Alicja M. Olszewska

Piano training as a model for studying the dynamics of experience-dependent neuroplasticity

PhD Thesis
Completed in the Laboratory of Brain Imaging
of the Nencki Institute of Experimental Biology
Polish Academy of Sciences

SUPERVISOR
Prof. Artur Marchewka, Ph.D., D.Sc.

Auxiliary supervisor
Dr. Aleksandra M. Herman, Ph.D., D.Sc.

Warsaw, 2024

This research was funded by the National Science Center Grant 2018/30/E/HS6/00206

There is nothing permanent, except change.

— Heraklitus

Table of Contents

Abstract

Training-related neuroplasticity is a phenomenon where the brain undergoes reorganisation to support the acquisition of a new skill. Existing research suggests that musical training influences how the brain processes sound through adaptations in the auditory network, and might lead to adaptations in the motor network and auditory-motor integration. However, many studies rely on cross-sectional designs, or longitudinal approaches limited to "before-after" designs, potentially missing the dynamic nature of the neuroplastic processes hinted at by studies on motor learning. Finally, most research has focused only on auditory adaptations.

The current project combines longitudinal and cross-sectional approaches in three studies to investigate the changes in brain activation of novice adult pianists undergoing a naturalistic piano training for twenty-six weeks. By employing multiple measurements during training, it approximates the time-course of these changes. Additionally, the ecological tasks and multiple control measures help to isolate training-related effects from other phenomena such as task repetition.

Study 1 focuses on changes in auditory processing by comparing the novice pianists with a passive control group. Using a music listening fMRI task, it shows no effects of training on the neural correlates of listening to music. In a tonal working memory behavioural task, no transfer effects occurred to a cognitive task of tonal working memory during piano training. Due to a lack significant of effects in time, it is impossible to discuss the dynamics of training-related changes in the auditory domain.

In Study 2, I investigate training-related adaptations within the motor system and auditory-motor interactions with the use of two fMRI tasks in the group of novice pianists. The first task involves sequential pressing of keys on an MRI-compatible piano in three conditions of increasing bimanual demands. It shows complex and dynamic training-related changes in brain activation in the cortico-cerebellar motor network and auditory-motor integration areas, depending on the stage of the training and task demands. The second fMRI task encompasses the naturalistic music playing paradigm. Its outcomes include overall decreases in brain activation in the cortico-cerebellar and cortico-striatal motor networks, as well as auditory-motor integrative areas. These findings are indicative of an optimisation processes and shift from spatial attention to automated movement, in line with studies on motor learning.

Study 3 combines longitudinal and cross-sectional approaches to compare novice pianists before and after training with trained musicians. The piano key pressing fMRI task shows increased activation in auditory-motor integrative areas for the novices before training. After training, the findings suggest that similar brain networks underlie task execution regardless of expertise, as there are no more differences between the groups. However, musicians outperformed novices both before and after training in the tonal working memory task, suggesting no transfer effects occur from musical training to a cognitive domain related to auditory processing.

These three studies show that the neuroplastic processes related to piano training affect mostly the motor networks and auditory-motor integration with limited impact on auditory processing. The motor and auditory-motor integration networks demonstrate substantial and dynamic adaptations in response to piano training. The complexity of the observed adaptations emphasises the importance of ecologically valid training paradigms and longitudinal designs with multiple measurements to capture the intricacies of brain plasticity during real-world skill learning, which relies on coordinated involvement of multiple brain systems.

Streszczenie w języku polskim

Nabywanie nowych umiejętności, takich jak gra na pianinie, wiąże się z procesami plastyczności mózgu, prowadzącymi do jego funkcjonalnej reorganizacji. Dotychczasowe badania sugerują, że nauka gry na instrumencie wpływa na przetwarzanie dźwięków poprzez adaptacje w sieci słuchowej mózgu, oraz może prowadzić do zmian w sieci motorycznej i obszarach integracji słuchowo-ruchowej. Jednakże wnioski te opierają się głównie na badaniach przekrojowych lub krótkich badaniach podłużnych i analizach typu "przed-po", co uniemożliwia badanie dynamicznej natury neuroplastyczności mózgu.

Niniejszy projekt unikatowo łączył podejścia podłużne i przekrojowe aby zbadać zmiany aktywności mózgu u początkujących dorosłych pianistów uczących się gry przez 26 tygodni. Dzięki wielokrotnym pomiarom podczas treningu możliwe było przybliżenie przebiegu tych zmian w czasie. Dodatkowo, naturalistyczne podejście do procesu nauki oraz zadań eksperymentalnych i liczne warunki kontrolne pomogły wyizolować efekty swoiste dla procesu uczenia się.

Badanie 1 skupiało się na zmianach w przetwarzaniu słuchowym, porównując początkujących pianistów z pasywną grupą kontrolną. Wyniki zadania w skanerze rezonansu magnetycznego pokazały brak wpływu treningu na neuronalne podstawy słuchania muzyki. W behawioralnym zadaniu pamięci roboczej (tonalnej), nie zaobserwowano efektu przeniesienia z treningu muzycznego na zadanie poznawcze związane z pamięcią tonalną. Ze względu na brak statystycznie istotnych efektów analiz w czasie, nie można omówić dynamiki zmian związanych z treningiem w zakresie przetwarzania słuchowego.

Badanie 2 miało na celu zrozumienie adaptacji związanych z treningiem muzycznym w obrębie układu motorycznego i interakcji słuchowo-ruchowych w grupie początkujących pianistów. Pierwsze zadanie polegało na sekwencyjnym wciskaniu klawiszy na pianinie w trzech warunkach o rosnących wymaganiach koordynacji oburęcznej. Wykazało ono złożone i dynamiczne zmiany aktywności mózgu w sieci motorycznej korowo-móżdżkowej i obszarach integracji słuchowo-ruchowej. Zmiany te były zależne od etapu treningu i wymagań zadania. Drugie zadanie polegało na grze na pianinie w naturalny sposób. Jego wyniki wykazały spadek aktywności mózgu w sieciach motorycznych korowo-móżdżkowej i korowo-prążkowiowej, oraz w obszarach integracji słuchowo-ruchowej. Wskazuje to na optymalizację procesów wspierających wykonywanie sekwencji ruchów, i przesunięcie zaangażowania neuronalnego

z obszarów odpowiedzialnych za uwagę przestrzenną na zautomatyzowany ruch, zgodnie z badaniami nad uczeniem się sekwencji ruchowych.

Badanie 3 łączyło podejścia podłużne i przekrojowe porównując aktywność mózgu początkujących pianistów przed i po treningu z wykwalifikowanymi muzykami. Zadanie polegające na naciskaniu klawiszy pianina pokazało zwiększoną aktywność w obszarach integracji słuchowo-ruchowej u początkujących pianistów przed treningiem. Wyniki sugerują, że po treningu podobne sieci mózgowe leżały u podstaw wykonywania zadania w obu grupach, ponieważ nie było już istotnych różnic w aktywności mózgu pomiędzy grupami. Jednakże w zadaniu pamięci tonalnej muzycy osiągali lepsze wyniki niż początkujący zarówno przed, jak i po treningu. To sugeruje, że trening muzyczny nie prowadzi do efektu przeniesienia na domenę poznawczą związaną z przetwarzaniem dźwięków.

Przedstawione wyniki niezależnych eksperymentów pokazują, że nauka gry na pianinie skutkuje funkcjonalną reorganizacją mózgu głównie w sieci motorycznej i obszarach integracji słuchowo-ruchowej, przy ograniczonym wpływie na przetwarzanie słuchowe. Obszary motoryczne i integracji słuchowo-ruchowej wykazują znaczne i dynamiczne adaptacje w odpowiedzi na trening. Obserwowana złożoność adaptacji podkreśla wagę naturalistycznego podejścia do treningu w warunkach eksperymentalnych i projektów podłużnych z wielokrotnymi pomiarami, aby uchwycić złożoność plastyczności mózgu podczas nauki umiejętności, które wymagają skoordynowanej aktywności wielu układów mózgu.

Abbreviations

AAL3 atlas - automatic anatomic labeling atlas, version 3
BOLD - Blood-Oxygen Level Dependent
EEG - electroencephalography
EPI - echo planar imaging
fMRI - functional magnetic resonance imaging
M - mean
MEG - magnetoencephalography
MNI - Montreal Neurological Institute
MRI - magnetic resonance imaging
PROMS - Profile of Music Perception Skills
ROI - region of interest
RRID - Research Resource Identifier
SD - standard deviation
TMS - transcranial magnetic stimulation
TP - time-point

1. Neuroplasticity and music

1.1. The neuroplastic process

> ***Any man could, if he were so inclined, be the sculptor of his own brain.***
> **— Santiago Ramón y Cajal**

The central nervous system evolved as a solution to the ever-growing sensory and effector needs of ever larger, more complex and mobile animals. Neuroplasticity, or the idea that the nervous system changes in time, has been coined to reflect that the brain is shaped not only via inherited factors, but also in relation, and as a response, to repeated behaviours and environmental exposures and demands. Instabilities and changes in the environment created an evolutionary pressure for the nervous systems to be malleable - able to adapt and learn in response to the variable demands of dynamic environmental conditions. This malleability of the nervous system, understood as structural and functional changes in synaptic communication between neurons induced by external and internal factors, was put forward already in the late 19th century by James (1890), Tanzi (1893) and Cajal (1894), but not developed into a theory of synaptic plasticity until the work of Konorski and Hebb more than fifty years later (Konorski 1948; Hebb 1949).

Currently, we understand that the nervous system has to be responsive and adaptable on multiple timescales, from milliseconds of synaptic connections (Bliss and Lomo 1973) to longer processes of epigenetic regulation of cell excitability (Lisman et al. 2018), to weeks, months and years required for skill acquisition (Draganski et al. 2004; Maguire et al. 2000). There exists evidence that plasticity might occur in cascades, where changes in certain parts of the brain influence other parts in a sequential order. For example, in one study it has been shown that rapid changes in basal ganglia precede slower adaptations in the prefrontal cortex, suggesting that the output of the striatum 'trains' learning mechanisms in the frontal cortex (Pasupathy and Miller 2005).

The prevailing evidence in this domain comes from cell cultures or animal studies, where neuroplastic processes are studied in a particular context of a cell or an animal, such as the original studies of enriched environment on rhodent’s behaviour (Hebb 1947; Rosenzweig, Bennett, and Krech 1964). In such experiments, animal’s environment is enhanced in a controlled manner to elicit improved physical fitness, memory or problem-solving abilities, which have also been linked to metabolic and neuroplastic adaptations, such as synaptogenesis, neurogenesis, gliogenesis, angiogenesis, and synaptic plasticity and pruning.

Neuroplasticity is considered to take context-dependent forms. In humans, *developmental plasticity* is the result of the interaction between pre-programmed development of the nervous system and experiences occurring during childhood and adolescence, resulting in basic functions such as speech, coordinated movement (e.g., grasping, walking, running, jumping) or cognitive skills (such as language, mathematical thinking, intuitions about the laws of physics, abstract reasoning, imagination). The two other types of neuroplasticity persist through the lifespan: one related to healing and compensation after trauma, and the other related to learning and skill acquisition also in adulthood, dubbed the *experience-dependent neuroplasticity.* Those experience-dependent neuroplastic processes allow us, humans, and many other animals, to learn novel behaviours and adjust to environmental changes throughout the lifespan, albeit this ability diminishes as we grow older.

However, animal models fall short when it comes to studying human behaviours. It is possible to stimulate neurons to form connections in a Petri dish, train a rat to navigate a maze, or observe a mouse's mating and feeding behaviour. Many experimental interventions require animals to be sacrificed in order to study their brains and other tissues under a microscope, or implant one in a living animal. Still, the cells and the animals cannot tell us how they feel, calculate elliptic integrals, or play and experience music (at least not in the manner we are used to, even if they present common basic elements with our experiences (Ito et al. 2022)). While certainly many fundamental aspects of neuroplastic processes are universal and translate well from laboratory models to humans, there are some particular human behaviours which can only be studied in humans themselves. To understand the neuroplastic processes underlying the acquisition of human-specific skills, such as language or music, it is necessary to study human subjects, what has to be performed in a safe and non-invasive manner.

In the following chapters of the introduction section, I describe how neuroimaging fMRI techniques can be utilised to investigate neuroplasticity in living humans. Next, music and musical training are presented as a valuable model for studying brain plasticity. Following this, I discuss some of the proposed models that attempt to explain the dynamics of brain plasticity. Finally, a specific study design employing musical training is introduced. This design served as a framework to investigate the time-course of functional brain reorganisation, which allowed me to address specific research questions and test relevant hypotheses related to these phenomena.

1.2. Neuroplasticity through the lens of MRI neuroimaging methods

The biological basis of neuroplasticity in animal models is usually explained through the dynamics of strengthening and weakening of the synaptic connections between neurons. However, this cellular-level understanding of *long-term potentiation* and *long-term depression* is far from exhaustive when the nervous system is examined in a more holistic approach. Multiple other phenomena add up to explain how the brain changes, including but not limited to: epigenetic processes, adaptations in neuronal architecture, axonal myelination, changes in astrocytes and other glia, neurogenesis, changes in the extracellular matrix or brain vasculature, and neurochemistry (Tardif et al. 2016). All of these phenomena can affect the magnetic properties of brain tissue, which allows us to track macroscopic signatures of brain plasticity using magnetic resonance imaging (typically abbreviated MRI or NMR, from nuclear magnetic resonance) *in vivo* in a non-invasive manner.

Magnetic resonance imaging is a tool commonly employed in clinical and research settings to study brain structure and function in living humans. It is able to contrast tissues which vary in magnetic properties related to their chemical composition. This is achieved by depositing small amounts of energy in tissues, which later radiate it in the form of radio frequency photons, picked up by a receiver coil. For this discovery in the 1970s, Sir Peter Mansfield and Paul Lauterbur received a Nobel Prize in Medicine and Physiology in 2003. The grey and white matter of the brain, as well as the skin, skull, meninges and cerebrospinal fluid, do differ in chemical composition and magnetic properties. Therefore, magnetic resonance imaging can be used to noninvasively reveal their geometry, and does it with a spatial resolution usually in the order of a millimetre.

A breakthrough in visualising brain function occurred when a group of scientists from the AT&T Bell Laboratories (currently Nokia Bell Lab) in New Jersey, USA, discovered that the oxygenation of blood also changes its magnetic parameters (Ogawa and Lee 1990; Ogawa, Lee, Kay, et al. 1990; Ogawa, Lee, Nayak, et al. 1990). Soon afterwards, this was proven useful as an indirect measure of neuronal activity related to task activation (Bandettini et al. 1992; Kwong et al. 1992). The postulated mechanisms behind signal changes were related to brain metabolism. Neural processing requires large amounts of glucose and oxygen; in fact, the energy consumption of the brain is disproportionally high with respect to its size (in humans, about 2% of an adult's weight is the brain, and it consumes roughly 20% of daily energy intake). The influx of new, oxygenated blood, follows neuronal activity with a peak around 4-6 seconds after stimulus onset (Logothetis 2008; Poldrack, Mumford, and Nichols 2011), leading to a blood-oxygen-level-dependent (BOLD) response. And as such, the idea of *haemodynamic response function* was born. It describes the changes in magnetic properties of tissue related to the influx of oxygenated blood supporting neuronal activity, and, in turn, in the signal measured by the magnetic resonance imaging apparatus. Thus, by using the BOLD signal, it is possible to indirectly infer about the underlying neuronal activity, which has been confirmed with neurophysiological methods (Logothetis et al. 2001; Mukamel et al. 2005).

Measuring the differences in BOLD signal when a study participant (human or otherwise) performs a task while in an MRI scanner allows researchers to attribute neuronal activity in a certain brain area to a particular behaviour or cognitive process. Although this "neophrenological" perception of how brain regions or structures are involved in behaviours or cognitive process is the subject of debate and certain criticism (e.g., Westlin et al. 2023), the results of well-conducted fMRI studies seem to be largely repeatable and corroborated by other research techniques, such as studies using transcranial magnetic stimulation (TMS), or research on the loss of function linked to brain lesions and traumatic injuries. It is generally accepted that, given enough subjects, functional magnetic resonance imaging can accurately represent central tendencies in human functional brain organisation among groups (Marek et al. 2022).

The first studies which used structural MRI and BOLD to hint at neuroplastic processes compared central tendencies of human brain structural and functional organisation between groups of participants with different life experiences, in an assumption that those experiences led to the observed differences. For example, Maguire and colleagues (2000) found that London taxi drivers have significantly larger posterior (and smaller anterior) hippocampi compared to those of control subjects, and that the size of the hippocampi correlated with the amount of time spent as a taxi driver. Since being a taxi driver required extensive skill and practice in spatial navigation, especially in the era before smartphones and the Global Positioning System (GPS), it was postulated that the differences in hippocampal size reflect training-related adaptations. Similarly, a study on professional judo players (Jacini et al. 2009) suggested that higher-than-average physical activity in life is associated with increased grey matter volume in the areas of the motor network, such as the motor cortex and the cerebellum, and visual areas.

Very quickly, neuroscientists started to employ MRI techniques in longitudinal, interventional studies to be able to distinguish between nature and nurture behind the differences observed between groups. Even though the exact biological underpinnings underlying cortical reorganisation are still debated (Makin and Krakauer 2023), longitudinal studies with the use of MRI are used to provide evidence for training-related neuroplastic adaptations. In the following chapter, I will describe some of these longitudinal studies with a focus on musical training, and why musical training is used for this purpose in the first place.

1.3. Neuroplasticity through the lens of musical skill

Musical training is a more potent instrument than any other,
because rhythm and harmony find their way into the inward places of the soul.
— Plato

Many humans undertake musical training in the form of playing an instrument, due to cultural reasons or for personal satisfaction and enjoyment. In fact, music accompanies humans in every culture and every known historical period (Nettl 2015). The human brain can even perceive music in regular environmental sound, as beautifully captured in the opening phrases to the *Cell Block Tango* from the 2002 musical *Chicago (Catherine Zeta-Jones et al. 2022)* or featured in the compositions created by Einstürzende Neubauten. The origins of music are proposed to stem from social bonding functions, such as singing lullabies to children and/or chanting war songs to the rhythm of the war drums (Mehr et al. 2020). Singing and drumming require no specialised tools; the first known archeological findings of musical instruments, tools for the creation of melodic music, are mammoth-tusk-carved flutes dating back 45 000 years (Higham et al. 2012). In the modern day, there exists a plethora of musical instruments, styles and preferences, and music is considered an important aspect of many people's daily life, culture and identity. Up till today, music listening and music making, with and without the use of musical instruments, play an important role in phenomena such as social bonding or emotion regulation (Greenberg, Decety, and Gordon 2021; Saarikallio and Baltazar 2018; Tarr, Launay, and Dunbar 2014).

In the field of neuroplasticity, musical training, especially when related to learning to play an instrument, is considered a useful model because it combines auditory and motor aspects, as well as many other sensory and cognitive domains, can be used on various time-frames, or as a human model for life-long training in musicians (Herholz and Zatorre 2012; Münte, Altenmüller, and Jäncke 2002; Olszewska et al. 2021; Schlaug 2015). With the use of neuroimaging, it is possible to identify the areas which change in response to musical training.

Cross-sectional studies investigated the relationship between musical training and the structure and activation of brain regions while listening to music between groups of musicians and non-musicians. One of the first findings, utising early methodology on the analysis of neuroimaging data, was the increased volume of the corpus callosum in musicians compared to non-musicians (Schlaug et al. 1995). In the following years, multiple studies showed various differences associated with musical training, particularly in the temporal and frontal areas (Bermudez et al. 2009; Elmer et al. 2013; Gaser and Schlaug 2003; Groussard et al. 2014; James et al. 2014; Karpati et al. 2017; Sato et al. 2015; Schneider et al. 2005). Functional studies comparing musicians and non-musicians revealed that the regions required to perform musical tasks are located in the *dorsal auditory stream* (Figure 1.3.1). This proposed distributed network of auditory processing includes, apart from the brain areas directly involved in auditory processing, the inferior parietal cortex and the dorsal premotor cortex, which support auditory-motor integration (Chen, Penhune, and Zatorre 2009; Rauschecker 2011; Herholz et al. 2016; Zatorre, Chen, and Penhune 2007). In addition, playing a musical instrument engages the canonical structures involved in the processing of acoustic stimuli, such as the belt and parabelt regions of the auditory cortex (Heschl's gyrus), the superior and middle temporal gyri (Bangert et al. 2006; Bianchi et al. 2017; Habermeyer et al. 2009; Limb et al. 2006; Ohnishi 2001; Seung et al. 2005). Many cortical and subcortical structures were identified relevant to the motor aspect of playing an instrument, such as the primary somatomotor cortex, supplementary motor area, thalamus or the striatum (Zatorre, Chen, and Penhune 2007). Additionally, the inferior frontal gyrus seems to play a role in the auditory-motor integration (Segado, Zatorre, and Penhune 2021), processing of musical syntax (Koelsch 2005; Maess et al. 2001) and error monitoring (Li et al. 2006; Olszewska et al. 2023; Pfordresher et al. 2014; Rae et al. 2014). Cognitively, musical performance requires the engagement of memory and, often, emotional processing as well (Zatorre, Chen, and Penhune 2007).

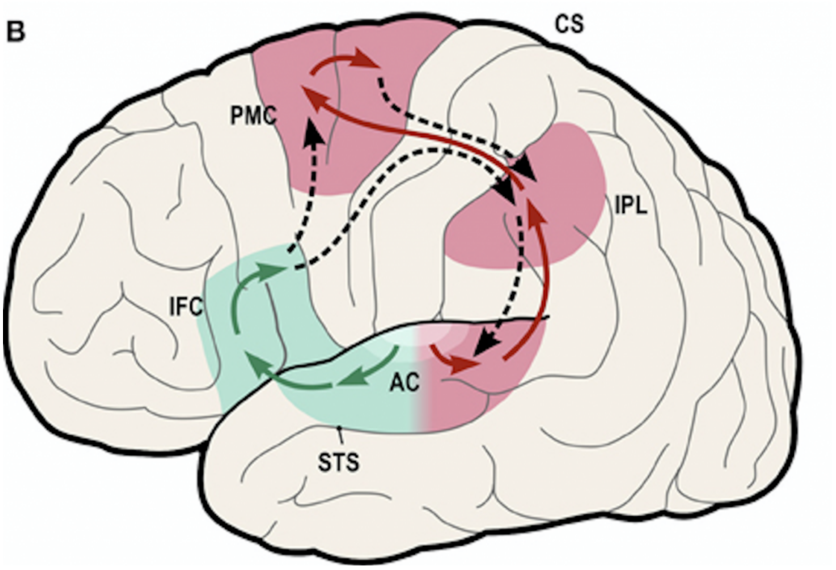


Figure 1.3.1. Model of dual-stream auditory processing in the human brain, from Rauschecker (2011). Dorsal (red) and ventral (green) auditory pathways are shown. Solid arrows indicate ascending projections from the auditory cortex, while dashed arrows indicate reciprocal projections back to the auditory cortex. AC - auditory cortex; CS - central sulcus; IFC -, inferior frontal cortex; IPL -inferior parietal lobule; PMC - premotor cortex; STS - superior temporal sulcus. Source: (Patel and Iversen 2014) License: ("CC BY 3.0 Deed," n.d.) Modifications: Removed the A panel (primate brain).

Some of the cross-sectional studies provided evidence that the size of the observed structural and functional differences between musicians and non-musicians was correlated with musical experience (Bianchi et al. 2017; Habermeyer et al. 2009; Oechslin et al. 2013; Ohnishi 2001). This suggests that musical training might have been the causal factor behind them, but cannot provide causal evidence due to cross-sectional designs in these studies.

The longitudinal approach offers a unique possibility to distinguish casual relationships in the observed phenomena. By measuring group differences before the onset of training, researchers can control for any predisposing factors. Consequently, by recruiting groups matched on variables of interest, any observed changes in performance or brain activation can be confidently attributed to the training-induced neuroplasticity, rather than pre-existing factors.

A number of studies explored the impact of musical training on brain function within a longitudinal framework. However, these experiments varied considerably in their employed methodologies. These variations included the number of measurements taken (time-points), the intervals between measurements, the presence and specifics of control groups or conditions, and the outcome measures employed. The nature of the musical training itself varied as well. While the majority of prior research focused specifically on piano training (Brown and Penhune 2018; Chen, Rae, and Watkins 2012; Herholz et al. 2016; Li et al. 2018), some researchers investigated training-related changes using training on other instruments such as the cello

(Wollman et al. 2018) or the drums (Amad et al. 2017). Most commonly, these experiments used listening fMRI tasks to investigate training-related changes associated with musical training (Brown and Penhune 2018; Chen, Rae, and Watkins 2012; Herholz et al. 2016; Wollman et al. 2018). The duration of training programs also varied across experiments. Some studies focused on short-term plasticity, with training which took place within a single scanning session (Brown and Penhune, 2018; Chen et al., 2012). These were the only two studies to date which used longitudinal design with piano playing fMRI tasks. Conversely, other studies explored effects delayed further in time, investigating brain changes observed after weeks or months of training (Amad et al., 2016; Li et al., 2018; Wollman et al., 2018).

Despite these differences, the longitudinal studies all converged into supporting the evidence gathered from cross-sectional studies, namely that, indeed, musical training induces plastic changes in the activation or the areas constituting the dorsal auditory stream. The two longitudinal studies on piano training during a single fMRI session (Brown and Penhune 2018; Chen, Rae, and Watkins 2012) also showed a decrease in brain activation in the parietal, premotor and auditory regions during the late compared to the early phase of training.

As I described above, the longitudinal studies on training-related brain plasticity delivered important insights into the process of functional reorganisation related to musical training. Nevertheless, there are questions which still remain unanswered. Firstly, apart from the single-session studies which asked participants to play during an fMRI task (Brown and Penhune 2018; Chen, Rae, and Watkins 2012), the remaining research concentrated solely on auditory processing or resting-state brain connectivity. Thus, the process of functional brain reorganisation specific to the task of playing a musical instrument remains largely unexplored on longer timeframes. Additionally, these studies focused on playing only with the right hand, whereas playing the piano, as well as most other musical instruments, is a bimanual task demanding the integration of separate movements of each hand. Secondly, the studies on musical training lasted from a single day to a couple of months. It has not been investigated how the chosen study duration compares to the life-long training of musicians, and whether the observed functional adaptations are comparable between the novices in the studies and professionals with years of experience. Lastly, the vast majority of the studies employed a before-after design, assuming implicitly a linear relationship between training duration and brain activation. However, based on the insights from motor sequence learning studies, this is not necessarily the case.

In the following chapter, I will describe some of the proposed models of brain plasticity, which may put the linearity assumption into question, and introduce the concept of neuroplasticity dynamics.

1.4. Models of neuroplasticity dynamics

The most that can be expected from any model is that it can supply a useful approximation to reality: All models are wrong; some models are useful.
— George E.P. Box

Neuroplasticity is a process of changes in time. While many studies focused on *what* changes in the brain as it develops, learns, or heals, other researchers concentrated on the idea of *time-course*: not only *what*, but also *how* this change occurs. In the case of functional reorganisation of brain activity, several models have arisen to describe the possible time-course of plastic changes in the brain.

J. Grafman (2000) proposed that functional changes can occur in one of the four modes: map expansion, cross-modal reassignment, homologous area adaptation, and compensatory masquerade. *Map expansion* was originally described as the enlargement of a functional brain region in response to increased usage or practice. Even though map reorganisation is supported by some research (e.g. Hofstetter et al. 2021), nowadays map expansion in humans is more frequently understood in the context of increased brain activation in a certain functional brain region when performing a particular task. This phenomenon is particularly evident in individuals with specialised skills, such as musicians. For example, expert musicians exhibit enhanced auditory processing abilities, including pitch perception, compared to non-musicians, which were tied to increased fMRI activation in temporal brain regions (Bangert et al. 2006; Bianchi et al. 2017; Habermeyer et al. 2009; Limb et al. 2006; Ohnishi 2001; Seung et al. 2005). These effects have been replicated in studies using neurophysiological methods, such as electroencephalography (EEG) (Herholz, Boh, and Pantev 2011; Kuchenbuch et al. 2014).

The other mode of functional plastic changes, the *cross-modal reassignment*, entails the repurposing of neural structures that were originally dedicated to processing a particular sensory modality to handle input from a different sensory modality. For instance, learning to read Braille in both blind and sighted individuals can lead to the activation of visual areas in response to tactile stimuli (Matuszewski et al. 2021; Siuda-Krzywicka et al. 2016).

The phenomenon of *homologous area adaptation* refers to the takeover of a particular cognitive function by a corresponding region in the opposite cerebral hemisphere. This process enables the brain to retain its overall functionality even in the presence of injury or damage to a specific brain region.

Finally, the *compensatory masquerade* represents the utilisation of alternative brain regions or strategies to perform a specific task.

Of these four, the *map expansion* would be the most relevant in the discussion of training-related neuroplastic processes, as it is most directly related to training-induced neuroplasticity in healthy individuals.

More recently, Penhune and Steele (2012) presented an *integrated model of motor sequence learning*, building on the work by Doyon and colleagues (2009) and Hikosaka and colleagues (2002). This model (Figure 1.4.1.) aims to explain how the motor cortex interacts with the cerebellum and striatum at different stages of training to produce automatised movement behaviour. The proposed mechanisms involve processes such as error monitoring and correction, formation of the internal model, sequence representation at different time-frames, and stimulus-response association (such as auditory-motor integration). Each of the brain regions is associated with particular functions necessary for the learning process within the motor learning network, which includes both the cortico-striatal and the cortico-cerebellar systems. The striatal system's role is to learn associations between stimuli and responses (both probabilistic and predictive), or within sequences of movements. It is responsible for learning the likelihood of specific responses following specific cues, and tying consecutive movements into a sequence in the chunking process, as well as reward-based learning mechanisms. In contrast, the cerebellum's function is related to the mastering of an optimal internal model for executing context-specific movement. This mastery entails fine-tuning motor control by correcting errors and controlling ongoing movements. Finally, the primary motor cortex (M1) is considered a repository for the learned sequence representation. The parietal lobe and the premotor and supplementary motor cortices also contribute to the motor representation, which prepare and monitor movement and integrate it in the context of other stimuli processed at the same time. Importantly, in this model, the involvement of each of the regions within the cortico-striatal and the cortico-cerebellar loops depends on both the task demands and the learning stage. In the context of musical training, this model will be relevant to the motor aspects of the training.

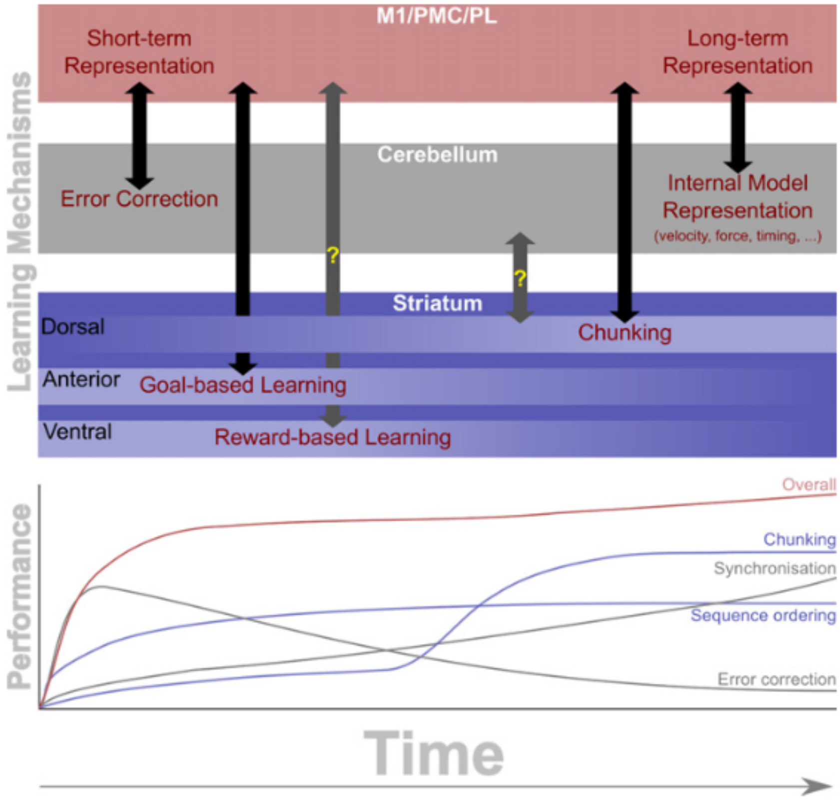


Figure 1.4.1. The integrated model of motor sequence learning. Top: brain regions, their connectivity, and associated mechanisms involved in motor sequence learning; arrows depict interactions between regions. The colour gradient within the striatum represents the relative contribution of each learning mechanism (light= greater contribution; dark= lesser contribution). Bottom: idealised learning curve for different components of performance over time, colour-coded to their associated brain regions. M1 - motor cortex, PMC - premotor cortex, PL - parietal lobe. Reprinted with permission from Penhune and Steele (2012).

Finally, Wenger and colleagues (2017) proposed an *expansion-renormalisation* model of training-related brain plasticity that abstracts from the particulars of motor learning. Although their paper focuses on structural plasticity, they provided examples of functional changes which followed this pattern as well, including human motor sequence training over a timeframe of four weeks (Ma et al. 2010). In this model, initial increases in brain activation, akin to the map expansion model, represent additional neuronal population involved initially in skill performance. This is followed by a plateau and then a decrease, as optimal networks supporting skill performance are established.

Even though these models inherently differ from each other in their predictions, all of them are qualitative: they describe how the changes might occur, but do not place them in particular time-frames. The underlying studies which served as bases for constructing the models are also often based on different animal models and study timeframes. For example, the expansion of functional representation related to a rat reaching task lasted for eight days and subsided afterwards (Molina-Luna et al. 2008). Similarly, the rat's auditory cortex underwent an expansion-renormalisation trajectory over 10 days of appetitive operant conditioning (Takahashi et al. 2010). In humans, a similar time-course of changes was observed for the activation of visual cortex in response to perceptual learning over 25 days (Yotsumoto, Watanabe, and Sasaki 2008). However, much of the studies on which the integrated model of motor sequence learning was built, lasted only for a few days (Penhune and Steele 2012). As studies on musical-training induced neuroplasticity often use arbitrary training durations and before-after designs, it is difficult to quantify which stage of the training-related plasticity is examined in a particular study, and which exact processes result in a change of brain activation. Additionally, it is difficult to predict how these models can be used in the context of much longer processes, such as learning for months or years.

In the last chapter of the introduction, I will integrate the concepts from longitudinal studies on musical training and the models of brain plasticity dynamics to construct a research framework and pose experimental questions on the time-course of functional brain reorganisation related to piano training.

1.5. Musical training as a model to study the dynamics of brain plasticity

An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer. But before an experiment can be performed, it must be planned—the question to nature must be formulated before being posed. Before the result of a measurement can be used, it must be interpreted—nature's answer must be understood properly.

