental research. Our influential White-paper on clinical applications of music has become the gold standard for existing research on music interventions in health care, used by health workers and policy makers alike, contributing to the integration of music as a health care supplementary tool. Our impact includes multiple consultations with the Scandinavian Ministries of Health and Culture on the potential of music to meet health challenges including an invitation to speak to the culture and health committees of the Danish Parliament in January 2024. Furthermore, we have a strong influence on music making and education including many consultations and talks at music schools, academies and music associations.

In 2023, we welcomed a new brood of PhD students, Paul Maublanc, Athanasia Kontouli and Silvia Genovese - Silvia being a part of the European project Lullabyte - and a new assistant professor, Ana Zamorano, a former close collaborator. We were also happy to welcome back to Aarhus former postdoc, now Associate Professor, Leonardo Bonetti who had spent 2 years at University of Oxford, strengthening our collaboration with University of Oxford.

We are equally proud that many of our students and former employees thrive in new positions and job functions. Henrique Fernandes, who has been with us since the very beginning of the centre, is now pursuing a career in the private sector. Also, our part time professor Andrea Ravignani, was successful in landing a full professorship in Rome. Fortunately he will be affiliated with MIB in the future as an honorary professor.

2023 was characterised by a number of events important for the internal as well as the international relations in the center. In the beginning of the year, we had an invigorating 3-day retreat with RITMO (Centre for Interdisciplinary Studies in Rhythm, Time and

Motion), Oslo University in Copenhagen where MIB and RITMO researchers worked together on creating new research projects, reinforcing the collaboration between the two centres. In July we ran our 3-week Summer School as part of the annual Aarhus University Summer University with 25 participating students and involvement from most of the centre's employees. Later in the summer almost the entire scientific staff and PhD students travelled to Japan for the ICMPC (International Conference on Music Perception and Cognition), chairing three symposia and presenting a symposium in addition to numerous posters. At the annual Neuroscience Day at Aarhus University, Leonardo Bonetti was awarded the Marco Capogna Young Scientist Prize, and later in 2023, he received the Award for Scientific Article of the Year for 2023 by the Nordic Mensa Fund. Mensa also supported Gemma Fernández Rubio's project "Puzzling out the neurophysiology of auditory memory and intelligence in dementia".

Again in 2023, MIB received generous external funding of which we are extremely thankful. Many thanks to SDC, William Demant Fonden, Carlsbergfondet, AUFF, Parkinsonforeningen and Nordic Mensa Fund among others.

We finally wish to thank MIB and CFIN scientists and collaborators, The Danish National Research Foundation, Central Denmark Region, Department of Clinical Medicine at Aarhus University, The Royal Academy of Music Aarhus/Aalborg, Aarhus University and our other generous funding sources for their continued support.

On behalf of
Center for Music in the Brain
Peter Vuust

Center for Music in the Brain and Centre for Interdisciplinary Studies in Rhythm, Time and Motion, Oslo at the joint retreat in Copenhagen.

PREDICTIVE CODING OF MUSIC

Peter Vuust

The predictive coding of music model (PCM) is the central theoretical framework behind MIB's research and has been formulated in a number of papers[1-4], most recently in our 2022 review in Nature Reviews Neuroscience (NRN). It states that when we listen to music with melody, harmony and rhythm, the brain deploys a predictive model — based on prior experience — that guides our perception. This combines music theory with active inference, an influential theory of predictive brain processing[5] into a comprehensive understanding of brain processes and structures implicated in music perception, action, emotion and learning.

Fundamentally, active inference highlights that the brain is not a passive receiver but contributes actively by anticipating and adapting to novel situations, generating innovative actions. This makes active inference part of all levels of musical processing. This active listening process forms the basis of emotional responses to music and musical learning and updates our underlying predictive model over time. A prominent example of this is the experience of musical groove[6,7] —the "Pleasurable Urge to Move to Music (PLUMM)"— which is known to follow an inverted U-shape as rhythms become increasingly syncopated[8,9]. There is a paradox at the heart of PCM explanation of the inverted u-shaped curve: If the primary purpose of the brain is to minimise prediction error, why is a medium amount of prediction error more attractive than both a little and a lot of prediction error? We have previously modelled this U-shape as the product between the metrical predictability (precision) and the stimulus deviations from the meter. Recently, Tomas Matthews and Jonathan Cannon used Bayesian modelling to refine this idea and showed that the U-shape curve may be determined by the affordance to minimize precision-weighted prediction error. In other words, the reason why we tap our feet to music is that it helps us to reduce prediction error, making the musical rhythm understandable to our brain. We have formulated this in the light of the "learning progress" hypothesis and proposed that the rhythms associated with the most pleasure are the rhythms, where we have the most opportunity to reduce prediction error when moving to the beat[10]. We are currently investigating PLUMM in patients with Parkinson's disease[11,12], and in participants with cochlear implants[13-15].

Closely related to the inverted U-shape, also involving the motor system, is our surprising discovery of the bodily hierarchy of rhythm (Fig. 1). We have shown that it is easy to sing a rhythmic figure whilst tapping the musical beat with the right hand, while the opposite is virtually impossible. Try clapping the typical football stadium rhythm (da, da, da-da-da, da-da-da-da, da-da) while keeping the beat (1, 2, 3 ,4) with your mouth. Without a lot of training,

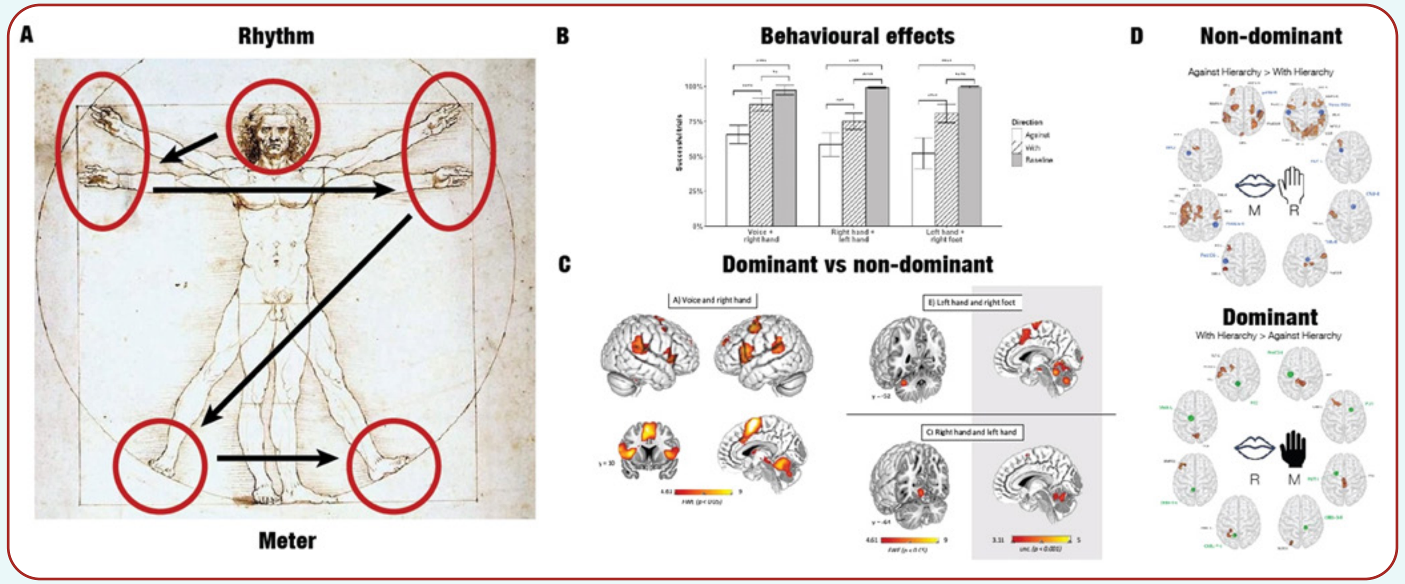

*Figure 1. Bodily Hierarchy. A) The bodily hierarchy places the voice at the top, followed by the right and left hand, and the right and left foot. B) The behavioural effects showing the bodily hierarchy with successful trials in each condition. Bars represent the percentage of trials completed successfully in each condition, averaged across participants. "Baseline" is defined as performing the beat with both limbs. Asterisks (*) mark the statistically significant differences as assessed by Wilcoxon signed-rank tests with Bonferroni correction applied. (** p < .0001; * p <.001; ** p < .01) Error bars represent 95% confidence interval. C) Neuroimaging show the main effects of hierarchy. The figure shows that brain regions going with and against the hierarchy elicited different levels of activity. These differences are found in the parietal cortex (angular gyrus, precuneus, supramarginal gyrus), frontal cortex (superior frontal gyrus, supplementary motor area, frontal pole), temporal cortex (middle temporal gyrus), occipital cortex, anterior insular cortex, posterior cingulate cortex, and cerebellum. D) Seed-based connectivity analyses show increased functional connectivity between primary motor effector areas and somatosensory cortex when going against the hierarchy.*

this is very difficult for most people. In a complex fMRI design, we have shown that the difference in experience of performing the same rhythm with the same two effectors e.g., the mouth and the hand but in two different ways yield activity in premotor areas of the brain as well as higher order rhythm-related areas in the inferior frontal gyrus[16]. The existence of a bodily hierarchy poses important questions to the way prediction errors arise from the interaction between different body parts, especially since this bodily hierarchy manifests itself as a cognitive dichotomy between rhythm and meter, not dependent on the difficulty of the two parts of the rhythm/meter. Furthermore, one cannot help wondering if the bodily hierarchy is learned or innate and as such a human condition.

Unrelated to the motor system, we have also made significant progress in our understanding of the predictive coding of melody[17], in particular through the studies of Leonardo Bonetti, who has developed a paradigm to study how music memory is encoded and decoded in the human brain over fast timescales. In a series of studies, he has used MEG in combination with dynamic causal modelling and whole-brain modelling to track the hierarchical brain activity to known and unknown melodic material[18,19]. He applied dynamic causal modelling (DCM) to a restricted set of brain regions of interest (from AAL) involved in the processing of these melodies: left Heschl's gyrus, right Heschl's gyrus, left hippocampus, right hippocampus, anterior cingulate gyrus, and medial cingulate gyrus. Consistent with PCM this revealed a functional hierarchical organisation during the recognition of auditory sequences where the auditory cortices feed forward prediction error to a higher order network consisting of the left and the right hippocampus and the medial cingulate gyrus of the brain[20,21]. This paradigm has proven highly relevant to the study of memory-related brain function in the aging brain[22,23] and for understanding cultural transmission of musical sequences[24].

The PCM framework was initially developed to describe the music processing in a single brain[25]. However, social interactions are fundamental to the way we experience and perform music[26-28]. In our NRN review[29], we provided a preliminary expansion of the PCM model to encompass how interacting musicians may adjust and coordinate schematic and short-term predictions while playing together. We have proposed how joint action may be understood within a predictive coding framework[30,31], where the emphasis is on establishing a shared narrative and mutual predictability. In collaboration with Marc Leman and IPEM in Ghent, Mattia Rosso who is employed in a joint position co-financed by IPEM and MIB, has identified a candidate neurobiological mechanism involving beta oscillation bursts, which turns out to be crucial for successful predictions of other people's tapping[32]. This mechanism may not only underlie music interactions but generalise to social cognition and synchronisation.

Synthesizing the work described above we are currently shedding light on the brain mechanisms underlying the art of improvisation[33]. We are trying to elucidate the brain mechanisms underlying the pleasure of the improvisational process, and thus more generally the proximal reasons for humans to engage in creative activities. In combination with whole-brain computational modelling, improvisation provides a new well-defined, quantifiable framework for studying the brain processes underlying human creativity as it unfolds on different timescales. This may offer more general evidence for the networks involved in creativity, including those involved in the planning of complex behaviour, decision making, emotional/arousal regulation, semantic processing, memory, imagery and motor control. This work will be presented at the Neuroscience & Music conference in Helsinki in June 2024.

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PREDICTIVE CODING OF MUSIC

Leonardo Bonetti

Harmonizing the aging mind: Exploring predictive coding in musical memory across the lifespan

As we age, our cognitive faculties undergo a complex transformation, presenting both challenges and opportunities for scientific inquiry. Understanding the neurophysiological changes that accompany aging is essential, not only for shedding light on the fundamental mechanisms of cognitive function but also for addressing the growing health concerns associated with an aging population. In this pursuit of knowledge, we have directed our focus towards exploring the predictive coding of memory for musical sequences, a fascinating domain that offers unique insights into the human brain across the lifespan.

In the past years, we have widely investigated the neural mechanisms involved in memory recognition for musical sequences in healthy young adults. In one study, using magnetoencephalography (MEG), we measured the brain activity of 83 participants while recognizing memorized musical sequences. Results revealed a hierarchical brain network involving auditory cortices, hippocampus and cingulate gyrus with distinct patterns of activity for memorized sequences and variations[1]. This study expanded the predictive coding theory, providing quantitative evidence of hierarchical brain mechanisms during conscious memory processing.

This study has been expanded by additional investigations, focusing on the relationship between different memory subsystems, musical complexity and brain networks. For instance, we examined the relationship between working memory (WM) abilities and brain activity during auditory sequence recognition. Positive correlations were found between WM and brain activity in regions associated with auditory processing and visual processing, highlighting the complex interplay between memory subsystems and brain networks[2].

Similarly, we investigated neural activity during recognition of tonal and atonal sequences. Results showed qualitative differences in neural activity based on stimulus complexity, with tonal sequences engaging hippocampal and cingulate areas, while atonal sequences activated the auditory processing network[3]. These findings underscored the complexity of the brain mechanisms underlying memory recognition for music and highlighted the potential of musical sequences to investigate the brain.

Building on our previous research on the predictive coding of musical memory in healthy young adults, we extended our investigation to aging, exploring behavioural differences between young and older adults as well as their associated brain functioning.

Previous literature clearly outlined that age-related cognitive decline is marked by a gradual reduction in various cognitive functions, including encoding, retention, and retrieval of information. However, it was not entirely clear how different memory systems related to each other in aging, especially with regards to the auditory system. Thus, we sought to evaluate the auditory short-term memory (STM), long-term memory (LTM), and working memory (WM) capacities among both young and older adults through musical and numerical tasks. Furthermore, we explored the influence of musical training on auditory memory performance.

Results revealed distinct differences between age groups: while young adults exhibited superior performance in rhythmic STM tasks compared to older adults, both groups performed similarly in melodic STM tasks[4]. Interestingly, higher levels of musical training were associated with enhanced STM capacity for melodic sequences across age groups. Regarding LTM, young adults demonstrated better identification of new musical sequences compared to older adults, with musical training amplifying this effect. However, no significant group differences were observed in the recognition of previously memorized musical sequences. Similarly, no significant changes were detected in WM capacity between age groups, although a trend suggested that young adults tended to outperform older adults.

Then, we wished to expand our investigation to the brain mechanisms underlying long-term memory for music and predictive coding in healthy older adults. Here, the prevailing notion linked aging with diminished brain processing power and predictive capabilities.

In one of our recent studies, we used MEG and magnetic resonance imaging (MRI) to investigate the neural activity of older adults (over 60 years old) and young adults (aged 18-25 years) during the long-term recognition of memorized and novel musical sequences. Our results challenged previous knowledge by revealing a functional reorganization of the brain associated with aging[5]. Specifically, older adults exhibited increased early activity in sensory regions, such as the left auditory cortex, when recognizing memorized sequences, alongside moderate decreased activity in higher-order brain regions of the medial temporal lobe, including the hippocampus and inferior temporal cortex (Fig. 1). Conversely, when processing variations in novel sequences, older adults displayed a marked reduction in fast-scale functionality in several brain regions, including the hippocampus and ventromedial prefrontal cortex. Furthermore, WM abilities were associated with heightened brain activity underlying recognition of novel sequences in both age groups. Our findings underscored the complexity of the aging brain's processes, challenging simplistic notions of general decline and shedding light on age-related changes in predictive and memory functions.