— Max Planck

The goal of my research is to investigate the time-course of the neuroplastic processes governing the acquisition of a new skill - in this case, playing the piano. As mentioned previously, the concept that the brain undergoes plastic changes in response to environmental change, training, or experience, is already established in neuroscience, but the exact patterns of brain reorganisation are still investigated. To avoid the interference between developmental plasticity, ageing processes, and the training-induced plasticity in question, the project focuses on a young adult population.

So: the organism learns, and brain changes facilitate this learning. But how do these changes happen in time? What is the relationship between the plastic changes in the brain and the demands of the training or experience that provoke them?

The simplest relationship which can be studied is the linear relationship (Figure 1.5.1. a), where changes in the independent variable (e.g., training duration) provoke proportional, monotonous changes in the dependent variable (e.g., BOLD signal in a brain area), and the rate of change is constant. Such a relationship could be the illustration to the map expansion model of brain plasticity (Grafman 2000). As described in the previous sections, most of studies on training-related neuroplasticity in music are limited two a before-after design, usually in an assumption that what happens in-between is linear enough from the commencement of training to the end-point of the study (which typically is arbitrarily chosen by the researchers). This type of assumption is so fundamental in most analyses that it is not overtly stated, but assumed in the study design and statistical analyses used for the investigation of research hypotheses. Linear relationships are easy to model and well-understood, and can be a good approximation of underlying phenomena in many cases even if the actual relationship is not, in fact, linear. However, in other situations, the deviation from linearity might be significant enough that linear approximations might only be viable on limited timescales. Indeed, the newer models of brain plasticity and studies on motor learning suggest that the relationship between brain activation and task acquisition might significantly deviate from linearity (Penhune and Steele 2012, Wenger et al. 2017). The expansion-renormalisation model postulates initial increase in brain activation followed by a decrease (Wenger et al. 2017) which may exhibit different trajectories depending on the studied period (Figure 1.5.1. b, f). In the integrated model of motor sequence learning (Penhune and Steele, 2012) even the rate of changes is non-constant, giving rise to higher-order complex dynamic behaviours (Figure 1.4.1., Figure 1.5.1. d). Mathematically, if we permit the change and the rate of change of the observed parameter, such as brain activation, to be non-zero, non-constant, and non-monotonous, there is an infinite number of possible dynamics fitting the observed before-after data (e.g., Figure 1.5.1. b-f). Moreover, in the case of these complex dynamics, there exist possible unfortunate study designs which might happen to lead to false-negative findings, i.e., claim no change is happening even though the system itself, in fact, is exhibiting dynamic behaviour (e.g., Figure 1.5.1. b, c), or, contrarily, false-positive ones, when random noise is interpreted as an actual effect (Figure 1.5.1. e).

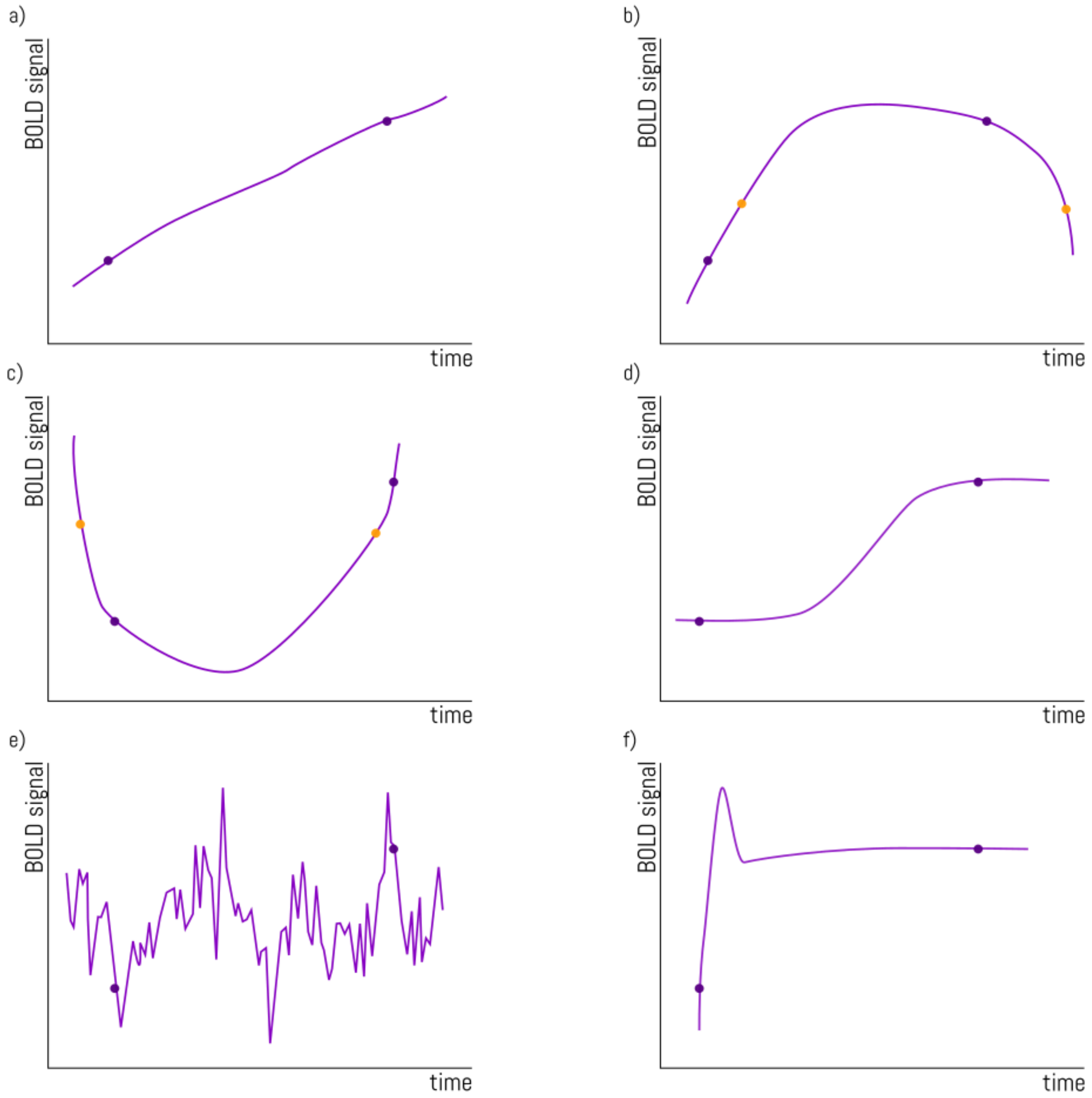


Figure 1.5.1. Possible time-courses of brain activation changes. If we relax the assumption that the relationship between the BOLD signal and time is linear (a), there exist an infinite number of dynamic behaviours which can characterise the time-course of changes, with some examples being the (b) inverse U-shaped, (c) U-shaped, (d) logistic, (e) random noise, or (f) the underdamped impulse-response behaviour. For certain relationships, false-negative findings can be obtained if the time-frame of the study coincides with the dependent variable returning to a previously occupied value (orange points in (b) and (c)), potentially leading to contradictory results between studies which differ in experimental paradigm.

The qualitative nature of proposed models of brain plasticity makes the choice of time-frame to investigate the neuroplastic processes difficult and arbitrary. One way to address this issue is to study multiple time-frames simultaneously. By using a long study period and sampling it in shorter intervals, it is possible to obtain an approximation of the time-course to a certain degree[1]. Furthermore, segmenting the time-course of a potentially nonlinear process into smaller, more manageable units makes it possible to leverage linear approximations for each segment. This approach reduces the risk of false-negative findings associated with undersampling (Figure 1.5.1 b, c). The current project design incorporates these ideas by employing a twenty-six-week (six-month) musical training program. This duration aligns with the longest time-frame employed in prior neuroimaging studies investigating musical training-induced brain plasticity in adults (Li et al., 2018). To be able to infer about the dynamic nature of the neuroplastic process, this period has been further segmented based on the timeframes used in shorter studies, after one and six weeks of training (Herholz et al., 2016; Wollman et al., 2018). Additionally, to ensure a balanced design, an additional measurement has been scheduled at the thirteen-week mark, corresponding to the midpoint of the training program. In this manner, rapid changes in brain activation at the beginning of the training, as well as their stability over time, can be tested. Finally, an extra control time-point has been added a week before the onset of training. This choice has been made to control for possible repetition effects, where brain activation changes due to performing the same task multiple times, and not due to training. The project also includes a follow-up period with a final measurement eight to twelve weeks after the completion of training, to test the persistence of any effects observed during the training period.

Even though the duration of the project was based on literature, its validity should also be considered. The twenty-six week training period and findings based on the training have been evaluated by comparing the novice musicians with participants who had completed at least secondary music education. The comparison has been performed twice, before and after the musical training course.

Piano training is used as the model to study training-related neuroplastic processes. The piano is a tempered instrument, which means that the relationship between a key press and the frequency and timbre of the sound is very stable. This makes piano an attractive and relatively simple instrument, where musical training can result in quick progress in a limited time-frame employed in a scientific study. Additionally, the piano provides the ability to play

---

[1] For the more signal-processing inclined reader, the degree to which one can approximate the time-course of a studied phenomenon is limited by the Nyquist rate in the Nyquist-Shannon sampling theorem (Shannon 1949). In order to correctly reconstruct a repetitive waveform, the sampling frequency needs to be more than twice of the highest frequency to be sampled. Therefore, if something changes twice in a month, this can only correctly be inferred if the sampling occurs more frequently than four times a month. Otherwise, a phenomenon called *aliasing* occurs, where higher-frequency signal is misrepresented as a lower-frequency signal. In principle, any signal, even an aperiodic one such as the time-course of brain activation in time, can be represented as a collection of repetitive signals with varying frequencies; this is, however, beyond the scope of the current thesis.

complex homophonic and heterophonic melodies (with accompaniment such as chords) or polyphonic musical textures. The selection of piano and similar keyboard instruments in research environment stems from their versatility and near-ubiquitous use in Western music education and practice. However, piano playing tasks in the MRI are not frequently used in research. In fact, there is no standardised approach to studying music production on the piano with fMRI, and the experimental designs, instruments and approaches vary by research team, since they are chosen by researchers for the sole purpose of their study. Therefore, a study setup validated in a group of musicians (Olszewska et al. 2023) has been employed.

The task of playing the piano (music playback fMRI task) has been chosen to resemble how participants learned to play (listen and imitate) and based on the original study by Chen, Rae, and Watkins (2012), where novice pianists were hearing a fragment of a melody and then asked to play it back. This task, admittedly, cannot be used before the participants have learned how to play a simple melody. Thus, a similar fMRI task, which requires pressing keys on a keyboard in a sequential manner, has been employed (piano key pressing task). Finally, a music listening fMRI task serves as a control task, and a tonal working memory behavioural task (tonal n-back) has been used to investigate transfer effects on a cognitive domain, as most of the previous research on musical training was focused on auditory processing.

In essence, musical training can be understood as a complex process where auditory and motor systems interact to produce structured behaviour with a particular auditory feedback. Playing a musical instrument was shown to involve a wide range of processes, from fine and gross motor control to auditory-motor integration, memory, error monitoring, emotion, and reward (Zatorre, Chen, and Penhune 2007). In contrast, most studies on motor sequence learning focus on single sequences, such as a Serial Reaction Time task, or structured sequences of button presses. Musical training can be considered a richer and more ecological intervention, at the cost of it being less controlled (from a research standpoint) and thus harder to interpret. One feature of such intervention is that the difficulty of the task increases with time. From very simple melodies to etudes and more complex musical pieces, the musical training course material progresses in difficulty to pose a challenge at every stage, which is also reflected in the stimuli used for the music playback fMRI task. Similar approaches have been employed to study neuroplastic processes related to linguistic processing in a naturalistic setting (Banaszkiewicz et al. 2020; Kuper et al. 2021; Matuszewski et al. 2021), but they have rarely been used in the context of musical training and functional plasticity. A study by Herholz and colleagues (Herholz et al. 2016) implemented a similar design, but only in a time-frame of six weeks and concentrated on listening tasks without the use of music playing tasks. Apart from this study, most research concentrated on learning fixed sequences uniform throughout the training (e.g., Brown and Penhune 2018; Chen, Rae, and Watkins 2012; Wollman et al. 2018; Tavor et al. 2019). In the current project, a progressive curriculum was designed to make the learning process naturalistic and generalisable to real-life situations.

Learning to play a musical instrument represents a form of intensive, long-term fine motor skill training which necessitates the coupling of complex bimanual movements with auditory processing (Herholz & Zatorre, 2012). The two abovementioned fMRI studies (Brown and Penhune 2018; Chen, Rae, and Watkins 2012) have focused on piano performance with just the right hand. However, bimanual coordination is a fundamental aspect of playing a musical instrument, such as the piano, and often requires independent movement of each hand. Recent fMRI case studies have begun to explore bimanual piano performance in trained pianists (Barrett et al. 2020; Endestad et al. 2020), showing differences in brain activation between tasks of varying demands. In general, asymmetric bimanual tasks, compared to symmetric tasks, are known to elicit more extensive activation in brain regions associated with motor planning and control. This is likely due to the increased demands placed on the motor system, particularly in non-dominant motor areas (Aramaki, Osu, and Sadato 2010; Matsuda et al. 2009). Interestingly, classic studies have shown that musicians exhibit lower brain activation compared to non-musicians during asymmetric bimanual tasks in areas such as the supplementary motor area, anterior insula, cerebellum, and basal ganglia (Haslinger et al. 2004; Jäncke, Shah, and Peters 2000), pointing to a more specialised processing of these increased-demand tasks. So far, the impact of the bimanual aspect of piano playing on brain activation in novices undergoing musical skill acquisition remains unexplored. In the current project, a specific design introduces conditions of varying bimanual demands in the piano key pressing task. In this manner, the relationship between bimanual task demands and the time-course of brain reorganisation can be investigated.

1.6. Goals of the project, research questions and hypotheses

In summary, the literature postulates that musical training is associated with adaptations of the auditory brain network during processing of acoustic stimuli, and auditory-motor adaptations related to auditory-motor integration and motor sequence learning, which support the motor aspect of skill execution (playing the instrument). However, much of the evidence comes from cross-sectional studies, or longitudinal studies with an arbitrarily short time-frame and before-after designs, and concentrated on the auditory, not motor adaptations; brain activation in novice musicians playing music has been hardly investigated. Importantly, the time-course of functional adaptations has not been the subject of investigation. Therefore, to address these concerns and combine cross-sectional and longitudinal designs, the current project was divided into three studies, each with its own goals and set of hypotheses. In Study 1, I focus on the time-course of neuroplastic adaptations related to auditory processing of acoustic stimuli, as this is the aspect most studied in the context of musical training. In Study 2, I employ naturalistic music playing tasks to understand auditory-motor interactions in the context of musical training, and the dynamics of the changes in the motor domain and regions related to auditory-motor integration. Finally, the Study 3 uses a cross-sectional approach to compare the results from novice pianists to trained musicians, and give insights into the effects of the twenty-six week training period against lifelong training.

Study 1. Auditory processing.

Research question: ***What is the time-course of changes in auditory processing (music listening and tonal working memory) during the first weeks and months of learning to play the piano?***

To answer this question, musical-training-related changes in auditory processing were investigated by comparing novice pianists longitudinally to passive controls. Because much previous research has been dedicated to measuring the differences in auditory processing between people with musical background and musically naïve controls, this study was set to explore how these differences arise in time. Auditory processing was measured in two tasks: the music listening fMRI task and the tonal n-back behavioural task. The following main hypotheses were tested:

H1.1° Novice pianists and passive controls do not differ in auditory processing of melodies before the start of training.

H1.2° Differences in auditory processing between novice pianists and passive controls arise in the areas of the auditory cortex within six weeks of training.

H1.3° After the completion of training, novice pianists display improved tonal working memory compared to controls.

Study 2. Playing the piano.

Research question: ***How the brain activation relating to playing the piano reorganises during the musical training, and how does this reorganisation depend on task demands?***

To answer this question, novice pianists performed a piano key pressing fMRI task with conditions differing in bimanual motor coordination demands, and a music playback fMRI task. The following main hypotheses were tested:

H2.1° The brain activation changes during the piano key pressing fMRI task occurs due to piano training and not task repetition.

H2.2° During the training period, training-related changes can be observed in the dorsal auditory stream for both tasks. The extent of the changes and how rapidly they occur depends on the task demands. The order of the engaged structures resembles the integrated model or motor sequence learning.

H2.3° After the cessation of training, no further changes are observed.

Study 3. Cross-sectional approach - novices vs musicians

Research questions: ***Is the tonal working memory performance in novice pianists comparable to trained musicians after twenty-six weeks of training? Is the brain activation in novice pianists comparable to trained musicians?***

To answer these questions, novice pianists were compared cross-sectionally to trained musicians at two time-points: before and after their training. The comparison involved the tonal working memory behavioural task and a piano key pressing fMRI task. The following main hypotheses were tested:

H3.1° Before training, trained musicians outperform novice pianists in the tonal working memory task. This difference is not found after training.

H3.2° Before training, novice pianists exhibit increased brain activation when performing the piano key pressing fMRI task compared to trained musicians. This difference is not found after training.

H3.3° Before training, the difference between the *asymmetric* and *symmetric* conditions is greater in novice pianists than trained musicians. After training, the increased task demands in the *asymmetric* condition are the same for both groups.

2. Methods and materials

[…] ***Achilles cannot overtake the tortoise so long as their progress is considered piecemeal, endlessly halving the distance between them. However, as it is not Achilles but the method of measurement which fails to catch up with the tortoise, so it is not man but his method of thought which fails to find fulfilment in experience.***

— Alan Wilson Watts

2.1. Participants

A total of sixty-six participants were recruited to participate in the project. The inclusion criteria were: female gender identification, current student status (young adult age range 18-26, M=21.3, SD=1.4), right-handed, Polish as native language, lack of psychiatric, psychological and neurological disorders, normal hearing, normal BMI, normal or corrected-to-normal vision. The exclusion criteria were incompatibilities with MRI safety protocols. Written informed consent was collected from all participants.

Of the sixty-six participants, twenty-one had completed at least secondary musical education on a keyboard instrument (piano, pipe organ, harpsichord, clavichord). These were assigned to the *musicians* group and had between eleven and twenty years of experience in playing keyboard instruments (M=15.2, SD=1.88). Fifteen musicians declared their age of onset of musical training (minimum 6 years old, maximum 8 years old, median 7 years old).

The remaining forty-five participants were musically naïve, defined as having no history of musical training (such as choir participation, singing or instrumental lessons, self-learning) except for the 'music and arts' compulsory classes in the Polish primary education curriculum. These participants were further divided into the *novice pianists* and *passive controls* groups (twenty-four and twenty-one participants, respectively). Because of expected dropout, which is typical for longitudinal interventions, about 15% more participants were included into the active intervention (*novice pianists*). The *novice pianists* underwent a twenty-six weeks piano training course (described below), and the *passive controls* underwent no specific training and were blinded to the nature of the project. These two groups did not differ in musical competence, as measured by the Polish adaptation of the Musical Ear Test (Wallentin et al. 2010).

Unfortunately, not all participants completed the project. From the *musicians* group, one participant could not be scanned and withdrew from the project. Two participants from the *passive controls* group withdrew from the project before completion. None of the *novice pianists* withdrew or were excluded. Thus, the final group sizes were twenty for the *musicians*, twenty-four for the *novice pianists* and nineteen for the *passive control* groups. No significant age differences were present between the *novices* and *musicians* groups (p=0.32) or *novices* and *passive controls* groups (p=0.26).

The Research Ethics Committee at the Institute of Psychology of the Jagiellonian University in Kraków, Poland, provided ethical approval for the current project, and the experimental procedures were performed according to The Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Piano training course

The twenty-six-week piano training intervention employed a standardised protocol to investigate the effects of musical training on brain activation during musical tasks. Training duration was chosen based on a recent study on training-related neuroplasticity in young adults (Li et al, 2018), and is in line with training durations used in certain interventions e.g., in the elderly (Jünemann et al. 2022). A professional instructor (Mrs Katarzyna Kiwior, a Suzuki method certified teacher) designed consistent teaching materials and methods based on study goals and requirements, which were approved by the author. The Suzuki method is a music curriculum and teaching philosophy created by Shinichi Suzuki, originally intended for children. Shinichi Suzuki believed that musical ability is learned similarly to how language is learned. Specifically, musical talent is not an inborn quality, and every child is capable of acquiring musical ability given the right instruction and supportive environment. The piano training course in this project did not utilise the exact Suzuki method, but drew inspiration from this approach. Similarly to the early Suzuki curriculum, all of the material was learned by mimicking the teacher, without the use of musical score, and participants learned in pairs to foster collaboration and engagement.

The progressive curriculum was delivered by the instructor through (mostly) bi-weekly sessions of forty-five minutes each. The learning sessions were attended by participants in-person, but occasional remote sessions were made possible when necessary because of the effective COVID-19 restrictions or participant health status. The bi-weekly schedule was occasionally adjusted to account for unforeseen circumstances such as participant illness. National holidays (e.g., winter and spring break) were taken into account in the planned schedule and not included in training duration. Please refer to Table 2.2.2 for a full overview of the training course schedule.

The curriculum advanced systematically, ensuring all participants progressed at the same rate. It tackled eight piano pieces of increasing complexity (Table 2.2.1) alongside fundamental technique elements such as staccato and legato, or basics of music terminology. The eight piano pieces were selected by Mrs Kiwior in collaboration with dr Agnieszka Widlarz, a consulting expert from The Chopin University of Music. They included three nursery rhymes ("*Wlazł kotek na płotek*", "*Panie Janie*", "*Jedzie pociąg z daleka*"), three folk songs ("*W murowanej piwnicy*", "*Jingle Bells*", "*Czerwone Jabłuszko*"), one music piece from a movie score (Waltz from the movie Amelia by Y. Tiersen), and one classical music piece ("*Minuet in G-minor*" by Ch. Petzold, formerly attributed to J.S. Bach). This selection balanced the capabilities of novices and playing difficulty with the limitations of the keyboard (C3-C5 register and articulation options) and the constraints imposed by the supine position during scanning.

Despite the seemingly simple nature of the musical stimuli due to the restrictions of the experimental setup, the chosen pieces presented diverse musical challenges in terms of theirs texture. Two-hand melodies were used in the training course, with one of them (most often the right) acting as a melody and the other as an accompaniment (block or broken chords), including examples that use non-imitative polyphonic texture (M07 & M08). The musical pieces have different keys (C major, F major, E minor, F minor, G minor), demanding quick adaptation to the specific keyboard layout for each key change.

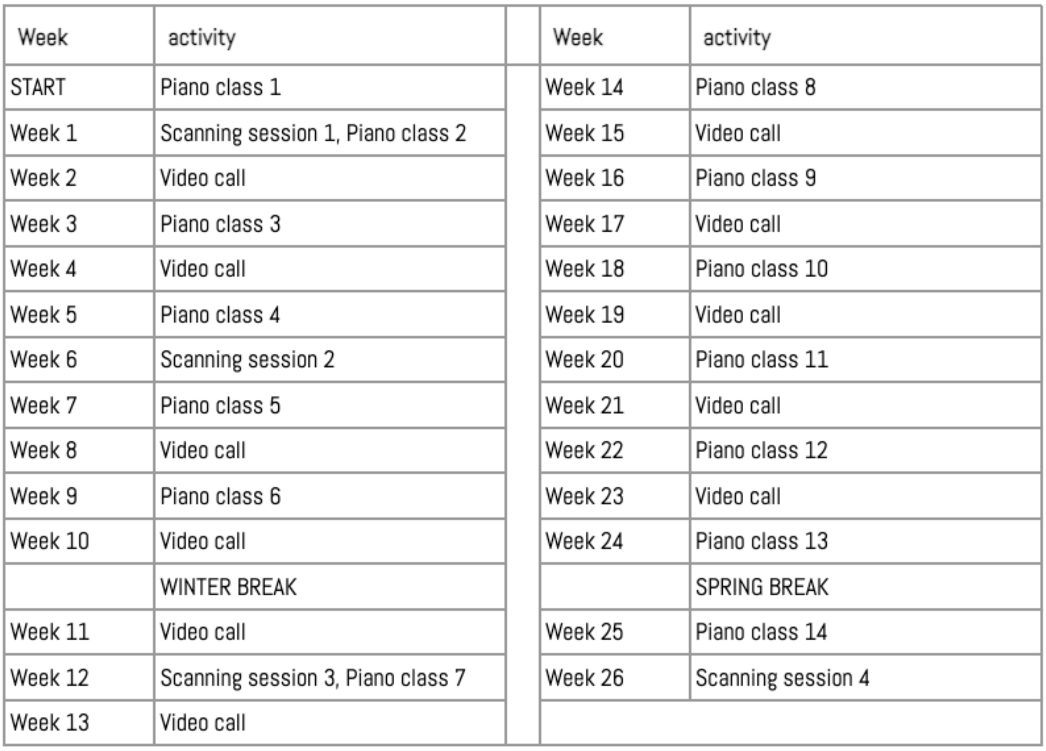
The curriculum was introduced gradually, with the easiest three musical pieces introduced during weeks one, two, four and six, followed by more complex ones in weeks eight and eleven, and two most difficult pieces presented gradually and simultaneously in weeks 18-21. To accommodate the restricted two-octave range of the MRI-compatible keyboard, all musical pieces underwent appropriate adaptations, including transpositions or rearrangements, enabling performance within the scanner constraints by the novices.

Additionally, participants were introduced to motor exercises which aimed at improving their gross and fine motor skills necessary for playing the piano. Electronic keyboards were provided for home practice, which followed a recommended schedule of approximately four hours weekly, or thirty minutes daily. To ensure adherence and monitor progress, fifteen-minute video calls with the researcher (AMO) occurred bi-weekly between the learning sessions, tracking practice time and engagement with the training plan.

Table 2.2.1. Piano training course material and music playback fMRI task stimuli.

No	composer/source	title (original title)	difficulty	introduced	Measured experimentally
M01	Polish nursery rhyme	*A cat climbed a fence* *(Wlazł kotek na płotek)*	easy	Week 1	$TP_{week\,1}$, $TP_{week\,6}$, $TP_{week\,13}$, TP_{end}
M02	French nursery rhyme	*Frère Jacques* *(Panie Janie)*	easy	Week 2	$TP_{week\,6}$, $TP_{week\,13}$, TP_{end}
M03	Highlander folk song	*In a brick cellar* *(W murowanej piwnicy)*	easy	Week 4	$TP_{week\,6}$, $TP_{week\,13}$, TP_{end}
M04	Polish nursery rhyme	*A train comes from afar* *(Jedzie pociąg z daleka)*	easy	Week 6-7	$TP_{week\,13}$, TP_{end}
M05	American holiday song	*Jingle bells*	difficult	Week 8-9	$TP_{week\,13}$, TP_{end}
M06	Y. Tiersen	*Amélie - Nursery Rhyme from Another Summer* *(Amelie - Comptine d'un autre été)*	difficult	Week 11-15	TP_{end}
M07	Kuyavian folk song	*Red Apple* *(Czerwone Jabłuszko)*	difficult	Week 18-21	TP_{end}
M08	Ch. Petzold (formerly attributed to J.S. Bach)	*Minuet in G Minor from the Notebooks for Anna Magdalena Bach*	difficult	Week 18-21	TP_{end}

Table 2.2.2. The general schedule of the musical training course (minor deviations occurred to accommodate individual participants experiencing illness).



Week	activity	Week	activity
START	Piano class 1	Week 14	Piano class 8
Week 1	Scanning session 1, Piano class 2	Week 15	Video call
Week 2	Video call	Week 16	Piano class 9
Week 3	Piano class 3	Week 17	Video call
Week 4	Video call	Week 18	Piano class 10
Week 5	Piano class 4	Week 19	Video call
Week 6	Scanning session 2	Week 20	Piano class 11
Week 7	Piano class 5	Week 21	Video call
Week 8	Video call	Week 22	Piano class 12
Week 9	Piano class 6	Week 23	Video call
Week 10	Video call	Week 24	Piano class 13
	WINTER BREAK		SPRING BREAK
Week 11	Video call	Week 25	Piano class 14
Week 12	Scanning session 3, Piano class 7	Week 26	Scanning session 4
Week 13	Video call		

Furthermore, to isolate the intervention's effects from possible linguistic aspects of music processing, reading music score (sheet music) was excluded, and the participants were explicitly required not to engage in learning it on their own before the end of the project. Foot pedal usage was omitted from the curriculum as well, as foot pedals were not included in the electronic keyboards for home practice nor the MRI-compatible keyboard.

2.3. fMRI compatible keyboard and experimental setup

2.3.1. Keyboard description

The fMRI MIDI keyboard (Figure 2.3.1. a) used in the current project was designed in a collaboration with a company which produces MRI-compatible equipment (SMIT-lab) (Olszewska et al. 2023). The keyboard features 25 dynamic keys (2 octaves + 1 key) with electric sensors and enables wireless connection with latency under 20ms (most events latency <10ms). It is fully compatible and operational in a magnetic field of a 3T scanner and the dimensions fit within most scanner boreholes (outer dimensions 395 mm width × 62 mm height × 160 mm length). Since there are no formal guidelines to the dimensions of piano keys, a commercially available piano keyboard was used as a reference and the full-sized keys yield 163 mm octave width. During the experimental procedures, the electronic keyboard was placed on a dedicated piano stand (Figure 2.3.1. b) and connected wirelessly to a receiver in the scanner room, which translated the signal into an optical signal, later translated again into an electrical signal delivered to a dedicated computer gathering behavioural data as well as a synthesiser converting the signal into a timbre delivered as acoustic feedback to the participant (Figure 2.3.1. c). The mean sound latency of the setup was about 8ms, with 99% of events having latency under 20ms, what makes the setup viable for studying music-related phenomena (Lester and Boley 2007).

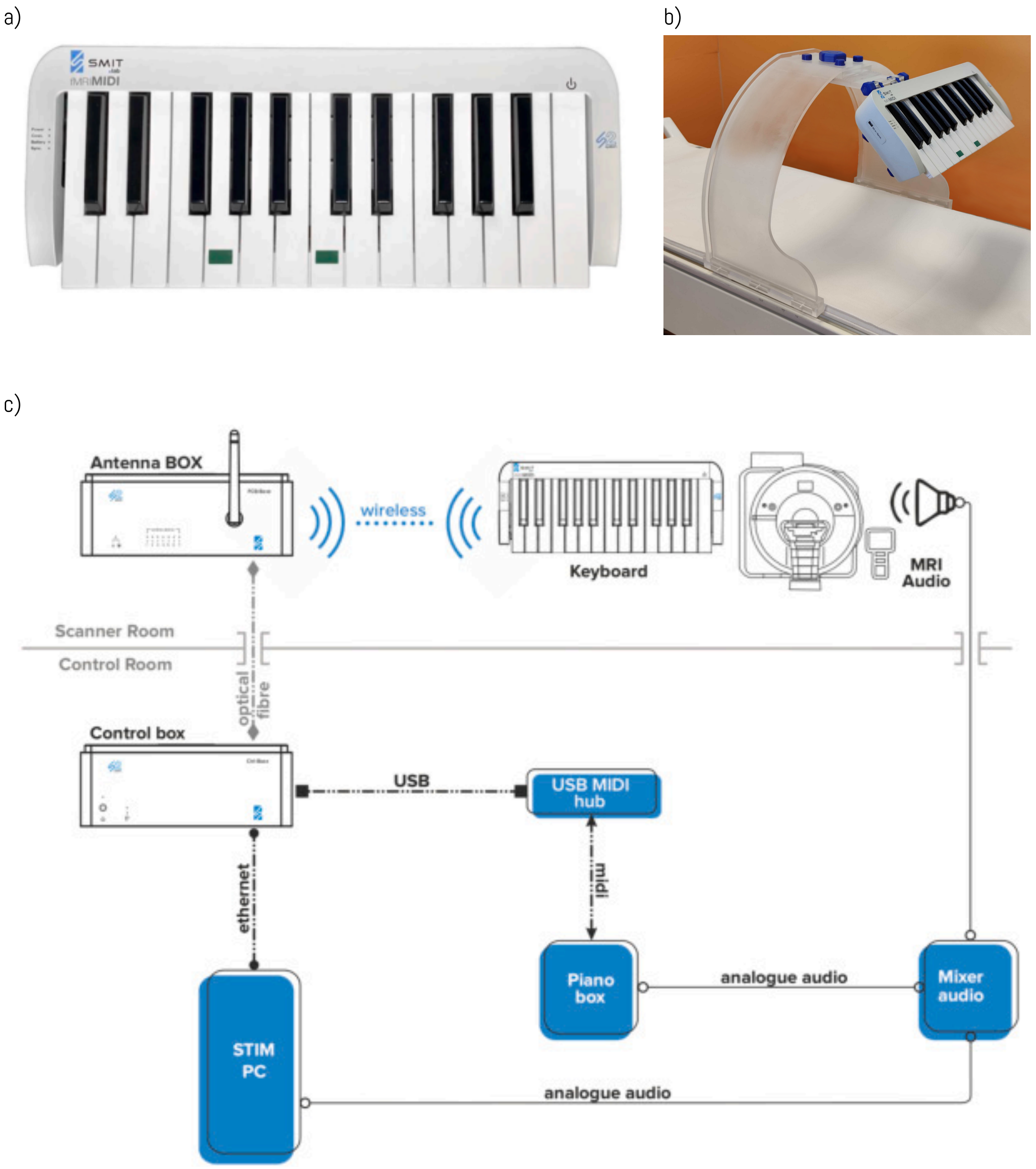


Figure 2.3.1. The wireless fMRI MIDI keyboard and the experimental setup. (a) A photograph of the keyboard; (b) the keyboard mounted on the keyboard stand for MRI experiment; (c) The information about key pressing (timing & force) is sent wirelessly to an Antenna Box, which in turn sends it to the control box via an optical fibre (◆). The Control Box communicates with the stimPC via ethernet (●), thus the timing and the force of key presses can be logged. The control box forwards the signal via USB (■) to a USB MIDI hub, which translates it into MIDI encoding (▲), and sends it to the PianoBox which synthesises the sound in grand piano timbre. Analogue audio (○) from the PianoBox (corresponding to key presses) and the stimPC (other auditory stimuli) is collected via an audio mixer and sent to the MRI audio system. Figure reprinted from (Olszewska et al. 2023) under the Creative Commons licence (CC BY 4.0).

2.4. Neuroimaging data collection

2.4.1. Anatomical data collection

To create a high-resolution anatomical reference for subsequent analysis, an anatomical T1-weighted scan was acquired at the end of each scanning session. These scans used a magnetisation-prepared rapid gradient-echo sequence (MPRAGE) with a voxel size of 1 × 1 × 1 mm isotropic (field of view = 256 × 176 × 256 mm [anterior-posterior; right-left; feet-head]) in sagittal orientation.

2.4.2. Functional data collection

Neuroimaging data were acquired on a 3-Tesla Siemens Magnetom Trio scanner equipped with a 32-receive channel head coil. An echo-planar imaging (EPI) sequence with an Interleaved Silent Steady-State (ISSS) paradigm (Schwarzbauer et al. 2006) was employed to capture brain activity during the three tasks described above: the listening task, the piano key pressing task, and the music playback fMRI task. All acquisitions utilised a multi-band acceleration factor of 3, repetition time [TR]=1550 ms, echo time [TE]=30.4 ms, and flip angle [FA]=56°. The 'silent' TRs were utilised for the delivery of auditory stimuli and playing musical stimuli by the participants.

A total of sixty slices per volume were acquired in transverse plane orientation with an isotropic voxel size of 2.5 × 2.5 × 2.5 mm. Before each scan, two spin-echo EPIs with an inverted phase-encoding direction were also acquired for magnetic field inhomogeneities estimation.

2.5. Experimental design and time-course

The longitudinal experiment spanned a time-frame from a week before the start of training to a follow-up session, which took place eight to twelve weeks after the completion of training (Fig 2.5.1., Table 2.5.1.). During this time, participants were invited to participate in up to seven experimental sessions in increasing time intervals (Table 2.5.1). These time intervals were based on previous neuroimaging studies with adult novices learning to play the piano (Amad et al. 2017; Herholz et al. 2016; Lappe et al. 2008; Paraskevopoulos et al. 2012; Wollman et al. 2018). The time-point a week before the onset of training ($TP_{pre\text{-}training}$) was used as a control time-point to account for repetition effects (from $TP_{pre\text{-}training}$ to TP_{onset}) in *novice pianists*. The following five time-points spanned the period of the piano training course (TP_{onset}, $TP_{week\ 1}$, $TP_{week\ 6}$, $TP_{week\ 13}$, TP$_{\text{end}}$) and both the novice pianists and the passive controls participated in these sessions. Finally, the TP$_{\text{follow-up}}$ occurred eight to twelve weeks after the completion of training by the novice pianists, and both the novices and the passive controls took part in this experimental session. Trained musicians participated in a single scanning session and were compared cross-sectionally to novice pianists.

During the study, participants were asked to perform various behavioural and fMRI tasks, which differed based on the participant group and the project stage (Table 2.5.1). Conceptually, these were divided into three tracks: (1) auditory processing and (2) playing the piano, and (3) comparison between novice pianists and trained musicians.

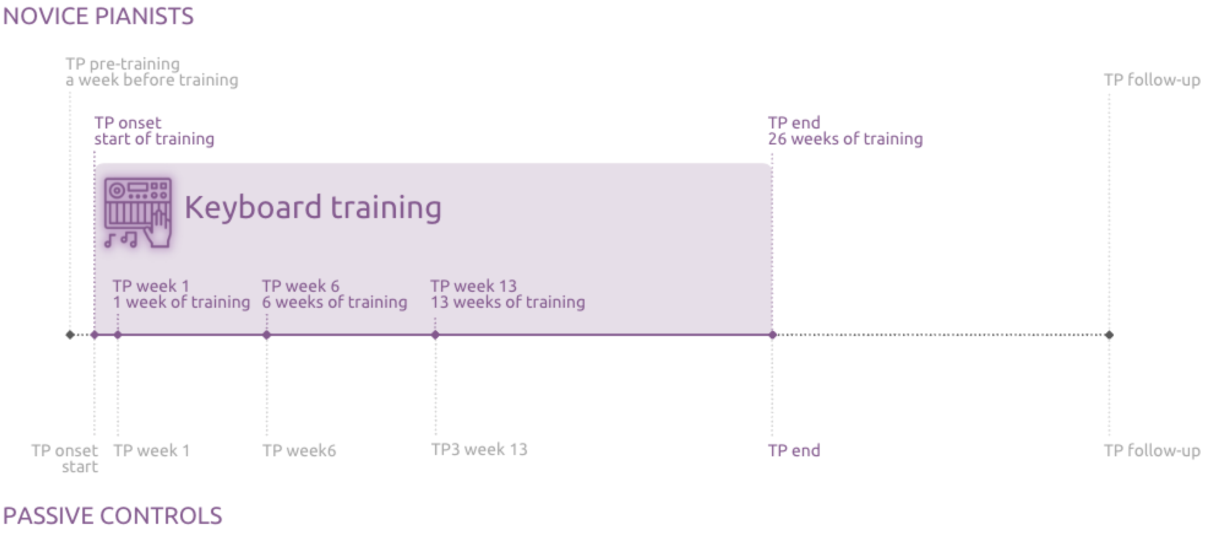


Figure 2.5.1. The time-course of the longitudinal study.

2.5.1. Study 1: Auditory processing

The Musical Ear Test was performed once by both novice pianists (at TP$_{\text{pre-training}}$) and passive controls (at TP$_{\text{follow-up}}$) as a measure of musical competence. The music listening fMRI task was performed by the novice pianists and the passive controls at all time-points and the behavioural tonal working memory task (tonal n-back) was performed by the participants from both groups at the onset of training (TP$_{\text{onset}}$), end of training (TP$_{\text{end}}$) and follow-up (TP$_{\text{follow-up}}$).

2.5.2. Study 2: Playing the piano

The piano key pressing fMRI task was performed exclusively by the novice pianists at all time-points, while the music playback fMRI task was performed by the novice pianists only at time-points during the training ($TP_{week 1}$ - TP_{end}).

2.5.3. Study 3: Cross-sectional approach - novices vs musicians

The novice pianists and the trained musicians were compared on two tasks: the piano key pressing fMRI task, and the behavioural tonal working memory task. The comparison was performed cross-sectionally at the onset of training (TP_{onset}) and at the time-point at the end of training (TP_{end}). Since trained musicians underwent only a single experimental session, this data was used in both comparisons.

2.5.4. Additional considerations

Prior to their initial experimental session, all participants underwent dedicated familiarisation procedures. These procedures aimed to acquaint participants with the nature of the upcoming tasks and acclimate them to the MRI environment to minimise potential anxiety and uncertainty associated with the primary experiment while ensuring adequate preparation for optimal performance. The familiarisation protocols consisted of abbreviated versions of the actual scanner tasks (detailed below), shortened to three repetitions of the task stimuli, and took place in a mock-scanner directly before the first scanning session.

Table 2.5.1. An overview of the experimental design of the study. The shaded period corresponds to the training period of the novice pianists.

Group	Time-point (TP)	Task (task type)					Time interval
		music playback (fMRI, behavioural)	piano key pressing (fMRI, behavioural)	music listening (fMRI)	tonal n-back (behavioural)	Musical Ear Test (behavioural)	
Novices	$\text{TP}_{\text{pre-training}}$		✓	✓		✓	1 week before training
	TP_{onset}		✓	✓	✓		training onset
	$\text{TP}_{\text{week 1}}$	✓	✓	✓			1 week
	$\text{TP}_{\text{week 6}}$	✓	✓	✓			6 weeks
	$\text{TP}_{\text{week 13}}$	✓	✓	✓			13 weeks
	TP_{end}	✓	✓	✓	✓		26 weeks (training ended)
	$\text{TP}_{\text{follow-up}}$		✓	✓	✓		+8-12 weeks (follow-up)
Controls	TP_{onset}			✓	✓		Study onset
	$\text{TP}_{\text{week 1}}$			✓			1 week
	$\text{TP}_{\text{week 6}}$			✓			6 weeks
	$\text{TP}_{\text{week 13}}$			✓			13 weeks
	TP_{end}			✓	✓		26 weeks
	$\text{TP}_{\text{follow-up}}$			✓	✓	✓	+8-12 weeks
Musicians		✓	✓		✓		

2.6. Experimental procedures and statistical analyses

2.6.1. Study 1: Auditory processing

2.6.1.1. Musical Ear Test

To ensure comparable baseline levels of musical processing between the novice and control groups, a standardised assessment of musical competence was conducted using an online adaptation of the Musical Ear Test (Correia et al. 2021; Wallentin et al. 2010). The Musical Ear Test is a validated tool for measuring musical aptitude across melody and rhythm domains. The procedure was hosted on the Gorilla Experiment Platform (Anwyl-Irvine et al. 2020) and its instructions were translated from English into Polish by me. The translation has been subsequently reviewed and approved by the other members of the research team to ensure cultural and linguistic accuracy.

Novices completed the Musical Ear Test during a pre-scan session prior to the commencement of their training program (TP_{onset}), while passive controls undertook the assessment at session $TP_{follow-up}$ (please refer to table 2.5.1. for the timeline). The test was administered in a controlled laboratory environment, utilising noise-cancelling headphones to minimise extraneous auditory stimuli and ensure optimal testing conditions.

During the Musical Ear Test, participants were presented with a total of 108 trials divided into two distinct conditions: 54 Melody trials and 54 Rhythm trials. Each trial showcased two sequential audio stimuli, prompting participants to assess their auditory perception of identity. Participants indicated their judgement utilising on-screen buttons labelled "TAK" (yes) for identical and "NIE" (no) for non-identical, within a maximum response time of 1.5 seconds. To familiarise participants with the task format and response system, the two first trials had no maximum response time limit and were treated as practice trials preceding each condition, their results excluded from the final score calculation. Participants received feedback on the correctness of their answers for the practice trials only. Individual scores were determined by calculating the percentage of correct responses out of the maximum of 52 in each condition.

To evaluate whether the novice pianists differed from the passive controls in the processing of musical stimuli, means of the percentage of correct responses, the number of missed responses, and response times were compared using a two-sided independent t-test with Pingouin 0.5.1 (Vallat 2018) running on Python 3.10 (Van Rossum and Drake 2009).

2.6.1.2. Tonal n-back task (tonal working memory)

To investigate the potential influence of musical training on tonal working memory, a modified tonal n-back paradigm adapted from Ding and colleagues (2018) was employed. The task was administered using Presentation® software (Version 20.1, Neurobehavioral Systems, Inc., Berkeley, CA) (RRID:SCR_002521)). Novice pianists and passive controls completed the task at three time-points (TP_{onset}, TP_{end}, $TP_{follow-up}$), while musicians performed it once (please refer to Table 2.5.1 for study timeline).

During the task, participants were presented with pseudo-randomised auditory sequences, containing between nine and twelve tones drawn from the twelve half-tones of the fourth octave (C4-H4). Following each sequence, they were required to judge whether the final tone was identical to a previously presented reference tone a specified n number of tones back in the sequence (n-back). The participants provided their answer (“identical” or “different”) using the two lateral buttons of the CEDRUS RB-540 response pad (left for identical, right for different). For instance, consider a hypothetical sequence (Figure 2.6.1): in the 2-back condition, the reference tone would be identical to the final tone (G4#), while in the 3-back condition, it would be B4, leading to a "different" response. The maximum allotted response time was 1.5 seconds. The task comprised an equal number of "identical" and "different" trials, delivered without performance feedback. The stimulus sequences adhered to the same constraints regarding target note repetition as outlined in the original study by Ding and colleagues (2018). A bespoke Python script generated new sequences at each time-point, and the order of "identical" and "different" trials was pseudo-randomised and counterbalanced across participants.

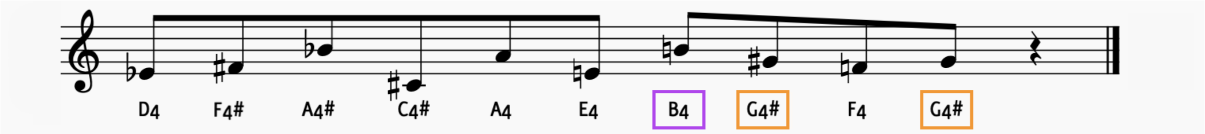


Figure 2.6.1. A hypothetical tone sequence for a tonal working memory n-back task. The final note is compared to a note which occurs (n) notes prior to it. In the 2-back condition, the final note is identical to the reference note [orange], but not in the 3-nacl condition [purple].

Because in the original study non-musicians performed at chance level for n>4, this study employed a shortened, seven-minute version of the task, incorporating only the 2-back and 3-back conditions with 37 trials each (excluding the first five non-scored training trials). Since the original study reported no significant differences between quarter-note and eighth-note conditions, solely the quarter-note presentation was chosen for this study.

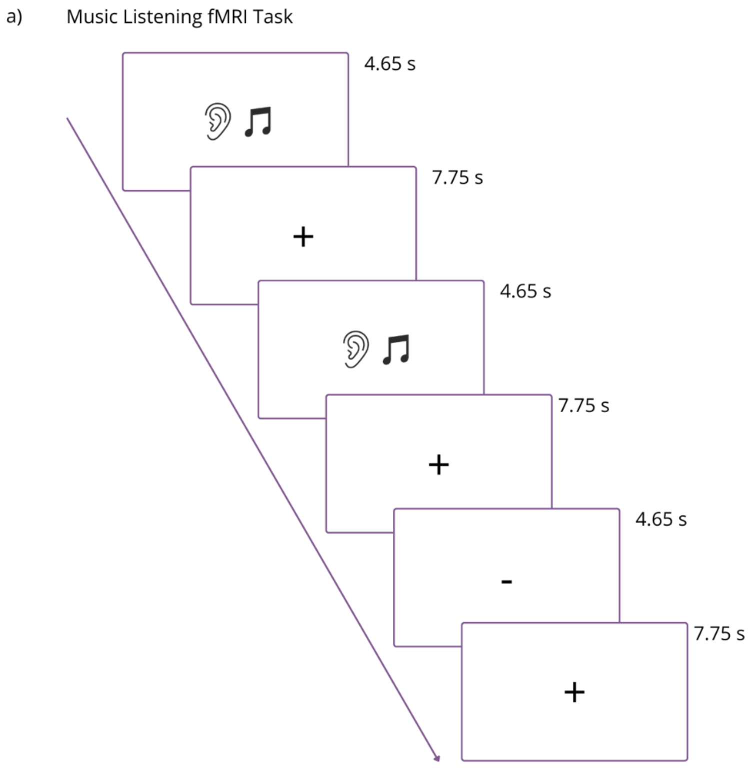
Initial logfile preprocessing was performed using MATLAB R2022b (Mathworks, http://www.mathworks.com) and participants who omitted at least 20% of trials in at least one condition were excluded from the analyses. Accuracy scores were computed based on the percentage of correct responses. The remaining participants' responses were analysed with a two-way mixed-model ANOVA with time as within-subject factor and group as between-subject factor to compare the accuracy scores of the novices and passive controls between TP_{onset} and TP_{end}, and between TP_{end} and $TP_{follow\text{-}up}$.

2.6.1.3. Music listening fMRI task

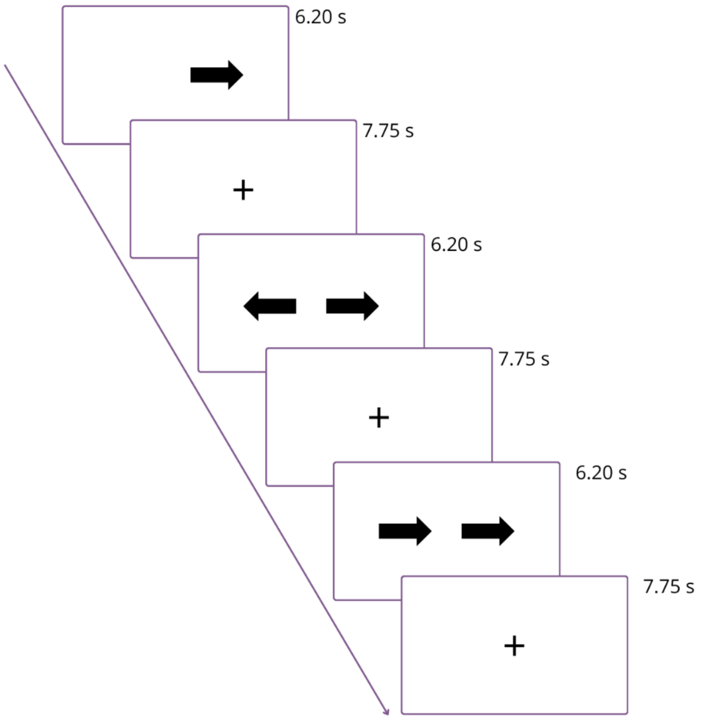
The goal of this task was to investigate brain activation patterns evoked by listening to musical stimuli. To ensure all participants were unfamiliar with the auditory stimuli, a subset of short piano pieces was selected from the MUST dataset (Clemente et al. 2020). In this task, the neuroimaging data were collected with ISSS structure composed of five TRs (7.75s) of image acquisition followed by three 'silent' TRs (4.65s). Auditory stimuli were presented only during the 'silent' TRs.

The compositions in the MUST dataset varied in Balance, Contour, Symmetry, and Complexity and were presented in eight blocks across the study. Each block included four musical stimuli from each category (Balance, Contour, Symmetry, and Complexity) in semi-randomised order and one 'silence' matching the duration of the musical stimuli, where no stimulus was presented and only auditory background was present. The participants were instructed to keep their eyes open and pay attention to visual cues, which corresponded with the nature of the stimulus (♫: listen to music; ▬: listen to silence) and to listen carefully to auditory stimuli presented (Figure 2.6.2). To prevent participants from becoming overly familiar with the presented musical pieces, half of them were repeated throughout the study, while the other half were entirely new at each time-point. The order of stimuli presentation was pseudo-randomised and counterbalanced across participants.

There were no behavioural data associated with this task.



b) Piano motor fMRI Task



c) Music Playback fMRI Task

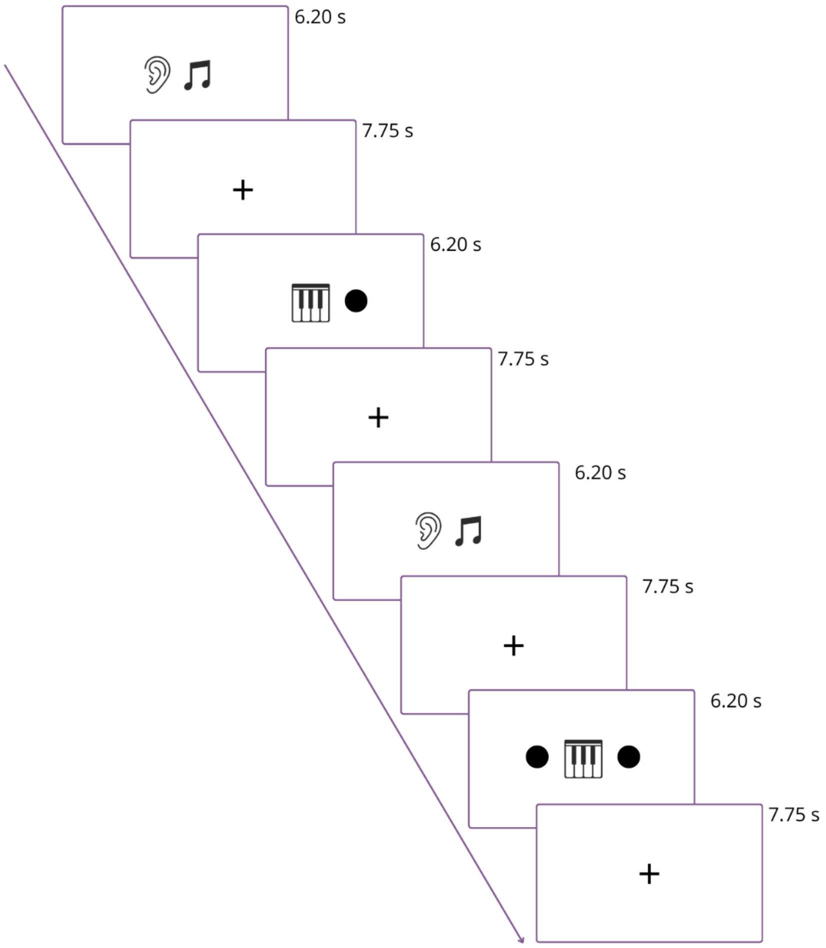


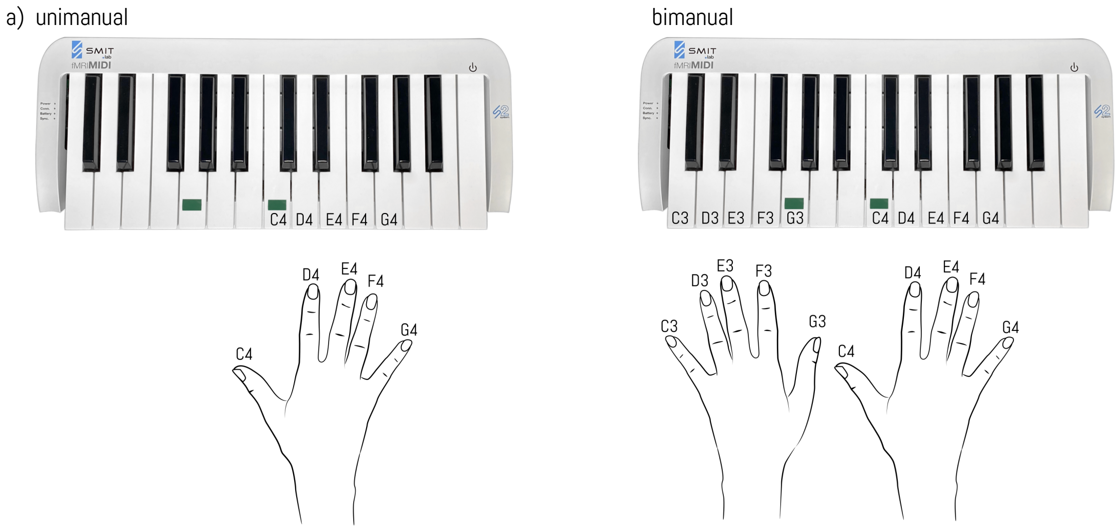
Figure 2.6.2. (previous pages) A schematic representation of the fMRI task designs. (a) the music listening task; participants were listening to short musical pieces or 'silence' in the time windows corresponding to the 'silent' TRs of the ISSS design (b) the piano key pressing task; participants were pressing keys on the fMRI compatible keyboard according to visual cues (c) the music playback fMRI task; participants were asked to play back exactly the excerpt they heard in the preceding listen trial, using one (a cue with a single dot as presented) or both hands (black dots on both sides). Each rectangle indicates the cues presented to the participants with their durations in seconds; cues with a fixation cross (+) correspond to signal acquisition. Arrow indicates the passage of time.

2.6.2. Study 2: Playing the piano

2.6.2.1. Piano key pressing fMRI task

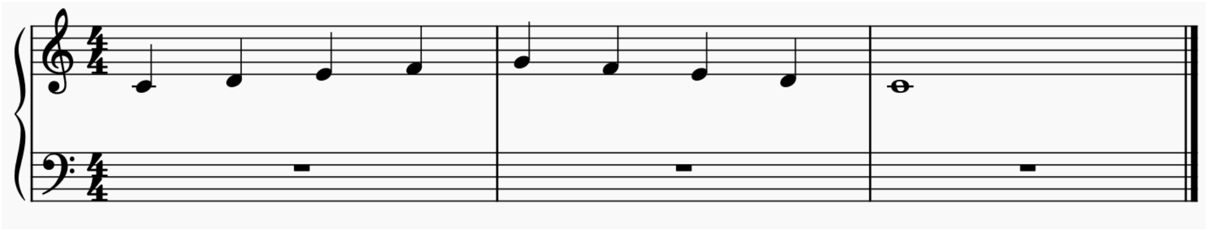
The piano key pressing fMRI task was designed to resemble playing the piano but simple enough to be performed in the scanner even before the onset of training. This design allows accounting for repetition effects in pre-training scans and study training-related changes in the whole training period, including the first week. While in the scanner, in the supine position, the MRI-compatible keyboard was placed on a dedicated keyboard stand above the participants' hips (Figure 2.3.1. b). Auditory feedback was provided, but the participants could not see their hands. The participants were asked to locate the convex stickers on an MRI-compatible piano (Olszewska et al. 2023) with their thumbs and keep their hands' position fixed throughout the task; the thumbs were placed on the keys marked with stickers, and the remaining fingers on consecutive white keys next to it, so that the left hand covered the C3-G3 register and the right hand covered the C4-G4 register (Figure 2.6.3a). The task consisted of three conditions, inspired by basic exercises used in piano training (Fig 2.6.2.b, Figure 2.6.3.b):

- *Unimanual (right-hand)*: a cue with a single arrow (→) was presented. The participant was asked to press the keys consecutively from left to right and backwards with their right hand only (C4 D4 E4 F4 G4 F4 E4 D4 C4).
- *Bimanual symmetric*: a cue with two symmetric arrows (←→) was presented. The participant was asked to press the keys consecutively using both hands simultaneously, starting with the thumbs (right hand: C4 D4 E4 F4 G4 F4 E4 D4 C4, left hand: G3 F3 E3 D3 C3 D3 E3 F3 G3).
- *Bimanual asymmetric*: a cue with two asymmetric arrows (→→) was presented. The participant was asked to press the keys consecutively using both hands simultaneously, unisono, starting with the thumb of the right hand (C4 D4 E4 F4 G4 F4 E4 D4 C4) and the little finger of the left hand (C3 D3 E3 F3 G3 F3 E3 D3 C3)

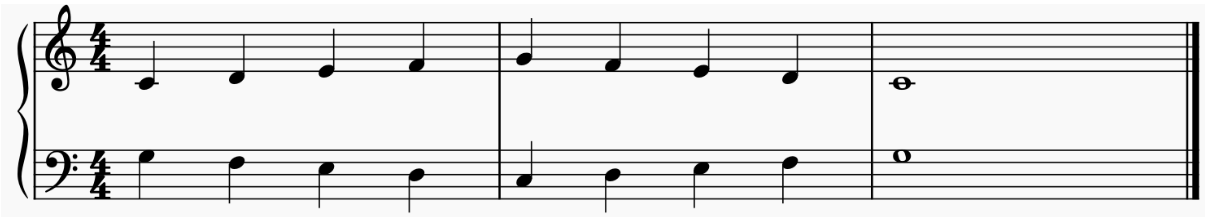


b)

Unimanual (right hand)



Symmetric



Asymmetric

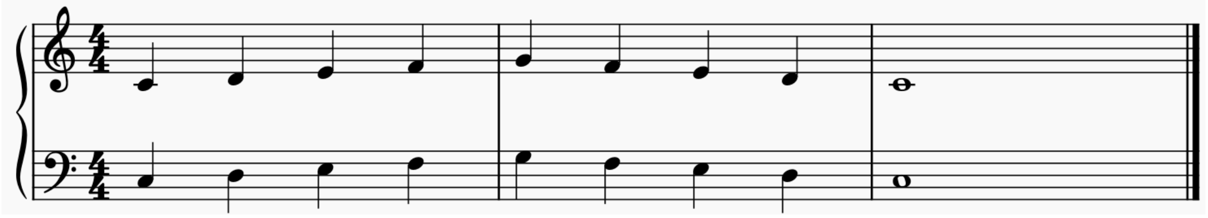


Figure 2.6.3. The methods and stimuli for the piano key pressing task. (a) Fixed-fingers position for the piano key pressing task. Green rectangles are convex stickers used to mark the keys G3 and C4. (b) The notation for the target stimuli of each of the conditions in the piano key pressing fMRI task.

The three conditions always appeared in the same order (*unimanual /right hand/ -> bimanual symmetric -> bimanual asymmetric*), which was repeated 12 times. The conditions took place during the 'silent' TRs of the neuroimaging data collection ISSS paradigm, consisting of five acquisition TRs (7.75s) followed by four 'silent' TRs (6.20s).

Behavioural data were collected to analyse the participant's responses and calculate the accuracy of pressing keys on the MRI-compatible keyboard using Levenshtein ratio (Levenshtein et al. 1966) and rhythmic accuracy using relative rhythmic deviance based on the Tapping-PROMs method (Georgi, Gingras, and Zentner 2022).

The Levenshtein ratio is a method to compare sequences (Levenshtein et al. 1966; Olszewska et al. 2023) which relates the number of differences between sequences to their length. The Levenshtein ratio is defined as:

$$1 - \frac{L_{distance}}{L_{sum}},$$

where $L_{distance}$ is the number of insertions, omissions and substitutions in the sequence performed by the participant compared to errorless performance, and L_{sum} is the sum of the lengths of both the performed sequence and the errorless performance (here, the sequence based on the score notation of the stimulus learned by the participant). Therefore, the Levenshtein ratio can be understood as the relative measure of how often the participant made a mistake while playing the target stimulus by measuring the similarity of the played sequence to errorless performance and yields a score between 0 (no similarity) and 1 (perfect accordance).

The relative rhythmic deviance was estimated using an approach based on tapping-PROMS, a method to compare rhythmic accuracy (Georgi, Gingras, and Zentner 2022; Olszewska et al. 2023). Only trials where the correct number of notes were pressed can be qualified for the score of rhythmic accuracy. First, the relative duration of each note in the errorless performance is calculated with respect to its complete duration. For example, if the sequence expects four quarter-notes and two half-notes, the quarter-notes should last 12.5% of the whole sequence, and each half-note 25% of the total sequence duration. A similar transformation is calculated for the actual participants' performance. In an actual performance, the notes might last 11.7%, 12.3%, 13.1%, 12.9%, 26.1% and 23.9% instead. The average relative rhythmic deviance is calculated:

$$\frac{\sum_{t=1}^{n} \frac{\left| t_{played} - t_{target} \right|}{t_{target}} \cdot 100\%}{n},$$

where t_{played} are the relative durations of each the played notes, and t_{target} their nominal durations, and n is the number of notes in the sequence. In this example, this yields 6.4%, 1.6%, 4.8%, 3.2%, 4.4%, 4.4% for each note, with a mean score of 4.3% deviation from nominal note duration. This score has a minimum of 0% and no maximal possible deviance score.

Outliers (±3 standard deviations from the mean) were removed for both scores. Statistical analysis of each of the scores was performed using Pingouin 0.5.1 (Vallat 2018) in Python 3.10 (Van Rossum and Drake 2009). Repetition effects were investigated using paired t-tests between the $TP_{pre\text{-}training}$ and TP_{onset}. The training period was modelled using repeated-measures ANOVA with time-point and hands-condition (unimanual right hand, bimanual symmetric, and bimanual asymmetric) as within-subject factors and time-point as between-subject factor, yielding the effects of time-point (TP_{onset}-TP_{end}), hands-condition, and the interaction between time-point and hands-condition. Finally, the follow-up period was analysed using repeated-measures t-tests between TP_{end} and $TP_{follow\text{-}up}$. The resulting p-values were corrected via the Greenhouse-Geisser correction in the case of repeated-measures ANOVAs where sphericity assumption was violated ($p_{GG\text{-}corr}$) or Bonferroni correction in the case of t-tests ($p_{Bonf\text{-}corr}$). Subsequent visualisations were performed in Seaborn 12.0 (Waskom 2021) and matplotlib 3.7 (Caswell et al. 2023) in Python 3.10 (Van Rossum and Drake 2009).

2.6.2.2. Music playback fMRI task

This task was designed to investigate the changes in brain activation of novice pianists playing naturalistic musical stimuli.

The task consisted of two conditions (Figure 2.6.2.c):

- *Listen:* a cue with an ear and notes symbol was presented. The participants heard a fragment of one of the melodies from the course curriculum. They were asked to recognise the fragment and refrain from pressing any keys during the *listen* condition and the scanning time that followed immediately afterwards when a fixation cross was presented. Depending on the following playback block, the heard fragment was played either bimanually or the unimanually with the right hand only.
- *Playback:* a cue with a keyboard symbol was presented with a single dot on the right side of the keyboard for the unimanual playback or two dots on both sides of the keyboard for bimanual playback. The participants were asked to play exactly the fragment that they

heard in the listen condition directly preceding the current trial, either unimanually with their right hand or bimanually, as indicated by the dots. The participants were asked to continue and finish playing the current fragment even if they made a mistake or the time ran out and the scanning time started, recognised by scanner noise and a fixation cross cue.

The conditions were alternating in such a way that after every listen condition came a corresponding playback condition. Two easily identifiable excerpts were selected for each musical piece. Those excerpts were always presented consecutively one after the other (listen1 - playback1 - listen2 - playback2), in the same order as they appear in the musical piece and under the same hand condition (unimanual or bimanual). E.g., if the participant heard the first excerpt from melody M03, after the playback condition the next excerpt would also come from melody M03 and would naturally occur later in the musical piece than the first excerpt. At TP_{onset}, this was a single simple melody (*Wlazł kotek na płotek*), which was divided into two parts and played sixteen times, half unimanually with the right hand and half bimanually (unisono). To maintain task difficulty throughout the course, at each time-point, the participants would perform the material already mastered in the training course. Thus, the number and difficulty of melodies increased while the number of repetitions decreased, corresponding to participants' progress in the course. The total task duration was kept at a constant of 32 trials occurring during the 'silent' 6.2s of the ISSS paradigm, each trial consisting of a listen and a playback phase interlocked with 'scanning' 7.75s of the ISSS paradigm. This resulted in each melody being played twice, once with the right hand and once with both hands, at TP_{end}. The listen-playback design of the task was chosen to resemble how the participants learned their course material during classes, as no musical notation was introduced and the musical pieces were played by ear. The order of the melodies was semi-randomised and counterbalanced across participants.

Behavioural data was collected and computed similarly to the piano key pressing fMRI task. However, statistical analysis of the behavioural data was performed using a generalised linear model in R (R Core Team 2020), including the effect of time-point, the melody×hands condition interaction, and the time-point and hands condition. This model was chosen because, contrary to the piano key pressing task, not all of the stimuli were repeated at each time-point; only stimuli repeated at least twice were included in the model.

2.6.3. Study 3: Cross-sectional approach - novices vs musicians

In this study, longitudinal and cross-sectional designs were combined to compare the twenty-six week training course duration and the outcomes of the previous two studies including novice pianists to lifelong learning in musicians. As such, it compared novice pianists pre- and post-training to trained musicians using two previously described tasks: the behavioural tonal working memory task and the piano key pressing fMRI task. In the behavioural tonal working memory task, the task performance in novice pianists was compared to that of trained musicians using t-test at TP_{onset} and TP_{end}. In the piano key pressing fMRI task, the brain activity related to each of the conditions (*unimanual*, *bimanual symmetric*, *bimanual asymmetric*) was compared directly between the groups, as well as the difference between the *bimanual asymmetric* and *symmetric* conditions related to the increased bimanual coordination demands in the *asymmetric* condition.

2.7. Neuroimaging data preprocessing and analyses

2.7.1. Preprocessing

The structural and fMRI data preprocessing utilised a standardised approach based on the default fMRIPrep pipeline at the subject level [fMRIPrep 21.0.0 (Esteban et al. 2019; Esteban, Markiewicz, Goncalves, et al. 2021) RRID:SCR_016216, which is based on Nipype 1.6.1 (Esteban, Markiewicz, Burns, et al. 2021; Gorgolewski et al. 2011); RRID:SCR_002502]. The pipeline applied the two spin-echo EPIs with an inverted phase-encoding direction for filedmap correction. Due to sparse-sampling acquisition, slice-time correction was omitted.