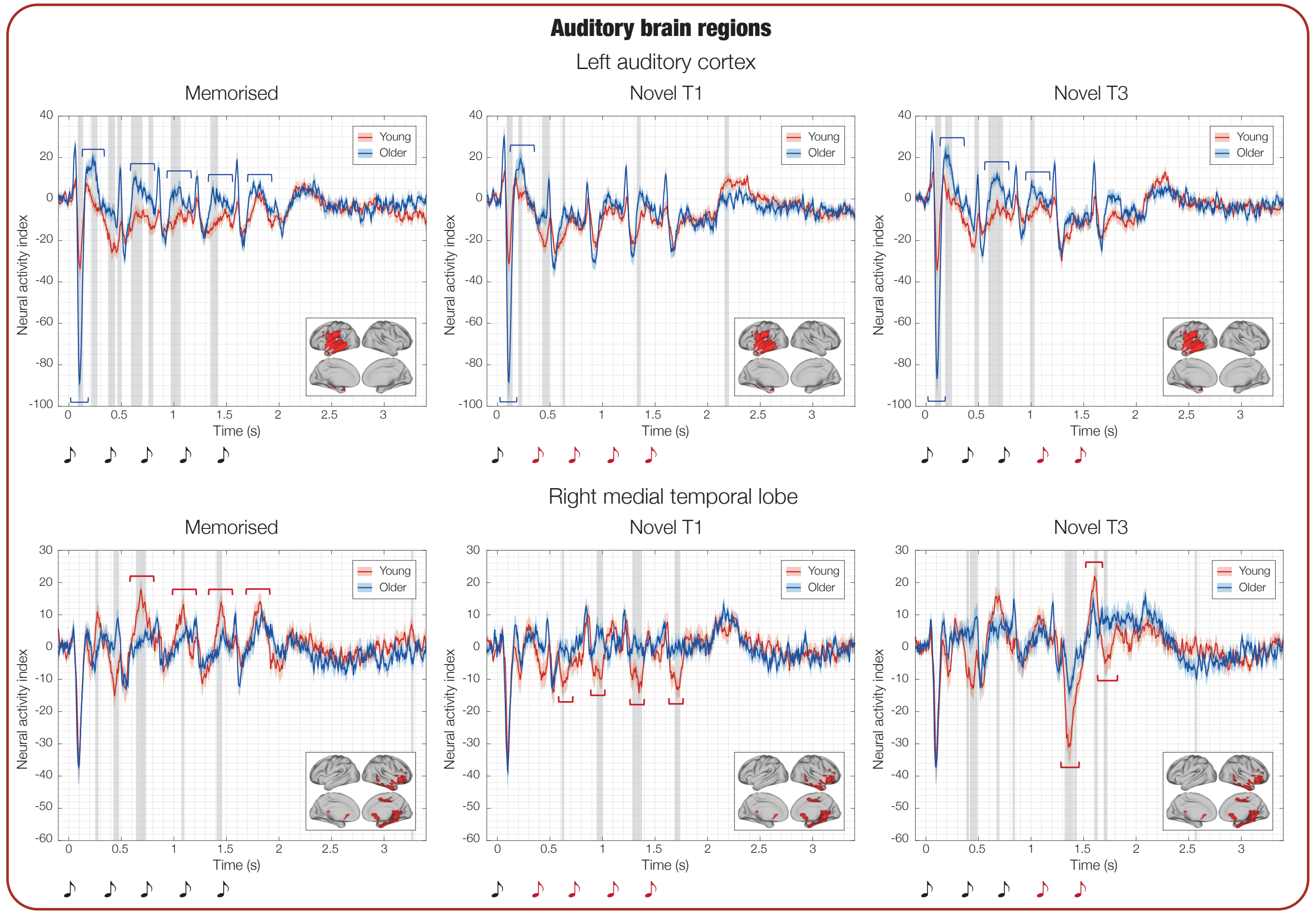

Figure 1.

Older adults show stronger activity in auditory cortex and reduced responses in medial temporal lobe when recognizing musical sequences.

The figure presents localized brain activity for each experimental condition (M, NT1, NT3) in two key regions of interest (ROIs): the left auditory cortex (top) and the right medial temporal lobe (bottom). Statistically significant differences in brain activity between young and older adults are depicted in grey areas, with solid red lines indicating young adults and solid blue lines representing older adults (shading indicates standard error for both). The red and blue graphs highlight neural components of particular interest. Additionally, the sketch of musical tones represents the onset of sounds forming the musical sequences, while the brain templates illustrate the spatial extent of the ROIs. Older adults demonstrate significantly stronger activity in the left auditory cortex when recalling previously memorized melodies compared to young adults. This is evident in the top graphs, which depict a component occurring approximately 300 ms after the onset of each tone, showing stronger responses for older adults across all tones in the memorized (M) condition and before introducing variations in the non-memorized (NT) conditions (i.e., one tone for NT1 and three tones for NT3). Additionally, the N100 response to the first tone of the sequences is notably stronger in older adults across all conditions. Conversely, older adults display diminished activity in the medial temporal lobe, including the hippocampal and inferior temporal regions, particularly noticeable in NT1 and NT3 conditions. The bottom red graphs highlight reduced prediction error responses in older adults compared to young adults when the sequence is varied, especially noticeable for the first tone introducing the variation in the melodies (i.e., tone two for NT1 and tone four for NT3).

Through our investigation of memory processing for music in both healthy young and older adults, we have gained noteworthy insights into the complex psychological and neural changes accompanying the human lifespan. Moreover, our findings not only shed light on the nuances of cognitive aging but also highlight the potential benefits of interventions such as musical training in mitigating age-related cognitive decline. Furthermore, by comprehensively studying musical memory processing in healthy aging, we open future perspectives in the investigation of pathological conditions such as dementia, where impairments in predictive coding of memory for music may play a relevant role.

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MULTIMODAL THEME
Boris Kleber

In 2023, the research within this strand emphasizes the critical role of multimodal experiences in shaping our perception, skilled sensorimotor production and cognitive processes. A key focus has been on elucidating the effects of individual differences and how perceptual processes interact to support our decisions and actions.

Individual differences in beat perception
Within the realm of polyrhythms, a prior study conducted by Assistant professors Jan Stupacher, Cecilie Møller and Alexandre Celma-Miralles and Professor Peter Vuust[1] found that individuals tend to align their movements with pulses in polyrhythms that are divisible into groups of two or four evenly spaced units, known as binary subdivisions, rather than those divisible into three or five. A follow-up study[2] investigated how individual differences in spontaneous motor tempo (SMT), the level of musicianship, and the choice of musical instrument may influence rhythmic alignment and beat perception. Focusing on polyrhythms (2:3 and 3:4 ratios) as a medium to examine participants' synchronization with binary or ternary subdivisions, participants' SMT was assessed before they tapped along to the polyrhythms. One notable result was that individuals who naturally move at a slower pace are more likely to match their movements with the slower rhythms present in the music. Importantly, this synchronization with slower rhythms occurs specifically when those rhythms are also based on binary subdivisions, meaning they can be broken down into groups of two or four evenly spaced units. This indicates a profound connection between our inherent movement pace through life and how we perceive musical tempo (read more on page 18).

Crossmodal predictions in aesthetic perception
Expanding the scope of our investigation to the intersection of sensory modalities, a recently published study[3] has shed light on the dynamic interplay between auditory and visual domains in shaping aesthetic judgments, particularly focusing on how top-down modulated affective and representational (i.e., semantically meaningful) predictions between these modalities influence neural processing. This groundbreaking research elucidates the brain's remarkable capacity for crossmodal integration, demonstrating that anticipatory signals in one sensory modality can significantly alter the neural processing of aesthetic information in another. Participants were exposed to aesthetic stimuli, including visual patterns and musical chords, preceded by primes from the opposing modality to measure neural responses via EEG and MEG. This setup facilitated a nuanced examination of how auditory predictions impact visual aesthetic assessments and vice versa. The study uncovered that early auditory-cortex responses to chords were significantly influenced by valence compared to visual-cortex responses. Furthermore, assessments of visual targets benefitted more from the affective congruency of crossmodal primes than acoustic targets did. These findings highlight the brain's early use of affective information from one modality to predict and shape aesthetic responses in another, illustrating a predominant crossmodal affective transfer from audition to vision. The insights open new avenues for understanding the cognitive mechanisms underlying aesthetic appreciation, revealing the fine balance between sensory predictions and perceptual experiences.

Musical sophistication and perception abilities
In our endeavor to explore the dimensions of musical sophistication, a focused evaluation of the Danish version of the Goldsmiths Musical Sophistication Index (GOLD MSI)[4] within a Danish cohort by Cecilie Møller, Niels Chr. Hansen, Peter Vuust, and Daniel Müllensiefen has yielded intriguing results concerning mistuning perception abilities[5]. Mistuning perception abilities refer to the capacity of an individual to detect deviations or discrepancies in pitch from a given reference pitch or an expected musical harmony. By comparing the impact of general musical sophistication and various subscales on mistuning perception scores in samples with different degrees of representativeness, they observed a nuanced picture of musical sophistication's influence on perceptual abilities. The analyses, adjusted for sample representativeness, revealed a diminishing effect of the independent variables on mistuning perception scores, emphasizing the importance of representativeness in musical research. This meticulous approach not only validated the GOLD MSI as a tool for assessing musical sophistication in the Danish population but also underscored the critical role of sample composition in understanding the multifaceted nature of musical sophistication and its relation to perceptual abilities.

Neuroplastic correlates of singing training
Staying within the realm of music sophistication, singing represents a distinct musical skill, rooted in a system extensively honed throughout the maturation of speech motor abilities. Within the literature on how the brain adapts to the development of musical skills, the corpus callosum (CC) has been well-studied in instrumental musicians, highlighting its crucial role in facilitating interhemispheric communication to support fine-motor skills. However, research focusing on this structure in singers is notably sparse. Leveraging a collaboration with Prof. Eileen Lueders and Dr. Florian Kurth (University of Auckland, New Zealand), Associate Professor Boris Kleber investigated structural adaptations within the corpus callosum among opera singers relative to non-singers. Findings demonstrate that an early start to singing training correlates with increased callosal thickness in several CC subregions, specifically within the genu connecting prefrontal cortices, the border between the anterior and posterior midbody linking motor and sensory areas, crucial for sensorimotor integration, and the isthmus, relevant for auditory processes

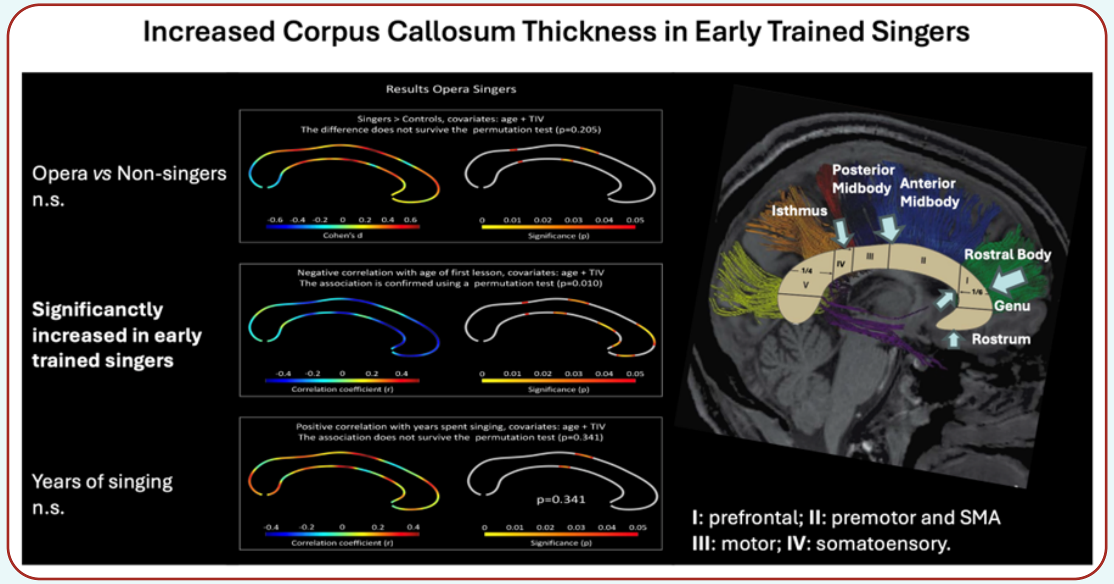

Figure 1. Findings show that early singing training correlates with increased callosal thickness in specific CC subregions, including the genu (prefrontal connectivity), the anterior-posterior midbody (sensorimotor integration), and the isthmus (auditory processing).

(Fig. 1). Together, these data highlight the significance of early and continued vocal training in inducing neural adaptations that bolster interhemispheric communication, specifically impacting CC subregions that subserve cognitive and embodied multimodal sensorimotor processes relevant to singing.

Altered responses to vocal vibrato in opera singers

Staying within the realm of singing, a collaboration between Associate Professor Boris Kleber and the groups of Professor Zoltán Vidnyánszky at the HUN-REN, Brain Imaging Centre, Research Centre for Natural Sciences (Hungary) investigated the influence of long-term Western operatic singing training on the sensitivity and specificity of neural responses to familiar, style-specific perception of singing voices[7]. Using functional magnetic resonance imaging (fMRI) to probe the brain's response to vocal vibrato—a defining feature of operatic singing—this study examined trained opera singers and musically untrained controls listening to operatic versus natural singing voices. Findings revealed that opera singers exhibited enhanced responses to operatic singing across bilateral auditory cortical regions and the default mode network (DMN), including the precuneus/posterior cingulate cortex (pCunPCC), medial prefrontal cortex (PFCm), and left inferior parietal lobule (IPL) (Fig 2). Conversely, controls showed significant activations predominantly within the auditory cortex. Subsequent region of interest (ROI) analysis confirmed these differences in response to operatic versus natural voice stimuli, with opera singers showing a unique activation pattern within the DMN regions. This pattern suggests an embodied cognition framework, where extensive vocal training not only fine-tunes the auditory

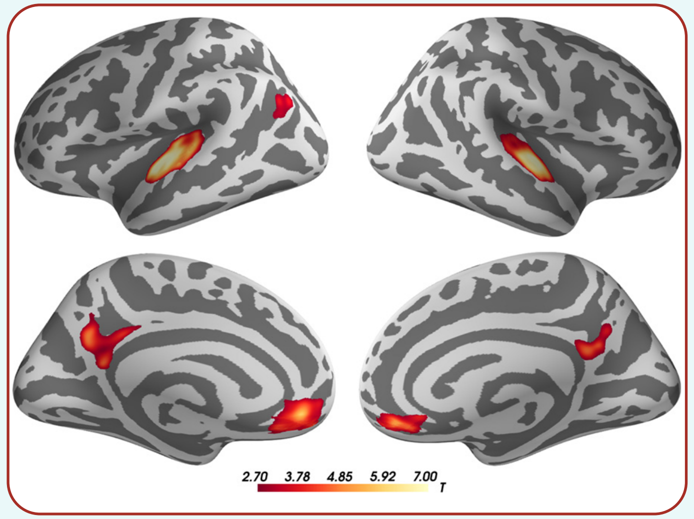

***Figure 2.** fMRI results reveal that trained opera singers exhibit differential activations in bilateral auditory cortical regions and the default mode network (DMN) when listening to operatic singing with vibrato compared to a straight voice. In contrast, musically untrained controls show differences only in bilateral auditory cortex. These findings suggest that operatic singing training induces experience-dependent neural changes, engaging self-referential networks linked to the embodiment of vibrato as a salient acoustic feature[7]*

system for style-specific acoustic characteristics of operatic singing but also implicates a multimodal processing network integrating sensory, motor, and cognitive aspects of musical experience.

Studying the embodied perception of operatic singing, this research moreover contributes to our understanding of the neural mechanisms of multimodal integration and the role of the DMN in processing complex, self-relevant auditory information.

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MULTIMODAL THEME

Cecilie Møller

Spontaneous motor tempo influences perception of pitch and temporal regularities in music.

Multimodal rhythms are all around us. Many everyday events and actions display stable rhythmic patterns, such as walking, talking and making music. The rates at which individuals perform such actions vary considerably. For instance, when asked to tap our fingers on a table-top at a comfortable regular pace, some people will do so at a rather slow rate while others may naturally tap at faster rates. Researchers have used such simple finger-tapping tasks to assess participants' spontaneous motor tempo (SMT) and their wide inter-individual variability, and they have sought to characterize ways in which SMT relate to individual factors such as age[1] and musical experience[2] and to more fluctuating contextual factors such as arousal level[3] and time of day[4].

Spontaneous rates tend to cluster around 500-600 ms and overlap with average perceptual preference for musical tempo[5,6], indicating that the SMT reflects the activity of an intrinsic timekeeper that underlies not only rhythmic motor behaviors but also preferred perceptual tempo, as proposed by the *preferred period hypothesis*[1]. Endogenous rhythms facilitate detection of events in our environment because they influence our brains' sensitivity to sensory information structured in time[7]. Their functional relevance is evident, e.g., in musicians who show smaller asynchronies when performing a piano piece at their preferred rate[8]. As such, investigating SMT is beneficial for gaining insights into the intrinsic temporal processing that underlies prediction and perception across various modalities.

While previous studies have assessed the stability of spontaneous rates within specific domains, e.g. music production, comprehensive studies simultaneously assessing several spontaneous rates across domains are rare. At MIB, we are currently investigating how SMT and other spontaneous motor rates relate to each other within participants, and how individual differences in such rates relate to perceptual and cognitive processes more generally.

Stability of spontaneous rates across domains within participants

In one behavioral study conducted at Aarhus University's COBElab by BA student Ben Engler from University of Salzburg, we assessed the spontaneous rates of 60 participants during walking, clapping and music making and during tapping under different conditions (online several times over the course of the day and in the lab, with and without sound production)[9]. For the

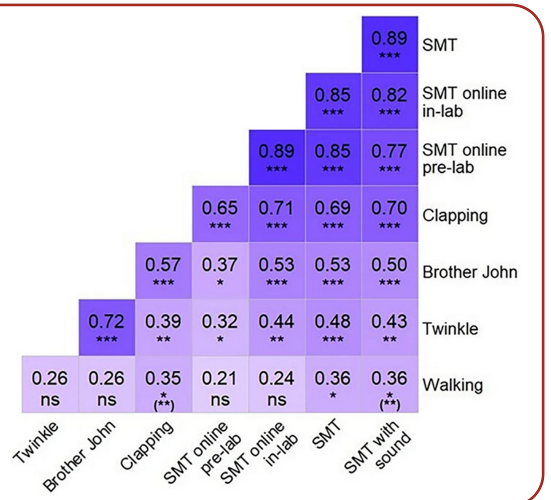

***Figure 1**. Heatmap displaying Spearman rank correlations between all spontaneous rates with FDR-corrected significance levels and uncorrected levels in parentheses. Significance level indicated by asterisks: ns = not significant, p > = .05; * p < .05; ** p < .01; *** p < .001. Fig 2 from Engler et al., (2024)*

music making task, we developed a paradigm which allowed participants even without musical training to play simple well-known melodies by tapping on a device. Judging from participants' comments after the experiment, this task was particularly engaging.