For each subject, the T1-weighted (T1w) images were corrected for intensity non-uniformity (INU) with N4BiasFieldCorrection (Tustison et al. 2010), distributed with ANTs 2.3.3 (Avants et al. 2008), RRID:SCR_004757). The T1w-reference was then skull-stripped with a Nipype implementation of the antsBrainExtraction.sh workflow (from ANTs), using OASIS30ANTs as target template. Brain tissue segmentation of cerebrospinal fluid (CSF), white-matter (WM) and grey-matter (GM) was performed on the brain-extracted T1w using fast (FSL 6.0.5.1:57b01774, RRID:SCR_002823, (Zhang, Brady, and Smith 2001). A T1w-reference map was computed after registration of the present T1w images (after INU-correction) using mri_robust_template (Reuter, Rosas, and Fischl 2010). Volume-based spatial normalisation to one standard space (MNI152NLin2009cAsym) was performed through nonlinear registration with antsRegistration (ANTs 2.3.3), using brain-extracted versions of both T1w reference and the T1w template. ICBM 152

Nonlinear Asymmetrical template version 2009c [(Fonov et al. 2009), RRID:SCR_008796; TemplateFlow ID: MNI152NLin2009cAsym] was selected for spatial normalisation.

For each of the present BOLD runs per subject (across all tasks and sessions), the following preprocessing was performed. First, a reference volume and its skull-stripped version were generated using a custom methodology of fMRIPrep. Head-motion parameters with respect to the BOLD reference (transformation matrices, and six corresponding rotation and translation parameters) were estimated before any spatiotemporal filtering using mcflirt (FSL 6.0.5.1:57b01774, (Jenkinson et al. 2002). The estimated fieldmap was then aligned with rigid-registration to the target EPI reference run. The field coefficients were mapped on to the reference EPI using the transform. The BOLD reference was then co-registered to the T1w reference using mri_coreg (FreeSurfer) followed by flirt (FSL 6.0.5.1:57b01774, (Jenkinson and Smith 2001) with the boundary-based registration (Greve and Fischl 2009) cost-function. Co-registration was configured with six degrees of freedom. A set of physiological regressors were extracted to allow for component-based noise correction (CompCor) (Behzadi et al. 2007). The head-motion estimates were calculated in the correction step. The BOLD time-series were resampled into standard space, generating a preprocessed BOLD run in MNI152NLin2009cAsym space. First, a reference volume and its skull-stripped version were generated using a custom methodology of fMRIPrep. Gridded (volumetric) resamplings were performed using antsApplyTransforms (ANTs), configured with Lanczos interpolation to minimise the smoothing effects of other kernels (Lanczos 1964). Non-gridded (surface) resamplings were performed using mri_vol2surf (FreeSurfer).

Finally, the preprocessed functional files from the fMRIPrep output underwent smoothing with a 6 mm FWHM Gaussian kernel within SPM12 (Wellcome Trust Centre for Neuroimaging, University College, London, UK, http://www.fil.ion.ucl.ac.uk/spm/software/spm12) running on MATLAB 2019b (Mathworks, http://www.mathworks.com).

2.7.2. fMRI data analysis

All fMRI data analyses were performed using SPM12 (Wellcome Trust Centre for Neuroimaging, University College, London, UK, http://www.fil.ion.ucl.ac.uk/spm/software/spm12) running on MATLAB 2019b (Mathworks, http://www.mathworks.com). Region-of-interest and cluster peak activation values were extracted using MarsBaR (Brett et al. 2002) version 0.45 running on SPM12 (Wellcome Trust Centre for Neuroimaging, University College, London, UK, http://www.fil.ion.ucl.ac.uk/spm/software/spm12) and MATLAB 2019b (Mathworks, http://www.mathworks.com). For all significant results, anatomical localisation was determined using the AAL3 atlas in bspmview (Spunt 2016)for peaks at least 8mm apart. Visualisations were performed using Seaborn 12.0 (Waskom 2021) and matplotlib 3.7 (Caswell et al. 2023) in Python 3.10 (Van Rossum and Drake 2009).

2.7.2.1. First-level analyses

All first-level analyses used a general linear model (Friston et al. 1994) on a whole-brain level. For all tasks, a separate first-level model was computed for each participant at each time-point. In order to correct for sparse acquisition (ISSS), the first acquired volume was inserted as a dummy scan to fill in the 'silent' TRs gaps, and six head movement regressors (translation and rotation in X, Y and Z directions) were expanded by a '0'-vector accordingly. A single regressor was added to each session to indicate actual scans from dummy scans (Peelle 2014).

At the first level, contrast images were computed to provide task-related activity for each participant at each time-point. In the music listening task, the contrast *music>silence* was computed. In the piano key pressing fMRI task, contrasts for each condition (*unimanual (right hand)*, *bimanual symmetric*, *bimanual asymmetric*) and the comparison between bimanual conditions (*bimanual asymmetric>symmetric*) were extracted. In the music playback fMRI task, the contrast for *playing music* vs global baseline was computed. Participants' movement was analysed for excessive motion (framewise displacement > 7.5) and framewise displacement peaks were regressed out.

Additionally, in order to properly compute the Main Effect of Group in the listening task (McFarquhar 2019), two within-subject models per subject were computed, one for the training period including five time-points (TP_{onset}, TP_{week1}, $TP_{week\ 6}$, $TP_{week\ 13}$, TP_{end}), and one for the follow-up period including two time-points (TP_{end}, $TP_{follow-up}$). For each of these models, a contrast was computed representing the average within-subject brain activation over the included time-points in the *music>silence* contrast.

2.7.2.2. Group (second-level) analyses

2.7.2.2.1. Listening task

This task was designed to investigate training-related effects of music training intervention on brain activation while listening to music. First, the brain activation during music listening was compared between novice pianists and passive controls at baseline ($TP_{pre-training}$

for novice pianists and TP_{onset} for the passive controls). A two-sample t-test model was constructed, and the contrasts *novices* ($TP_{pre\text{-}training}$) > *passive controls* (TP_{onset}) and *passive controls* (TP_{onset}) > *novices* ($TP_{pre\text{-}training}$) were extracted.

Before conducting training-related analyses, the brain activation of novice pianists during music listening was analysed for repetition effects pre-training. The music>silence contrast from the two scans before training ($TP_{pre\text{-}training}$ and TP_{onset}) were analysed for increased and/or decreases in brain activation using a paired t-test model. From this model, two contrasts between the first two time-points in the novice pianists were extracted ($TP_{pre\text{-}training}$>TP_{onset} and TP_{onset}>$TP_{pre\text{-}training}$).

A longitudinal flexible factorial model was employed to understand how piano training affects auditory processing during the *music>silence* contrast. This model incorporated both the novice pianists and the passive control group, encompassing time-points from TP_{onset} to TP_{end} (inclusive). The Main Effect of Task and Main Effect of Time, as well as the Group×Time Interaction were extracted. To obtain the Main Effect of Group (McFarquhar 2019), a two-sample t-test model was constructed including both groups, using the average brain activation per subject in the training period.

The follow-up period (TP_{end}-$TP_{follow\text{-}up}$) was analysed to check whether any changes occurred after the cessation of training. For this purpose, a full factorial design was constructed including both groups and time-points TP_{end} and $TP_{follow\text{-}up}$. The Main Effect of Time, as well as the Group×Time Interaction were extracted. To obtain the Main Effect of Group (McFarquhar 2019), a two-sample t-test model was constructed including both groups, using the average brain activation per subject in the follow-up period.

To correct for multiple comparisons, a voxel-level height threshold of $p<0.001$ (uncorrected) was combined with a cluster-level height threshold of $p<0.05$ (FWE).

2.7.2.2.2. Piano key pressing task

In this task, longitudinal and cross-sectional designs were combined to explore the time-course of neuroplastic changes associated with learning to play the piano and differences on task-demands based on hand conditions (*unimanual*, *bimanual symmetric*, and *bimanual asymmetric*).

Brain activations in novice pianists were tracked longitudinally throughout the study period. Cross-sectional comparisons were made between brain activation in novices pre- and post-training (TP_{onset} and TP_{end}) with the brain activation of trained musicians.

Separate models were constructed for each of the first-level contrasts (*unimanual (right hand)*, *bimanual symmetric*, *bimanual asymmetric*) as well as the comparison between conditions *bimanual asymmetric>symmetric* .

Before training-related analyses were performed, repetition effects were investigated using a paired t-test model including data for the two scans before the onset of training ($TP_{pre\text{-}training}$ and TP_{onset}). This allowed for the identification of potential increases ($TP_{pre\text{-}training} < TP_{onset}$) and decreases ($TP_{pre\text{-}training} > TP_{onset}$) in brain activation which were connected to the repetition of the task, and not training itself.

Training-related changes in novice pianists were evaluated using separate longitudinal flexible factorial models that incorporated time (TP_{onset}-TP_{end}) and subject factors. These models extracted the Main Effects of Task (average activation regardless of time) and Time, as well as pairwise comparisons between time-points.

To correct for multiple comparisons, a voxel-level height threshold of $p<0.001$ (uncorrected) was combined with a cluster-level height threshold of $p<0.05$ (FWE).

2.7.2.2.3. Music playback task

This task was analysed longitudinally for the four time-points during the training course ($TP_{week\ 1}$, $TP_{week\ 6}$, $TP_{week\ 13}$ and TP_{end}). Second-level group analyses were performed in a flexible factorial model including time and subject factors. To correct for multiple comparisons, a cluster-level height threshold of $p<0.05$ (FWE), together with a cluster-level extent threshold of 5 voxels were applied. The contacts for the Main Effect of Task and the Main Effect of Time were extracted.

Furthermore, three independent regions-of-interest (ROIs) were analysed to investigate the differences in time-courses between regions within different brain networks. The regions representing the right auditory and the left and right motor regions were based on data published in a recent meta-analysis on bottom-up and top-down music processing in the brain by Pando-Naude and colleagues (2021) and downloaded from Open Science Framework. The left sensorimotor ROI included the left postcentral and precentral gyri with a peak at x=-43 y=-22 z=46 MNI. The right motor ROI was located in the precentral gyrus with a peak at x=53 y=6 z=30 MNI. The right auditory ROI encompassed the planum temporale, extending into the superior temporal gyrus and Heschl's gyrus, with a peak at x=59 y=-21 z=7 MNI. For each region of interest, first-level contrast estimates were extracted and the interaction between region and time was analysed using two-way repeated-measures ANOVA in the Pingouin v0.5.1 package (Vallat 2018) in Python 3.10 (Van Rossum and Drake 2009) and the Bonferroni correction for multiple comparisons was applied.

Finally, a conjunction analysis (Main Effect of Task ∩ Main Effect of Time) was performed to identify regions of the brain associated with task performance (*playing music*) which changed activation in response to training. The second-level contrasts were converted to z-scores with convert_spm_stat script by Josh Brown (Jahn 2015). The conjunction was performed using the easythresh_conj script (Nichols 2007) which is a part of the FSL package (Smith et al. 2004) and uses minimum statistic compared to the conjunction null to test for the logical intersection (AND) between the two contrasts; thus, the result includes only the areas where both contrasts are simultaneously significant (Nichols et al. 2005). The whole-brain was used as a mask and default thresholds of $z > 2.3$ and $p=0.05$ were applied.

3. Results

Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are part of nature and therefore part of the mystery that we are trying to solve. Music and art are, to an extent, also attempts to solve or at least express the mystery. But to my mind, the more we progress with either, the more we are brought into harmony with all nature itself.

— Max Planck

3.1. Study 1: Auditory processing

The time-course of changes in auditory processing, represented in the neural correlates of passive music listening, was studied in novice pianists as they became more proficient with the piano skill. Additionally, near-transfer effects to a cognitive domain of tonal working memory were assessed in a behavioural task. Novice pianists were compared longitudinally to passive controls in both tasks.

3.1.1. Behavioural results

3.1.1.1. Musical Ear Test

The novice pianists and the controls did not differ on either the Melody or the Rhythm conditions in the total score, number of missed responses or the mean response time in both conditions (Melody score: t=-0.592, df=4-.963, p=0.557, 95%CI=[-3.85, 2.1] missed responses t=1.340, df=10.000, p=0.210, 95%CI=[-0.72, 2.9]; Rhythm score: t=0.560, df = 40.694, p=0.579, 95%CI=[-2.12, 3.74] missed responses t=1.389, df=10.601, p=0.19, 95%CI=[-0.41, 1.79]; Mean response time (both conditions): t=0.684, df_1=81, df_2=272, p=0.496, 95%CI=[-37.58, 76.95]).

3.1.1.2. Tonal working memory (tonal n-back task)

In the 2-back condition, two participants from the passive control group were excluded from the analysis due to missing more than 20% of responses in at least one time-point, yielding the final group counts of 24 and 17 for the novice pianists and passive controls, respectively. The two-way mixed-model ANOVA analysis revealed no significant effects of group (F=2.224, df_1=1, df_2=39, p=0.144, η_p^2=0.054) or time-point (F=0.002, df_1=1, df_2=39, p=0.964, $\eta_p^2<0.001$) nor their interaction (F=0.455, df_1=1, df_2=39, p=0.504, η_p^2=0.012) for the study period (TP_{onset}-TP_{end}).

During the follow-up (TP_{end}-$TP_{follow-up}$), no significant effect of group was observed ($F=0.955$, $df_1=1$, $df_2=39$, $p=0.335$, $\eta_p^2=0.024$), but a significant effect of time-point ($F=4.237$, $df_1=1$, $df_2=39$, $p=0.046$, $\eta_p^2=0.098$) and no significant interaction between them ($F=1.346$, $df_1=1$, $df_2=39$, $p=0.253$, $\eta_p^2=0.033$). Post-hoc comparison between the TP_{end} and the $TP_{follow-up}$ showed a significant increase in performance with time ($T=-2.049$, $df=40$, $p=0.047$, 95%CI = [-7.87, -0.05].

In the 3-back condition, one participant from the novice pianists group and two participants from the passive control group were excluded due to missing at least 20% of responses in at least one time-point, yielding the group counts to be 23 and 17, respectively. However, the mean performance at TP_{onset} for the novice pianists ($M=49.492\%$, $SD=9.896$) and passive controls ($M=49.816\%$, $SD=9.406$) and at TP_{end} for novice pianists ($M=53.397\%$, $SD=10.615$) and passive controls ($M=51.471\%$ $SD=5.753$) was around chance level. Therefore, no group or time-point comparisons were performed in the 3-back condition. A visualisation of the results from both 2-back and 3-back conditions is presented in Figure 3.1.1.

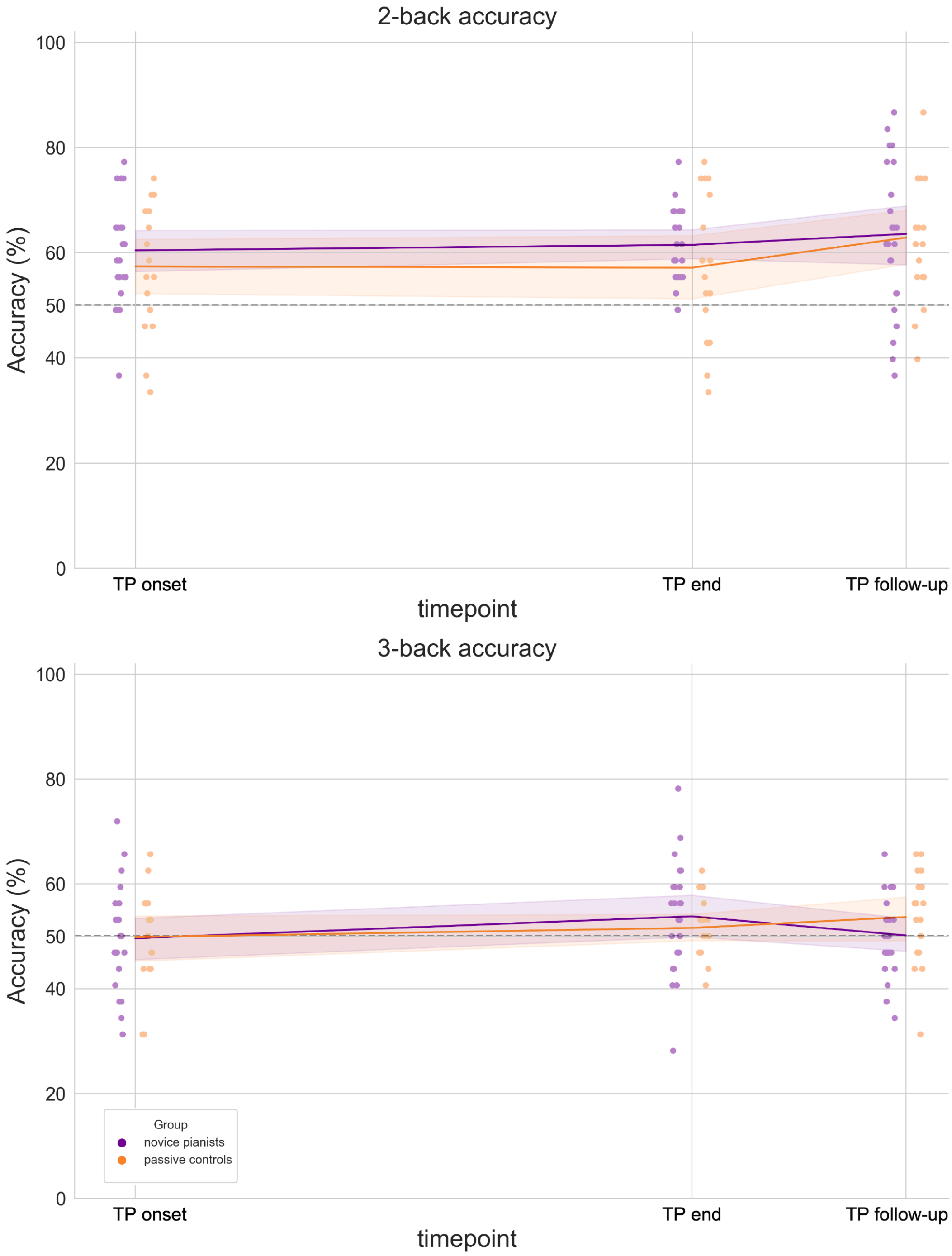


Figure 3.1.1. Participants' performance in the tonal memory task. Dots represent individual participant's scores: purple for novice pianists, orange for passive controls. Error bands represent the 95% confidence intervals.

3.1.2. Neuroimaging results

3.1.2.1. Music listening fMRI task

First, group differences at baseline were investigated, however the contrasts: *novices*($TP_{pre\text{-}training}$)>*passive controls*(TP_{onset}) and *passive controls*(TP_{onset})>*novices*($TP_{pre\text{-}training}$) revealed no significant differences between the groups. Furthermore, no significant repetition effects i.e., differences in brain activation between the $TP_{pre\text{-}training}$ and the TP_{onset} were found in novice pianists.

Subsequently, study period corresponding to the piano training of the novices group in novices and passive controls (TP_{onset}-TP_{end}) was analysed. The Main Effect of Task (regardless of group and time) revealed brain activation in regions typical for auditory tasks (Figure 3.1.2, Table S1), such as the bilateral superior temporal gyri, extending into the temporal poles and inferior frontal gyrus on the right. Additionally, activation in the right inferior occipital gyrus extending into the calcarine and fusiform cortex, and the left lateral occipital cortex extending into the fusiform and lingual gyri and the cerebellum was observed. The Main Effect of Group and the Main Effect of Time, as well as the Group×Time Interaction revealed no significant clusters.

Finally, no changes with time or group differences were identified in the follow-up period.

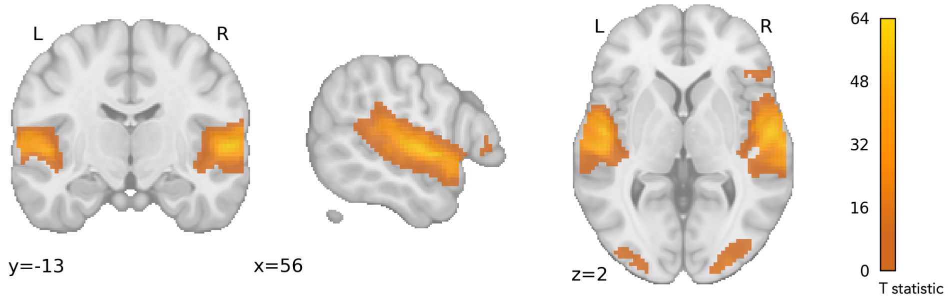


Figure 3.1.2. Statistical maps representing the contrasts for the Main Effect of Task in the listening task (*music*>*silence*). x, y, z - MNI coordinates. Colour bar represents the T test-statistic range.

3.1.3. Summary and discussion

The first study was conducted to investigate the time-course of training-related changes in auditory processing of novice pianists with two tasks: a behavioural tonal working memory task and a passive music listening fMRI task.

3.1.3.1. Tonal working memory (tonal n-back)

To date, this is the first study which employed the tonal working memory task in a longitudinal design. However, contrary to hypothesis H1.3°, no association between piano training and improved tonal working memory in novice pianists was found, indicating a lack of near-transfer effects from musical training to a cognitive domain associated with auditory processing. The follow-up period revealed significant improvement in task performance for the 2-back condition, with no differences between groups. This finding is intriguing, as none of the groups received targeted auditory training during this time, and might be a chance false-positive finding. Further research is necessary to determine whether this improvement could be attributed to potential long-term effects of piano training, or repeated exposure to the task itself.

3.1.3.2. Music listening fMRI task

In line with the first hypothesis H1.1°, the novices and passive controls did not differ in neural correlates at baseline, and no significant effects were observed in the novice pianists due to task repetition. Thus, any differences between the groups during the study period can be attributed to the musical training intervention.

However, for the period of musical training, there were no significant effects. This indicates that piano training did not affect the processing of musical stimuli in the novice pianists. Therefore, there is no evidence in favour of training-related adaptations in the auditory processing of musical stimuli. This outcome does not support hypothesis H1.2°, as no training-related differences in the neural correlates of auditory processing of musical stimuli could be observed in the novice pianists, at the six-week mark or otherwise. Additionally, it stands in contrast to much of previous research comparing musicians and non-musicians or musical-training interventions, where such adaptations were observed (Bangert et al. 2006; Bianchi et al. 2017; Habermeyer et al. 2009; Limb et al. 2006; Ohnishi 2001; Seung et al. 2005) and warrants further study.

Previous studies which found training-related adaptations in the processing of musical stimuli typically used music listening tasks where the stimuli constituted trained melodies (e.g., Chen, Rae, and Watkins 2012; Lahav, Saltzman, and Schlaug 2007; Wollman et al. 2018; de Manzano et al. 2020). This approach provides information on the processing of a very specific type of musical stimuli. Because the participants were actively learning to play the listened melodies, the familiarity and salience of these stimuli might be different by the end of study compared to other sounds, even though the stimuli themselves might be very similar. Thus, the differences in the processing of trained melodies compared to other sounds might not reflect only auditory features of music, but other processes. In the current study, the stimuli in the listening task were all unfamiliar to the participants, were not trained in the piano course, and the stimuli set was designed in a way that included both novel and repeated stimuli at each time-point. In this manner, I argue that the current study better reflects the auditory processing of music compared to previous studies which focused on trained melodies. The discrepancies in results might be associated with the aforementioned familiarity, attention and salience of stimuli in previous studies, compared to the more general sounds used in the current project.

Several explanations are possible for these null findings for time-related adaptations in both tasks. The relatively short training duration in this study, compared to the lifelong training of most musicians, might be a factor, if the adaptations are very slow. Additionally, the later age at which these novices began training compared to children typically enrolled in music programs could play a role. Previous research indicates that certain brain adaptations related to musical training might only occur in the sensitive period, if the training starts before a musician is nine years old (Penhune 2022). Finally, it is possible that pre-existing differences in auditory processing abilities between the current participants and those who typically enrol in music programs might also be relevant. There is evidence that pre-training differences affect musical training and might predict training success (Bianco et al. 2019; Burgoyne, Harris, and Hambrick 2019; Herholz et al. 2016; Vaquero et al. 2018; Wollman et al. 2018). Therefore, it is possible that the differences in brain activation and tonal working memory observed between musicians and non-musicians in previous studies are driven by predispositions, and not plasticity, or an interaction between predispositions and developmental plasticity.

3.2. Study 2: Playing the piano

In this study, auditory-motor interactions were investigated in the context of the neuroplasticity dynamics related to musical training. Novice pianists performed a piano key pressing fMRI task with conditions differing in bimanual motor coordination demands, and a music playback fMRI task. Additional time-points were introduced to account for repetition effects and study potential follow-up effects after the training was completed.

3.2.1. Behavioural results

3.2.1.1. Piano key pressing fMRI task

To assess the impact of repetition before piano training, participants' performance was compared between the two pre-training time-points ($TP_{pre\text{-}training}$ and TP_{onset}). Melodic performance, measured with the Levenshtein ratio, was assessed using a repeated-measures ANOVA which revealed a significant effect of time-point ($F=14.036$, $df_1=1$, $df_2=23$, $p_{GG\text{-}corr}=0.001$, $\eta_p^2=0.379$) and hands-condition ($F=421.357$, $df_1=2$, $df_2=46$, $p_{GG\text{-}corr}<0.001$, $\eta_p^2=0.948$) but not their interaction ($F=2.943$, $df_1=2$, $df_2=46$, $p_{GG\text{-}corr}=0.069$, $\eta_p^2=0.113$). Rhythmic performance, measured as the mean percentage deviation from the target rhythm, was assessed similarly and yielded significant effect of time-point ($F=6.195$, $df=1$, $p=0.020$, $\eta_p^2=0.212$).

Next, training-related changes in task performance measures were investigated for time-points spanning the piano course period, from TP_{onset} to TP_{end} (inclusive). For the Levenshtein ratio, repeated-measures ANOVA revealed significant effects of hands-condition ($F=1287.887$, $df_1=2$, $df_2=42$, $p_{GG\text{-}corr}<0.001$, $\eta_p^2=0.984$) but not time-point ($F=2.273$, $df_1=4$, $df_2=85$, $p_{GG\text{-}corr}=0.080$, $\eta_p^2=0.098$) or their interaction ($F=1.779$, $df_1=8$, $df_2=168$, $p_{GG\text{-}corr}=0.155$, $\eta_p^2=0.078$). Post-hoc pairwise t-test analysis yielded a significant difference between the *bimanual asymmetric* and *unimanual (right hand)* conditions ($T=-41.302$, $p_{Bonf\text{-}corr}<0.001$), the *bimanual symmetric* and *unimanual (right hand)* conditions ($T=-37.391$, $p_{Bonf\text{-}corr}<0.001$). These differences were significant at all time-points (TP_{onset}, $TP_{week\ 1}$, $TP_{week\ 6}$, $TP_{week\ 13}$, TP_{end}). The difference between the *bimanual symmetric* and the *bimanual asymmetric* conditions was significant at the end of training TP_{end} ($T=-3.912$, $p=0.012$).

For the rhythmic score, a significant effect of time-point was found (F=2.947, df=4, p=0.025, η_p^2=0.134). However, none of the post-hoc comparisons between time-points survived the Bonferroni correction for multiple comparisons.

Lastly, the follow-up period was investigated for any changes occurring after the cessation of training. For the Levenshtein ratio, the repeated-measures ANOVA shown no significant effect of time-point (F=0.216, df_1=1, df_2=23, $p_{GG\text{-}corr}$=0.646, η_p^2=0.009) but a significant effect of hands-condition (F=658.962, df_1=2, df_2=46, $p_{GG\text{-}corr}$<0.001, η_p^2=0.966) and time-point×hands-condition interaction (F=5.052, df_1=2, df_2=46, $p_{GG\text{-}corr}$=0.016, η_p^2=0.180). Post-hoc pairwise comparisons revealed differences between the *bimanual asymmetric* and the *unimanual (right hand)* conditions (T=-33.322, $p_{Bonf\text{-}corr}$<0.001), which was also significant at both TP_{end} (T=-27.338 $p_{Bonf\text{-}corr}$<0.001) at $TP_{follow\text{-}up}$ (T=-34.620 $p_{Bonf\text{-}corr}$<0.001). Similarly, a significant difference was present between the *bimanual symmetric* and the *unimanual (right hand)* conditions (T=-24.545 $p_{Bonf\text{-}corr}$<0.001), which was also significant at TP_{end} (T=-23.687 $p_{Bonf\text{-}corr}$<0.001) and $TP_{follow\text{-}up}$ (T=-23.066 $p_{Bonf\text{-}corr}$<0.001). A difference between the *bimanual symmetric* and the *bimanual asymmetric* conditions was significant (T=-3.294 $p_{Bonf\text{-}corr}$=0.010), which was driven by a difference at TP_{end} (T=-4.493 $p_{Bonf\text{-}corr}$<0.001) but not $TP_{follow\text{-}up}$. Finally, the comparison between time-points for rhythmic score revealed no significant changes between TP_{end} and $TP_{follow\text{-}up}$ (F=0.866, df=1, p=0.362, η_p^2=0.038).

A visualisation of the behavioural performance results can be found in Figure 3.2.1.

3.2.1.2. Music playback fMRI task

Successful musical training should result in improved performance over time. To verify this, the participants' behavioural performance while playing musical pieces was evaluated.

For melodic performance, a generalised linear model revealed a significant effect of time (t=2.360, p=0.018), hand condition (*unimanual/bimanual*) (t=6.022, p<0.001), and their interaction (t=-2.147 p=0.032). Overall, *bimanual* performance (playing with both hands) exhibited lower accuracy compared to unimanual performance, but improved over time. Conversely, unimanual performance with the right-hand remained stable throughout the study. Furthermore, difficulty level influenced performance, and participants showed lower accuracy on more complex melodies introduced later in the course compared to the earlier, simpler melodies (Figure 3.2.2.).

Similarly, for the rhythmic performance, a significant effect of time (t=-2.419, p=0.015), hand condition (t=4.663, p<0.001), but not their interaction (t=1.763, p=0.078) (Figure 3.2.2.) were observed.

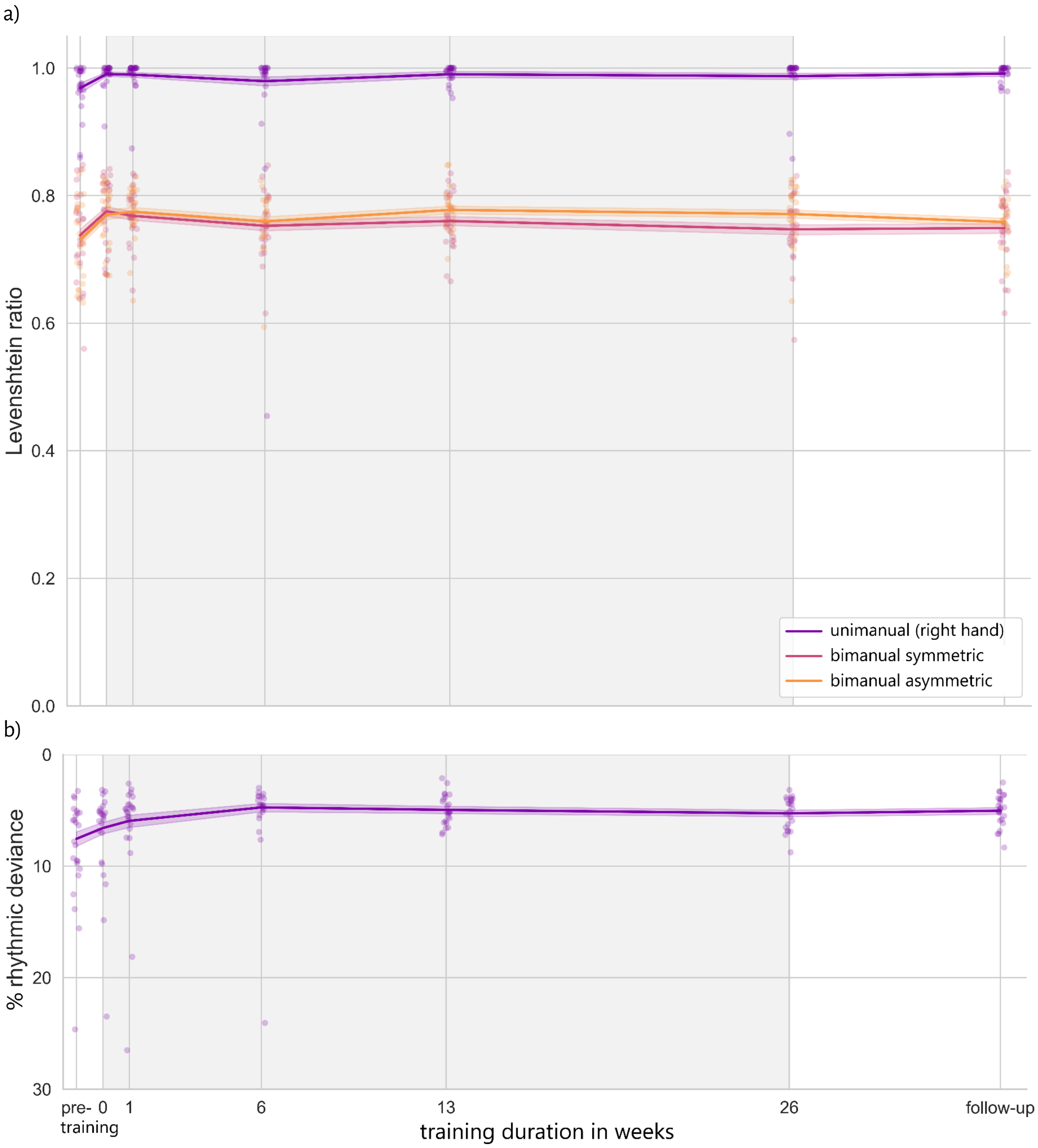


Figure 3.2.1. Behavioural performance in the piano task. (a) Levenshtein ratio (melodic performance) (b) Relative rhythmic deviance score (rhythmic performance). Dots represent individual participant performance means per time-point and hand condition. Error bands represent the 95% confidence intervals. The shaded area corresponds to the training period. The data is presented such that higher accuracy is always shown at the top of the plots (1 being the perfect score for the Levenshtein ratio and 0% being the minimal possible rhythmic deviance).