Results showed highly consistent rates across these different domains of behaviour (Fig. 1), indicating the existence of a common underlying timekeeper, which guides a highly diverse set of spontaneous rates. Notably, music production rates correlated with all clapping and tapping rates. Even when constrained by a musical context in which only a certain range of tempi is meaningful, relative differences in SMT between participants are evident, showing the impact of SMT on tempo preferences in production of musical melodies.

SMT influences beat perception in polyrhythms

The effect of SMT on perception of musical rhythms, specifically beat perception in polyrhythms, was investigated in another study using only online data collection[10]. When tapping or clapping along to the regular beat of a musical piece, listeners choose one of several possible metrical levels, each characterized by distinct rates. In polyrhythms, two metrical structures co-exist. This unique configuration not only offers a diverse range of metrical levels to tap along with but also minimizes the tempo difference between them. This makes polyrhythms ideal stimuli for assessing subtle effects of tempo on beat perception, whether the tempo of interest is stimulus-driven or internally generated within the perceiver.

To assess stimulus-driven effects, we previously asked online participants to tap along to different kinds of polyrhythms played at different tempi. We showed that regardless of tempo, listeners limit tapping to pulses that admit binary (1-and-2-and-3-and…) rather than ternary (1-and-then-2-and-then-3-and-then…) grouping of subdivisions[11]. In the new study, we kept the stimulus tempi constant and assessed the extent to which participants tapping behaviour related to their SMT as measured before the experiment.

The results showed that indeed SMT significantly predicted participants' tapping behaviour. Specifically, in 2:3 polyrhythms, the probability of

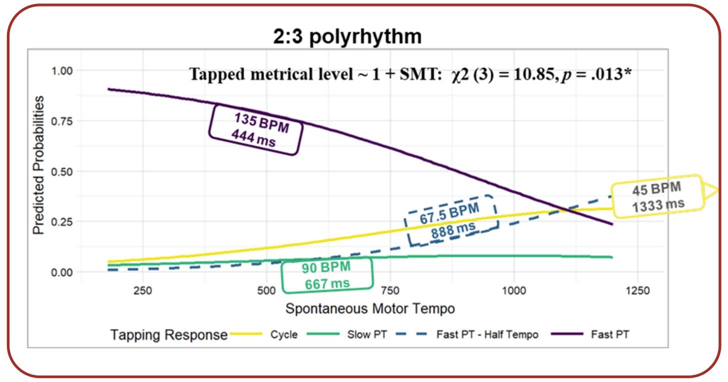

Figure 2. Predicted probabilities of tapping in time with different metrical levels depending on SMT. Adapted from Stupacher et al[10]

synchronizing with the fast 3-pulse train (binary subdivisions) was larger for participants with faster SMT (Fig. 2). In comparison, participants with slower SMT were more likely than participants with faster SMT to tap every other beat of the 3-pulse train (binary subdivision) or even the very slow cycle level, i.e. the shared initial downbeat. Owing to the ternary grouping of subdivisions, participants generally avoided synchronizing with the 2-pulse train.

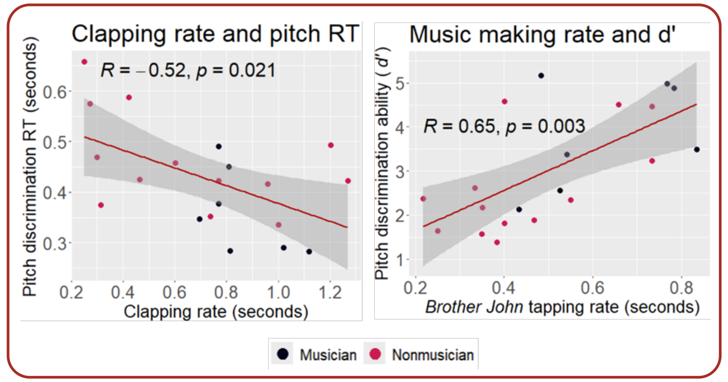

Figure 3. Spearman rank correlations between spontaneous rates and pitch discrimination abilities. Pitch presentation rate is 550 ms for all participants. (Manuscript in prep.)

These findings indicate a connection between individuals' natural movement pace and how they perceive the tempo of musical beats. They also refine the notion of a common preferred tempo of around 120 BPM[5]. While rhythmic accents in music can draw listeners away from this tempo[12], our use of unaccented polyrhythms elucidates how the stimulus-driven binary subdivision bias and individual variations in SMT interact to draw listeners towards metrical levels that fall beyond the common tempo preference.

Slower tappers detect smaller changes in pitch

Occasionally, data draws researchers towards ideas that fall beyond common expectations. In the lab study described above, participants also completed a series of pitch discrimination tasks to assess if anchoring the rate at participants' individual SMT increases sensitivity to pitch changes. While this main hypothesis was not confirmed, interestingly, participants with slower rates responded faster and were capable of detecting smaller changes in pitch (Fig. 3).

One interpretation of these incidental findings of an association between pitch discrimination abilities and spontaneous motor tempo is that individuals with slower SMT are better able to utilize rhythmic environmental cues for guiding perception and optimizing pitch discrimination performance. This is in line with results of a recent study which assessed individual differences in rhythmic modulation of visual discrimination and found that modulation was stronger in participants with slower compared to faster spontaneous tempi[13]. Of course, spontaneous rates may also be directly related to increased sensory processing abilities, or the association may be driven by better allocation of attentional resources leading to better test-taking abilities more generally. Identifying the mechanisms underlying this first empirical evidence of better performance on pitch discrimination tasks in participants with slower SMT will be addressed in future studies specifically designed to test the influence of SMT on perceptual sensitivity in audition and other modalities.

To sum up, the work on spontaneous rates undertaken at MIB in 2023 reinforces the idea of an intrinsic preferred period that extends across both music perception, music production and motor domains[1]. The correlations observed among the eight different kinds of spontaneous rates (Fig. 1) extends previous findings of intra-individual stability, as they offer a more comprehensive understanding of temporal preferences across different behavioural domains and contexts within individuals. The new music making task, which was highly engaging according to participants' comments after the experiment, expands the scope of research by enabling the measurement of preferred music production rates even among non-musicians, a practice previously limited to musicians. This task can easily be applied as a short and fun addition to future studies in various domains in order to further investigate the intriguing relationship between spontaneous rates and multimodal perceptual sensitivity.

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MUSIC INTERACTIONS

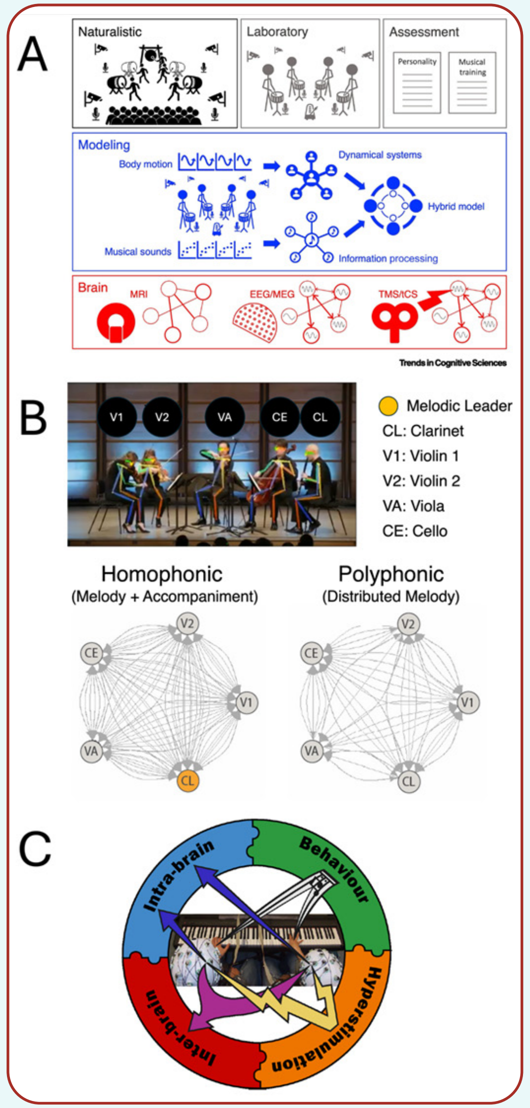
Peter Keller

MIB research on musical interaction addresses how the human brain supports sensory-motor and cognitive capacities that fulfill social functions related to interpersonal bonding and nonverbal communication through music. Work on this topic is guided by a research strategy that combines investigations of behavior in naturalistic settings and controlled lab studies with computational modeling and neuroscientific methods for probing brain structure and function[1]. The past year has seen advances in three key domains: (i) interpersonal synchronization, (ii) social entrainment, and (iii) communication.

Interpersonal synchronization

Musicians in groups coordinate their sounds with exquisite precision and flexibility. Such coordination requires interpersonal synchrony at the level of body movements and brain activity. Musicians produce 'instrumental' movements that directly trigger sounds and 'ancillary' movements, such as head motion and body sway, that are not necessary for sound production but nevertheless accompany performance and serve communicative functions[2]. Research conducted in collaboration with the University of Genoa has focused on links between ancillary motion and musical structure, particularly how musical texture affects the strength and directionality of coupling between co-performers. Musical texture varies from 'homophonic' structures with a hierarchical distinction between melody and accompaniment parts to 'polyphonic' textures with less clear distinction. Earlier work that used automatic pose estimation algorithms to track co-performer motion in concert videos of a string quartet and a clarinet quintet found that interpersonal coupling was stronger in polyphonic than homophonic textures, possibly due to evenly distributed (co-)leadership in the former[3]. A new study[4] tested this hypothesis by assessing the directionality of coupling between co-performers' body motion. Greater directionality was observed for homophonic than polyphonic textures, with the melody instrument influencing accompanying instruments more than vice versa (Fig. 1B). In addition to confirming links between leader-follower relations and musical texture, these findings demonstrate the sensitivity of automatic pose estimation techniques for studying the dynamics of interpersonal coordination in naturalistic videos.

Whereas the coordination of body movement is directly measurable, interpersonal synchrony at the level of the brain presents a more challenging puzzle. Enthusiasm for 'hyperscanning'—the simultaneous measurement of brain activity from multiple people, as increasingly done in musical groups, team sports and psychotherapy settings[5]—has been tempered by concerns that inter-brain coupling may be a side effect of shared sensory input and similar motor output[6]. Numerous articles have addressed technical aspects of analyzing hyperscanning data, but guidelines for dealing with conceptual issues and methodological questions concerning experiment design have been lacking. To fill this gap, together with researchers in the School of Communication and Culture, Aarhus University, we have published practical guidelines that cover fundamental questions, ranging from whether hyperscanning is appropriate for answering one's research questions to considerations for study design and data analysis[7] (Fig. 1C).



Social entrainment

Interpersonal synchrony promotes social processes that generalize beyond musical interaction to other domains of everyday life[8]. These transfer effects may stem from links between interpersonal synchrony and rhythm-related reward. Music based on a regular underlying beat with moderate levels of rhythmic complexity is temporally predictable[9] yet surprising and rewarding[10]. These qualities, which are maximized in groove-based music that encourages the pleasurable urge to move[11, 12], enable rhythm to provide a scaffold for social entrainment and motivation for prosocial behavior[13, 14]. Assistant Professor Jan Stupacher's recent work investigating relations between rhythm and social connectedness suggests that shared, predictable movement patterns facilitated by high-groove music enhance trust and affiliation, while rhythmic deviations allow for unpredictable expressions of individuality[15].

Figure 1. (A) Telescopically tiered research strategy combining behavioral measures, computational modeling, and brain imaging and noninvasive stimulation techniques to investigate musical interaction. (B) Effects of musical texture on leadership dynamics assessed by using Granger Causality to quantify directional information flow in co-performers' body motion during an ensemble concert. (C) Studying the neuroscience of musical interaction benefits from complementary levels of analysis (inter-brain, intra-brain, and behavioral) and complementary techniques (hyperscanning and hyperstimulation).

Social effects of interpersonal synchrony may be especially potent in large groups[16], like live concert audiences. Practical challenges of manipulating coordination en masse can be circumvented by virtual reality setups. A study with collaborators in Germany and Spain used a virtual group walking paradigm to investigate how synchrony

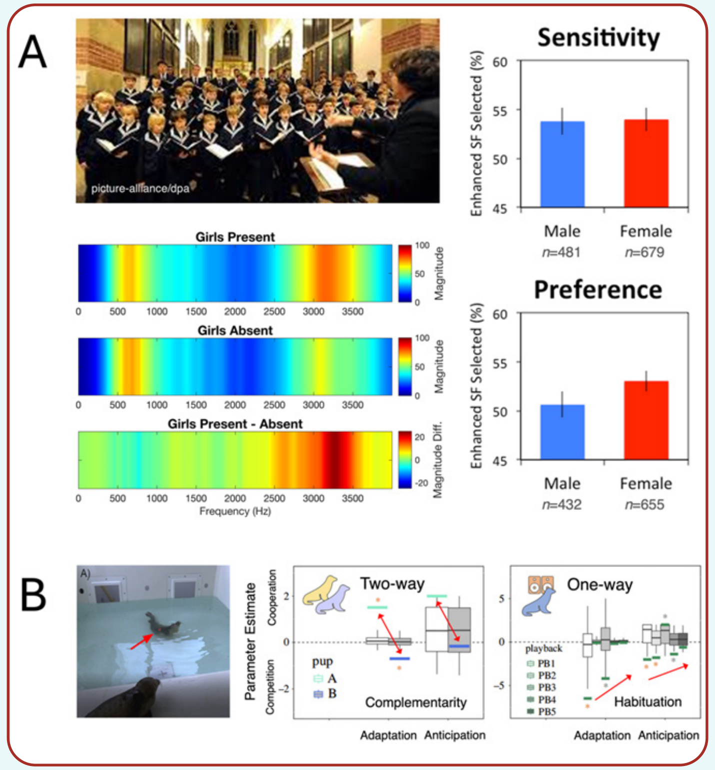


Figure 2. (A) An online study found that female and male listeners were similarly sensitive to increased high-frequency spectral energy in choirboys' voices elicited by girls in an audience, but only females preferred the enhancement. (B) Computational modeling revealed that two-way interaction between seal pups is characterized by complementary patterns of adaptation and anticipation while one-way interaction with recorded playback leads to weakening adaptation and anticipation indicative of habituation. Colored bars are model parameter estimates for seals and grey boxes are chance estimates from randomly permuted data.

and similarity with partners influences the balancing of psychological representations of self and others[17]. Participants synchronized their footsteps with a metronome while listening to the sounds of eight virtual partners walking at the same or different tempi with similar or different sounding footwear. Coordination was best, presumably due to optimal self-other balance, when participants heard distinct but synchronous virtual others, and this was associated with feelings of enhanced strength and happiness. Extending this paradigm to group dance and virtual concert participation is a promising avenue to test hypotheses about effects of group size on social entrainment.

Communication

Communicative functions of interpersonal synchrony and social entrainment can transcend individual lives to shape culture and possibly drive evolution. Such transformative effects are facilitated by ritualistic practices, where the potency of collective experiences is augmented through group music-making and dance. In a landmark publication, PhD student Olivia Foster Vander Elst presents a conceptual framework and systematic review that provides a blueprint for research on the neuroscience of dance[18], which has received less attention than music despite often being inseparable. Indeed, to the extent that both activities engage common brain networks involved in perception, action, memory and emotion[11], they together support sustained knowledge and hedonic pleasure cycles that enable effective communication of thoughts and feelings while promoting the eudaimonic sense of wellbeing[19].

Although research on musical communication usually focuses on cooperative forms of coordination, evidence is mounting for the relevance of competitive mechanisms. A study with the St Thomas Choir of Leipzig found that the basses—the oldest boys with deep voices—boosted their acoustic prominence by increasing energy in a high-frequency band of the vocal spectrum when girls were in an otherwise male audience[20]. A recent follow-up study tested female and male sensitivity and preferences for this subtle vocal modulation in large-scale online listening tasks[21]. Results indicate that, whereas female and male listeners are similarly sensitive to enhanced high-spectral energy elicited by the presence of girls in the audience, only female listeners exhibit a reliable preference for it (Fig. 2A). In apparent analogy to collective signaling animals like crickets and frogs[22], group singing appears to be a flexible form of social communicative behavior that allows simultaneous group cohesion and sexually motivated competition. This parallel highlights the value of cross-species comparison in generating hypotheses about the evolution of human musical capacities[23].

Along these lines, a proof-of-concept study with seal pups used complementary methodologies to test how the presence and type of a vocalizing partner affect rhythmic patterns of interactive communication[24]. One method, which has been used extensively with humans[25], involved the computational modeling of temporal adaptation and anticipation processes. Two-way interaction between seals was characterized by complementary patterns of adaptation and anticipation, leading to consistent non-overlap between calls (which helps to attract their mothers' attention)[26]. However, presenting non-interactive audio recordings across a series of trials led to behavior suggestive of initially testing its reactivity but eventually losing interest upon learning that the playback is non-responsive (Fig. 2B).

While comparative work examining similarities and differences across species sheds light on the evolutionary origins of musical communication, within-species variations in musical capacities are potentially informative about cultural development[27]. Related research by Associate Professor Massimo Lumaca explores the implications of such diversity, and its bases in variations in brain structure and function, for musical innovation and stylistic evolution that characterizes the formation of cultural traditions (see p. 27).

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MUSIC INTERACTIONS

Massimo Lumaca

How Brain Asymmetry Drives Musical Innovation and Diversity

How do cultural traditions stay stable, yet also evolve over time? Part of the answer lies in our ability to pass information accurately from one person to another[1]. Music, with its long history of being orally taught and shared across people, demonstrates this process effectively. Whether it is parents singing lullabies to their offspring or musicians jamming together, sharing music preserves traditions while subtly making room for new twists that lead to fresh styles and forms. A key question follows: do the brains of true 'transmitters' – who meticulously recreate music – look different from those of 'innovators'? If so, tiny differences in brain structure and function within a population may ultimately have a profound effect on large scale cultural phenomena, such as stability and diversification[2].

In past work, we put this hypothesis to test using brain scans and a musical transmission experiment, the signaling games[3] (Fig. 1A). In this game, a musical 'sender' and 'receiver' repeatedly interact, trying to create a shared musical language —a common artificial musical system consisting of tone patterns mapped to emotional labels. It blends aspects of social interaction models with the complex transmission dynamics of 'Chinese-Whispers' experiments. In this experiment, each participant played the game twice, first learning the musical system (game 1), then transmitting it to someone else (game 2). We examined their skills in coordination (social learning), transmission (how faithfully they reproduced the music) and innovation (adding new elements). We found that the strength of interhemispheric auditory connectivity – how well left and right auditory brain regions sync up at rest – predicted musical accuracy[4]. Those introducing changes tended to have weaker functional links. A physical 'bridge' called the callosal splenium lets these brain areas "talk" to each other. In a second study, we observed that callosal splenium fibers tended to be less 'robust' in innovators[5]. These results show that less efficient left-right auditory communication may hinder accurate copying of sounds and introduce new variants in the musical pool.

In our most recent work[6], we further explored the role of auditory asymmetries – the fact that the left and right auditory cortex are not perfect mirror structures, but differ in volume and thickness[7]. These asymmetries influence how hemispheres divide labour for integrating musical sounds and, ultimately, how these sounds are perceived and learned. We analysed neuroanatomical images and computed an asymmetry coefficient for three key regions of the auditory cortex: the planum temporal, the Heschl's sulcus and the Heschl's

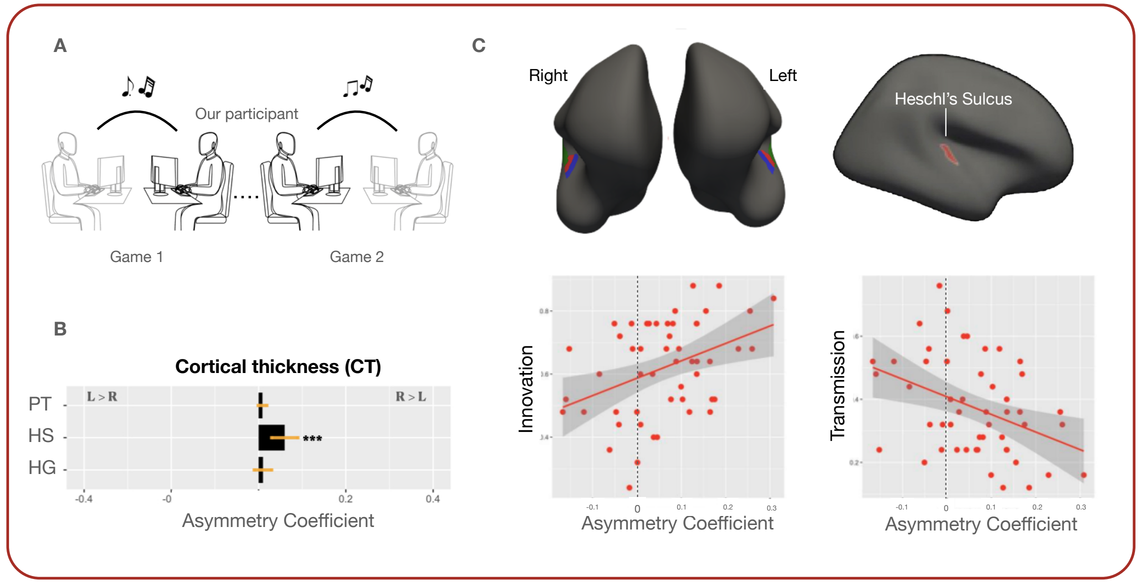

Figure 1. Neuroanatomical asymmetry in a primary auditory region predicts innovation and transmission in signaling games. A) Experimental design of signaling games. Each participant plays two games: in the first game, they play as a receiver (learner) of an artificial melodic system; in the second game, the player's role changes to that of a sender (transmitter), and they are asked to reproduce the original sounds as faithfully as possible. B) Average regional asymmetries in cortical thickness across three auditory-related cortical regions: Planum Temporale (PT), Heschl's Sulcus (HS) and Heschl's Gyrus (HG). C) Asymmetry of cortical thickness (CT) in Heschl's Sulcus predicts intergenerational innovation and transmission. At the top is Heschl's sulcus projected on the inflated average surface of the right hemisphere. Each point in the scatterplots represents a participant (N=52)

gyrus. This coefficient is positive for rightward asymmetries (right auditory cortex is larger, or thicker, than the left) and negative for leftward asymmetries (left is larger or thicker than right). Most people, as shown in previous work, have a slightly thicker right side in the Heschl's sulcus (Fig. 1b). Crucially, this asymmetry was much more pronounced in innovators. (Fig. 1c). In conclusion, weaker interhemispheric auditory communication and less balanced interhehemispheric auditory integration could create challenges for accurately processing music during learning. This would lead to potential changes as the music is passed along.

Historically, we have looked at how musical diversity springs from cultures blending –consider how composers like Debussy actively infused Western music with Asian musical elements, or how George Gershwin fused classical music with the harmonies and rhythms of American jazz. Our findings suggest that also individual (neuro)biology matters, no matter if someone is (or is not) a professional musician. Small brain variations in a population may act as numerous seeds of change, fueling the ever-evolving styles of music. This research underscores the complexity of music's evolutionary trajectory, highlighting how brain pressures, in addition to socio-cultural factors, may affect the continued transmission of music. It shows the utility of experimental models of social interaction to understand large-scale cultural phenomena, with implications that go beyond dyadic communication[8]. This line of studies advocates for an expanded theoretical framework that considers both biological and cultural pressures to fully understand the dynamic genesis of musical diversity.

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MEANING OF MUSIC

Elvira Brattico & Morten Kringelbach

Meaning for music... and music for meaning? Making sense of sounds in the world of 'intelligent' machines.

In 2022 OpenAI introduced to the world what became the most powerful generative AI tool, ChatGPT, which generated a lot of hot air and highly inflated claims about the power artificial intelligence, seemingly primarily aimed at keeping stock prices high for companies involved. The argument made by tech companies is that AI is creating an epochal turning point, reminiscent of the introduction of the Personal Computer in the 80s or of the smart phone in the 2000s. Importantly, however, the machine learning technology underlying ChatGPT has been widely studied since the 1980s, and recently only the scale of the underlying networks and the availability of large training sets of data (seemingly illegally) harvested from newspapers and books have changed. The technology is driven by large server farms which are consuming untold energy to perform the feats that are not comparable of human feats but have captured the public imagination. While mostly ignorant of the underlying technology, some philosophers, entrepreneurs, scientists, artists and economists have expressed worry about a potential future where machines could surpass human intelligence. Others have pointed out this is unlikely given the rather meagre feats of learning performed by these networks on an energy budget many orders of magnitude larger than that available to biological brains. Still others have argued that these artificial machines will never be able to have a sense of self and to conceive a meaning for their own life[1].

Seen in this context, our research theme focusing on the meaning making in music can shed new light. It is certainly true that the active updating of models that allow us listeners (or performers) to attribute a sense to the music we are hearing thanks to learning and predictive processing could in theory be mimicked by a machine (see Fig.1 for an imaginary illustration of this)[2]. Such learning processes are also contributing to the shaping of cognitive biases shared within a societal group, hence dictating how the perception and classification of for example melodies within and between musical cultures[3] (see page 36), although always starting from neurobiological[4] and genetic[5] constraints.

Our studies also use machine learning techniques to study the formation of short-term or longer-term episodic memories of melody sounds. For instance, we used them to classify memorised versus new motifs of a Bach prelude from MEG data[6].

But crucially these models are not embodied and far from possessing sense organs and multisensoriality, or a flesh-and-bones body, nor a sense of self, and possibly can never have them. As such, in music, the capacity to predict and create meaning from incoming sounds via learning and active inference cannot yet be mimicked by machines.

Figure 1. AI generated image representing a machine making music (PromeAI).

Meaning of music from all the senses

Instead, think about the importance of embodiment for meaning making in music. For example, when we attend a concert, music acquires meaning while listening, but also thanks to the surrounding environment, the other people, the lightning, the physicality of the artist and her gestures. The sounds alone contribute to the sense making but become even more meaningful when they are inserted in the situation, when they serve an affective, social or cognitive purpose for the listener, and when they come along with gestures and images[7]. Empirical evidence for the multisensoriality and embodiment of the musical aesthetic experience (cf.[8]) include, for instance, aesthetic appreciation enhanced by audio-visual information[9] or eye contact between the artist and the audience[10].

We have tested whether predictive processes and sense attribution could blend across senses[11]. We aimed to determine whether semantically meaningful (representative) primes in one modality would top-down modulate the responses to abstract (non-representative) targets in another modality. The prime-target pairs were either positively and negatively congruent or incongruent in their affective content and could be either conveyed via the auditory or the visual modality. The results confirmed the hypothesis: for the visual targets, the P1 amplitudes were larger when the auditory prime valence was congruent compared to incongruent, and the N1 amplitudes were larger when the auditory prime valence was incongruent compared to congruent; in turn, for the auditory targets, larger P2m amplitude was observed for incongruent compared to congruent positive visual prime valence, confirming the interaction between modalities of sensory inputs during the predictive processing of aesthetic stimuli.

Making meaning of music from the whole body
The lack of embodiment is a key difference between humans and any existing machine learning entity. Most do not possess a body, and even when they do possess it as in the case of robots, they do not have awareness of their body. The continuous adapting and monitoring of posture and body in musicians is a corollary of active inferring sounds to come, how to produce them, and how they can affect own internal states and emotions. In a study by Zamorano et al. (submitted), we demonstrated that the interoceptive abilities of tracking the heartbeat and pain threshold in musicians are superior to those of non-musicians and alike the ones possessed by athletes, who are also involved in an intensive sensorimotor training.

The body also contributes to dancing and the experience of groove. The active anticipation of rhythms and harmonies with our body is of course orchestrated by the brain. and specifically in networks linked to reward such as in the ventral tegmental area and nucleus accumbens and mediated by dopaminergic neurotransmission. This cyclical phenomenon feels highly meaningful as well as both fun and motivating[12,13]. This groove phenomenon in adults can be described and hence simulated with a quadratic function between specific musical parameters and the induced pleasure and drive to move[14]. However, the phenomenon is of course dependent on learning and on the interaction between the brain and body across the lifespan. MIB is unravelling the complexity of groove by studying several different populations. For instance, a longitudinal study with preadolescents indicates that rhythm complexity drives more the groove response than harmony complexity, possibly due to the slower curve of acculturation with tonality and harmony (Stupacher, Lippolis et al. in preparation). Addiction to drugs can also alter the quadratic function of groove (Vuust, Brattico et al. in preparation).

Overall, the individual sensitivity to the various kinds of musical pleasure and reward, such as social reward, sensory-motor drive to move, absorption and so on, depends on unique human body/brain/mind characteristics[15, 16].

Meaning of music and music for meaning of the self
Music often leads to highly meaningful experiences, and this is perhaps strongest under the influence of psychedelic drugs. Interestingly, these psychedelic experiences are often linked to a sense of ego dissolution, yet deeply meaningful. Together with some of the foremost psychedelic researchers, MIB has been pursuing a deeper understanding of the orchestration of meaningfulness, towards promoting innovative therapeutic approaches combining music with controlled psychedelic use[17].

Overall, we propose that music is a reflection of our very humanity and can serve for self-knowledge, introspective thinking and, in general, for the formation of the self and cultural belonging, especially in adolescence[18]. Indeed, the same mental and brain processes enacted during the mental journey in time and space that allows to form a sense of self and self-worth are also enacted during music listening and meaning formation

Figure 2. Elderly participants of an intervention study currently ongoing in Italy during a music theatre performance.

for music. Specifically, during music listening the default mode network (DMN), a neural circuit between medial cortical regions related to mental states of self-awareness and introspection, is more connected[19]. The DMN allows integration of all the information of the ”diachronic” self (the set of experiences, experiences, emotions, mental states memories that belong to us and that we have experienced throughout our entire lifespan) with the ”synchronic” self, that is, the self in the current moment. This leads to the experience of a self characterised by coherence, continuity and stability and finally to the sense of identity that we are ”one”, the same person over time despite all the changes in our psychological and physiological characteristics[20]. As described by us[21] listening to music has the ability to affect the connectivity in the DMN, and this is phenomenologically linked to the experience of mind-wandering, self-reflection and possibly self-formation in the developmental age.

When memory goes, musical meaning stays
This also means that the role of music for formation of the self and meaning in life continues across the lifespan. Our studies on elderly individuals demonstrate some resilience in the brain processes supporting music perception and memory even with ageing. While behavioural evidence confirms the age-related cognitive decline in specific memory tasks (although mediated by music training), such as discrimination of rhythmic sequences, recognition of learned melodies and numerical working memory[22], neurophysiological measures provide an even more complex picture. In our recent study[23], elderly participants listened to repetitive musical melodies of medium complexity and to real music of high complexity. For the medium complex music, older participants had reduced brain responses to sound onsets, but for highly complex musical stimuli these reductions were less evident. One could speculate that the richer value and meaning of the music as compared to artificial laboratory stimulus might activate the brain more efficiently even in presence of the inexorable cognitive decline of the older age, shedding light on the neural mechanisms responsible of the positive effects of music interventions in ageing (Fig. 2).

Taken together, then, music is a unique human endeavour, and while so-called AI has made some progress in natural language production, this has not been mirrored by progress in machine-made music. Even if given a large musical corpus, it is not clear that machines will ever be able to make music that will be experienced as meaningful by humans. Instead, the study of meaning making in music is bound to tell us more about how the human brain is orchestrating the necessary pleasure for a flourishing life.

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ICMPC 2023

The 17th International Conference on Music Perception and Cognition (ICMPC) took place at Nihon University College of Art in Tokyo, Japan 24-28 August 2023. A large group from MIB attended. During the conference they chaired three symposia as well as presented a symposium in addition to numerous posters.

Victor Pando-Naude (*An fMRI Study on the Groove Experience in Parkinson's Disease*) and David Quiroga (*The Neural Representation of Musical Thoughts*) won two out of three Young Researcher Awards.

The Young Researcher Award is awarded to students and young (meaning "new") researchers who submit a high quality research paper and demonstrate the potential to be leading researchers in the field of Music Perception and Cognition.





MEANING OF MUSIC

Mathias Klarlund

Decoding cultural complexity in music through predictive models

Music allows a blurring of both linguistic and geographical boundaries making it a suitable strategy for studying cross-cultural dynamics. From ethnomusicology to neuroscience, the world's music reveals depths of complexity that transcends mere compositional techniques. As such, cultural idiosyncrasies act as yet another layer of complexities in music, adding to the already existing sophistication of rhythms, harmonies and melodies[1]. But whereas a perceived understanding of these musical structures correlates with musical training[2], perceived cultural complexity arises from the familiarity with the musical idiosyncrasies of different cultures' music[3]. For example, Chinese music is famously rooted in the pentatonic scale, allowing for generally greater intervallic jumps throughout melodies, simpler harmonic structures with distinctively different cadences as normally seen in traditional Western music.

Central to understanding these complexities is the framework of predictive coding of music[4] . Predictive coding posits that the brain continuously generates and updates predictions about sensory input, based on a lifetime of accumulated experiences. In the context of music, these predictions originate from an internal model that is intricately shaped by the musical conventions of the culture one has grown up in. As such, for an enculturated human being, making precise predictions about the melodic progression of music is crucial for the overall perception and enjoyment of music[5]. However, as the predictive models are rooted in one's musical enculturation, making predictions about the music from another culture, say a Western listener aiming to make sense of Chinese music, may inherently come across as less precise. This is because the listener's predictive model, refined through consistent and cumulative exposure to Western music may not readily align with the structural and tonal principles of Chinese music. From childhood lullabies to the melodies that occasionally fill supermarkets and public spaces, these musical experiences collectively shape an implicit understanding of Western music conventions[6].