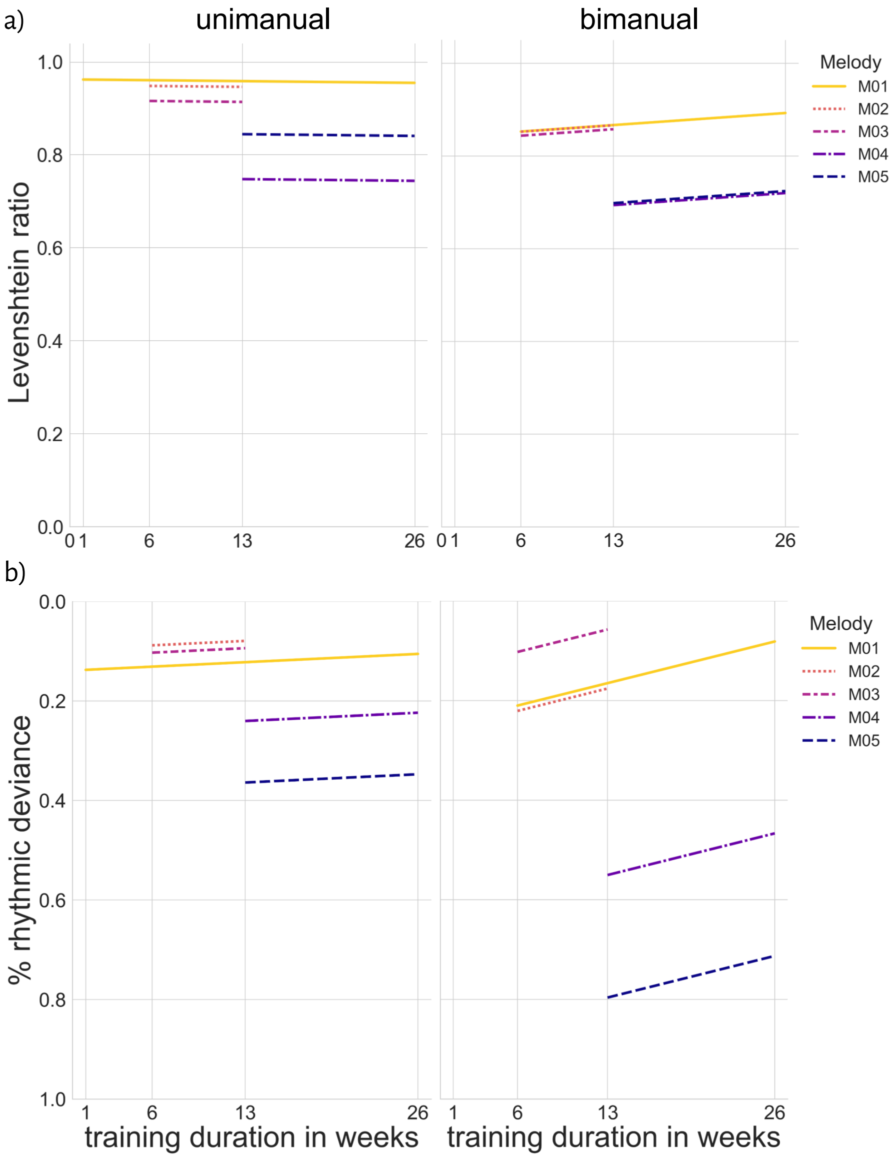


Figure 3.2.2. Behavioural performance for repeated melodies played in the *unimanual* condition (left) and the *bimanual* condition (right). (a) melodic accuracy using Levenshtein ratio, (b) rhythmic accuracy using percentage deviance from expected note duration. The data is presented in such a way that higher accuracy is always shown at the top of the plots.

3.2.2. Neuroimaging results

3.2.2.1. Piano key pressing fMRI task

3.2.2.1.1. Repetition effects

Significant decreases in brain activation during the period before the start of training ($TP_{pre-training}>TP_{onset}$) were found in the *unimanual (right hand)* and the *bimanual symmetric* conditions. In the *unimanual (right hand)* condition, activation decreased in the right caudate nucleus and the left thalamus. In the *bimanual symmetric* condition, the activation decreased in the bilateral middle occipital gyrus, right precuneus extending into the right superior parietal gyrus and the right superior occipital gyrus, and the left thalamus (Figure 3.2.3., Table S2).

3.2.2.1.2. Main Effects of Task

The Main Effects of Task reveal activation related to performing the piano task regardless of time, i.e., with all of the training time-points (TP_{onset}-TP_{end}) pooled together. In each of the three conditions (*unimanual (right hand)*, *bimanual symmetric*, *bimanual asymmetric*), the main effect of task revealed a widespread brain activation encompassing bilaterally the superior temporal gyri, Heschl gyri, postcentral and precentral gyri (including the dorsal premotor cortex), superior frontal gyrus and inferior frontal gyri, supplementary motor areas, thalami, caudate nuclei and the anterior insulae, the left putamen, the right pallidum and the bilateral inferior parietal and left superior parietal gyri, and the cerebellum, among others (Figure 3.2.4.a-c, Tables S3-5). The difference between the bimanual conditions (*asymmetric>symmetric*) encompassed the bilateral superior frontal gyrus, supplementary motor areas, precuneus and calcarine cortex, bilateral superior and inferior parietal gyri, bilateral anterior insulae, the right postcentral and precentral gyri (including the dorsal premotor cortex), right middle cingulate gyrus and the left cerebellum (Figure 3.2.4.d, Table S6).

3.2.2.1.3. Main Effects of Time and training-related changes

No significant effect of time was present in the *unimanual (right hand)* condition.

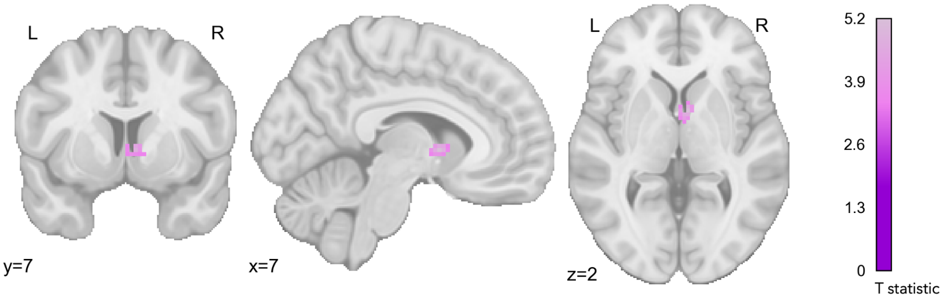
A significant Main Effect of Time was found in the *bimanual symmetric* and the *bimanual asymmetric* conditions. For the *bimanual symmetric* condition, the changes in time were mainly in the left angular and inferior parietal gyrus (Figure 3.2.5., Table S7). Pairwise comparisons between time-points revealed that the activation decreased within the first thirteen weeks of the training ($TP_{onset}>TP_{week\ 13}$) in the right insula, extending into the inferior frontal gyrus (pars triangularis) (Figure 3.2.6., Table S8). Additionally, there was an increase in the activation of the right angular gyrus during the training period (TP_{end}>TP_{onset}, Figure 3.2.7., Table S8), which was followed by an increase in the activation of the left inferior parietal cortex and angular gyrus as well as the right cerebellum, among others, after the first week of training (TP_{end}>$TP_{week\,1}$, Figure 3.2.8., Table S8). After six weeks of training (TP_{end}>$TP_{week\ 6}$, Figure 3.2.9., Table S8), an increase in activation of the right middle frontal gyrus and the left inferior parietal cortex and angular gyrus was observed. Lastly, in the second half of training (TP_{end}>$TP_{week\,13}$, Figure 3.2.10, Table S8), widespread changes occurred in the bilateral parietal cortex (including the angular and supramarginal gyri), bilateral superior and middle frontal gyri, bilateral supplementary motor area, bilateral precuneus, the left precentral gyrus and the left caudate nucleus.

In the *bimanual asymmetric* condition, the main changes were localised in the right inferior parietal cortex and the cerebellum (Figure 3.2.5, Table S9). Pairwise comparisons between time-points revealed a decrease in activation within the first six weeks of training on the bilateral parietal cortex (TP_{onset}>$TP_{week\ 6}$, Figure 3.2.11., Table S9). Further decreases (TP_{onset}>$TP_{week\ 13}$, Figure 3.2.12, Table S9) were observed in the left cerebellum, left superior frontal and precentral gyri, bilateral inferior parietal cortex including the angular gyrus, bilateral supplementary motor area, and the right anterior insula. The decrease in activation of the cerebellum continued through the whole period training (TP_{onset}>TP_{end}, Figure 3.2.13, Table S9).

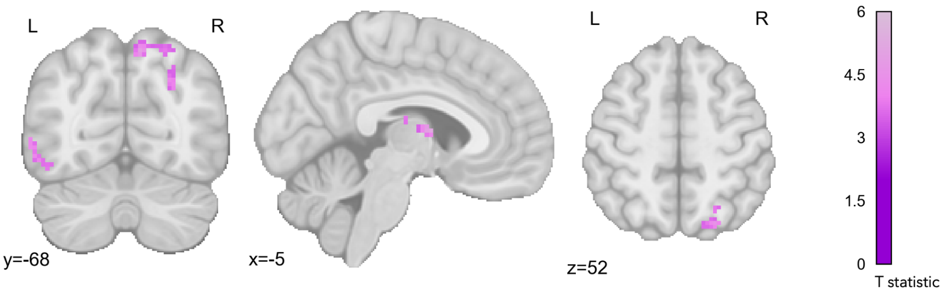
3.2.2.1.4. Follow-up

No significant differences were found between the TP_{end} and $TP_{follow\text{-}up}$ in any of the experimental conditions, therefore these results are not presented in the tables or visualisations.

a) Repetition effect ($\text{TP}_{\text{pre-training}}>\text{TP}_{\text{onset}}$) in the *unimanual (right hand)* condition



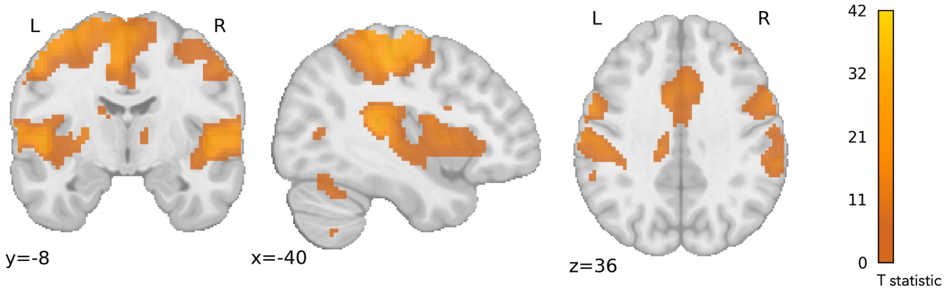
b) Repetition effect ($\text{TP}_{\text{pre-training}}>\text{TP}_{\text{onset}}$) in the *bimanual symmetric* (←→) condition



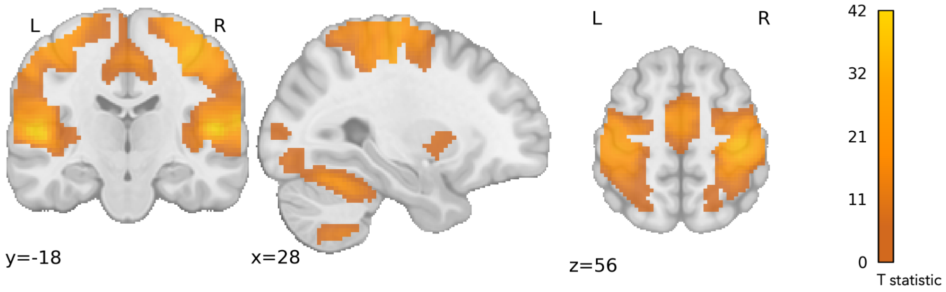
c) Repetition effect ($\text{TP}_{\text{pre-training}}>\text{TP}_{\text{onset}}$) in the *bimanual asymmetric* (→→) condition

Figure 3.2.3. Repetition effects ($\text{TP}_{\text{pre-training}}>\text{TP}_{\text{onset}}$) in the (a) *unimanual (right hand)* and the (b) *bimanual symmetric* conditions. The *bimanual asymmetric* condition revealed no significant clusters.

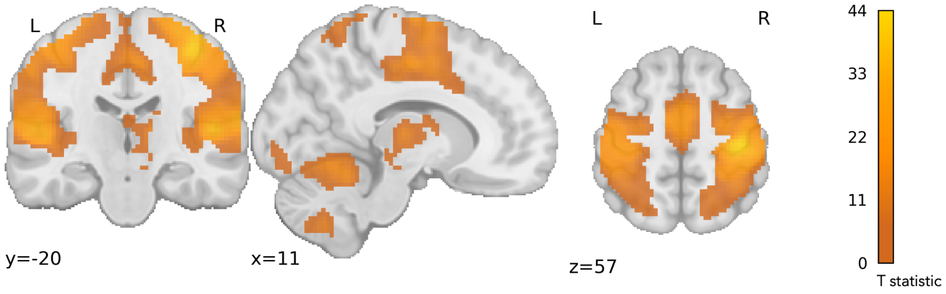
a) Main Effect of Task in the *unimanual (right hand)* condition



b) Main Effect of Task in the *bimanual symmetric (←→)* condition



c) Main Effect of Task in the *bimanual asymmetric (→→)* condition



d) The comparison *bimanual asymmetric>symmetric*

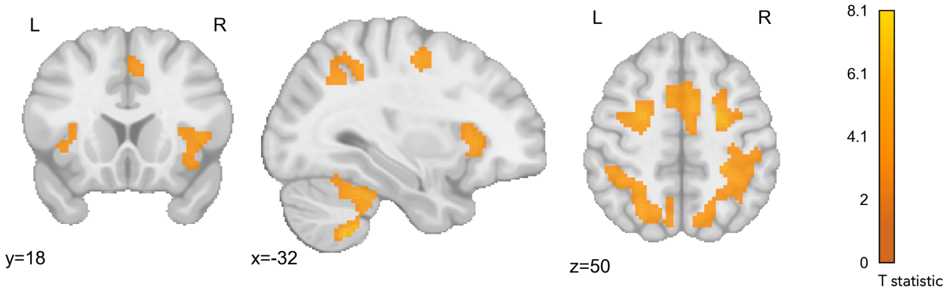
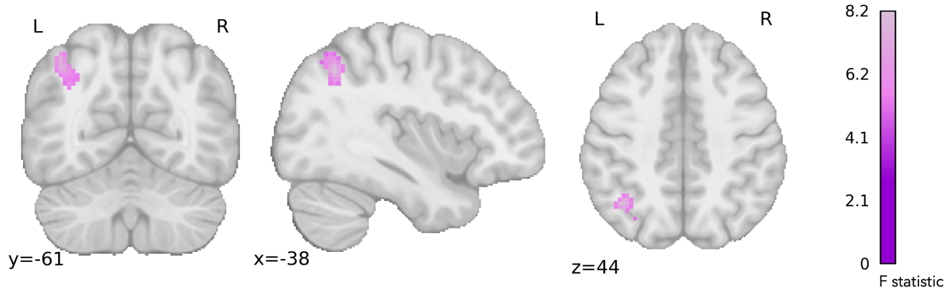


Figure 3.2.4. Statistical maps representing the contrasts for the Main Effects of Task in the piano task in each of the investigated conditions and their comparisons. x, y, z - MNI coordinates. Colour bars indicate the T test-statistic range.

a) Main Effects of Time in the *unimanual (right hand)* condition

b) Main Effects of Time in the *bimanual symmetric* (←→) condition



c) Main Effects of Time in the *bimanual asymmetric* (→→) condition

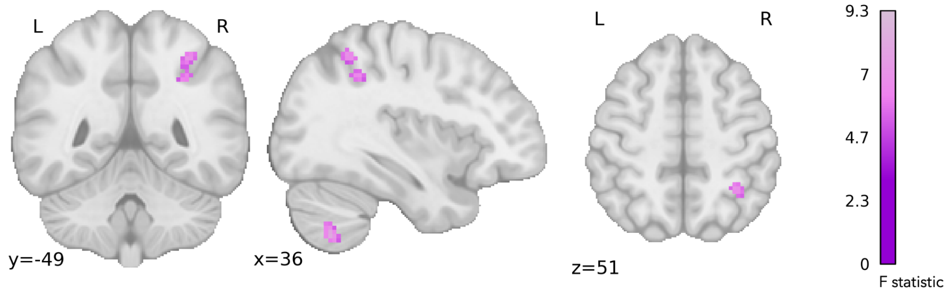
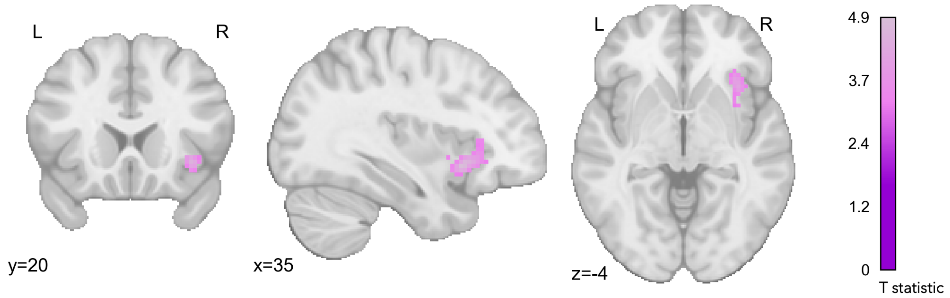


Figure 3.2.5. Statistical maps representing the contrasts for the Main Effects of Time in the piano task in each of the investigated conditions and their comparisons. x, y, z - MNI coordinates. Colour bars indicate the test-statistic range.

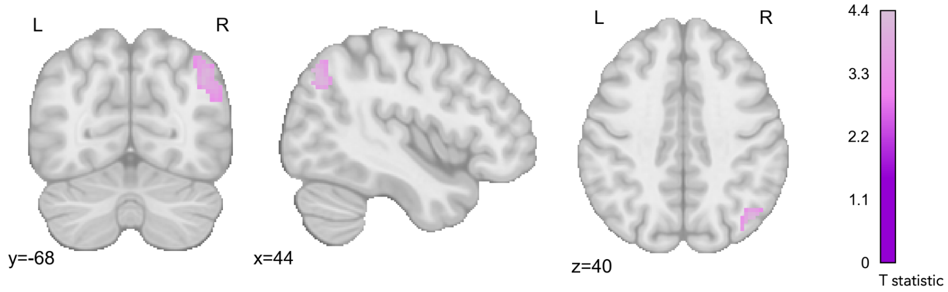
a) *bimanual symmetric* TP_{onset}>$TP_{week\ 13}$ - significant clusters



b) time-course of peak activations

Figure 3.2.6. Changes in activation in the *bimanual symmetric* condition in the TP_{onset}>$TP_{week\ 13}$ contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point ($TP_{pre\text{-}training}$).

a) *bimanual symmetric* $\mathrm{TP}_{\mathrm{end}}$>$\mathrm{TP}_{\mathrm{onset}}$ - significant clusters



b) time-course of peak activations

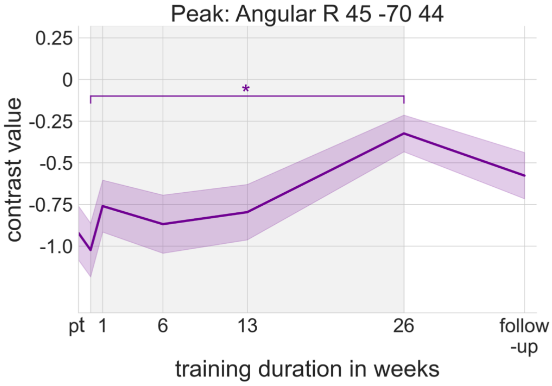
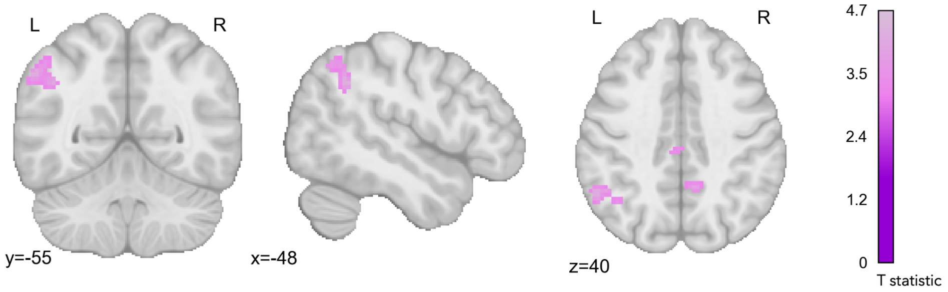


Figure 3.2.7. Changes in activation in the *bimanual symmetric* condition in the $\mathrm{TP}_{\mathrm{end}}$>$\mathrm{TP}_{\mathrm{onset}}$ contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point ($\mathrm{TP}_{\mathrm{pre\text{-}training}}$).

a) *bimanual symmetric* $TP_{end}>TP_{week\ 1}$ - significant clusters



b) time-course of peak activations

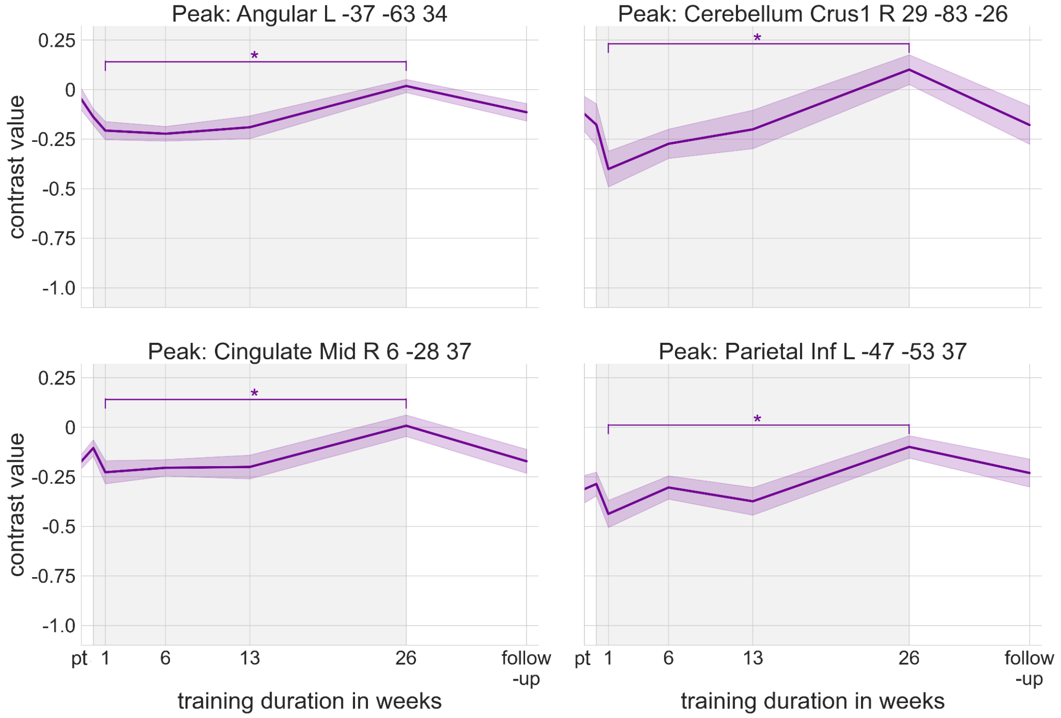
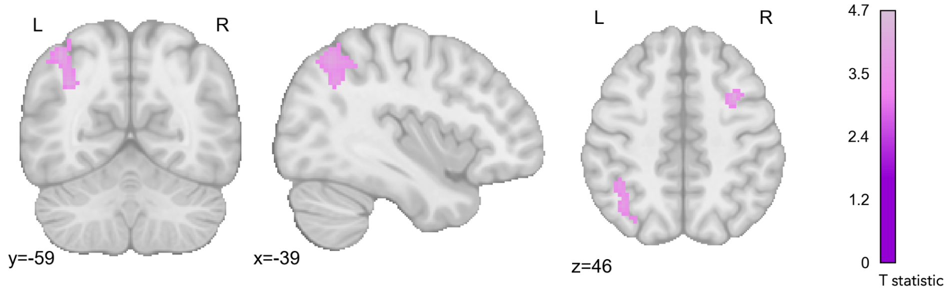


Figure 3.2.8. Changes in activation in the *bimanual symmetric* condition in the $TP_{end}>TP_{week\ 1}$ contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point ($TP_{pre\text{-}training}$).

a) *bimanual symmetric* $\mathrm{TP}_{\mathrm{end}}$>$\mathrm{TP}_{\mathrm{week\ 6}}$ - significant clusters



b) time-course of peak activations

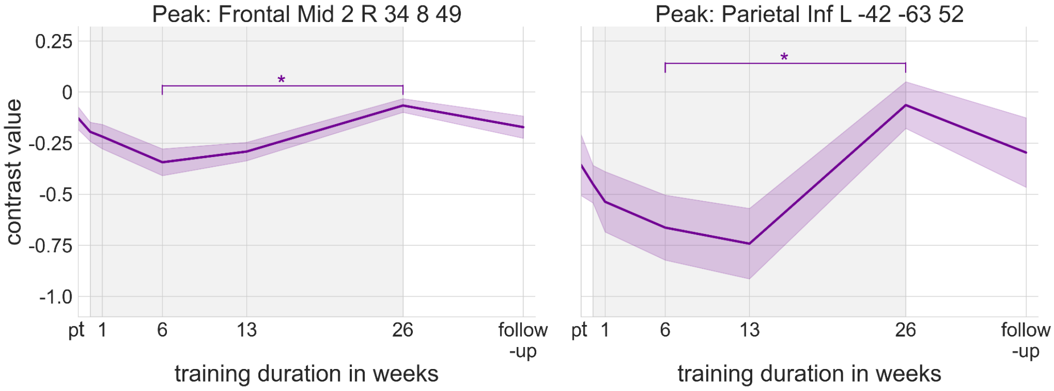
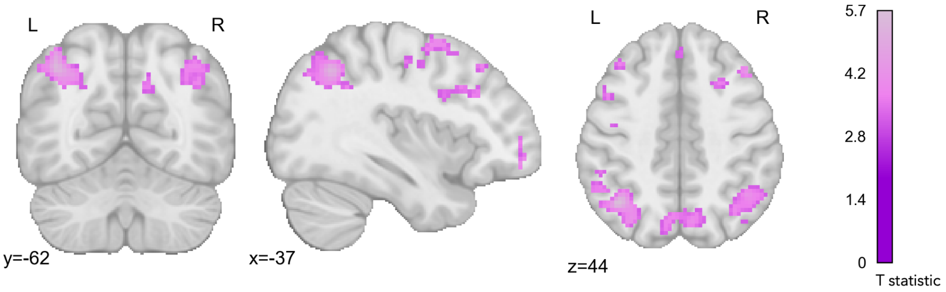
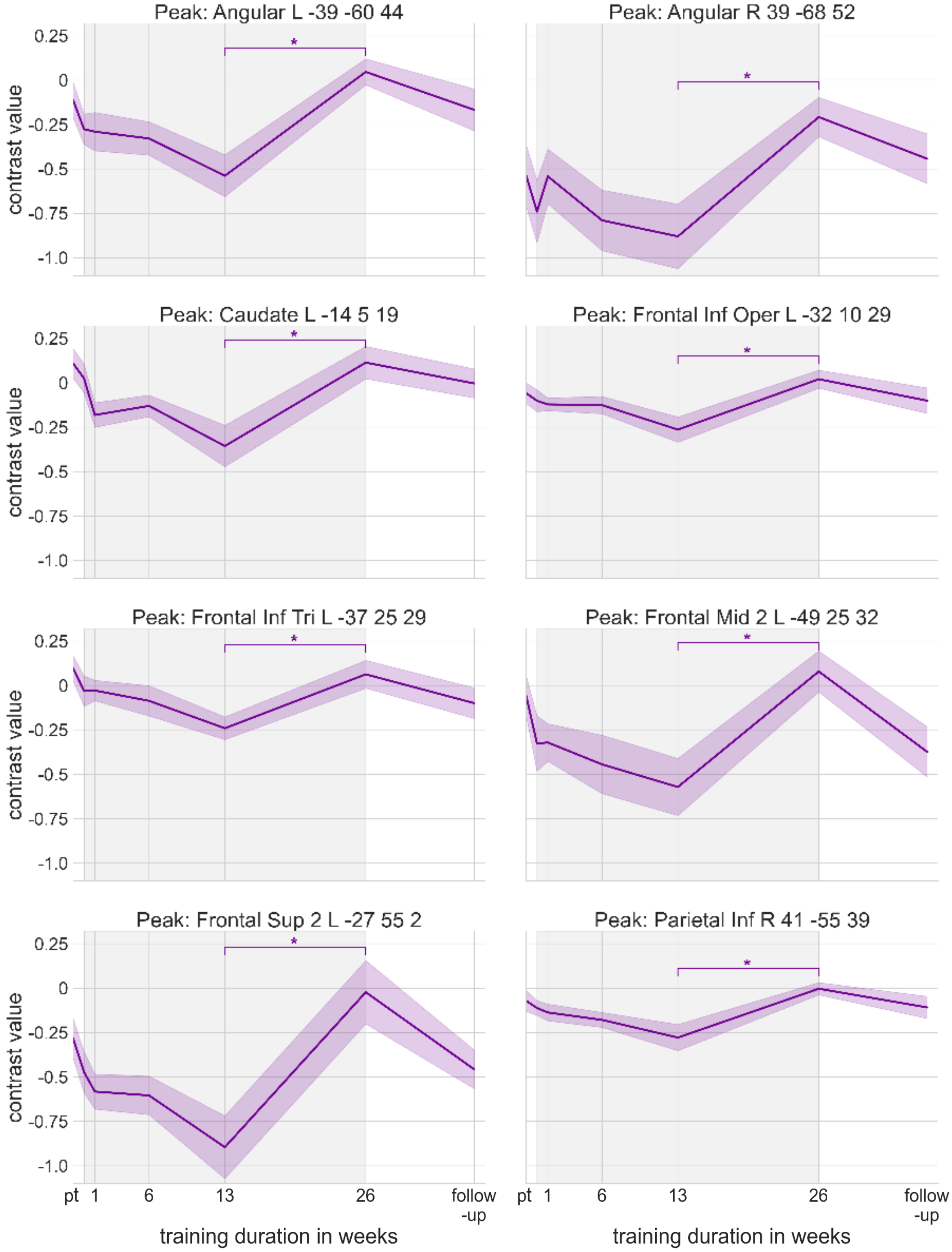


Figure 3.2.9. Changes in activation in the *bimanual symmetric* condition in the $\mathrm{TP}_{\mathrm{end}}$>$\mathrm{TP}_{\mathrm{week\ 6}}$ contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point ($\mathrm{TP}_{\mathrm{pre\text{-}training}}$).

a) *bimanual symmetric* $\mathrm{TP}_{\mathrm{end}}>\mathrm{TP}_{\mathrm{week\ 13}}$ - significant clusters



b) time-course of peak activations



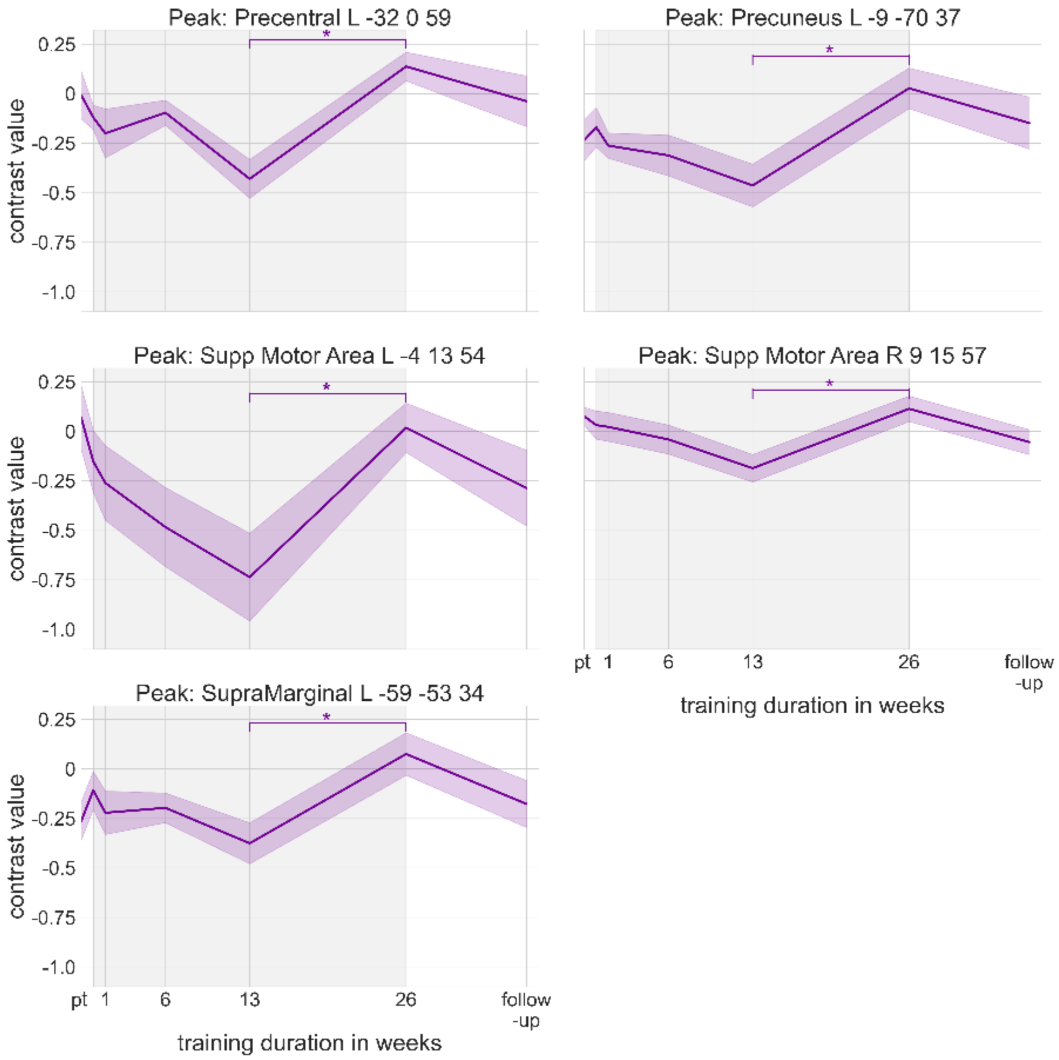
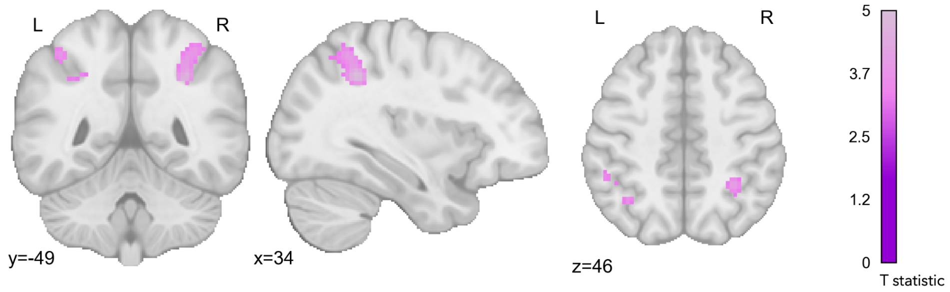


Figure 3.2.10. (continued from previous page) Changes in activation in the *bimanual symmetric* condition in the $\mathrm{TP_{end}}$>$\mathrm{TP_{week\ 13}}$ contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point ($\mathrm{TP_{pre\text{-}training}}$).