The cultural distance hypothesis

This conceptualization of perceived complexity in music has been formulized in the 'cultural distance hypothesis' (CDH)[7]. A hypothesis adhering to the laid framework of predictive coding stating: "*the degree to which the musics of any two cultures differ in the statistical patterns of pitch and rhythm will predict how well a person from one of the cultures can process the music of the other*."[7] In other words, the difference in musical idiosyncrasies between cultures will determine the precision of an enculturated listener's prediction. CDH is an hypothesis that has gained further scientific merit after the emergence of computational modelling, specifically the Information Dynamics of Music (IDyOM) model[8], which has proven pivotal in bridging the gap between theoretical neuroscience and empirical ethnomusicology. IDyOM is a variable-order Markov model that employs both long- and short-term models to predict musical expectancy. When trained on a large corpus of music from a given culture, it simulates an enculturated listener by calculating the likelihood of each note at any given temporal position of a melody. By comparing the averaged note-to-note predicted expectancy of a melody between IDyOM models trained on two culturally distinct corpora, a computational quantification of the CDH emerges, providing a metric for evaluating how far or near a melody lies from enculturated listening expectations.

Testing empirically predictive processes for own vs. other's music

Utilizing the computational operationalization of cultural distance, the groundwork for an empirical validation of the cultural distance theory was laid out. As such, Klarlund et al.[9] investigated how listeners from Chinese and Central European (i.e., Western) backgrounds perceive and ultimately categorize melodies at the extremum points of the cultural distance spectrum. The study labelled a set of melodies into two groups per culture - ambiguous and unambiguous melodies - resulting in four distinctly labelled categories of melodies. Ambiguous melodies were defined as those with similar levels of IDyOM predicted note expectancies (and thus, familiarity) for both Chinese and Western simulated enculturated listeners, representing a low cultural distance. In contrast, unambiguous melodies were identified as those aligning closely with the statistical regularities of one culture's music but the other, indicating a high cultural distance. The

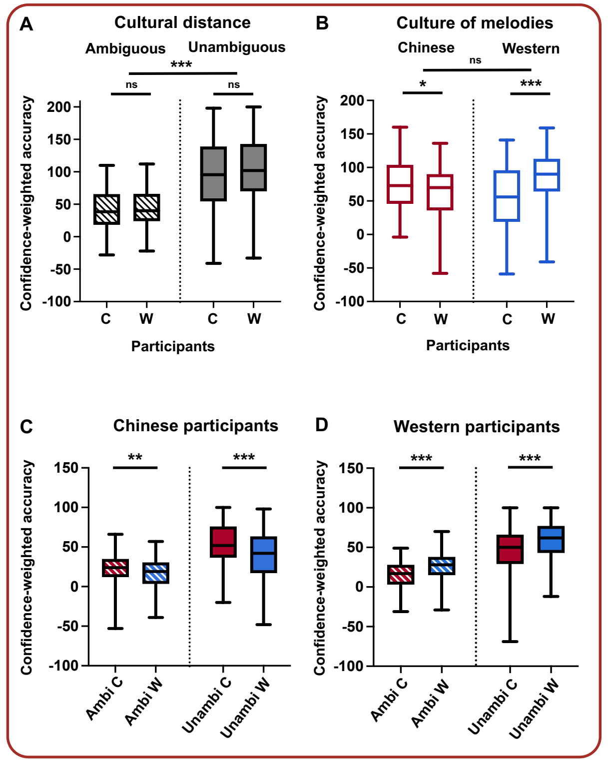

Figure 1. Categorization accuracy influenced by cultural distance in Chinese and Western participants. *(**A**) Accuracy for ambiguous (cross-hatched) and unambiguous (solid) melodies for both groups. (**B**) Accuracy for Chinese (red) and Western (blue) melodies by group. (**C-D**) Accuracy for ambiguous (cross-hatched) and unambiguous (solid) Chinese (red) and Western (blue) melodies in respective participant groups. Significance levels are denoted as ***p < .001, **p < .01, *p < .05,ns > 0.05.*

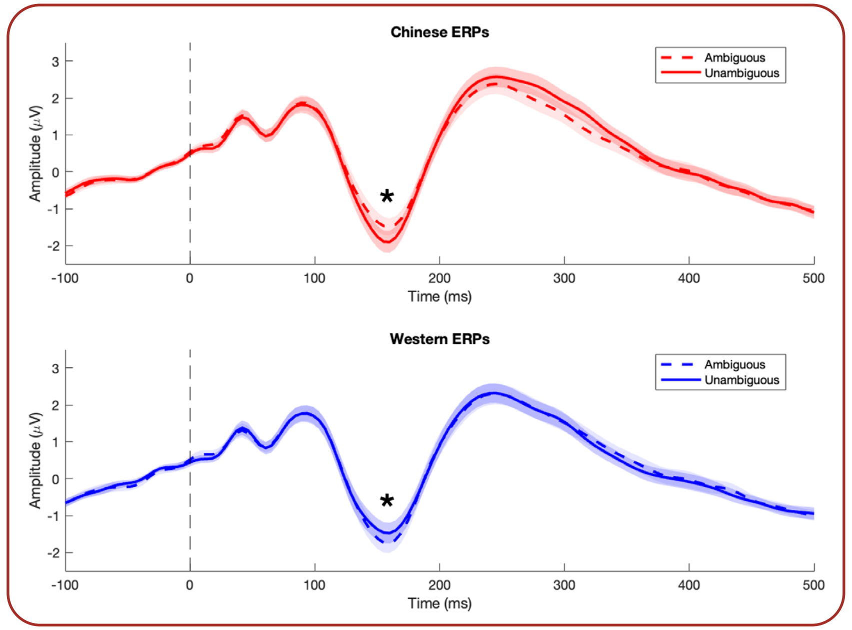

Figure 2. Event-related potentials (ERP) for individual notes in melodies from Western and Chinese origins across two levels of ambiguity. (Red) ERPs for Chinese melodies shown in red, with ambiguous (dashed) and unambiguous (solid) notes, and standard error of the mean (SEM) depicted by shaded areas. (Blue) ERPs for Western melodies in blue, with ambiguous (dashed) and unambiguous (solid) notes, including SEM (shaded fill).

main hypothesis of the study was that listeners would exhibit a higher accuracy in categorizing unambiguous melodies from their own culture, reflecting an in-culture advantage driven by the listeners' enculturated predictive models.
A total of 199 subjects (Chinese: n = 100, Western: n = 99) participated in the study, and subjects were prompted with categorizing the melody they listened to as either Western or Chinese, followed by 1-5 rating of how confident they were in their categorization. Utilizing a metric that weights the binary categorization accuracy with the confidence rating, the results revealed a pronounced in-culture advantage for both groups of participants.

As visible from Fig.1, Chinese listeners demonstrated significantly greater categorization performance in identifying Chinese unambiguous melodies than Western unambiguous melodies. Conversely, Western listeners exhibited a similar pattern of results, achieving a greater categorization performance for unambiguous Western melodies than that of Chinese unambiguous melodies. Together, these results underscore the role of enculturation in predictive models driving music perception.

Alongside the pronounced in-culture advantage demonstrated for unambiguous melodies, the study also yielded surprising results for the ambiguous melodies. The low cultural distance inherent in ambiguous melodies were hypothesized to dilute the in-culture advantage to an extent, where categorization performance differences between participant groups would be non-existent. Contrary to these expectations, listeners from both cultures managed to categorize ambiguous melodies with an adept level of proficiency. These findings not only validate the predictive coding theory of music as an appropriate framework to address cultural complexity in music perception, but also provides thought-provoking insights into how cultural nuances of music can transcend statistical patterns to help drive perception.

Future directions: the neural underpinnings of culture-based predictions

In a follow up study, Klarlund et al. (in prep.), have delved deeper into the neural mechanisms underlying cultural distance. With a similar experimental design, this study utilized electro-encephalography (EEG) on 30 novel Chinese participants to investigate the N1 complex as a neural signature of melodic surprise. The N1 is a component of the eventrelated potential known to be sensitive to violations of auditory expectancy. Preliminary analyses of the N1 in response to melodies have revealed distinct patterns based on their cultural congruency. As illustrated in Fig. 2, for Chinese melodies, the N1 deflections are notably more substantial for unambiguous melodies compared to ambiguous ones, suggesting that unambiguous melodies, which are more aligned with the participants' music enculturation, elicit a stronger neural response due to their deviations being more unexpected within their cultural context.

Conversely, a fascinating reversal occurs with Western melodies: ambiguous Western melodies elicit a more pronounced N1 response compared to their unambiguous counterparts. This could imply that the ambiguous Western melodies bear a closer resemblance to the musical structure of Chinese melodies, thereby inducing a stronger surprise response. In contrast, unambiguous Western melodies, being the most culturally distant from the Chinese participants' music enculturation, might not cause as significant surprise, due to the imprecision of the prediction in the first place. Cross cultural music researchers share the endeavour of trying to understand the differences across geographical boundaries to ultimately get closer to a universal understanding of human auditory perception. In this pursuit, looking at foreign culture's music through the lens of cultural distance, brain recordings and the added complexity of foreign musical conventions may substantially contribute to our general understanding of how we decipher and find meaning in complex music.

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MEANING OF MUSIC

Elisa Serra

Neurophysiological correlates of short-term recognition of sounds: Insights from magneto-encephalography.

Understanding the dynamic processes of information retrieval and updating within the brain is a central focus in memory research. Recently, it has been proposed that memory functions could be studied through the lens of information processing theories, such as Predictive Coding (PC)[1]. PC explains how our brain efficiently interacts with sensory scenes and suggests that the brain acts as a generative system, comparing internally generated predictions shaped by templates of previously encoded stimuli against incoming sensory data[2]. Prediction errors, arising from discrepancies between top-down predictions and bottom-up sensory inputs, drive the updating of expectations in the neural hierarchy. This continual integration of anticipation and processing forms a Bayesian-like heuristic framework in PC[3].

Here, we describe a study that we conducted at Center for Music in the Brain, harnessing the excellent temporal resolution of magnetoencephalography (MEG) and spatial resolution of magnetic resonance imaging (MRI) to investigate cognitive functioning associated with auditory information processing and expectation updating in the context of PC. To achieve this, we explored short-term auditory conscious recognition using a same-versus-

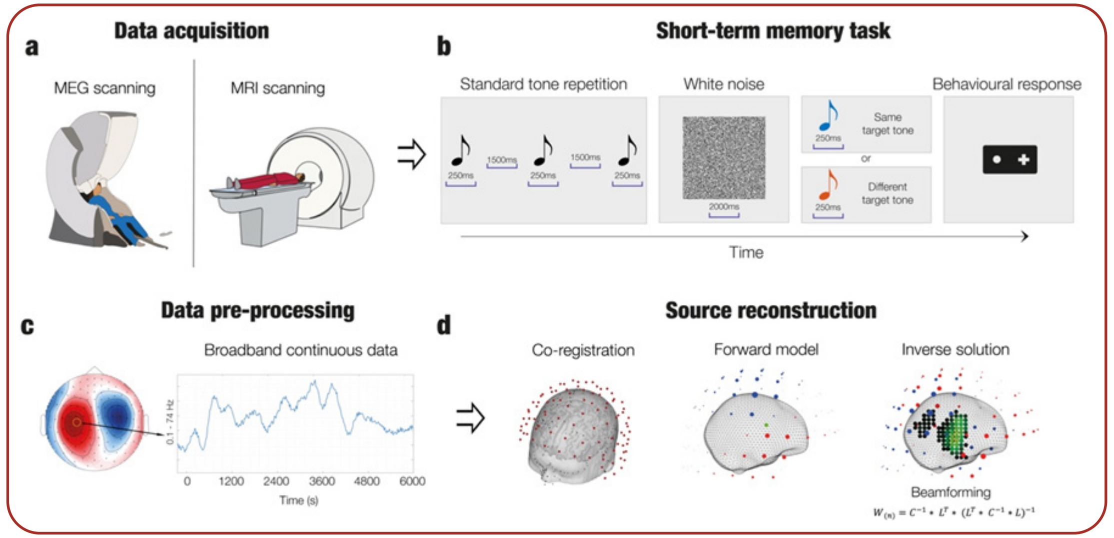

*Figure 1. Experimental design, stimuli and analysis pipeline. **a** - MEG recorded brain activity during an auditory task from 26 participants, and structural brain scans acquired with MRI; **b** - Participants listened to single-tone strings and identified if a subsequent tone matched the memorized one; **c** - Data was preprocessed to remove interference and artifacts; **d** - Source reconstruction identified brain regions generating neural activity by analyzing contrasts between responses to different tones.*

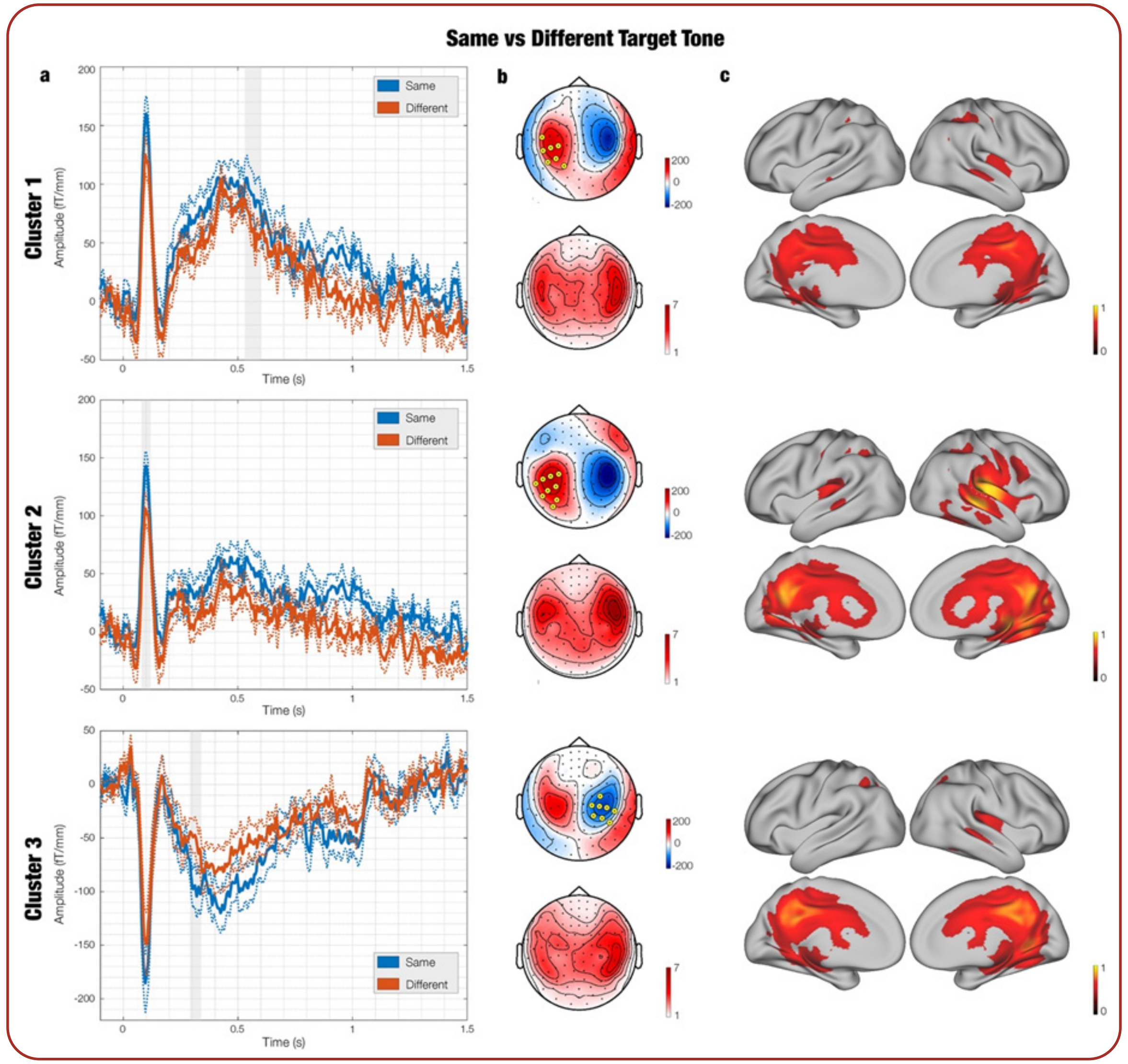

*Figure 2. Neural responses to same versus different target tones s. For each significant cluster: **a** - temporal dynamics, with gray shadows indicating the time-windows of significant differences between same and different timeseries; **b** - scalp distribution, with yellow circles within gradiometers showing channels constituting significant clusters; **c** - estimated neural sources.*

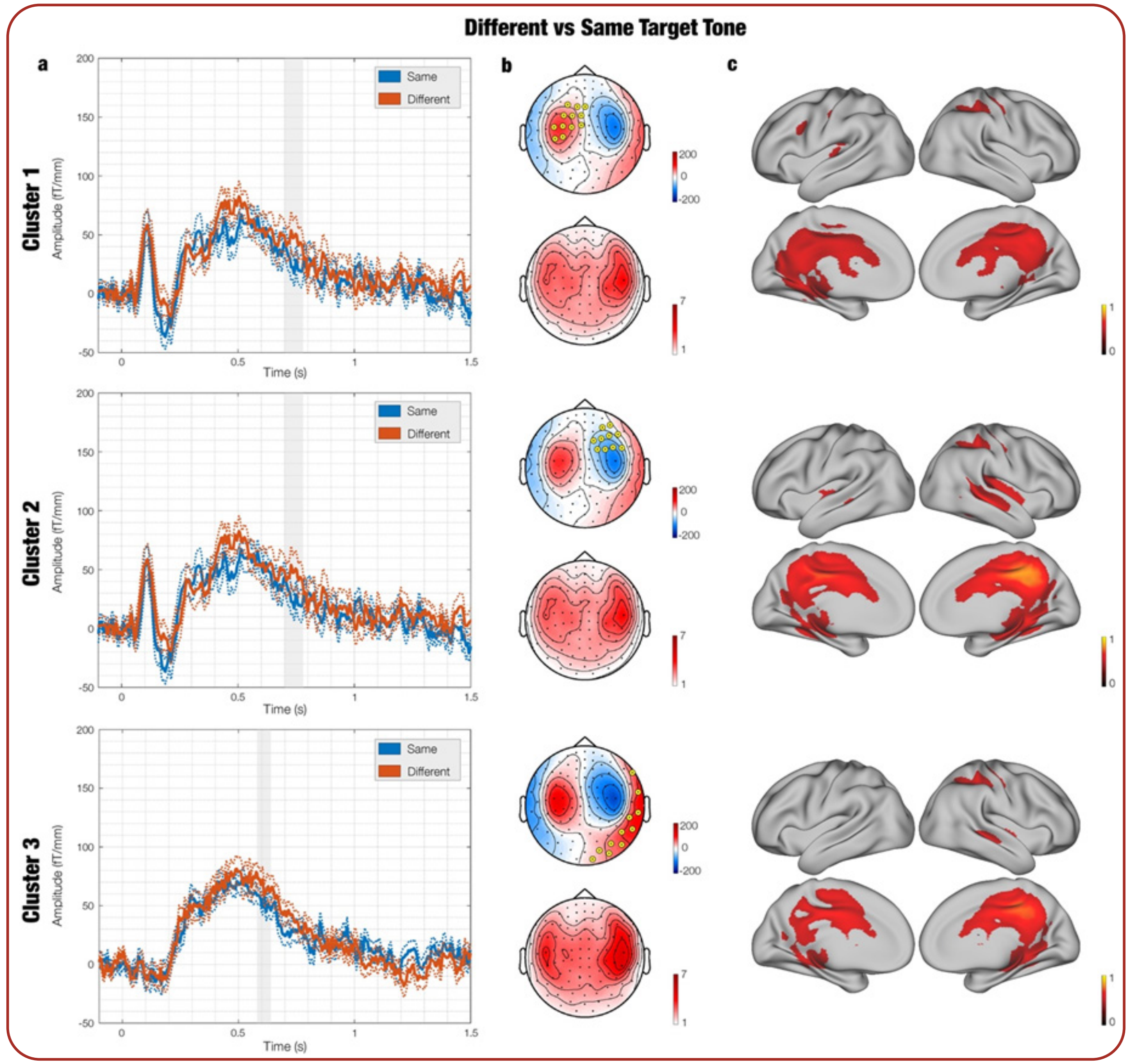

Figure 3. Neural responses to different versus same target tones. For each significant cluster: ***a*** *- temporal dynamics, with gray shadows indicating the time-windows of significant differences between same and different timeseries;* ***b*** *- scalp distribution, with yellow circles within gradiometers showing channels constituting significant clusters; c - estimated neural sources.*

different auditory paradigm. Twenty-six healthy participants were tasked with discerning whether presented target sounds matched standard stimuli strings, with a white noise interlude promoting conscious memory retention (Fig. 1a and b). We hypothesised differential expression of event-related potentials (ERPs) in response to same and different target stimuli, manifesting as unique temporal and spatial patterns. Such patterns would reflect perceptual inference grounded in memory traces and the integration of error detection.

Behavioural outcomes verified participants' proficient task execution, revealing a recognition rate of 98.15% for same target sounds and 95.41% for different target sounds. MEG sensor-level analysis (Fig. 1c) unveiled that recognition of same target sounds evoked two significantly stronger negative components in the event-related field compared to different sounds. The initial component, identified as N1, peaked 100ms post-target sound onset, while the second component manifested as a slower negative response between 300 and 600ms after target sound onset (Fig. 2a). These effects were prominent in various MEG sensor clusters, particularly in temporal and parietal regions of the scalp (Fig. 2b). Conversely, different target sounds produced scattered and smaller clusters of enhanced activity compared to same sounds, peaking beyond 600ms post-target sound onset (Fig. 3a). Source reconstruction through beamforming algorithms (Fig. 1d) identified the involvement of auditory cortices, hippocampus, and cingulate gyrus in both target sound conditions (Fig. 2c and 3c).

Our findings align with PC principles and previous research on the neural mechanisms underlying automatic auditory recognition[4,5] and short-term[6]. Notably, the study emphasizes the significance of early and later negative brain responses for the successful prediction of previously encountered sounds in the context of conscious short-term memory. Taken together, our findings suggest that negative components originated in the auditory cortices, medial temporal and parietal lobes are of primary importance for prediction and recognition processes of previously memorised sounds. These results contribute to our understanding of the intricate processes involved in auditory memory and have implications for the broader field of cognitive neuroscience.

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CLINICAL APPLICATIONS OF MUSIC

Kira Vibe Jespersen

In 2023, the focus on the potential of using music in clinical settings has been further established both nationally and internationally. In December, the National Institute for Health (NIH) in the United States organized a two-day workshop on Music as Medicine as a summary of the recent NIH sound health initiative. In line with this, the Danish Sound Day 2023 was held at Rigshospitalet, Copenhagen, focusing on the topic of Sound and Health including a MIB contribution by Associate Professor Kira Vibe Jespersen.

At MIB, 2023 has brought advances in the research on music and Parkinson's disease. Postdoc Victor Pando-Naude together with MIB colleagues Postdoc Thomas Matthews and Professor Peter Vuust published their results showing that dopamine dysregulation in Parkinson's patients flattens the pleasurable urge to move to musical rhythms[1]. In recognition of this interesting research on music and Parkinson's, Parkinsonforeningen (the Danish Parkinson's Association) awarded a 75,000 DKK grant to Assistant Professor Jan Stupacher and Postdoc Victor Pando-Naude for a project on rhythm, movement and social connection in Parkinson's.

Furthermore, MIB researchers are contributing to advancing the evidence base for rhythmic auditory stimulation for motor rehabilitation in Parkinson's in an upcoming Cochrane review. In 2023 the protocol for this systematic review was developed, reviewed and accepted in the Cochrane Database of Systematic Reviews[2]. For more information on this line of research, please see the feature article by Victor Pando-Naude page 48.

Other MIB researchers have also addressed new topics in the field of neurorehabilitation and neurodegenerative disorders. Together with colleagues from the Music Therapy department in Aalborg, Associate Professor Kira Vibe Jespersen published the results of a study evaluating the effectiveness of different types of music interventions for cardiorespiratory exercise in stroke rehabilitation[3]. This study highlighted the relevance of clinical characteristics by showing that participants with high gait functioning experienced no benefit of the music interventions, whereas participants with low gait functioning showed an increase in both exercise duration and intensity with the music.

Jan and Victor with the Her Excellency, Alexandra, Countess of Frederiksborg at Parkinson Association's award ceremony.

In the field of neurodegenerative disorders, a new line of research has been introduced by visiting PhD student Elisa Serra from Oxford University together with Associate Professor Leonardo Bonetti and Professor Morten Kringelbach. Using magnetoencephalography (MEG) they have initiated a study of how the brain processes, stores and retrieves music in elderly persons with dementia with the aim of exploring if these methods can be used for early detection of dementia.

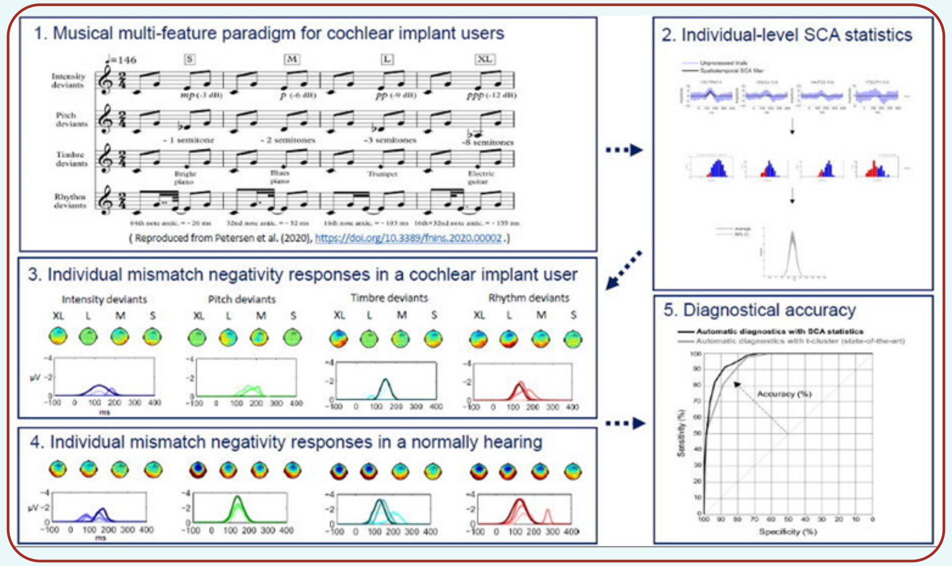

Figure 1. *Using the Musical multi-feature paradigm for CI users, MIB researchers applied a new method to evaluate individual MMN responses to musical deviants of different magnitudes5.*

In relation to ageing, MIB researchers also published new results on age differences in central auditory system responses to naturalistic music[4], and Professor Elvira Brattico published a book chapter reviewing music-based and neuromodulation interventions in rehabilitation among the elderly.

In the field of Cochlear Implants (CI) and music, MIB researchers have also contributed with new interesting results. Dr. Niels Trusbak Haumann together with Associate Professor Bjørn Petersen and Professors Peter Vuust and Elvira Brattico have used a new spike density component analysis on electroencephalography (EEG) data to detect individual mismatch negativity (MMN) responses to musical features in experienced CI users and normal hearing controls[5]. The results showed that individual MMN responses predicted discrimination ability of the music features with high accuracy in both groups and thereby support the use of MMN responses as a tool for testing music perception in CI users (Fig. 1).

In line with this research, PhD student Alberte Seeberg and MIB colleagues investigated the development in the ability to discriminate musical sound features after CI implantation using an MMN paradigm[6]. They found significant improvement in neural discrimination of pitch and timbre as reflected in increased MMN amplitudes three months after CI implantation that was not reflected in behavioural measures. This indicates that development of musical discrimination can be detected neurophysiologically early after CI implantation[6].

In June 2023, Associate Professor Kira Vibe Jespersen presented her research on music and sleep as part of the Music and Science festival organised by the Technical University of Dresden. The evening lecture was followed by an all-night sleep concert arranged by the Lullabyte network (photo by Eric Münch).

In 2023, Alberte has continued this line of research with a specific focus on rhythm and groove perception in CI users. She has collected behavioural and EEG data to investigate the effect of electro-haptic stimulation on rhythm perception using a wristband designed for haptic stimulation. In addition, Alberte visited New York University (NYU) for six months to collect data on rhythm perception and the experience of groove in single-sided deafened CI users and bilateral CI users in collaboration with Dr. David Landsberger, NYU. She thereby collected a very unique dataset that can provide new information about groove perception in CI users and the effect of listening with two ears rather than one.

In the line of research on music as sleep aid, 2023 included the publication of a systematic review on the effect of listening to music on sleep in hospitalized patients by Associate Professor Kira Vibe Jespersen in collaboration with Professor Peter Vuust[7]. The review included ten studies with a total of 726 participants, and the meta-analysis showed a large beneficial effect of music on sleep quality.

Also, a study on Spotify sleep music by PhD student Rebecca Jane Scarratt and MIB colleagues was published attracting a lot of international media attention, including radio interviews on BBC1 (UK), 3AW Breakfast (Australia) and P3 (SE) as well as interviews for El País (ES), Daily Mail (UK), Euronews.com and more. Rebecca has continued using online data to advance our understanding of the use of music as a sleep aid by collecting a dataset of comments from YouTube sleep playlists that is currently being analysed.

In September 2023, Silvia Genovese started her PhD at MIB as part of the Marie Curie Doctoral Network Lullabyte (www.lullabyte.de). In her PhD, she will investigate the role of individual variables in the choice and effect of sleep music. Silvia has already launched an international survey to evaluate how demographics, music preferences and motivations for using music as a sleep aid may shape the choice of sleep music (https://musicinthebrain.au.dk/contact/do-you-ever-listen-to-music-for-sleep).

In a related fMRI study, PhD student Rebecca Jane Scarratt investigated the role of music familiarity and energy in the use of music for relaxation.

The study is in collaboration with with Associate Professor Boris Kleber, Professor Peter Vuust and Associate Professor Kira Vibe Jespersen. Data was collected in the fall 2023 and is currently being analysed. The study aims to evaluate the interplay between familiarity and music characteristics in the experience of music used for relaxation with a specific focus on how prediction processes may facilitate this response.

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CLINICAL APPLICATIONS OF MUSIC

Victor Pando-Naude

Rhythm and time in the brain: a translational approach with Parkinson's disease

The perception and processing of time are fundamental aspects of human cognition and behaviour. Investigating how the brain handles temporal information is crucial for understanding our interaction with the world. Time underlies numerous cognitive processes and behaviours, such as language comprehension, motor control, and decision-making; thus, the study of rhythm processing in the brain can shed light on these complex phenomena. In addition, impaired temporal processing is associated with various psychiatric and neurological disorders, including Parkinson's disease (PD).

Recent studies at MIB have adopted a translational approach in which basic neuroscientific mechanisms, such as rhythm perception and production, are studied under the predictive coding framework[1], with PD as a 'knockout' model of brain temporal processing[2–4]. In turn, the knowledge and methods acquired from basic research are being applied in the context of rhythmic auditory stimulation (RAS), a non-conventional intervention with potential benefits for gait disorders and motor rehabilitation in PD[5]. In 2023, we concluded a year-long study that included PD participants and controls, and tested the effect of complex RAS, in the form of syncopated rhythms, on ratings of the pleasurable urge to move to music (PLUMM) and gait kinematics (speed, cadence, step length). The manuscript is in preparation.

Parkinson's disease as a model of temporal dysfunction

PD is a neurodegenerative disorder primarily characterized by motor impairments, including tremors, bradykinesia (slow body movement), and rigidity. These symptoms are associated with dysfunction in specific neural circuits, particularly the basal ganglia and its dopaminergic pathways, and temporal processing deficits are emerging as a fundamental aspect of the condition, which also affect cognitive and emotional mechanisms[6]. The ongoing neuro-structural and -functional changes in PD, reliant on adequate dopaminergic input and intricate disinhibition mechanisms, affect daily activities and quality of life. Therefore, studying rhythm and time processing in the brain can provide a unique window into understanding the neural mechanisms disrupted in PD.

Previous studies have shown that accurate timing is dependent on a complex brain network including the supplementary motor area (SMA), the putamen, and the cerebellum[7]. Presumably due to the dopaminergic dysfunction in the basal ganglia, individuals with PD display alterations of fine motor control[8], leading to impaired judgements of duration and timing of isochronous intervals compared to controls. Furthermore, people with PD

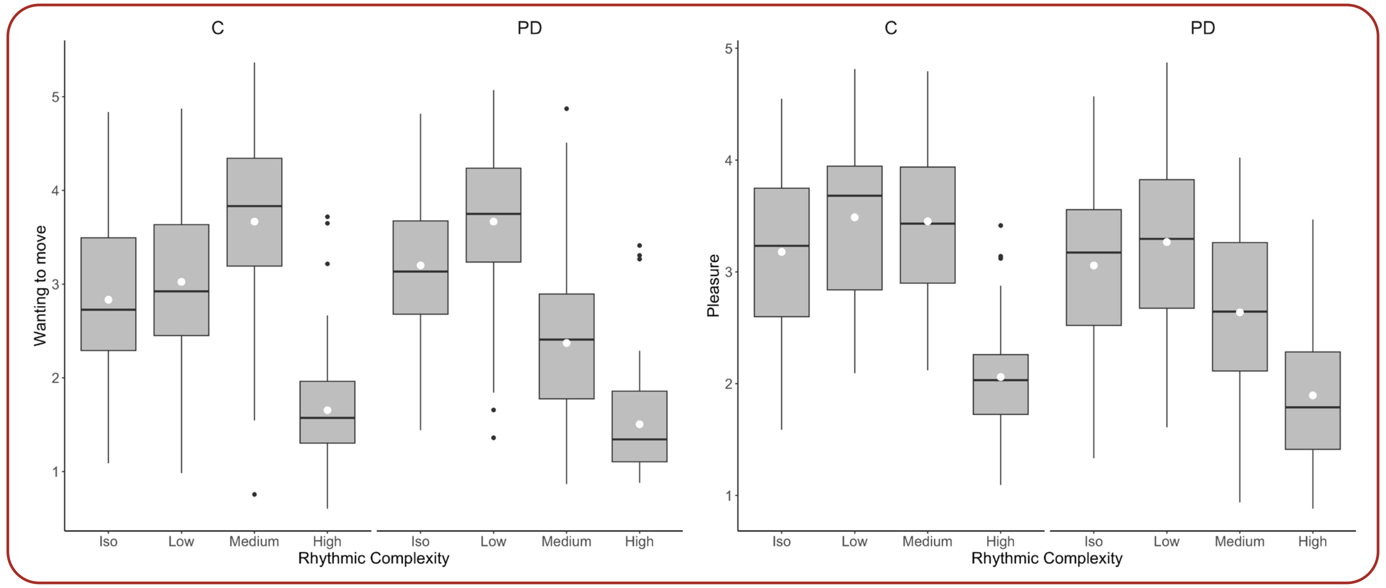

Figure 1. PLUMM in Parkinson's and controls (C).

show subnormal performance in a variety of perceptual and motor timing tasks and impaired discrimination of beat-based rhythms[9].