a) *bimanual asymmetric* TP$_{\text{onset}}$>TP$_{\text{week 6}}$ - significant clusters



b) time-course of peak activations

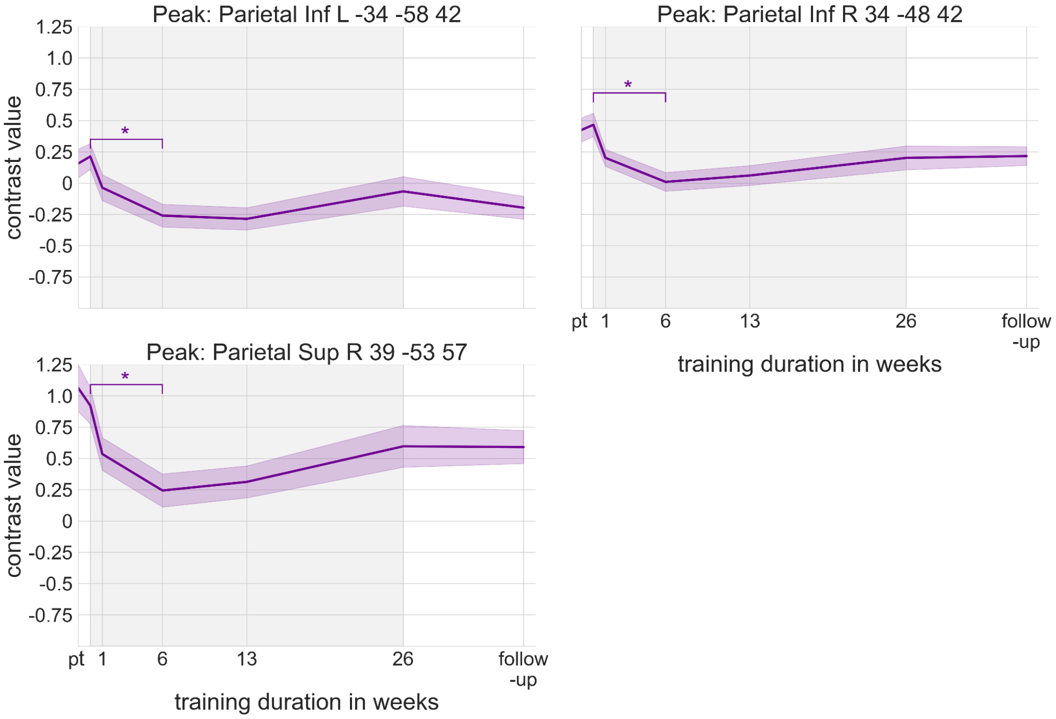
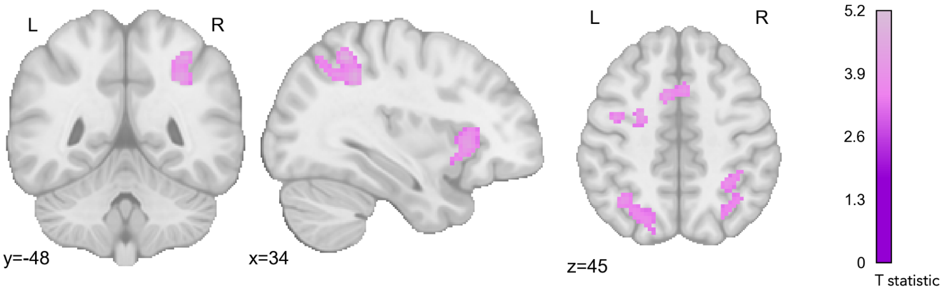


Figure 3.2.11. Changes in activation in the *bimanual asymmetric* condition in the TP$_{\text{onset}}$>TP$_{\text{week 6}}$ contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point (TP$_{\text{pre-training}}$).

a) *bimanual asymmetric* TP_{onset}>$TP_{week\ 13}$ - significant clusters



b) time-course of peak activations

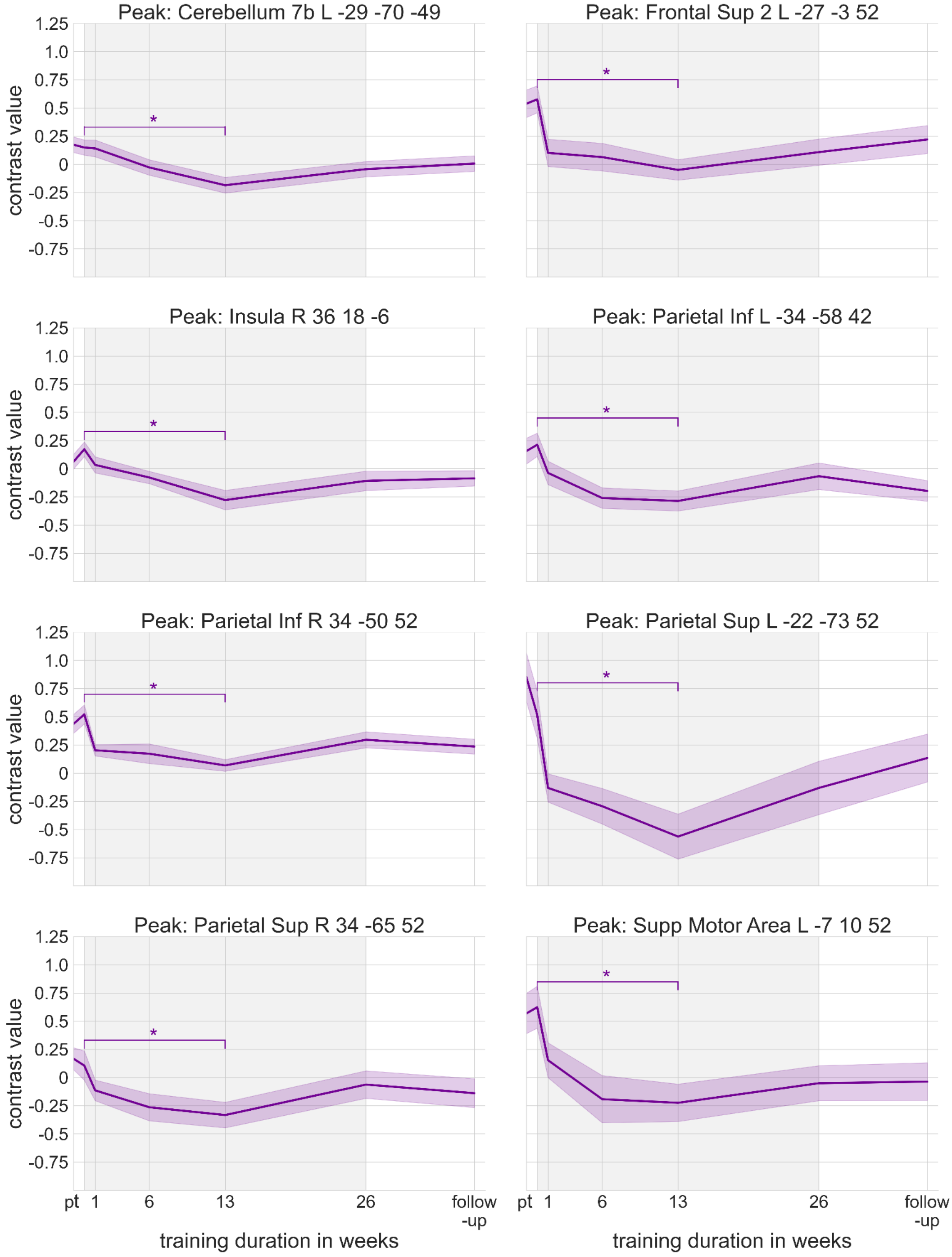
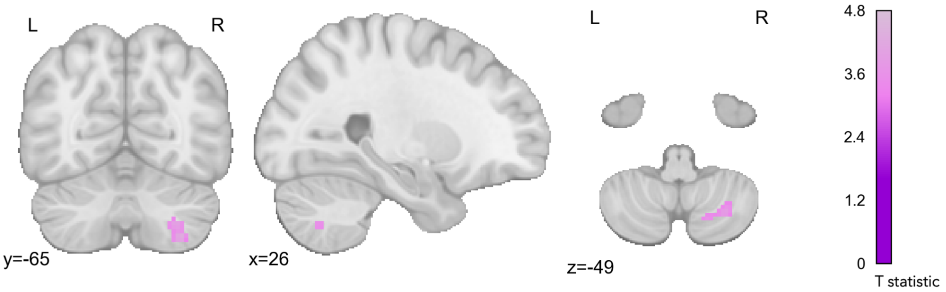


Figure 3.2.12. (previous page) Changes in activation in the *bimanual asymmetric* condition in the TP_{onset}>$TP_{week\ 13}$ contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point ($TP_{pre\text{-}training}$).

a) *bimanual asymmetric* TP_{onset}>TP_{end} - significant clusters



b) time-course of peak activations

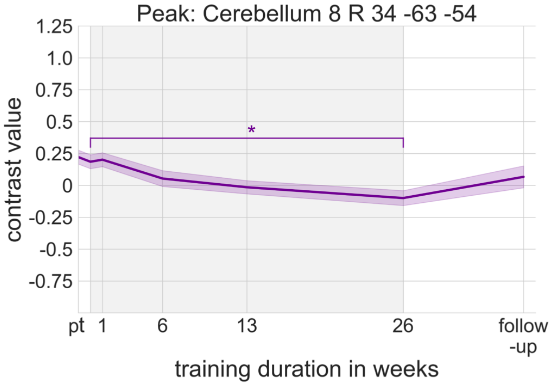


Figure 3.2.13. Changes in activation in the *bimanual asymmetric* condition in the TP_{onset}>TP_{end} contrast. (a) Statistical maps; x, y, z - MNI coordinates; colour bar indicates the test-statistic range. (b) time-courses from the cluster peaks; error band represents the standard error; the shaded area corresponds to the training period; pt denotes the pre-training time-point ($TP_{pre\text{-}training}$).

3.2.2.2. Music playback fMRI task

3.2.2.2.1. Main Effect of Task

Irrespective of time, the music playback fMRI task revealed brain activation in the left precentral and postcentral gyri; the right temporal pole extending into the inferior frontal gyrus (pars opercularis) and the planum temporale; the left superior temporal gyrus encompassing the left planum temporale; bilaterally in the supplementary motor cortex; and the vermis. A summary of the brain activation related to the music playback fMRI task can be found in Table S10 and Figure 3.2.14a.

3.2.2.2.2. Main Effect of Time

Musical training-related brain activation changes for the music playback fMRI task encompassed multiple brain regions (Table 3.2.1, Figure 3.2.14.a), such as the right postcentral gyrus, extending into the precentral and supramarginal gyri, and the parietal cortex; the right inferior frontal gyrus, extending into the frontal pole and the middle frontal gyrus; the right caudate nucleus; bilateral cerebellum; the left precuneus; the left inferior temporal gyrus (at the temporo-occipital junction); the left parietal cortex; or the left hippocampus, among others. For visualisation purposes, the time-courses of selected cluster peaks were plotted (Figure 3.2.14 b, Table S11). Pairwise comparisons between time-points showed a significant effect for $TP_{\text{week 1}}>TP_{\text{end}}$, $TP_{\text{week1}}>TP_{\text{week 13}}$ and $TP_{\text{week 6}}>TP_{\text{end}}$ (Figure 3.2.15).

3.2.2.2.3. Independent Region of Interest (ROI) analysis

The independent ROI analysis between the left sensorimotor ROI, the right motor ROI and the right auditory ROI revealed significant effects of time, region and their interaction (Table 3.2.1, Figure 3.2.16). In the pairwise comparisons analysis, there were significant differences between the following: $TP_{\text{week 1}}$ and TP_{end} for the left sensorimotor ROI ($t=4.521$, $p_{\text{Bonf-corr}}=0.003$) and right motor ROI ($t=7.542$, $p_{\text{Bonf-corr}}<0.001$); $TP_{\text{week 6}}$ and TP_{end} for the right motor ROI ($t=4.378$, $p_{\text{Bonf-corr}}=0.004$); the left sensorimotor ROI and the right auditory ROI at $TP_{\text{week 13}}$ ($t=-3.346$, $p_{\text{Bonf-corr}}=-0.034$); the right auditory ROI and the right motor ROI at $TP_{\text{week 13}}$ ($t=4.550$, $p_{\text{Bonf-corr}}=0.002$); and, at the TP_{end}, all three ROIS (left sensorimotor ROI and right auditory ROI $t=-5.048$, $p_{\text{Bonf-corr}}<0.001$; left sensorimotor ROI and right motor ROI $t=4.815$, $pp_{\text{Bonf-corr}}<0.001$, right auditory ROI and right motor ROI $=7.263$, $pp_{\text{Bonf-corr}}<0.001$).

3.2.2.2.4. Main Effect of Task ∩ Main Effect of Time

The conjunction analysis of the main effects of task and time revealed no significant clusters, and therefore is not presented in the tables or visualisations.

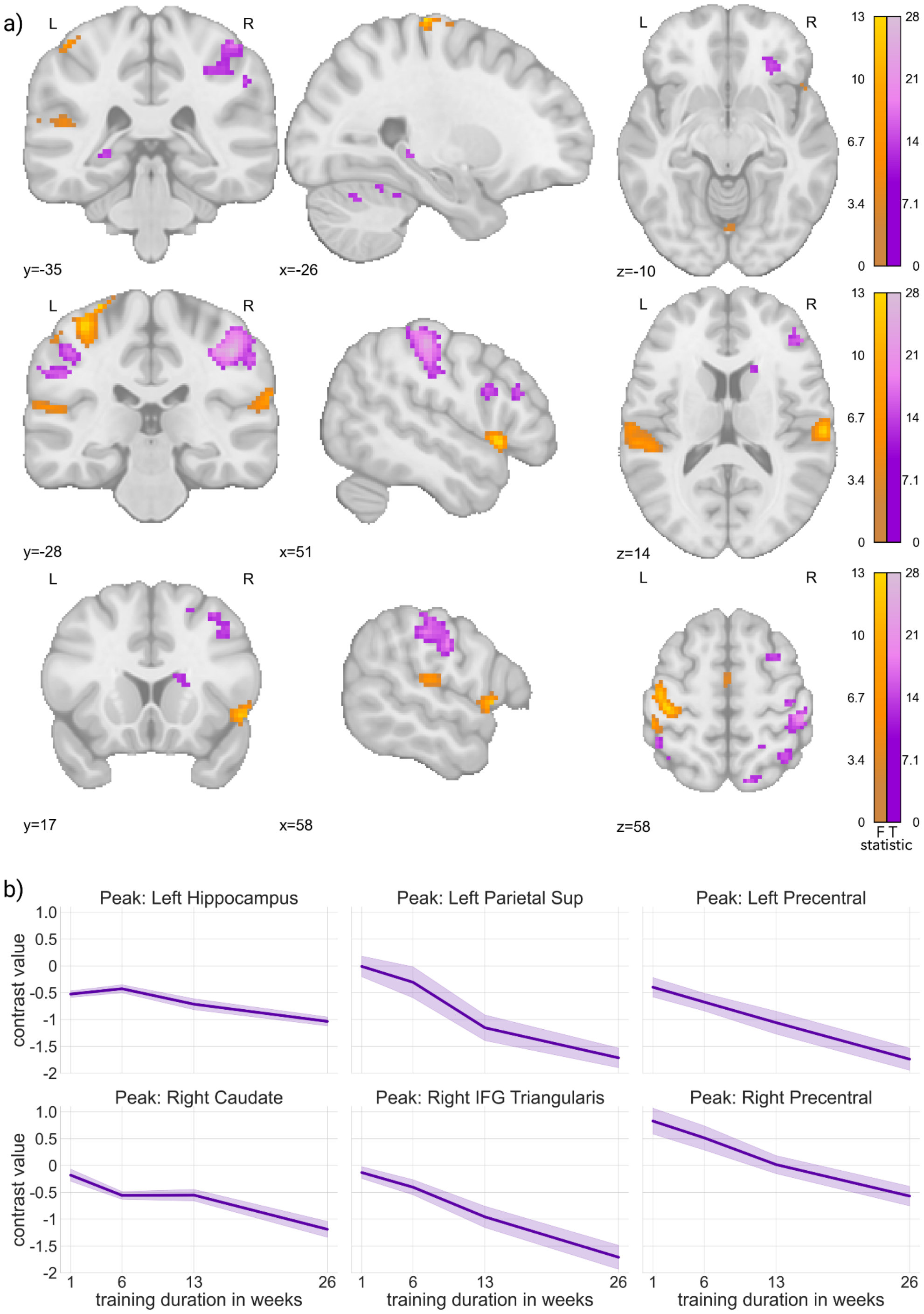


Figure 3.2.14. The results from the music playback fMRI task. (a) Statistical maps representing the contrasts for the Main Effect of Task (orange) and Main Effect of Time (purple). x, y, z - MNI coordinates. Colour bars represent test-statistic ranges. (b) Visualisation of musical-training-related changes in brain activation in selected cluster peaks; error band represents the standard error.

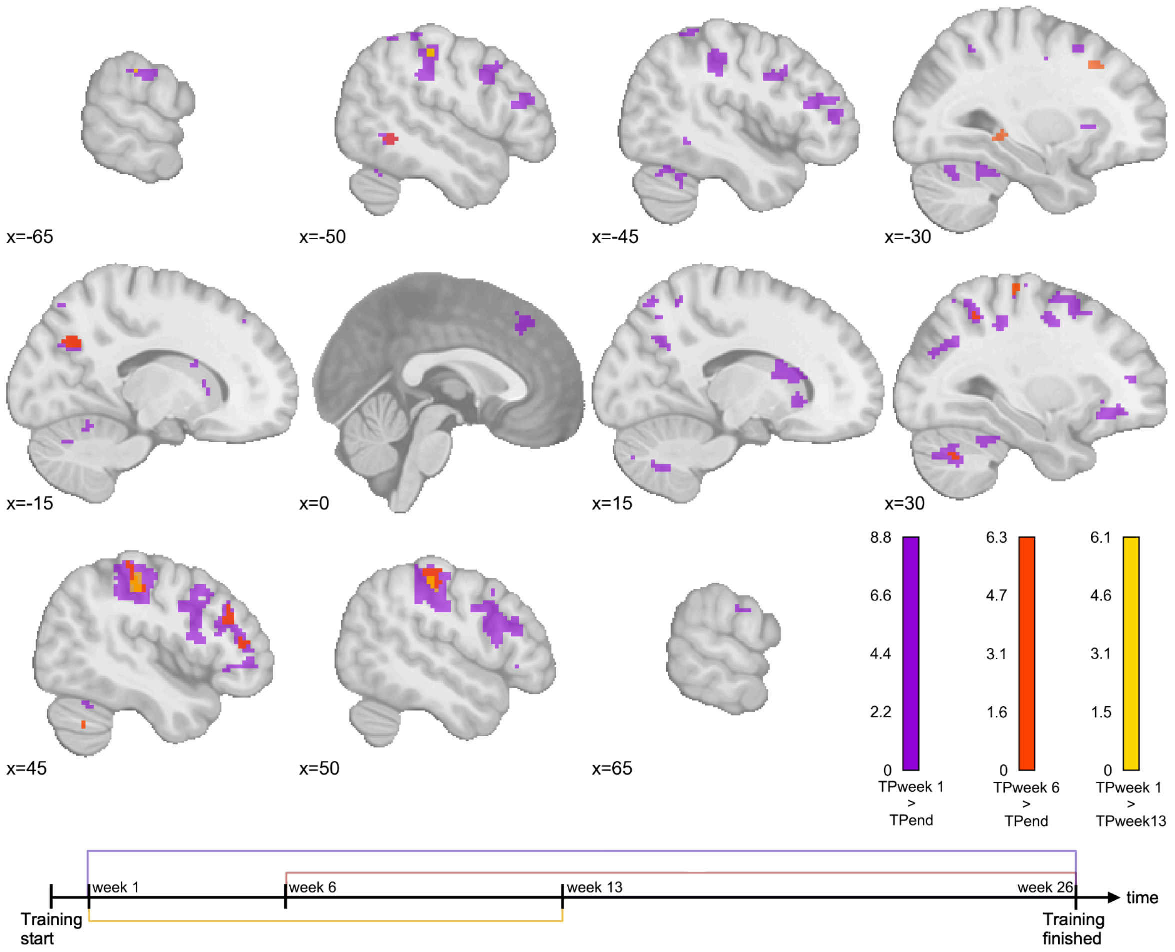


Figure 3.2.15. The results from the music playback fMRI task. Pairwise comparisons between $TP_{week\ 1}>TP_{end}$, $TP_{week\ 6}>TP_{end}$ and $TP_{week\ 1}>TP_{week\ 13}$. The remaining pairwise comparisons yielded no significant clusters. Colour bars represent the ranges of the T test-statistic.

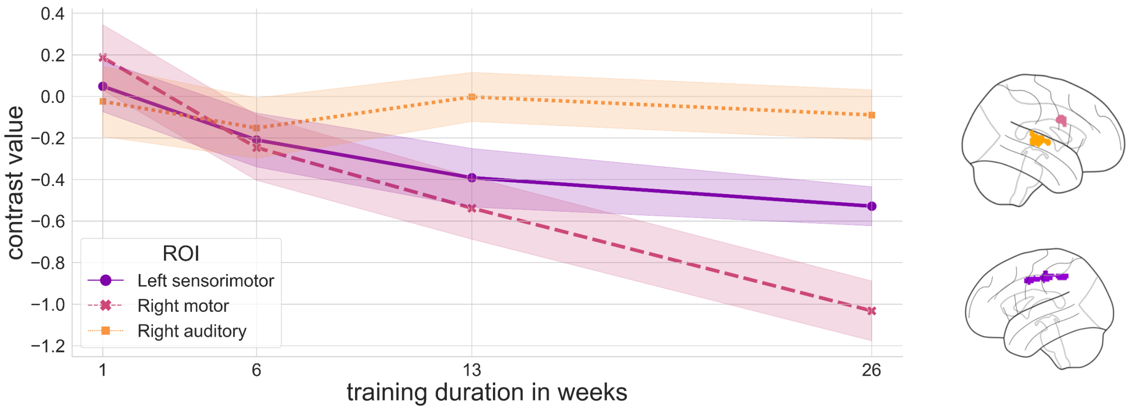
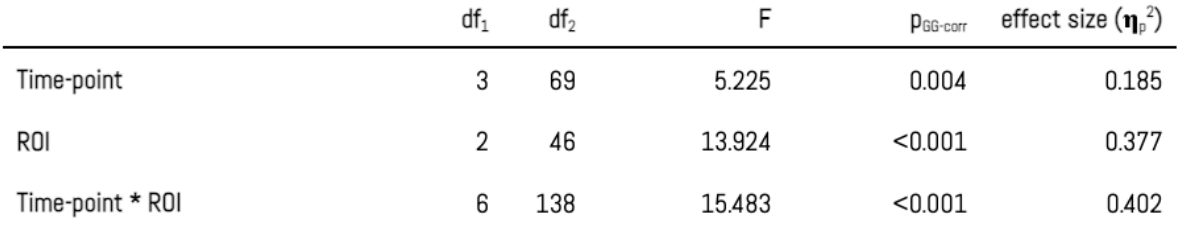


Figure 3.2.16. Music playback fMRI task. Visualisation of musical-training related changes in brain activation in three independent ROIs; error band represents the standard error. The anatomical localisation and shapes of the ROIs are depicted on the right.

Table 3.2.1. Music playback fMRI task. The results of repeated-measures ANOVA for the main effects of time, ROI and their interaction of training-related changes in independent ROIs. $p_{GG\text{-}corr}$: Greenhouse-Geisser corrected p-value; η_p^2 - generalised partial eta-squared effect size.



	df_1	df_2	F	$p_{GG\text{-}corr}$	effect size (η_p^2)
Time-point	3	69	5.225	0.004	0.185
ROI	2	46	13.924	<0.001	0.377
Time-point * ROI	6	138	15.483	<0.001	0.402

3.2.3. Summary and discussion

Study 2 investigated changes in brain activation of novice pianists performing auditory-motor tasks, such as playing the instrument or pressing consecutive keys on the fMRI-compatible piano. Contrary to many studies on motor training, the current experimental paradigm paralleled naturalistic training and gradually increased in difficulty.

3.2.3.1. Behavioural results

The behavioural results from the piano key pressing fMRI task revealed improvements in melodic accuracy across all three conditions due to task repetition. These improvements plateaued and remained stable throughout the training period. Similar findings were observed for rhythmic accuracy in the unimanual condition. However, rhythmic accuracy could not be reliably calculated for the bimanual conditions. Overall, performance on unimanual stimuli remained consistently more accurate compared to bimanual stimuli throughout the entire study. The music playback fMRI task yielded comparable results. Performance on unimanual stimuli remained stable throughout the training period and consistently surpassed performance on bimanual stimuli, which improved over time.

The behavioural results suggest a nuanced picture of performance improvement. Task repetition appeared to drive initial gains in melodic accuracy for all conditions in the piano key pressing task, potentially reflecting a basic level of motor skill acquisition. However, for the more complex bimanual tasks of playing the piano, the training itself seems to have played an additional role in promoting performance improvement beyond the plateau observed with simple stimuli. This supports that the training was necessary for the participants to obtain additional skills or strategies that specifically benefited bimanual coordination in piano playing. The increasing performance on the stimuli over time in the music playback fMRI task demonstrates the effectiveness of the learning process and translates to a heightened ability to play the piano.

3.2.3.2. Neuroimaging results

3.2.3.2.1. Main Effects of Tasks

The piano key pressing fMRI task elicited activation in brain regions known to be involved in auditory processing (superior temporal gyrus, Heschl's gyrus), sensory perception (postcentral gyrus), motor planning and control (precentral gyrus, supplementary motor cortices, cerebellum, thalami, putamen, caudate nuclei), higher-order movement monitoring, and auditory-motor integration (inferior frontal gyrus, parietal cortex) (Zatorre, Chen, and Penhune 2007) across all three conditions (Figure 3.2.4). The *bimanual symmetric* and *asymmetric* conditions additionally revealed complementary activation in the occipital cortex as well.

Consistent with previous findings on asymmetric bimanual tasks, the current results revealed significant activation differences between the *bimanual asymmetric* and *symmetric* conditions (Figure 3.2.4.d). These differences were observed in brain regions associated with spatial attention, auditory-motor integration, as well as supplementary motor areas and the dorsal premotor cortex. More activation in the left anterior insula might also be related to executive control of movement (Molnar-Szakacs and Uddin 2022; Tinaz et al. 2018) and auditory-motor integration (Kleber et al. 2013).

These findings likely reflect the increased demands placed on the motor system during the *asymmetric* condition compared to the *symmetric* condition, requiring more complex coordination of both hands. Similar observations were reported in a case study by Endestad and colleagues (2020), where a pianist exhibited a comparable network activation pattern (dorsal premotor cortex, primary somatomotor cortices, inferior parietal regions, precuneus, cerebellum) when playing more difficult versus easier musical pieces. These results align with research on non-musical bimanual coordination (Aramaki, Osu, and Sadato 2010; Matsuda et al. 2009) and highlight the importance of ecologically relevant paradigms for studying musicianship. The current study extends these findings by demonstrating that similar activation differences, associated with task difficulty, can be observed even in novice pianists.

In the music playback fMRI task, the evoked brain activation encompassed a network typically associated with playing a musical instrument, including bilateral auditory regions, the left motor cortex, and supplementary motor and cerebellar areas (Figure 3.2.14). This finding aligns with prior research on music production (Pando-Naude et al., 2021; Zatorre et al., 2007). The supplementary motor area is known to be involved in visuomotor coordination and learning (Kawashima, Roland, and O'Sullivan 1994). The dominance of left sensorimotor regions might be attributable to the inclusion of right-hand only trials or the right-handedness of the participants. Beyond the auditory and motor regions, activation was observed in the bilateral temporal poles and the inferior frontal gyrus (pars opercularis). The temporal poles are multifunctional regions implicated in various cognitive functions, including naming, word-object labelling, and semantic processing across modalities (Herlin, Navarro, and Dupont 2021), and were not expected to be related to music playback. In this task, which required melody recognition before playing, the involvement of temporal poles might be related to these aspects. Previous studies have linked damage to temporal poles with difficulty in music recognition and naming (Belfi, Kasdan, and Tranel 2019; Belfi and Tranel 2014; Johnson et al. 2011; Schneider et al. 2018). Alternatively, Abrams and colleagues (2011) suggest that activation in the temporal pole might be associated with decoding the temporal structure of music and speech. The pars opercularis, a subregion of the inferior frontal gyrus, is thought to be involved in representing syntactic and phonological processing, as well as motor control, in the context of speech and music (Asano, Boeckx, and Seiferd 2021).

In conclusion, both tasks effectively identified brain regions engaged in playing a musical instrument in novice pianists. Previously, this setup was only validated in trained musicians (Olszewska et al. 2023). Thus, the elicited brain responses in novices are in line with expectations and the tasks are suitable for studying training-related changes.

3.2.3.2.2. Longitudinal analyses

The longitudinal design of the second study employed a unique scanning schedule to isolate the effects of task repetition prior to the onset of training with the piano key pressing fMRI task. This design revealed significant reductions in brain activation for both the *unimanual (right hand)* and *bimanual (symmetric)* conditions between the $TP_{pre\text{-}training}$ and the TP_{onset} (Figure 3.2.3. a, b). In the *unimanual (right hand)* condition, these changes were localised in the brain regions associated with sequence automatisation, thalamus and caudate nucleus. The *bimanual (symmetric)* condition exhibited a different pattern, where the reduced activation was present in the precuneus and superior parietal cortex. In studies on motor sequence learning, a deactivation in these areas is typically linked to the acute phase of motor sequence learning (Doyon et al. 2009).

These findings suggest that, contrary to the hypothesis H2.1°, some of the observed decreases in brain activation might be attributable, at least in part, to task repetition itself, rather than being specific to piano training. However, in the case of the most demanding condition (*bimanual asymmetric*), the hypothesis was confirmed; pre-training reductions in brain activation were not present, even though task performance improved across all three conditions from the $TP_{pre\text{-}training}$ to the TP_{onset} (Figure 3.2.1).

Training-related changes were measured between time-points TP_{onset} (beginning of training) and TP_{end} (end of the piano course after 26 weeks in training). In the *unimanual (right hand) condition*, no significant functional adaptations were observed within this timeframe. Therefore, task repetition itself may have been the primary factor driving the earlier changes in brain activation observed in this condition (Figure 3.2.3). In contrast, the bimanual conditions exhibited diverse patterns of training-induced neuroplasticity.

The *bimanual symmetric* condition displayed the most dynamic changes, with a region-specific and time-specific reorganisation of brain activation, primarily localised in the left parietal cortex (Figure 3.2.5 b). A closer examination through pairwise comparisons revealed a decrease in activation between the beginning of training and the 13-week mark in the right inferior frontal gyrus and right insula (Figure 3.2.6). For other affected regions, mainly in the motor planning and control networks, sequential increases in activation were observed throughout training (Figures 3.2.7-3.2.10). Importantly, apart from the right angular gyrus, no significant effects were observed between the onset and the end of training, underscoring the importance of multiple measurement sessions during training to reveal the dynamic changes. Visual inspection of the training-related trajectories showed that the regions display a 'u-shaped' response, and a pre-post design would not have identified these adaptations (Figure 1.5.1. d). However, most of the significant changes were related to increases between the time-point characterised by the lowest activation, and the end of training. This lowest activation time-point differed per brain area, with some responding already after one week of training (the parietal cortex, cerebellum and middle cingulate gyrus), others after six weeks of training (parietal cortex and middle frontal gyrus), and most in the second half of training (left caudate, bilateral inferior frontal gyrus, left middle and superior frontal gyri, and the bilateral supplementary motor cortex, among others).

The *bimanual asymmetric* condition also revealed training-related changes in brain activation patterns, particularly within the right parietal cortex and cerebellum (Figure 3.2.5c). Pairwise comparisons between time-points indicated a sequential pattern of decreases, starting in the parietal cortex and followed by regions within the motor network and insula (Figures 3.2.11 - 3.2.13).

The observed changes in activation differed between the symmetric and asymmetric conditions, with opposite patterns emerging in all identified regions except the anterior insula. This finding suggests that the increased demands of the *asymmetric* condition necessitate adaptations within a distinct distributed network compared to the *symmetric* condition.

In the music playback task, The Main Effect of Time was computed for the period from TP_{week1} to TP_{end}, as the task could not be given to the novice pianists before they could actually play even the simplest of the musical pieces. This analysis revealed widespread training-related changes across multiple brain networks (Figure 3.2.14 a) including regions involved in procedural movements and motor planning (caudate nucleus, cerebellum), musical syntax processing and error monitoring (inferior frontal gyrus), memory retrieval (posterior hippocampus), and auditory-motor integration (superior parietal lobule). For all regions, brain activation decreased with time, what is visualised in trajectories of peak activations (Figure 3.2.14 b) and revealed by pairwise comparisons between time-points (Figure 3.2.15). Additionally, the conjunction analysis found no statistically significant overlap between the regions revealed in the Main Effect of Task and the Main Effect of Time. These results support the hypothesis H2.2°, as training-related changes were found in the dorsal auditory stream for both tasks, and are consistent with research on motor sequence training. A decrease in the activation of parietal and premotor cortices was associated with motor training, in a disjunction from regions involved in the task itself (Garzón et al. 2023). A decrease in brain activation in the late compared to early training was shown previously in the two single-session studies where novices learned to play simple melodies (Brown and Penhune 2018; Chen, Penhune, and Zatorre 2009). Yet, these results need to be interpreted carefully, as the decrease in activation within a single session might reflect a repetition-suppression effect (Brown et al. 2013; Garrido et al. 2009).

Furthermore, the music playback fMRI task revealed an asymmetry in the decrease of training-related activation within sensorimotor areas associated with left-hand movement, but not right-hand movement, as observed on a whole-brain analysis (Figure 3.2.14). This asymmetry might be attributable to the right-handedness of the participants. In right-handed individuals, fine motor control of the right hand is typically well-established by early adulthood, while the left hand requires more effort to achieve similar dexterity (Gut et al. 2007; Lee, Jin, and An 2019). This interpretation is further supported by the findings from the independent regions of interest analysis.

Three independent regions of interest associated with music production were identified based on a meta-analysis of Pando-Naude and colleagues (2021). They represented the right auditory, right motor and left sensorimotor regions. The analysis of these ROIs revealed distinct temporal dynamics in their activation patterns. The auditory ROI displayed no significant change over time, while both motor-related ROIs exhibited a significant decrease in activation at TP_{end} compared to $TP_{week\,1}$. After 13 weeks, a significant difference emerged between the auditory ROI and both motor ROIs. By 26 weeks, all three ROIs showed significant differences, including a distinction between the left and right motor regions. Activation in the right motor region, associated with left-hand movement, decreased at a faster rate than the activation in the left motor region. These findings suggest a process of distinct functional reorganisation within auditory and motor regions during the initial six months of piano training. Auditory regions maintained stable activation, while left sensorimotor ROI underwent gradual decreases in activation, and the right motor regions exhibited the most rapid changes. This pattern aligns with the interpretation based on the whole-brain analysis, suggesting that brain activation related to left-hand movement required more adaptations compared to the right hand in this right-handed participant group.

Finally, the follow-up period revealed no significant changes in brain activation for any condition within the piano key pressing fMRI task. This suggests a potential persistence of training-related effects for several weeks after the training concluded, even in the absence of further targeted intervention, and no spontaneous change, in line with the hypothesis H2.3°.

Overall, the observed neuroplastic changes associated with both fMRI tasks mirror those reported in motor training studies (e.g. Berlot, Popp, and Diedrichsen 2020; Garzón et al. 2023). These findings suggest a shift from spatial attention during motor control to a more automatised movement execution. It is important to note that a significant portion of the observed dynamic changes occurred during the later stages of training, and might not have been captured in a study with a shorter duration. Interestingly, no changes were localised in brain regions linked to auditory processing, which supports the null findings from Study 1 on auditory processing.