In addition, our previous studies have shown that PD affects meter- and beat-based timing as measured by the PLUMM[2–4]. The inverted U-shape relationship between rhythmic complexity and ratings of PLUMM is shifted in PD towards more predictable rhythms, without showing any difference in averaged ratings when compared to controls. In other words, PD participants still experience PLUMM, however, they prefer low complex rhythms over medium complex rhythms preferred by controls. Investigating rhythm and time processing in PD offers a unique avenue for understanding the neural mechanisms underlying rhythm in the brain and the motor and cognitive impairments in PD, potentially paving the way for innovative therapeutic interventions.

Rhythm and groove as audio-motor rehabilitation in Parkinson´s disease

RAS has emerged as a promising intervention for improving motor function and quality of life in individuals with PD. By synchronising movement with rhythmic auditory cues, RAS can enhance gait kinematics in individuals with PD through the modulation of features of RAS such as tempo and complexity.

Our latest study, aimed to investigate the effects of complex RAS on gait kinematics and the PLUMM experience, and timing abilities in individuals with PD and age-matched contols, showed that rhythmic complexity significantly influenced participants' subjective experience of PLUMM while walking, with a medium level of complexity

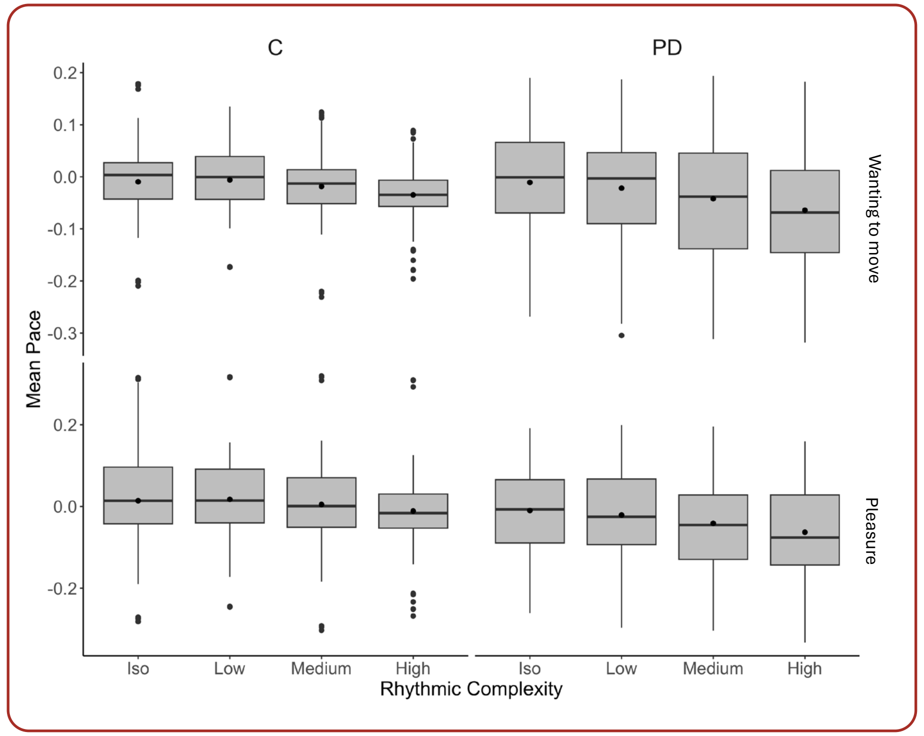

Figure 2. The effects of rhythmic complexity on mean pace for PD controls (C).

eliciting the highest groove scores on controls, while low complexity rhythms were the most preferred by PD, replicating previous results (Fig. 1). Additionally, rhythmic complexity had a small effect on gait kinematics, with high complexity associated with slower pace and cadence, and PD showing overall increased variablity when compared to controls (Fig. 2).

Moreover, tapping tasks revealed some differences in timing abilities between PD and controls. Our circular statistics unveiled subtle group distinctions during the synchronisation task. Specifically, the PD group exhibited a distinct circular mean compared to controls, suggesting potential disparities in temporal precision during rhythmic synchronisation (Fig. 3).

Our findings (1) suggest that complexity in RAS may modulate neurobehavioral processes involved in motor control and movement coordination in individuals with PD, (2) support the proposition that dopamine dysregulation in PD disrupts beat- and rhythm-based predictive timing processes, and (3) highlight the potential of RAS as a non-pharmacological, complementary intervention for PD.

Future implications

The importance of this line of research lies in its potential to inform and improve clinical strategies for managing PD. Understanding the neural mechanisms responsible for altered rhythm perception can offer insights into the development of innovative therapeutic approaches. By addressing temporal processing deficits, clinical strategies can be refined to enhance both motor and non-motor symptoms in PD. Such improvements can lead to better patient outcomes, improved daily functioning, and an overall enhanced quality of life for individuals living with PD. One of the most effective treatments for PD is deep brain stimulation (DBS), a surgical procedure involving the implantation of electrodes into specific brain regions 10. DBS has shown

promising results in alleviating motor symptoms, but its effectiveness in addressing non-motor symptoms, including temporal processing deficits, remains an area of ongoing research.

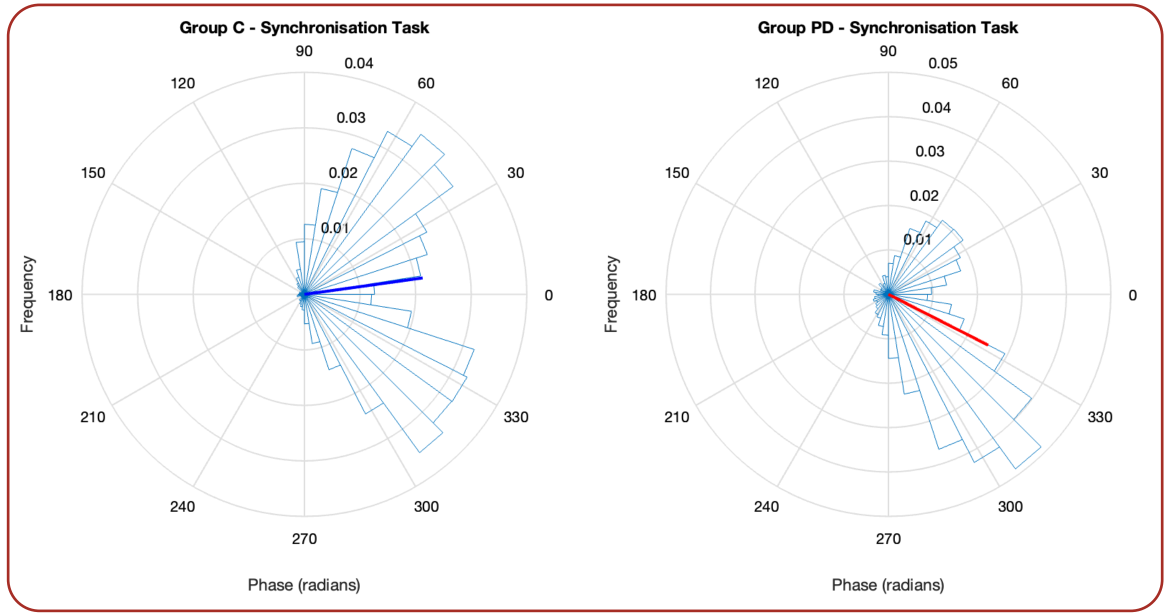

Figure 3. Circular histogram representing the angular distribution during a synchronisation task. Blue (C), red (PD).

Thus, by investigating the neural underpinnings of rhythm perception and how they are altered in PD, this study has the potential to provide crucial information for optimizing DBS targeting and stimulation parameters. This, in turn, can lead to more personalized and effective DBS treatments that address a broader spectrum of PD symptoms, ultimately improving the quality of life for individuals with PD.

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NEW FACE AT MIB: ANNA ZAMORANO

Following several years of collaboration with MIB during her post-doctoral time at the Center for Neuroplasticity and Pain (Aalborg University), Anna Zamorano has transitioned into a new role as assistant professor at MIB.

Anna is a skilled researcher with a background in physiotherapy, neurophysiology, and cognitive neuroscience. With broad experience in behavioural, EEG, TMS and fMRI techniques as well as experimental pain models. Anna's research interests involve understanding the neurobiological mechanisms that link long-term sensorimotor training (i.e., musical practice) with changes in sensory processing, particularly pain and interoception.

Anna Zamorano will collaborate with Associate Professor Boris Kleber in his research projects to study the dynamics of sensorimotor control and multisensory integration, including the modulatory effects of self-perceptual processes and musical practice (SEEMS project) and expand their already existing collaboration in voice and singing-related research.

NEW FACE AT MIB: SILVIA GENOVESE

Silvia Genovese started her PhD project at MIB in the Marie Skłodowska-Curie Actions Doctoral Network "Lullabyte" under the supervision of Associate Professor Kira Vibe Jespersen.

After a Specialization Master in Behavioural Neurosciences at Università Cattolica del Sacro Cuore (Milan) achieved in November 2022, Silvia worked as research assistant at SCALab, Université de Lille. Here, having the chance to assist in research on emotions, interroception and music, she realized her interest in the effects of music on the brain.

Silvia´s PhD project will investigate how music can be used as sleep aid exploring the influence of individual characteristics on the choice of music for sleep, as well as how this choice can be predicted by individual factors. Also, the features of music for sleep will be explored, leading to the creation of a dataset of music to be used for individual-based treatments of insomnia.

NEW FACE AT MIB: PAUL MAUBLANC

Paul Maublanc is a new PhD student at Center for Music in the Brain. He is a diplomed engineer from Supmicrothech ENSMM (Besançon, France). He did his master thesis in the Neuro Group in FEMTO ST (Besançon, France) under the supervision of directeur de recherche JJ Aucouturier. During this 6-month internship and the following year as contract engineer, he collaborated on multiple cognitive neuroscience projects including upgrading the vocal feedback manipulation software DAVID.

During this time, he became more interested in the cognitive and emotional consequences, and that is why Paul is delighted to start a neuroscience PhD at MIB under the supervision of Associate Professor Boris Kleber. He is excited to start working on his project on the cognitive and emotional effects of manipulating vocal feedback.

NEW FACE AT MIB: ATHANASIA KONTOULI

Athanasia Kontouli is a new PhD student at MIB. Nasia's research will mainly be focused on investigating neural correlates and entrainment to rhythmic music from non-Western and Western societies (shamanic drumming and Electronic Dance Music). She is also interested in music-induced altered states of consciousness and interpersonal synchronization processes in collective settings like shamanic rituals and rave parties. Furthermore, she will work together with MIB professor Peter Keller and Michael Hove on writing a review about rhythm-induced trance processes, bringing together literature from Anthropology and Neuroscience.

Nasia studied Psychology at the National and Kapodistrian University of Athens. Then she moved to the Netherlands, where she completed a master's in Cognitive Neuroscience at Utrecht University. During this period, she conducted two research internships about the role of locomotion in route learning and the differences in olfactory fear chemosignaling between Asians and Caucasians, respectively.

EDUCATIONAL ACTIVITIES & OUTREACH

Bjørn Petersen and Elvira Brattico

Weekly knowledge sharing

One of the key pillars of knowledge sharing and exchange at MIB is our weekly lab meetings. In 2023, Assistant Professor Cecilie Møller curated a program of 30 presentations for these gatherings, primarily focusing on updates from ongoing studies. These sessions often provided a platform to discuss methodological issues and approaches.

In addition to our regular activities, we hosted a couple of exceptional events. During one session, Associate Professor Søren Rastogi from RAMA shared insights from his team's research on musical interpretation, part of a longitudinal artistic research project funded by the Danish Artistic Research Funding Program. The talk featured captivating live piano examples.

On another occasion, MIB researchers participated in a new "dilemma game," an initiative by the Department of Clinical Medicine to foster open dialogue and address workplace challenges.

Furthermore, at two separate lab meetings, our researchers revisited highlights from the MIB/RITMO retreat and the ICMPC conference in Tokyo, Japan. They offered condensed versions of their presentations, including some dynamic 1-minute flash talks.

Workshops

Groove Workshop 2023

Over three days in January, MIB held a workshop centered around the topic of musical groove. The workshop took place on Zoom, was open to everyone and free of charge. The programme featured two keynote lectures from Dr. Anne Danielsen and Dr. Michael Hove, alongside 15-minute presentations (plus 10 min discussion) and 7-minute flash talks (plus 7 min discussion). The goal was to promote the work of both experienced and up-and-coming researchers, to provide ample time for the discussion and to facilitate communication both on- and off-line.

The workshop was organized by MIB researchers Jan Stupacher and Tomas Matthews in collaboration with Virginia Penhune (Concordia University & BRAMS, Montreal, Canada), Maria Witek (University of Birmingham, UK), Toni Bechtold (University of Birmingham, UK) and Deniz Duman (University of Jyväskylä, Finland).

Organisation of courses and conferences

RAMA Research

As part of his responsibilities overseeing RAMA's research and development activities, Bjørn Petersen organized a one-day research course for RAMA's faculty. The course, titled "A Reflection on the Creative Practice at the Royal Academy of Music Aarhus/Aalborg," was conducted by Lene Tanggaard, a professor at Aalborg University and the rector at the Design School Kolding.

Tanggaard, a leading expert in creative processes, has published several books on creativity and learning and has authored numerous articles in Danish and international journals. The course was attended by 26 RAMA teachers and featured a combination of lectures, group work, and a live interview.

Aarhus Summer School in Music Neuroscience 2023

Conveying and sharing knowledge and insights from the academic area of music and neuroscience is a high priority at MIB. Consequently, MIB has offered a number of courses over the years: Experimental musicology (2016; 15 talks/workshops), Introduction to Music in the Brain (2018; 17 talks/workshops) and Aarhus Summer School in Music Neuroscience (2021; 12 talks/workshops). The courses have been very successful and attracted students from both Denmark and abroad, representing a wide range of educational and scientific backgrounds.

Apart from offering participants the opportunity to learn about the many different approaches, methodologies and fields of research within MIB, the courses also offer MIB's PhD students the opportunity to gain experience with teaching and organising of such, qualifications that are much sought-after in academic job descriptions. As such the course activities represent a win-win scenario.

After the successful Aarhus Summer School in Music Neuroscience in 2021, MIB was asked to organize a course for AU Summer University, an annual program that offers a diverse range of over 85 courses and draws more than 2500 students each year. MIB agreed to host courses in 2023 and 2025. A committee, headed by Professor Elvira Brattico with Professor Peter Keller, Associate Professors Boris Kleber and Bjørn Petersen, and with the invaluable support from our centre administrator Tina Bach Aaen, was put together to outline the 3-week course.

Calls for the course were shared internationally, targeting students at master's and advanced bachelor's level whose topic of interest revolve around behavioural and brain science associated with music and sound cognition. A total of 25 students from 14 different countries signed up for the course.

The course was structured with week 1 online, followed by in-person sessions in weeks 2 and 3. Week 1 established a common foundation for participants, while weeks 2 and 3 featured morning lectures by international experts and afternoon hands-on sessions. The programme also featured a one-day guided tour of MIB's lab facilities at Aarhus University Hospital, offering real-world insight into the course methodologies.

Introductory Week

In the first week of the Summer School, PhD students Ana Teresa Queiroga and Rebecca Scarratt took on the huge task of meticulously organizing and leading the online programme. Their goal was to ensure students with diverse backgrounds gained a basic understanding of essential tools for music neuroscience research, including music theory, psychology, neuroanatomy, neuroimaging, programming and statistics. They achieved this through concise lectures and discussions on symposia from a leading conference.

To foster interaction, students worked in small groups to read and present scientific studies related to upcoming guest lectures. The week concluded with a simple online study, designed to develop critical thinking skills and provide data for the hands-on sessions in the following weeks.

Morning lectures

Morning lectures, led by experts such as Professors Maria Herrojo Ruiz from Goldsmiths University, Jonna Vuoskoski from the University of Oslo and Teppo Särkämö from the University of Helsinki, along with MIB specialists, aimed to provide a state-of-the-art overview of music neuroscience. The lectures covered key theoretical frameworks and current findings and prepared students for interdisciplinary research.

Hands-on sessions

The hands-on sessions were held at AU's IT-lab facilities, where individual computer workstations were provided for each student. The goal was to offer a practical approach to research, particularly in various types of data analysis. These sessions were organized, designed and led by MIB researchers, with contributions from 14 assistant professors, postdocs and PhD students, all of whom did an outstanding job in managing this significant task.

The sessions covered behavioral research approaches such as text mining and classification, music information retrieval, circular analysis of tapping data and clinical applications of music. Additionally, other sessions focused on topics like the principles of fMRI and data acquisition, preprocessing and epoching of EEG data, as well as filtering, averaging and analyzing MEG data using various scripts and toolboxes.

Evaluation

At the end of the course, participants were asked to evaluate it using the standard Summer University feedback form. Despite a response rate of only 46%, the feedback was valuable. Positively, the course received an average score of 3.91 on the question regarding overall course outcome (measured on a 1-5 Likert scale, where 1 is 'no outcome' and 5 is 'very great outcome'). Additionally, several respondents took the opportunity to provide personal remarks, such as:

- *"I feel like I've learned some things that will stick with me for a lifetime and in my opinion that's the sign of a very meaningful course."*
- *"I really enjoyed the course. I liked my classmates, the lecturers, the experiments, and everything else. It was very informative, interactive, and it helped me to better understand my place while following my career path."*
- *"My favorite part was the hospital excursion. Being able to actually go to a hospital and see the equipment that was being used to run experiments we discussed in lectures helped to put a lot of things into perspective."*
- *".... I gained so much insight into the field of music and neuroscience and learned a lot for my project and hopefully for future projects as well!"*
- *"This summer course was exciting both socially and academically, and the diversity within the class itself was astonishing."*
- *"... Getting to meet professionals from different countries was really nice. Having the range of people and experiences we did in class aided in me finding my place in my future career."*
- *"I am very happy to have had this opportunity to take part of a course that dives into areas of science that aren't a part of what I normally learn in medical school."*

On the negative side, individual feedback highlighted the programme's intensity and difficulties with IT programming.

- *"The teaching methods didn't support my learning, as it was too long lectures with too few breaks."*
- *".... too many hours every single day."*
- *"I'm sure all of the lecturers had amazing things to tell, but the format didn't work."*
- *"...in general everything was too rushed."*
- *"The hands–on sessions were occasionally a bit full–on..."*
- *"I was surprised that the course involved so much programming. I didn't always see the point on doing all of this."*

Aarhus Summer University in Music Neuroscience 2025

The experience and feedback from the 2023 summer school are crucial to the planning of the 2025 programme. We aim to create a less intense schedule, limiting daily activities and cognitive load. Additionally, we plan to include more lab visits and in-house presentations. To ensure a well-rounded and inclusive planning process,

HENRY PRIZE

At the yearly MIB & CFIN Christmas Party, the Outreach Henry Prize was awarded to PhD student Rebecca Scarratt and postdoc Victor Pando-Naude.

The communication of knowledge and ideas is key to CFIN and MIB: Not only to give back to Society, to private and public grant sources, and to the average citizen, who generously support our work - but also in the process of sharing knowledge and ideas across disciplines within CFIN and MIB.

three postdocs and PhD students have joined the organizing committee. Altogether, we hope to deliver an even more organized and thoughtfully planned summer school in 2025.

Supervision

Supervision of medical BA students

Dr. Victor Pando-Naude supervised a medical student in her BA-project that explored how rhythmic complexity and dopaminergic medication impact the ”Pleasurable Urge to Move to Music” (PLUMM) in Parkinson’s Disease (PD) patients.

Associate Professor Kira Vibe Jespersen supervised a medical student on her master’s thesis, ”The Role of Music Liking and Reward Sensitivity in Sleep Improvement”, building on their previous collaboration for the student’s bachelor’s thesis. Additionally, Jespersen supervised two BA projects: ”Music as a Sleep Aid in Children and Adolescents” and ”The Effect of Singing in Speech Rehabilitation.”

Conference participation

Researchers from MIB were prominently represented at the 17th International Conference on Music Perception and Cognition in Tokyo, Japan. A total of 21 individuals, including PhD students, postdocs, assistant professors, associate professors and full professors, participated in 13 oral sessions and 10 poster presentations. These numbers strongly indicate MIB’s significance within the international field of music and music neuroscience.

Peter Vuust at the Hearts and Minds Festival in Aarhus

Miscellaneous

MIB researchers actively share their knowledge and latest findings with diverse audiences through various platforms and events. As part of the Cognitive Science BA course ”Perception and Action” at AU, Assistant Professor Jan Stupacher delivered a guest lecture on groove as both a musical quality and a subjective experience. Similarly, Assistant Professor Alexandre Celma Miralles presented guest lectures on rhythm and groove for courses at the Cognitive Science programme and the Interacting Minds Centre. Associate Professor Leonardo Bonetti shared insights from his diverse research with students and faculty at universities in Oslo, Oxford, Bologna and Rome. Additionally, PhD student Ana Teresa Quieroga instructed participants at the Tec2Med Summit 2023 in Almada, Portugal and the AU PhD course, focusing on machine learning, MATLAB and their applications in health sciences. Dr. Tomas Matthews and Assistant Professor Alexandre Celma Miralles presented lectures at the Rhythm Perception and Production Workshop in Nottingham, UK. Furthermore, several MIB

PIs are constantly engaged in divulgating their research to vast audiences also thanks to their dual affiliations with international institutions (e.g., Oxford, Sydney and Bari). For instance, in November 2023 Professsor Keller participated in the Fourth Edition of the “Power of Music” conference-concert organized by Professor Brattico, attracting a hundred of students and general audience in Southern Italy. Last but not least, Director Peter Vuust continues his tireless outreach efforts both in Denmark and abroad with both talks, interviews, podcasts and jazz concerts.

Associate Professor Kira Vibe Jespersen had a notably active year, engaging both academic and the general audience. She presented on music and sleep in three events that included live performances by musicians playing specially composed ”sleep music.” Additionally, Jespersen taught at the Lullabyte Summer School at the Donders Neuroscience Institute in Nijmegen, a project on music and sleep funded by the EU.

International guest speakers in 2023

MIB has had a longstanding practice of inviting international guest speakers to Denmark ever since it was launched in 2015. These speakers have included both promising young researchers and well-known established experts in their field. In 2023, MIB had the pleasure of hosting visits from following researchers:

PhD student ***Deniz Duman***, Centre of Excellence in Music, Mind, Body and Brain, University of Jyväskylä, Finland.

Dr ***Keith Doelling***, Institut Pasteur, Paris, France.

Dr ***Thomas Wolf***, Central European University, Vienna, Austria.

Dr ***Giacomo Novembre***, Neuroscience of Perception & Action Lab, IIT, Italy.

Jelle van der Werff, Radboud University, Nijmegen, The Netherlands.

Professor ***Frederik Ullén***, Max Planck Institute, Frankfurt Germany.

Dr ***Anna Zamm***, Cognitive Science, Aarhus University.

Professor ***Robert Zatorr***e, McGill, Montreal, Canada.

PhD student ***Dhwani Sadaphal***, University of Vienna, Austria.

Professor Robert Zatorre, McGill, Montreal.

Professor Frederik Ullén, Max Planck Institute, Frankfurt.

PEOPLE

Peter Vuust
Professor
Director
Principal investigator

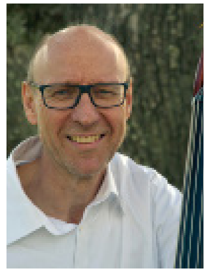
Elvira Brattico
Professor
Principal investigator

Morten Kringelbach
Professor
Principal investigator

Peter Keller
Professor
Principal investigator

Marcus Pearce
Honorary professor

Andrea Ravignani
Associate professor



Bjørn Petersen
Associate professor

Boris Kleber
Associate professor

Kira Vibe Jespersen
Associate professor

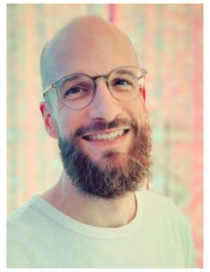
Leonardo Bonetti
Associate Professor

Massimo Lumaca
Associate professor

Alexandre Celma-Miralles
Assistant Professor

Anna Zamorano
Assistant professor

Cecilie Møller
Assistant professor



Jan Stupacher
Asssistant professor

Tomas Matthews
Postdoc

Victor Pando-Naude
Postdoc

Alberte Seeberg
PhD student

Ana Teresa Queiroga
PhD student

Athanasia Kontouli
PhD student

Gemma Fernández Rubio
PhD student

Marie Dahlstrøm
PhD student

Mathias Klarlund
PhD student

Olivia Foster Vander Elst
PhD student

Paul Maublanc
PhD student

Pelle De Deckere
PhD student

Rebecca Scarratt
PhD student

Signe Hagner Mårup
PhD student

Silvia Genovese
PhD student

Niels Trusbak Haumann
Technician

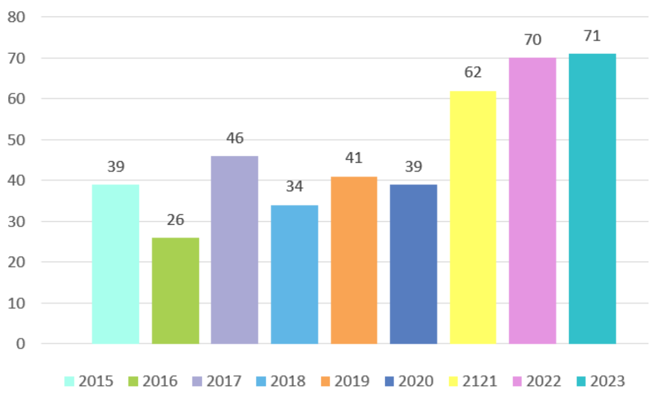
Tina Bach Aaen
Centre
administrator

Hella Kastbjerg
Centre
secretary

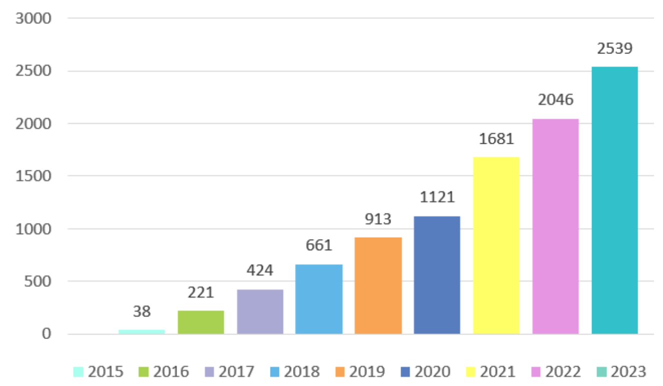
Emma Hillerup
Student assistant

PUBLICATIONS 2023

Number of peer-reviewed articles



Number of citations



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Book chapters

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Stark, Eloise A; Berridge, Kent C; Kringelbach, Morten L./ The neurobiology of liking. In; The Routledge International Handbook of Neuroaesthetics. London : Routledge, 2023. pp. 63-70

Stupacher, Jan; Hove, Michael J.; Vuust, Peter. The experience of musical groove: Body movement, pleasure, and social bonding. In; Performing Time: Synchrony and Temporal Flow in Music and Dance. Oxford : Oxford University Press, 2023. pp. 321-328

OUTREACH 2023

Talks at international conferences

Alberte Baggesgaard Seeberg
Mid-Atlantic Symposium on Hearing Cochlear Implant Conference, Maryland, USA.
Groove Workshop 2023, online.

Alexànder Celma Miralles
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.
19th Rhythm Perception and Production Workshop, Nottingham. UK.
Groove Workshop 2023, online.

Boris Kleber
Neuroscience Applied to Music Coference, Conservatorio Profesional de Música de Valencia. Spain.
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.

Cecilie Møller
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.

Elvira Brattico
2nd National Congress on Disability and Learning Disorders, Conservatory N. Piccinni of Bari, Italy.
2nd International Conference on Beauty and Change, Turin, Italy.
2nd International Congress on Geriatry and Gerontology, San Marino, Italy.
XXXI National AIRIPA Congress on Learning Disorders, Foggia, Italy.
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.
1st Scientific Meeting on Psychology, Art, and Neuroaesthetics of the Italian Association of Psychologists, Aula Magna, University of Bergamo, Italy.

Gemma Fernández Rubio
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.

Jan Alexander Stupacher
19th Rhythm Perception and Production Workshop, Nottingham. UK.
9th Joint Action Meeting, Budapest, Hungary.
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.

Kira Vibe Jespersen
Danish Sound Day, Copenhagen, Denmark.
Music and Science Festival, Dresden, Germany.

Morten Kringelbach
Green Light Symposium, Amsterdam, The Netherlands.
FALL DOX festival, Prague, Czech Republic.

Olivia Foster Vander Elst
SysMus23, Sheffield, UK.

Peter Keller
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.
19th Rhythm Perception and Production Workshop. Nottingham Trent University, UK.

Peter Vuust
19th Neuromusic Conference, McMaster University, Hamilton, ON Canada
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan

Rebecca Scarratt
17th International Conference on Music Perception and Cognition (ICMPC), Tokyo, Japan.
SysMus23, Sheffield, UK.

Other talks (selected)

Alexànder Celma Miralles
Institut for Kultur og Samfund - Interacting Minds (IMC), AU, Denmark

Cecilie Møller
Vingstedkonference, Region Syddanmark, Denmark.

Elvira Brattico
RITMO seminar series, University of Oslo, Norway.
“Neurosciences of Music” seminar for teachers and policy-makers, Salerno, Italy (online).
Conference-concert “The Power of Music III Edition” Bari, Italy.
Conference-concert “Out of the Lab – Neurosciences and Art”, Aula Magna, University of Bergamo, Italy.
Conference-concert “The multiple faces of music” [in Italian], Musical Middle School “Scuola Media Musicale De Amicis - Di Zonno”, Triggiano, Italy.
Symposium “Neurosciences and music – From basic research to clinical applications”, University of Bari, Italy.
Conservatory N. Rota of Monopoli, Italy.
Conference “Mystics & Scientists – The Healing Power of Sound and Light”, online conference. organized by The Scientific and Medical Network, UK.
Musical High School “G. Verdi”, Milan, Italy.

Kira Vibe Jespersen
Folkeuniversitetet, Ørum, Denmark.
Århundredets festival: Folkeuniversitet, Aarhus, Denmark.
Brain and Culture Seminar Series, Stockholm, Sweden.

Leonardo Bonetti
Aarhus Lindy Hoppers, Denmark.
University of Oxford, Oxford, UK.
University of Oslo, Norway.
University of Rome La Sapienza, Italy.
Nordic Mensa Fund.

Peter Keller
Conference-concert “The Power of Music III Edition” Bari.
Workshop at Harnack-Haus, Max-Planck Society, Berlin, Germany.
Aalto Brain Centre, Aalto University, Finland.
Centre of Excellence in Music, Mind, Body and Brain, & Department of Music. University of Jyvaskyla, Finland.
DOKK1, Aarhus, Denmark.
Syncposium 2023, Ghent University, Belgium.
Department of Life Sciences, Graduate School of Arts and Sciences, The University of Tokyo, Japan.
Department of Music. University of Sheffield, UK.
BRAMS-CRBLM Lecture Series. Montreal, Canada.
Centre for Eudaimonia and Human Flourishing. Department of Psychiatry. University of Oxford, UK.
Webinar on Academic Careers, European Society for the Cognitive Sciences of Music (ESCOM).

Peter Vuust
Syncposium 2023, Ghent University, Belgium.
META Platforms, Inc, USA.
Hearts and Minds Festival, Aarhus, Denmark
Parkinson Foreningen, Klub Randers, Denmark.
Neurodag 2023, KU, Denmark.
Danmarks Underholdningsorkester, Denmark.
Væksthus for Ledelse udviklingscamp, Denmark.
Odder Gymnasium, Denmark.
Landbohøjskolen, Denmark.
DEAs Partnerdag, Denmark.
Sangkraft Hjørring, Denmark.
Aarhus Universitetshospital, Denmark.
Københavns Professionshøjskole, Denmark.
Deloitte, Denmark.
Kulturmetropolen, Denmark.
Center for HR og Uddannelse, Denmark.
Emcon Virksomhedsseminar, Denmark.
Dansk Forening For Williams Syndrom, Denmark.
Huset No7, Denmark.
Ældresagen, Denmark.
Region Hovedstadens Ledelseskonference, Denmark.
Danske Gymnasiers Årsmøde, Denmark.
LOF Slagelse-Korsør-Skælskør, Denmark.
Nordjysk Praksisdag, Denmark.
Sangens Hus, Denmark.

MIB Annual Report 2023

THE DANISH NATIONAL RESEARCH FOUNDATION'S CENTER FOR MUSIC IN THE BRAIN

MIB

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