The current results underscore the complexity of functional neuroplastic processes. Training-related adaptations emerge as non-linear, dependent upon the brain region, training phase, and specific task demands. Because the spatial and temporal characteristics of plasticity induced by training are shaped by the interplay between engaged brain systems and their demands, they may not necessarily translate well to simpler versions of the task, as illustrated by the differences between the a*symmetric* and *symmetric* conditions. Furthermore, the results highlight the importance of ecologically relevant designs for investigating tasks involving complex movements.

3.3. Study 3: Cross-sectional approach - novices vs musicians

This study was conducted to complement the results from the longitudinal studies by comparing the novice pianists to a group of trained musicians. The two groups were compared cross-sectionally at two time-points: before and after the completion of the piano training course by the novices. The comparison involved the tonal working memory behavioural task and a piano key pressing fMRI task in all three experimental conditions differing in bimanual control demands (*unimanual*, *bimanual symmetric*, *bimanual asymmetric*).

3.3.1. Behavioural results

3.3.1.1. Tonal working memory (tonal n-back task)

The tonal n-back behavioural task investigated differences in tonal working memory between novice pianists and trained musicians before and after the musical training course. A t-test analysis revealed a significant difference in mean 2-back task performance between the two groups before training (T=-8.276, df=40.085, p<0.001, 95%CI=[-30.2, -18.34]) (Figure 3.3.1). Similarly, when the training completed, the difference between the novice pianists and the trained musicians continued to be significant (T=-8.775, df=34.276, p<0.001, 95%CI=[-28.61, -17.85]). Because the performance of novice pianists in the 3-back condition remained at chance level, no meaningful comparison could be performed.

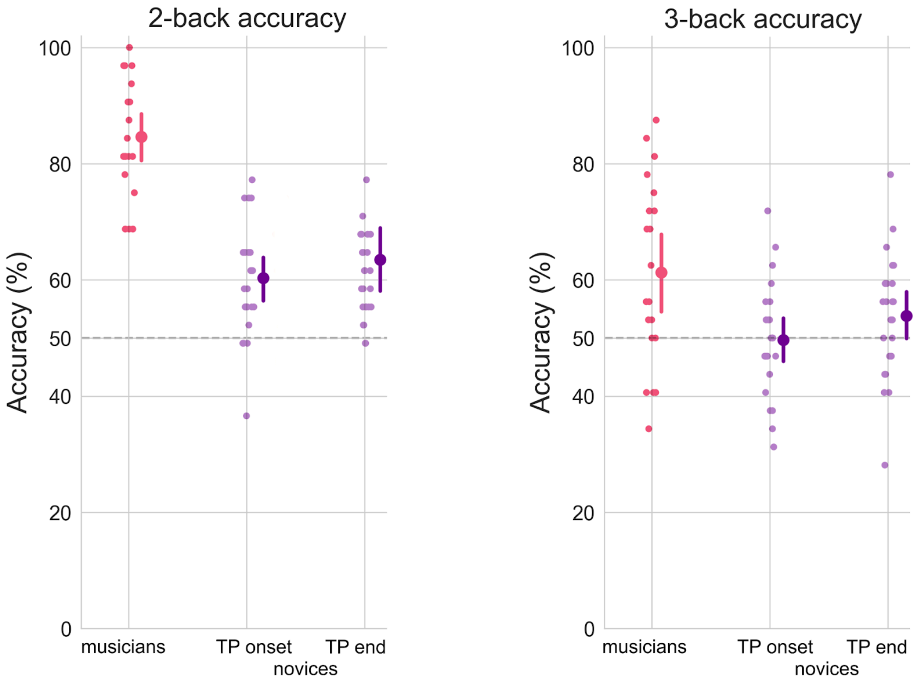


Figure 3.3.1. The performance of the tonal n-back (behavioural tonal working memory task) in the 2-back and the 3-back conditions in trained musicians and novice pianists. Dots with whiskers indicate the sample means and the 95% confidence intervals; smaller dots represent individual subject data.

3.3.2. Neuroimaging results

3.3.2.1. Piano key pressing fMRI task

This analysis compared brain activation patterns of novice pianists before (TP_{onset}) and after training (TP_{end}) to the brain activation pattern of trained musicians (Figure 3.3.2, Table S12). The comparison included all three of the experimental conditions of the piano key pressing fMRI task: *unimanual*, *bimanual symmetric* and *bimanual asymmetric*. Additionally, the contrast *bimanual asymmetric>symmetric* was examined as well.

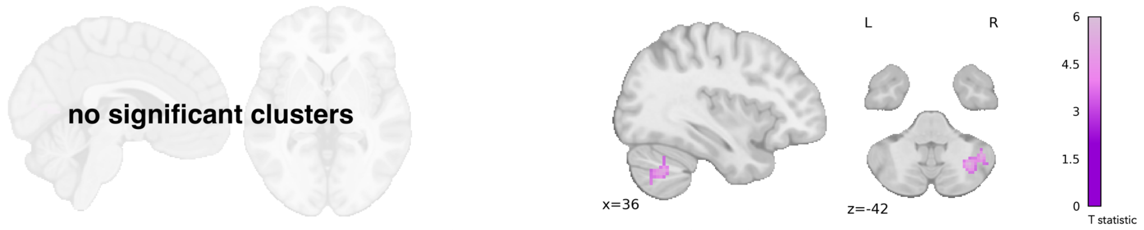
In the *unimanual (right hand)* condition, no differences were observed in brain activation patterns between the novices before training (TP_{onset}) and musicians. At the cessation of training (TP_{end}), increased activation was observed in the cerebellum (crus II and lobule VIIb) of trained musicians compared to novice pianists.

The comparison between trained musicians and novice pianists revealed no significant differences in brain activation patterns in the *bimanual symmetric* condition either at pre-training (TP_{onset}) or post-training (TP_{end}). At pre-training (TP_{onset}), novices exhibited greater activation compared to trained musicians during the *bimanual asymmetric* condition in the lobule VIII of the cerebellum, the superior frontal gyrus bilaterally in the region of the dorsal premotor cortex, and in the right superior parietal gyrus. However, no significant differences in activation were observed between novice pianists and trained musicians at post-training (TP$_{\text{end}}$) in this condition.

Finally, the comparison *bimanual asymmetric>symmetric* showed increased activation in novice pianists compared to trained musicians before training (TP$_{\text{onset}}$) in multiple brain areas. These included the left cerebellum lobule VIII and the right superior parietal gyrus extending into the inferior parietal and postcentral gyri and precuneus, the right superior frontal gyrus (including dorsal premotor cortex), and the left superior parietal gyrus, extending into the inferior parietal gyrus, precuneus and angular gyrus. No significant differences in activation were found in this contrast comparison between novice pianists at the end of training (TP$_{\text{end}}$) and trained musicians.

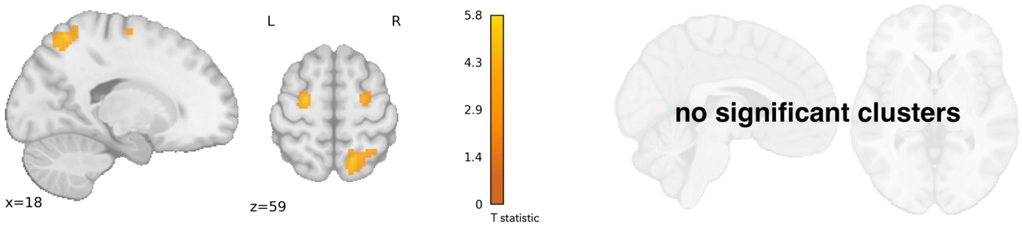
TP$_{\text{onset}}$ (before training) **TP$_{\text{end}}$ (after training)**

a) *unimanual (right hand)*



b) *bimanual symmetric (⟵⟶)*

c) *bimanual asymmetric (⟶⟶)*



d) *bimanual asymmetric>symmetric*

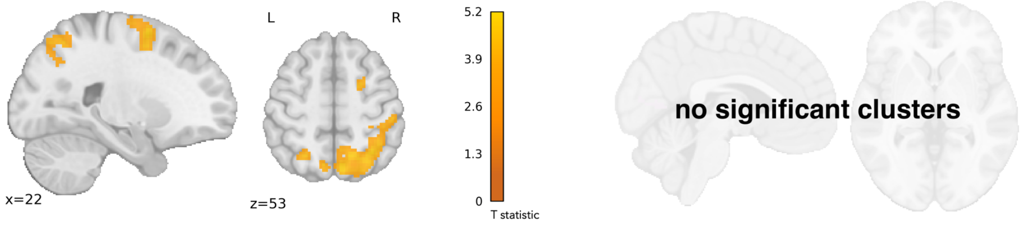


Figure 3.3.2. The comparison of brain activations during the piano task between novice pianists and musicians pre-training (TP$_{\text{onset}}$, left) and post-training (TP$_{\text{end}}$, right): *Novices>Musicians (orange)*, *Musicians>Novices (purple)*.

3.3.3. Summary and discussion

This study aimed to complement the results of the longitudinal designs with converging evidence from cross-sectional comparison between novice pianists before and after training to trained musicians. Using tonal working memory behavioural task and a piano key pressing fMRI task, aspects of auditory processing and neural correlates underlying playing the piano were compared before training started (TP_{onset}) and after it was completed (TP_{end}).

In the tonal working memory behavioural task, musicians significantly outperformed novices at both time-points. The performance difference between the musically trained and naïve groups replicates the result from the original experiment (Ding et al. 2018). However, the prediction (H3.1°) was not confirmed; the difference between the trained musicians and novice pianists in tonal working memory performance persisted after training was complete.

Similarly as in Study 2, the piano key pressing fMRI task was performed in three conditions differing in motor coordination demands, from the simplest requiring no bimanual coordination (*unimanual right hand*) to an intermediate (*bimanual symmetric*), to the most demanding (*bimanual asymmetric*). Before training, the only significant differences were observed in the most demanding task (*bimanual asymmetric*), where novice pianists exhibited increased activation in the dorsal premotor cortex bilaterally, the right parietal cortex and left cerebellum. These differences disappeared after the twenty-six weeks of training, when no differences were observed in brain activation between novice pianists and trained musicians in any of the *bimanual* conditions. However, by the end of training, the brain activation of novices was decreased compared to musicians in the cerebellum in the *unimanual (right hand)* condition, possibly due to high familiarity and continuous training of this particular sequence. The observed pre-training differences between novice pianists and trained musicians resemble differences between musicians and non-musicians on bimanual tasks in previous studies (Haslinger et al. 2004; Jäncke, Shah, and Peters 2000) and are localised in brain areas revealed by Study 2.

Additionally, a direct comparison between the two bimanual conditions (*bimanual asymmetric>symmetric*) revealed a larger difference in brain activation in novice pianists compared to trained musicians bilaterally in the parietal cortex, the right dorsal premotor cortex, and the cerebellum. After the cessation of training, the comparison between both *bimanual* conditions did not differ between the two groups. The identified regions are involved in auditory-motor coordination and motor control. Thus, before training, novices required additional involvement of these regions to perform the *bimanual asymmetric* task condition than the *symmetric* one, compared to the differences in musicians. Previously, differences in brain activation between musicians and non-musicians in complex bimanual tasks have been identified previously (e.g., Haslinger et al. 2004; Jäncke, Shah, and Peters 2000), albeit more in subcortical regions, what might be related to the nature of the task itself. In the current project, these differences disappeared after training, supporting the hypothesis H3.3°.

These results corroborate the findings of the longitudinal experiment, showing that playing the piano required increased brain activation from novices at the beginning of training in the demanding bimanual task condition. The *bimanual asymmetric* condition was designed to put increased demands on the motor system, in terms of motor coordination and motor control, similarly to piano playing. As the training reached its end, the cortical brain activation in novice pianists equalised with that of trained pianists. Thus, the hypothesis H3.2° was supported by the findings of Study 3.

4. General Discussion

To be an effective scientist one must be more than a scientist, and a philosopher must be more than a thinker. For the analytic measurement of nature tells us nothing if we cannot see nature in any other way.

— Alan W. Watts

Brain, as the source of all behaviours, changes and adapts in the process called training-related neuroplasticity to support novel skills going beyond its original capabilities. Playing the piano, as well as other musical instruments, is a complex and multifaceted skill which involves aspects of motor execution, auditory perception, auditory-motor integration, and cognitive processes such as memory, emotion or pleasure (Zatorre, Chen, and Penhune 2007). At the same time, playing a musical instrument is a typically human behaviour, engaged with by many individuals on a daily basis. Therefore, it is considered a useful model to study human brain plasticity on various time-frames, from short-term interventions to studying pianists as a human model of lifelong learning (Olszewska et al. 2021, Zatorre, Chen, and Penhune 2007). The current project investigated how brain activation changes in time in adult novice pianists performing various musical tasks, such as music listening or playing the piano. It concerned three studies, combining longitudinal and cross-sectional approaches to investigate auditory and motor aspects of musical training, and their interactions. The outcomes of the fMRI tasks were supported by the results from behavioural observations, and the longitudinal design was combined with the cross-sectional comparison between novice pianists and trained musicians. In this manner, musical training was used in a framework to understand functional brain reorganisation supporting the acquisition of a complex skill.

4.1. Summary of the discussed studies and their outcomes

4.1.1. Study 1: Auditory processing

Music is typically understood as a primarily auditory phenomenon (Honing 2021; Jaschke 2023); therefore it is understandable that studies on musical training investigate how it impacts auditory processing. In Study 1, the auditory processing of novice pianists was investigated in the manner inspired by previous research, via a passive music listening fMRI task. This was supplemented by the behavioural tonal working memory task (tonal n-back), which was employed to account for near-transfer of auditory processing adaptations to a cognitive domain. There were no differences at baseline between the novice pianists and the passive controls in the music listening task, and no repetition effects, which could point to pre-training differences between groups. However, this study resulted also in null findings for the training period, as there was an absence of effects of group, group×time interactions or any effect of time between the training onset and the end of training. Similarly, no changes in task performance with time were observed in the tonal n-back task, suggesting that the auditory processing or tonal working memory did not change with time or training in either of the novice pianists or passive control groups.

4.1.2. Study 2: Playing the piano

Playing a musical instrument is a behaviour which requires the brain to integrate motor activity with the auditory feedback resulting from it. Motor aspects and auditory-motor interactions related to playing the piano were assessed in Study 2, which used the piano key pressing fMRI task and the music playback fMRI task. This study revealed the complexities of the training-related functional neuroplasticity, which was dependent on the brain region investigated and the task demands for which the activation was measured. Some of the effects in the less demanding tasks (the *unimanual* and *bimanual symmetric* conditions of the piano key pressing fMRI task) could be attributed to repetition and not musical training. In the most demanding condition of the piano key pressing fMRI task (*bimanual asymmetric*), as well as in the music playback fMRI task, the brain activation changes were indicative of a shift from spatial attention during motor control to a more automatised movement execution. This shift was reflected by a decrease in brain activation in the parietal, supplementary motor, dorsal premotor and cerebellar regions, and the caudate nucleus, constituting the cortico-cerebellar and cortico-striatal motor networks. No further significant changes were observed in the follow-up period. Notably, training-associated changes were dependent on brain region and the phase of training.

4.1.3. Study 3: Cross-sectional approach - novices vs musicians

For many musicians, whether formally or autodidactically trained, playing a musical instrument starts in childhood and lasts many years. However, such long study time-frames are not viable in the context of a PhD project. Study 3 combined longitudinal and cross-sectional designs to compare the brain adaptations related to the twenty-six weeks of training in novice pianists with the lifelong training of musicians. Before training, novices exhibited increased brain activation in the *bimanual symmetric* condition of the piano key pressing fMRI task compared to trained musicians. After training, the brain activation in the novice pianists equalised with the level observed in the trained musicians. However, the performance of novices in the tonal working memory was lower than the performance of trained musicians both before and after the training.

The findings of all three studies were discussed in detail in previous sections. In the following sections, they are combined into a comprehensive insight on the dynamics of auditory and motor adaptations related to piano training in novice adult pianists, its importance and implications.

4.2. The complicated relationship between musical training and auditory processing

The proposed relationship between musical training and improved auditory processing is a recurring theme in the studies on neural adaptations stemming from learning to play an instrument (Herholz and Zatorre 2012; Olszewska et al. 2021; Papadaki 2023). However, as discussed in the introduction section 1.3, most of the evidence in favour of musical-training-related plasticity resulting in improved auditory processing comes from cross-sectional studies and correlational evidence (e.g. Bangert et al. 2006; Bianchi et al. 2017; Habermeyer et al. 2009; Limb 2006; Oechslin et al. 2013; Ohnishi 2001; Seung et al. 2005).

Based on Study 1, there is no evidence in favour of the impact of piano training on auditory processing of musical stimuli or the performance in the tonal working memory task of novice pianists. Studies 2 and 3 did not find any significant changes in the activation of the auditory cortices or auditory association areas related to musical training in novice pianists performing musical tasks, or differences between musicians and non-musicians in the auditory regions. As discussed in section 3.1.3, this may suggest that the training duration was too short to evoke adaptations in auditory processing, including ones leading to improved tonal working memory. Since musicians learn and engage with music for many years, it is likely that the twentys-six weeks training period was too brief to elicit training-related adaptations related to musical processing in a similar manner. However, given that previous longitudinal studies identified the responses in the auditory cortices to be a predictor of learning performance rather than learning effect (Herholz et al. 2016; Wollman et al. 2018), it is also possible that the differences in auditory processing observed between musicians and non-musicians found in cross-sectional studies (Bianchi et al. 2017; Habermeyer et al. 2009; Oechslin et al. 2013; Ohnishi 2001) might stem from predispositions and not training itself.

One explanation might be that the difference in brain activation in response to musical stimuli and in tonal working memory performance between musicians and non-musicians stems from a self-selection bias. Individuals with better-than-average auditory processing are more likely to pursue musical training in the first place. Additionally, the admission process to formal musical education in Poland, as well as many other countries, requires candidates to pass musical aptitude tests. Thus, one might expect a bias towards improved auditory processing in musicians who underwent formal music education compared to the general population. Since the novice pianists sample was drawn from the general student population in the current project, and they did not choose to pursue musical training in childhood, this bias would be present only in the trained musicians' sample.

Alternatively, it is possible that the age of onset in the novice pianists group was too high for the musical training to elicit adaptations seen in younger populations. Most musicians, including the ones in the current sample, start their musical training around the age of seven years old (Penhune 2022). Age of onset can be an important factor as there is evidence that auditory processing is shaped by the interaction between developmental and experience-related plasticity in the sensitive period in the first decade of life (Penhune 2022). Since the current sample of novice pianists consists of young adults, it might be that the plasticity of the auditory system has diminished by adulthood compared to the typical age of onset of musicians .

Lastly, with bulk of the evidence for auditory adaptations in response to musical training coming from listening tasks in cross-sectional designs (e.g. Bangert et al. 2006; Bianchi et al. 2017; Habermeyer et al. 2009; Limb 2006; Oechslin et al. 2013; Ohnishi 2001; Seung et al. 2005), it is possible that these training-related effects and differences between musicians and non-musicians might be related to other mechanisms than auditory processing itself. Instead of altering the fundamental sensory processing, these differences might reflect familiarity of the musical stimuli (Freitas et al. 2018; Schwarzbauer et al. 2006), or be related to attentional and salience effects. However, the unexplored role of attention and salience in shaping auditory responses to musical stimuli in novice musicians warrants further research.

4.2.1. Lack of transfer effects to a cognitive auditory domain of tonal working memory

To my knowledge, the current project was the first one to investigate the effect of instrumental musical training on tonal working memory longitudinally in novice musicians. In Study 1, no improvement was observed for the training period in task performance for the tonal working memory. The comparison between novice pianists and trained musicians performing the task in Study 3 supported the outcomes of Study 1. The musicians significantly outperformed the novices at both time-points, the results confirmed that the twenty-six weeks training period was not sufficient to improve tonal working memory of novice pianists to the level exhibited by trained musicians. These findings are in line with the conclusions from a recent review on the effects of music training on non-musical abilities (Schellenberg and Lima 2024).

The lack of impact of musical training on auditory processing and tonal working memory suggest that other mechanisms outside of training itself might be the source of differences observed between musicians and non-musicians. A recent meta-analysis of longitudinal studies has concluded that music training might have produced small neurobehavioral enhancements in auditory processing, albeit with a suspicion of publication bias contributing to this result (Neves et al. 2022). These findings have been assessed as inconclusive, as the study designs of many of the included publications suffer from limitations which hinder their ability to infer causal effects (Román-Caballero and Lupiáñez 2022). Indeed, scepticism about the transfer effects from musical training to cognitive domains increases, as pitfalls in methodological approaches of older studies with positive findings become apparent (Schellenberg and Lima 2024).

Notably, the lack of effects in time for auditory adaptations in any of the studies in the current project and investigated tasks makes it impossible to draw any conclusions about the time-course of auditory changes and their dynamics.

4.3. Motor system adaptations and auditory-motor interactions

Motor system adaptations and auditory-motor interactions in novice pianists were investigated using the piano key pressing fMRI task and the music playback fMRI task in Study 2. The current project was also the first one to investigate how bimanual aspects of piano playing affect the training-related changes in novice pianists. By a comparison to the expert group of trained musicians in Study 3, it was possible to assess whether the observed changes from Study

2 represent training-induced adaptations predicted from cross-sectional studies on musicians and non-musicians.

The approaches in Study 2 and Study 3 are challenging because the tasks themselves are difficult; the fMRI task should be simple enough to be performed by untrained participants, but also reflect aspects of real practice which will allow the conclusions to be generalised to the behaviour observed outside of the research environment. The piano key pressing fMRI task was designed for this purpose. Its three conditions varied in task demands, with the *bimanual symmetric* and *bimanual asymmetric* conditions, although engaging both hands in a similar manner and consisting of similar movements, resulted in vastly different findings. This was illustrated by the significant difference in brain activation evoked by the *symmetric* and *asymmetric* conditions in regions responsible for auditory-motor integration, such as the parietal cortex and the dorsal premotor cortex in Study 2. In Study3, in line with the studies on bimanual coordination (Aramaki, Osu, and Sadato 2010; Matsuda et al. 2009), novice pianists exhibited increased brain activation in the *bimanual asymmetric* compared to the *symmetric* condition before training. These findings supported the notion that the *asymmetric* condition was indeed more demanding than the symmetric one. The music playback fMRI task was used specifically to investigate training-related changes while actually playing the piano, filling a gap in literature; previous research concentrated mostly on listening tasks (e.g. Che et al. 2022; D'Ausilio et al. 2006; Herholz et al. 2016; Krishnan et al. 2018; Lister et al. 2023; Ohnishi 2001; Schmithorst 2005; Seung et al. 2005).

The piano key pressing fMRI task in its three conditions and the music playback fMRI task evoked varying time-courses of brain adaptations as training progressed. They localised in the dorsal auditory stream and areas of the motor network, but demonstrated complexity and dependence on context and task demands. They revealed a complex and multifaceted nature of changes within the motor system and regions associated with auditory-motor integration, as well as their relation to task performance. For instance, in the piano key pressing fMRI task, the training-evoked changes in specific brain areas, such as the parietal cortex, supplementary motor area, dorsal premotor cortex, insula or the cerebellum, occurred at different phases of the training. For some of these areas, such as the inferior parietal gyri or the supplementary motor area, the direction of the changes also differed between the task demands, as the activation increased in the latter part of the training in the *bimanual symmetric* condition and decreased in the early weeks of the *bimanual asymmetric* condition. The music playback fMRI task revealed modifications of brain activation in the striatum and premotor cortex from the first week of training, while hippocampal responses only emerged after six weeks. This regional and temporal heterogeneity is further supported by the ROI analysis, which showed distinct time courses for left and right sensorimotor regions. Such a specific patterning of brain reorganisation in space and time, previously hinted on by studies on motor skill training (Doyon et al., 2009; Penhune & Steele, 2012), has not been documented within the context of musical training before.

4.3.1. Bimanual coordination as a crucial component of motor adaptations

In the piano key pressing fMRI task, the *bimanual asymmetric* condition was the most demanding, compared to *bimanual symmetric* and *unimanual* conditions. Only in this *bimanual asymmetric* condition, task-related brain activations and the time-course of changes were similar to the music playback task, and thus characteristic to piano playing. Therefore, the *bimanual asymmetric* condition could be used to investigate training-related changes during the first week, where the music playback task itself was not viable due to the inability to perform any stimuli by the novices before training. While no significant effects were observed within this first week, a decrease in activation between the onset of training and 6 or 13 weeks of training were observed for many regions of the motor system, including regions involved in auditory-motor integrations (Figures 3.2.11 and 3.2.12).

In Study 3, the comparison between novices and musicians in the *bimanual asymmetric* condition of the piano key pressing task indicated that, indeed, early stages of training require novice pianists to involve additional resources in brain areas related to auditory-motor integration, such as the parietal and supplementary motor regions and the dorsal premotor cortex, to perform the task. By the end of training, as the brain activation of novice pianists decreased, it equalised to the activation of trained musicians performing the same task. The lack of differences between groups by the end of training suggest that the same brain networks support task execution by the end of training. Therefore, the twenty-six week training period was sufficient to evoke adaptations in the motor system and auditory-motor integrative areas for a highly demanding bimanual coordination task in novice pianists.

Previous research suggests that musicians exhibit lower brain activation compared to non-musicians during demanding bimanual tasks (Haslinger et al. 2004; Jäncke, Shah, and Peters 2000), pointing to a more specialised processing strategy employed by musicians for these complex tasks. This difference was observed in the comparison between the *bimanual asymmetric* and *symmetric* conditions of the piano key pressing fMRI task before training, when novices exhibited greater differences between conditions than trained musicians. After training, the differences in brain activation between the two conditions were the same in the novice pianists and the trained musicians, further supporting that the same brain networks supported the execution of the task in both groups.

As mentioned above, the conditions of the piano key pressing fMRI task in Study 2 presented a spectrum of bimanual task demands. They resulted in differential time-courses despite similar progress in behavioural task performance. However, all three tasks were simpler than actually playing music on the piano, which was performed in the music playback fMRI task. Only the time-course of the brain activation changes in the most demanding bimanual condition of the piano key pressing fMRI task resembled the dynamics of the changes observed in the music playback fMRI task. As Makin and Orban de Xivry (2019) emphasise, robust conclusions in longitudinal design require the use of appropriate control measures, such as control conditions, tasks, time-points, or participant groups. This is particularly crucial when experimental tasks diverge from real-world scenarios of the processes under investigation. The findings of the current project emphasise the importance of these design considerations, showing that seemingly similar task conditions, such as the *bimanual symmetric* and the *bimanual asymmetric* ones, can yield various results and strikingly different conclusions regarding training-related reorganisation of brain activation.

4.4. Musical-training-related neuroplasticity and the models of neuroplasticity dynamics

The time-course, or dynamics, of training-related changes during skill acquisition has been proposed to follow various trajectories described by different models. In light of these models of neuroplasticity dynamics, the *map expansion* model (Grafman 2000) could not explain any of the changes observed in all experimental tasks. Notably, the areas primarily activated by the music playback fMRI task remain unchanged in the course of training, as demonstrated by the null results of the conjunction analysis (section 3.2.2.4). The *expansion-renormalisation* model (Wenger et al. 2017) predicts an inverted ‘u-shaped’ response, also not present in the data. Even though the decrease of activation observed in the music playback task and the *asymmetric* condition of the piano key pressing task might reflect the latter ‘renormalisation’ phase of brain adaptations, the general shape of the observed changes resembles more a ‘u-shaped’ than an ‘inverted u-shaped' dynamic. Therefore, the *expansion-renormalisation* model also does not explain the observed dynamics of functional neuroplasticity in the current project.

Only the *integrated model of motor sequence learning* (Penhune and Steele 2012), which expects sequential involvement of regions within the cortico-striato-cerebellear network, can partly support the current findings. This model predicts e.g., the increasing involvement of the dorsal striatum in the later part of the training, as illustrated by the changes observed in the caudate nucleus in the *bimanual symmetric* condition of the piano key pressing fMRI task. These changes are proposed to represent the process of chunking and sequence consolidation. According to this model, the increased involvement of the cerebellum, occurring from week 1 to the end of training in the current project, reflects synchronisation mechanisms and the internal model representation. Also contributing to the internal model representation are the motor, premotor and supplementary motor areas, which involvement was increasing from week six to the end of training, and the parietal cortex, where various functional areas respond at various stages. However, the model does not predict changes in the activation of the inferior frontal regions or the insula. Therefore, it is possible their involvement is specific to the musical training aspect of the motor sequences, which cannot be explained only in the light of motor-related changes. The inferior frontal gyrus has been associated with aspects of performance monitoring in musical tasks (Olszewska et al. 2023; Pfordresher et al. 2014) and processes such as error monitoring (Li et al. 2006; Rae et al. 2014) or the processing of musical syntax (Koelsch 2005; Maess et al. 2001). Differences in the activation of the insula have been associated with musical proficiency in performing complex bimanual tasks (Haslinger et al. 2004; Jäncke, Shah, and Peters 2000).

In the *bimanual asymmetric* condition of the piano key pressing task, as well as in the music playback task, the significant findings consist of decreases in brain activation of various regions of the motor network in the first weeks and months of training, followed by a plateau. This pattern is more indicative of an optimization process within higher-order brain regions involved in motor control, auditory-motor integration, memory, and the processing of musical syntax specific to piano playing. At this time, it is not possible to explain such reorganisation in terms of the proposed model of brain plasticity, even though a similar pattern has been observed in a recent study on motor training (Garzón et al. 2023).

In summary, from the three proposed models of brain plasticity dynamics, only the *integrated model of motor sequence learning* can explain some of the observed dynamic changes, but limited to one of the conditions of the piano key pressing fMRI tasks. It is possible that training-related changes related to particular processes are too specific to be unified into a single brain-wide model which could be used for any arbitrary task.

4.5. Methodological considerations in the context of the replication crisis in science

4.5.1. The aspect of training duration and nonlinearity of the neuroplastic processes

Replication crisis is a term coined to describe issues with scientific conduct and publishing, which lead to the reporting of narrow findings specific to very peculiar study designs and over-inflation of false positive results, and, in consequence, failure to replicate the effects in subsequent studies (Ioannidis 2005). In the neuroimaging field, the multitude of approaches to conducting studies and data analyses can lead to contradictory results, even on the same datasets (Botvinik-Nezer et al. 2020). Therefore, current practices in neuroimaging studies emphasise methodological rigour, with meticulous attention paid to factors like sample size and data processing (Botvinik-Nezer et al. 2020; Poldrack et al. 2017; Szucs and Ioannidis 2020). However, study duration often receives less scrutiny, and is frequently based on previous studies or methodological and practical constraints, not theoretical insight. As such, it is rarely driven by the particulars of the studied processes. In a recent meta-analysis on behavioural and brain evidence for the music-training-related enhancement of auditory and linguistic processing (Neves et al. 2022), the training duration of interventions varied between 0.7 and 48 months (between 6 and 48 months for MRI studies). Even though the training period was not found to be a significant moderator of the behavioural outcomes, the neuroimaging findings were not analysed in this manner. Given the non-linear and task-specific nature of brain activation changes induced by piano training in the current experiments, it could be expected that inhomogeneity of the outcomes between studies presented in these meta-analyses might stem from differences in training durations, among other factors. Therefore, I argue that the length of a study deserves equal consideration, on a par with other methodological aspects, and should be chosen based on theoretical insights and prior knowledge.

4.5.2. The value of naturalistic interventions and study designs

One of the strengths of the current project is its naturalistic approach. The musical training intervention was delivered by a professional piano teacher in a setting inspired by a music curriculum proven outside of research (the Suzuki method). Both of the piano playing tasks, the piano key pressing fMRI task and the music playback task, were inspired by the teaching method and exercises used for training. Additionally, the stimuli used in the music playback task were increasing in difficulty as the training progressed, reflecting the piano course curriculum. Finally, trained musicians served as a model of life-long learning and real-life skills, as their musical ability was acquired outside of the research environment. Similar approaches were used previously in studies on training-related adaptations related to linguistic processing (Banaszkiewicz et al. 2020; Matuszewski et al. 2021; Kuper et al. 2021; Molendowska et al. 2021). These design choices reduce the possibility that the findings are very specific to particulars of the research environment, potentially increasing their generalisability and replicability of their conclusions.

4.6. Practical considerations for real-world interventions

The findings of the current project may have several implications for practical music-based interventions, where instrumental instruction is used to promote brain health. The lack of effect in the auditory domain in Study 1, whether in the brain responses to musical stimuli or the transfer effect on the cognitive domain of tonal working memory in novice adult pianists, is an important consideration for practitioners and policymakers involved in music-based interventions. With bulk of the evidence available in favour of improvements coming from cross-sectional and correlational studies, as depicted in a recent review (Schellenberg and Lima 2024), and scarce evidence or null findings from longitudinal studies such as the one from Lister and colleagues (2023) or the current project, there is little rationale for introducing music-based interventions for the improvement of auditory processing or cognition at this moment.

The dynamics of training-related changes also underscores the importance of specific time-frames when designing music-based interventions for the improvement of motor coordination and auditory-motor integrations. The findings from Study 2 show that initial training period has the most impact on movement isolation between the two hands, with training-related changes observed in the first weeks followed by a plateau in the music playback fMRI task and the *bimanual asymmetric* condition of the piano key pressing task, where movements of the hands pose high demands on the motor and task control system. Contrarily, the *bimanual symmetric* condition only revealed significant training-related adaptations in the latter part of the training. As this task condition required synchronous and symmetric coordination of hand movements, it might suggest that interventions aimed to improve such movement coordination require longer training periods. Importantly, the time-frames might also be specific to the population. Recent studies in elderly participants found that piano training only induced functional connectivity changes in the motor network, along with improvements in auditory-motor integration and motor dexterity, after twelve months, but not after six months of practice (Jünemann et al. 2023; Worschech et al. 2023).

These findings suggest that the design of music-based interventions aimed at improving auditory processing, cognitive functions, auditory-motor integration and fine motor control should carefully consider the necessary training timeframe and the specific transfer effects of interest, and test the effects and time-frames in the target population.

5. Limitations

It would be possible to describe everything scientifically, but it would make no sense; it would be without meaning, as if you described a Beethoven symphony as a variation of wave pressure.

— Albert Einstein

This project's strengths lay in its naturalistic design, validated methodology and multiple tasks addressing various aspects of piano training. Its findings are reinforced by a comparison to the passive control group and the expert group of trained musicians, and inclusion of multiple time-points, which effectively capture the dynamic nature of neuroplastic changes. However, as with any research endeavour, limitations require consideration when interpreting the results.

One limitation is that the piano key pressing fMRI task and the music playback fMRI tasks required the participants to use their auditory feedback only, as no visual feedback was possible (participants could not look at their hands). However, all participants were informed and accustomed to this limitation and practised playing without visual guidance at home prior to the experiment.

Additionally, in order to avoid the influence of developmental and ageing processes, the participant age was chosen to represent a narrow range within young adulthood. This choice limits the possibility of generalising the obtained results to children or elderly populations, as developmental and ageing processes might interact with the experience-driven neuroplasticity investigated here.

Moreover, due to the nature of the piano tasks, it was not feasible to employ a passive control group in Study 2. Control conditions and time-points were used instead. However, the design of Study 3 and the comparison to an expert group of trained musicians supported the validity of the findings in Study 2.

Finally, the 'u-shaped' dynamics of some of the observed brain activations was studied with finer time resolution early in the training, because the project's expectations were that most of the dynamic changes would occur there. While this was the case for some of the outcomes, such as the training-related dynamics in the *bimanual asymmetric* condition, it is possible that some of the dynamics in the second half of the training was still missed, and the lowest point of the 'u-shaped' dynamic might occur even later than the 13 week point. A study with additional measurements throughout the whole training period would be necessary to investigate whether such effects occur.

6. Conclusions

All human knowledge begins with intuitions, proceeds from thence to concepts, and ends with ideas.

— Immanuel Kant

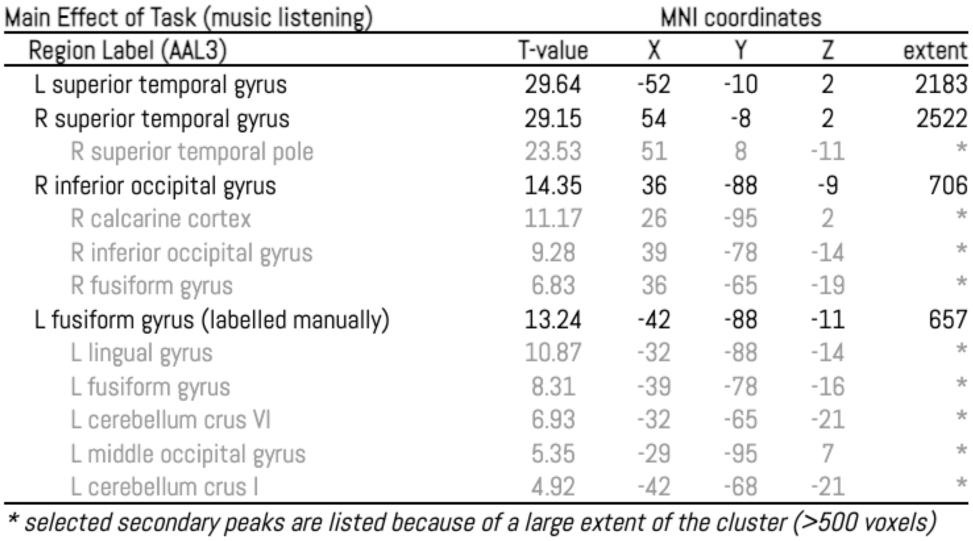
This project was aimed to understand the dynamics of training-related neuroplasticity in novice piano players over their first six months of training, investigating changes in auditory processing and motor control. The unique design including multiple time-points and the music playback fMRI task allowed this project to illustrate not only the extent of neuroplastic changes, but also their temporal dynamics. By employing complementary fMRI and behavioural tasks, and comparing the novices to the passive controls and the trained musicians, the current research provides converging evidence for the role of training in the observed differences between musicians and non-musicians in the motor, but not the auditory domain. The findings support a causal relationship between musical training and the differences observed in cross-sectional studies comparing musicians and non-musicians in motor control and auditory-motor interactions.

Using musical training as a window to explore the dynamic nature of neuroplasticity, I demonstrate that the observed changes cannot be fully explained by the proposed models of neuroplasticity dynamics, such as the expansion-renormalization model or the integrated model of motor sequence learning. This suggests the possibility that no single, universal model can sufficiently explain the dynamics of training-induced neuroplasticity.

These findings on the contextual and multifaceted nature of musical training-related neuroplasticity contribute to a deeper understanding of the processes involved in acquiring real-life skills. It provides insight into the interplay between bimanual coordination and the time-course of the changes which occur as novices learn and progress. Such real-life skills often require the coordinated involvement of multiple brain systems and movements composed of many elements. As the field of using musical training for various interventions, from autism to healthy ageing and motor rehabilitation, continues to grow (Viola et al. 2023), this knowledge can potentially improve the design of effective musical training-based programs.

Supplementary Tables

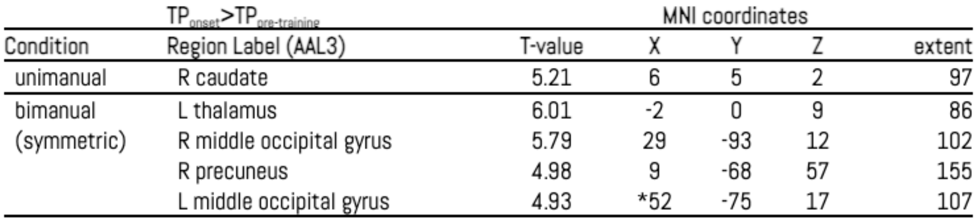
Table S1. Music Listening fMRI Task - Main Effect of Task (training period TP_{onset}-TP_{end}). Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Main Effect of Task (music listening)		MNI coordinates			
Region Label (AAL3)	T-value	X	Y	Z	extent
L superior temporal gyrus	29.64	-52	-10	2	2183
R superior temporal gyrus	29.15	54	-8	2	2522
R superior temporal pole	23.53	51	8	-11	*
R inferior occipital gyrus	14.35	36	-88	-9	706
R calcarine cortex	11.17	26	-95	2	*
R inferior occipital gyrus	9.28	39	-78	-14	*
R fusiform gyrus	6.83	36	-65	-19	*
L fusiform gyrus (labelled manually)	13.24	-42	-88	-11	657
L lingual gyrus	10.87	-32	-88	-14	*
L fusiform gyrus	8.31	-39	-78	-16	*
L cerebellum crus VI	6.93	-32	-65	-21	*
L middle occipital gyrus	5.35	-29	-95	7	*
L cerebellum crus I	4.92	-42	-68	-21	*

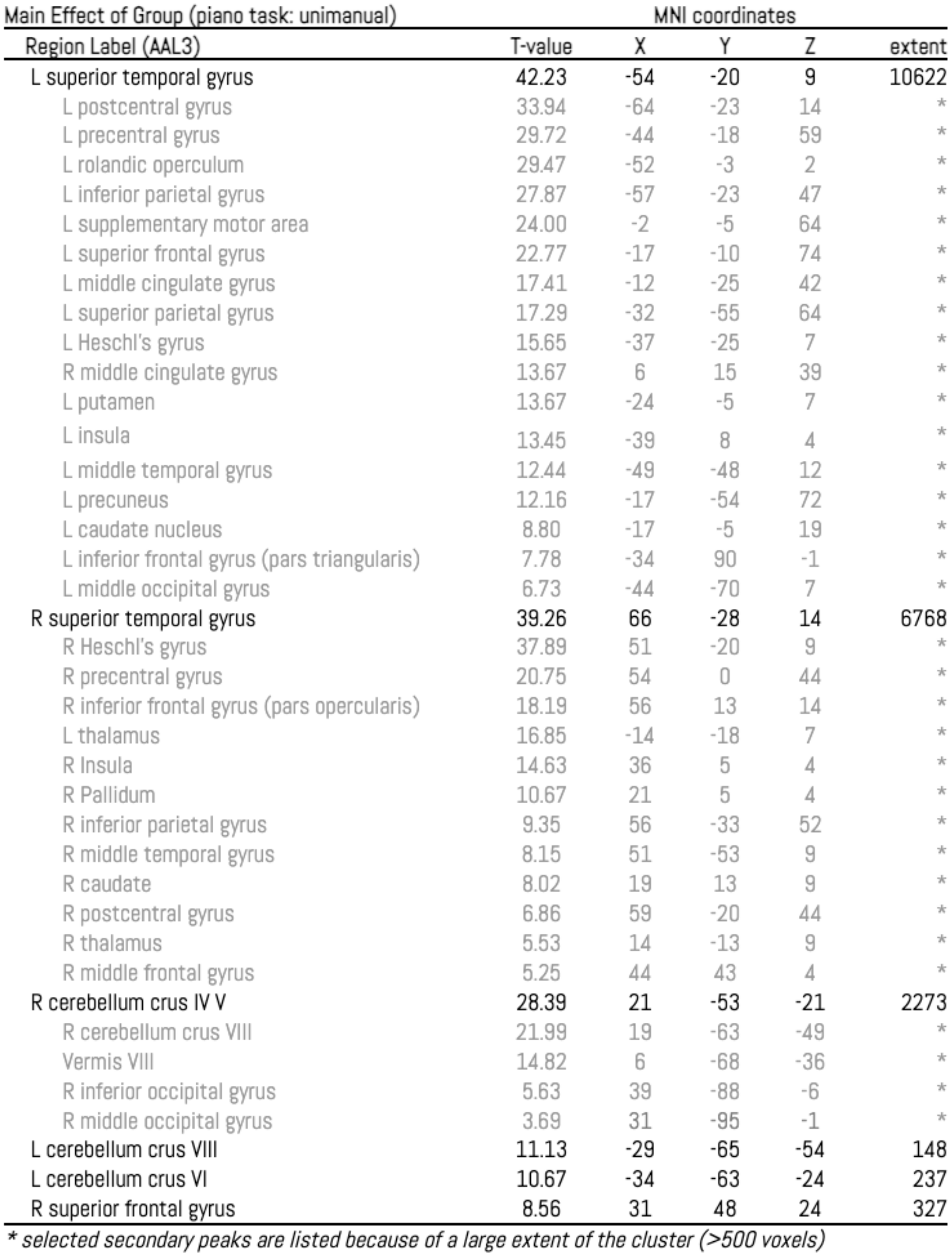
** selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)*

Table S2. Piano key pressing fMRI task - Repetition Effects. Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



	TP_{onset}>$TP_{pre-training}$		MNI coordinates			
Condition	Region Label (AAL3)	T-value	X	Y	Z	extent
unimanual	R caudate	5.21	6	5	2	97
bimanual (symmetric)	L thalamus	6.01	-2	0	9	86
	R middle occipital gyrus	5.79	29	-93	12	102
	R precuneus	4.98	9	-68	57	155
	L middle occipital gyrus	4.93	*52	-75	17	107

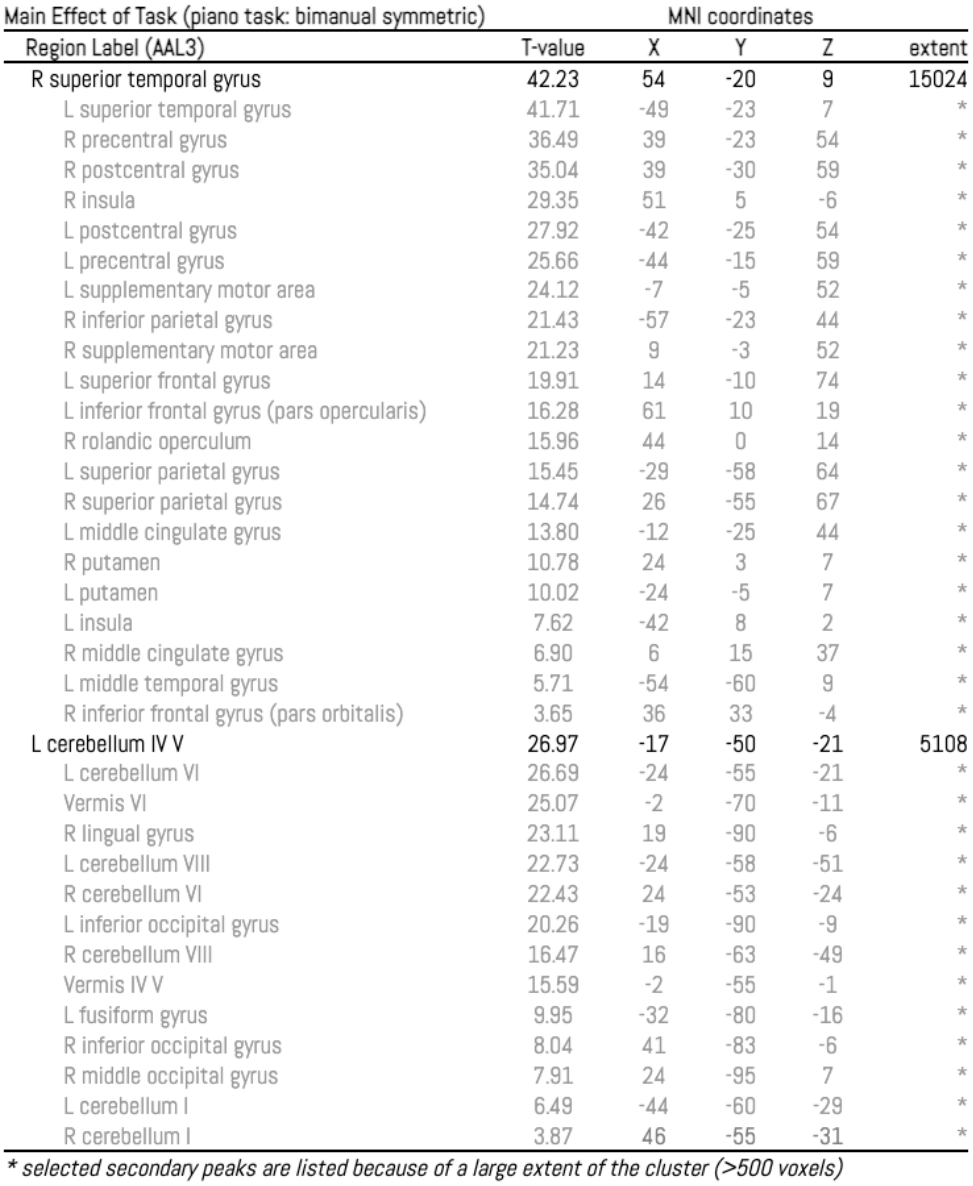
Table S3. Piano key pressing fMRI task - Main Effect of Task (unimanual). Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Main Effect of Group (piano task: unimanual)		MNI coordinates			
Region Label (AAL3)	T-value	X	Y	Z	extent
L superior temporal gyrus	**42.23**	**-54**	**-20**	**9**	**10622**
L postcentral gyrus	33.94	-64	-23	14	*
L precentral gyrus	29.72	-44	-18	59	*
L rolandic operculum	29.47	-52	-3	2	*
L inferior parietal gyrus	27.87	-57	-23	47	*
L supplementary motor area	24.00	-2	-5	64	*
L superior frontal gyrus	22.77	-17	-10	74	*
L middle cingulate gyrus	17.41	-12	-25	42	*
L superior parietal gyrus	17.29	-32	-55	64	*
L Heschl's gyrus	15.65	-37	-25	7	*
R middle cingulate gyrus	13.67	6	15	39	*
L putamen	13.67	-24	-5	7	*
L insula	13.45	-39	8	4	*
L middle temporal gyrus	12.44	-49	-48	12	*
L precuneus	12.16	-17	-54	72	*
L caudate nucleus	8.80	-17	-5	19	*
L inferior frontal gyrus (pars triangularis)	7.78	-34	90	-1	*
L middle occipital gyrus	6.73	-44	-70	7	*
R superior temporal gyrus	**39.26**	**66**	**-28**	**14**	**6768**
R Heschl's gyrus	37.89	51	-20	9	*
R precentral gyrus	20.75	54	0	44	*
R inferior frontal gyrus (pars opercularis)	18.19	56	13	14	*
L thalamus	16.85	-14	-18	7	*
R Insula	14.63	36	5	4	*
R Pallidum	10.67	21	5	4	*
R inferior parietal gyrus	9.35	56	-33	52	*
R middle temporal gyrus	8.15	51	-53	9	*
R caudate	8.02	19	13	9	*
R postcentral gyrus	6.86	59	-20	44	*
R thalamus	5.53	14	-13	9	*
R middle frontal gyrus	5.25	44	43	4	*
R cerebellum crus IV V	**28.39**	**21**	**-53**	**-21**	**2273**
R cerebellum crus VIII	21.99	19	-63	-49	*
Vermis VIII	14.82	6	-68	-36	*
R inferior occipital gyrus	5.63	39	-88	-6	*
R middle occipital gyrus	3.69	31	-95	-1	*
L cerebellum crus VIII	**11.13**	**-29**	**-65**	**-54**	**148**
L cerebellum crus VI	**10.67**	**-34**	**-63**	**-24**	**237**
R superior frontal gyrus	**8.56**	**31**	**48**	**24**	**327**

***** *selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)*

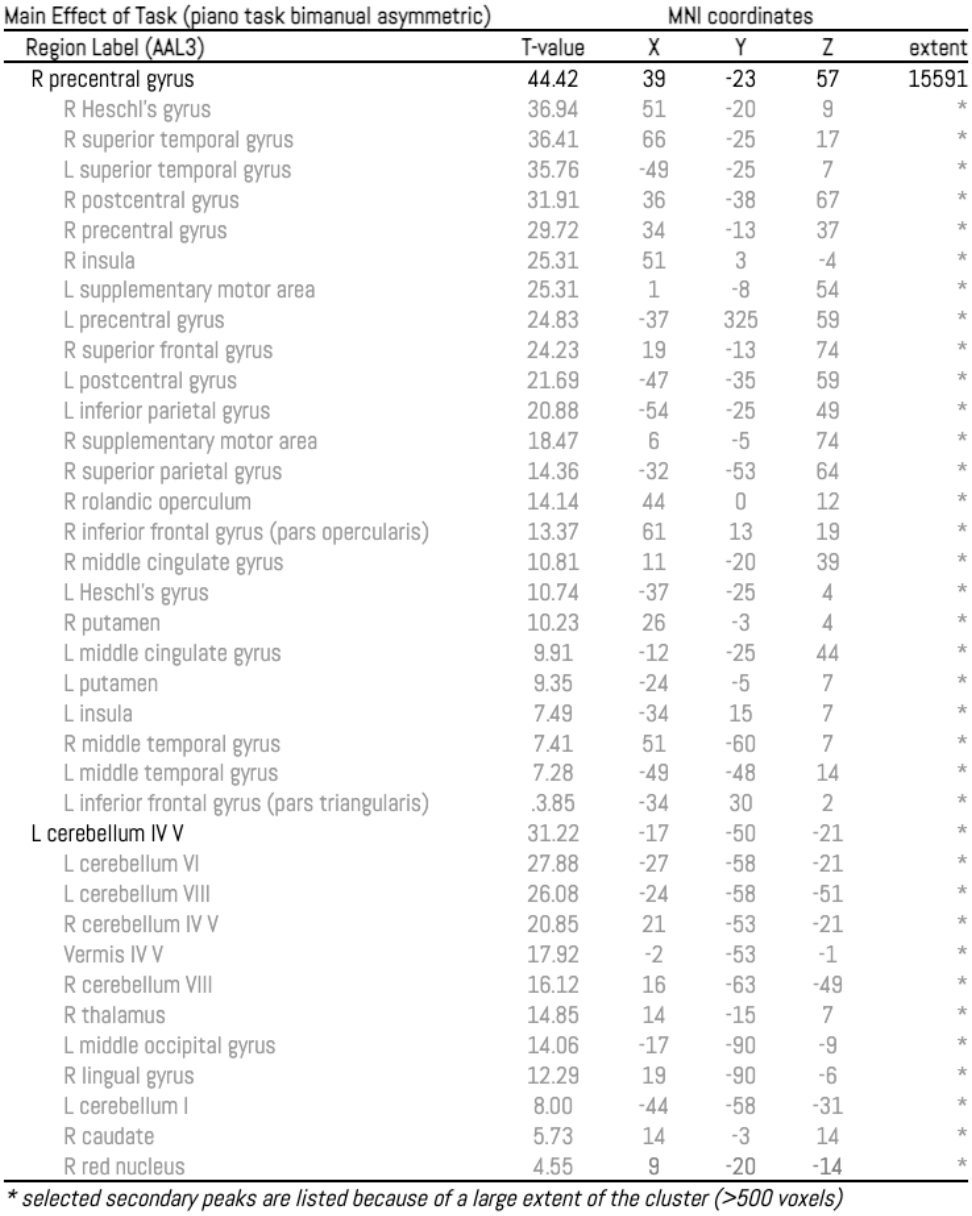
Table S4. Piano key pressing fMRI task - Main Effect of Task (bimanual symmetric). Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Main Effect of Task (piano task: bimanual symmetric)		MNI coordinates			
Region Label (AAL3)	T-value	X	Y	Z	extent
R superior temporal gyrus	**42.23**	**54**	**-20**	**9**	**15024**
L superior temporal gyrus	41.71	-49	-23	7	*
R precentral gyrus	36.49	39	-23	54	*
R postcentral gyrus	35.04	39	-30	59	*
R insula	29.35	51	5	-6	*
L postcentral gyrus	27.92	-42	-25	54	*
L precentral gyrus	25.66	-44	-15	59	*
L supplementary motor area	24.12	-7	-5	52	*
R inferior parietal gyrus	21.43	-57	-23	44	*
R supplementary motor area	21.23	9	-3	52	*
L superior frontal gyrus	19.91	14	-10	74	*
L inferior frontal gyrus (pars opercularis)	16.28	61	10	19	*
R rolandic operculum	15.96	44	0	14	*
L superior parietal gyrus	15.45	-29	-58	64	*
R superior parietal gyrus	14.74	26	-55	67	*
L middle cingulate gyrus	13.80	-12	-25	44	*
R putamen	10.78	24	3	7	*
L putamen	10.02	-24	-5	7	*
L insula	7.62	-42	8	2	*
R middle cingulate gyrus	6.90	6	15	37	*
L middle temporal gyrus	5.71	-54	-60	9	*
R inferior frontal gyrus (pars orbitalis)	3.65	36	33	-4	*
L cerebellum IV V	**26.97**	**-17**	**-50**	**-21**	**5108**
L cerebellum VI	26.69	-24	-55	-21	*
Vermis VI	25.07	-2	-70	-11	*
R lingual gyrus	23.11	19	-90	-6	*
L cerebellum VIII	22.73	-24	-58	-51	*
R cerebellum VI	22.43	24	-53	-24	*
L inferior occipital gyrus	20.26	-19	-90	-9	*
R cerebellum VIII	16.47	16	-63	-49	*
Vermis IV V	15.59	-2	-55	-1	*
L fusiform gyrus	9.95	-32	-80	-16	*
R inferior occipital gyrus	8.04	41	-83	-6	*
R middle occipital gyrus	7.91	24	-95	7	*
L cerebellum I	6.49	-44	-60	-29	*
R cerebellum I	3.87	46	-55	-31	*

***** *selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)*

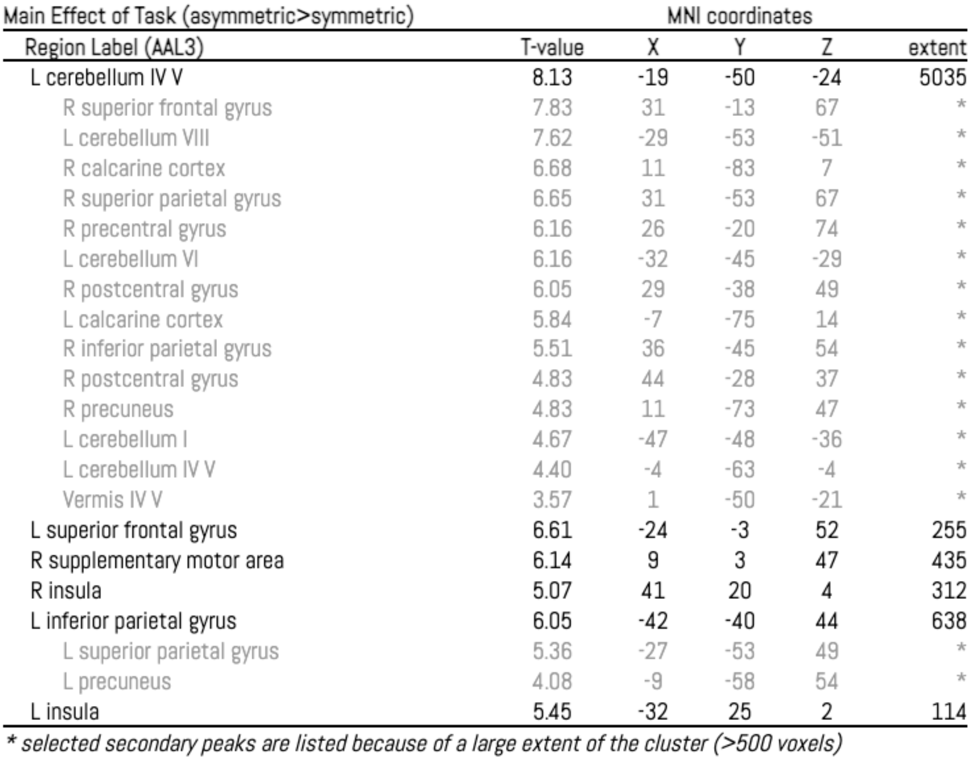
Table S5. Piano key pressing fMRI task - Main Effect of Task (bimanual asymmetric). Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Main Effect of Task (piano task bimanual asymmetric)		MNI coordinates			
Region Label (AAL3)	T-value	X	Y	Z	extent
R precentral gyrus	**44.42**	**39**	**-23**	**57**	**15591**
R Heschl's gyrus	36.94	51	-20	9	*
R superior temporal gyrus	36.41	66	-25	17	*
L superior temporal gyrus	35.76	-49	-25	7	*
R postcentral gyrus	31.91	36	-38	67	*
R precentral gyrus	29.72	34	-13	37	*
R insula	25.31	51	3	-4	*
L supplementary motor area	25.31	1	-8	54	*
L precentral gyrus	24.83	-37	325	59	*
R superior frontal gyrus	24.23	19	-13	74	*
L postcentral gyrus	21.69	-47	-35	59	*
L inferior parietal gyrus	20.88	-54	-25	49	*
R supplementary motor area	18.47	6	-5	74	*
R superior parietal gyrus	14.36	-32	-53	64	*
R rolandic operculum	14.14	44	0	12	*
R inferior frontal gyrus (pars opercularis)	13.37	61	13	19	*
R middle cingulate gyrus	10.81	11	-20	39	*
L Heschl's gyrus	10.74	-37	-25	4	*
R putamen	10.23	26	-3	4	*
L middle cingulate gyrus	9.91	-12	-25	44	*
L putamen	9.35	-24	-5	7	*
L insula	7.49	-34	15	7	*
R middle temporal gyrus	7.41	51	-60	7	*
L middle temporal gyrus	7.28	-49	-48	14	*
L inferior frontal gyrus (pars triangularis)	.3.85	-34	30	2	*
L cerebellum IV V	31.22	-17	-50	-21	*
L cerebellum VI	27.88	-27	-58	-21	*
L cerebellum VIII	26.08	-24	-58	-51	*
R cerebellum IV V	20.85	21	-53	-21	*
Vermis IV V	17.92	-2	-53	-1	*
R cerebellum VIII	16.12	16	-63	-49	*
R thalamus	14.85	14	-15	7	*
L middle occipital gyrus	14.06	-17	-90	-9	*
R lingual gyrus	12.29	19	-90	-6	*
L cerebellum I	8.00	-44	-58	-31	*
R caudate	5.73	14	-3	14	*
R red nucleus	4.55	9	-20	-14	*

***** selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)***

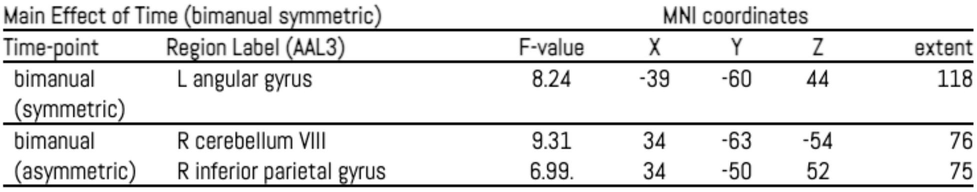
Table S6. Piano key pressing fMRI task - Main Effect of Task (bimanual asymmetric>symmetric). Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Main Effect of Task (asymmetric>symmetric)		MNI coordinates			
Region Label (AAL3)	T-value	X	Y	Z	extent
L cerebellum IV V	8.13	-19	-50	-24	5035
R superior frontal gyrus	7.83	31	-13	67	*
L cerebellum VIII	7.62	-29	-53	-51	*
R calcarine cortex	6.68	11	-83	7	*
R superior parietal gyrus	6.65	31	-53	67	*
R precentral gyrus	6.16	26	-20	74	*
L cerebellum VI	6.16	-32	-45	-29	*
R postcentral gyrus	6.05	29	-38	49	*
L calcarine cortex	5.84	-7	-75	14	*
R inferior parietal gyrus	5.51	36	-45	54	*
R postcentral gyrus	4.83	44	-28	37	*
R precuneus	4.83	11	-73	47	*
L cerebellum I	4.67	-47	-48	-36	*
L cerebellum IV V	4.40	-4	-63	-4	*
Vermis IV V	3.57	1	-50	-21	*
L superior frontal gyrus	6.61	-24	-3	52	255
R supplementary motor area	6.14	9	3	47	435
R insula	5.07	41	20	4	312
L inferior parietal gyrus	6.05	-42	-40	44	638
L superior parietal gyrus	5.36	-27	-53	49	*
L precuneus	4.08	-9	-58	54	*
L insula	5.45	-32	25	2	114

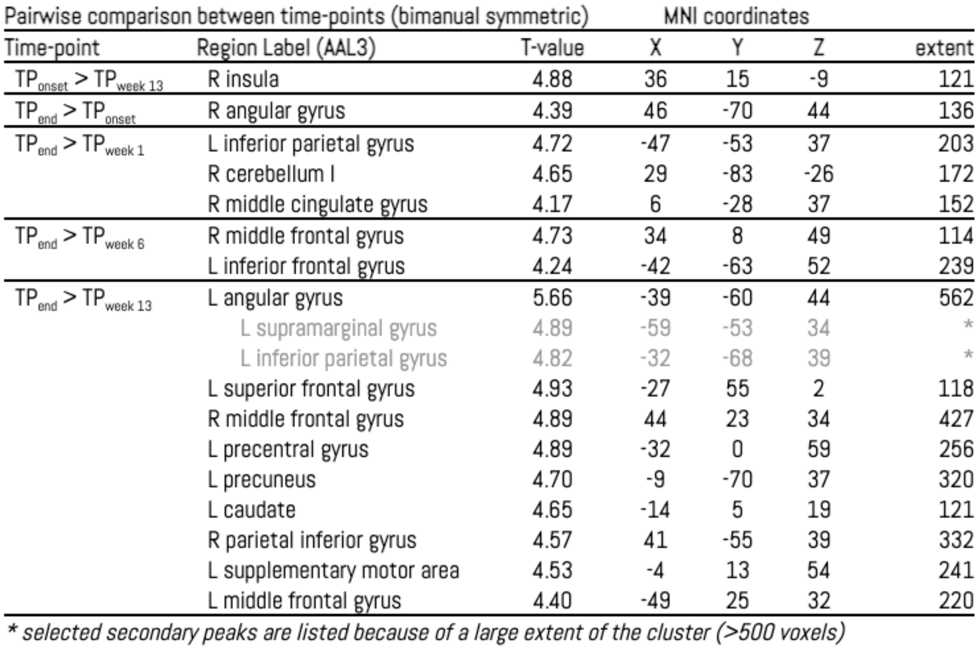
** selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)*

Table S7. Piano key pressing fMRI task - Main Effect of Time. Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Main Effect of Time (bimanual symmetric)			MNI coordinates			
Time-point	Region Label (AAL3)	F-value	X	Y	Z	extent
bimanual (symmetric)	L angular gyrus	8.24	-39	-60	44	118
bimanual (asymmetric)	R cerebellum VIII	9.31	34	-63	-54	76
	R inferior parietal gyrus	6.99.	34	-50	52	75

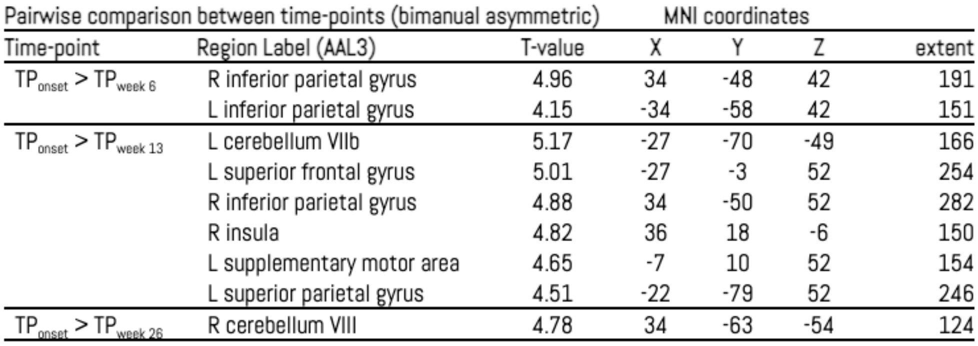
Table S8. Piano key pressing fMRI task - Pairwise comparisons between time-points (bimanual symmetric). Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Pairwise comparison between time-points (bimanual symmetric)			MNI coordinates			
Time-point	Region Label (AAL3)	T-value	X	Y	Z	extent
$TP_{onset} > TP_{week\ 13}$	R insula	4.88	36	15	-9	121
$TP_{end} > TP_{onset}$	R angular gyrus	4.39	46	-70	44	136
$TP_{end} > TP_{week\ 1}$	L inferior parietal gyrus	4.72	-47	-53	37	203
	R cerebellum I	4.65	29	-83	-26	172
	R middle cingulate gyrus	4.17	6	-28	37	152
$TP_{end} > TP_{week\ 6}$	R middle frontal gyrus	4.73	34	8	49	114
	L inferior frontal gyrus	4.24	-42	-63	52	239
$TP_{end} > TP_{week\ 13}$	L angular gyrus	5.66	-39	-60	44	562
	L supramarginal gyrus	4.89	-59	-53	34	*
	L inferior parietal gyrus	4.82	-32	-68	39	*
	L superior frontal gyrus	4.93	-27	55	2	118
	R middle frontal gyrus	4.89	44	23	34	427
	L precentral gyrus	4.89	-32	0	59	256
	L precuneus	4.70	-9	-70	37	320
	L caudate	4.65	-14	5	19	121
	R parietal inferior gyrus	4.57	41	-55	39	332
	L supplementary motor area	4.53	-4	13	54	241
	L middle frontal gyrus	4.40	-49	25	32	220

** selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)*

Table S9. Piano key pressing fMRI task - Pairwise comparisons between time-points (bimanual asymmetric). Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.



Pairwise comparison between time-points (bimanual asymmetric)			MNI coordinates			
Time-point	Region Label (AAL3)	T-value	X	Y	Z	extent
$TP_{onset} > TP_{week\ 6}$	R inferior parietal gyrus	4.96	34	-48	42	191
	L inferior parietal gyrus	4.15	-34	-58	42	151
$TP_{onset} > TP_{week\ 13}$	L cerebellum VIIb	5.17	-27	-70	-49	166
	L superior frontal gyrus	5.01	-27	-3	52	254
	R inferior parietal gyrus	4.88	34	-50	52	282
	R insula	4.82	36	18	-6	150
	L supplementary motor area	4.65	-7	10	52	154
	L superior parietal gyrus	4.51	-22	-79	52	246
$TP_{onset} > TP_{week\ 26}$	R cerebellum VIII	4.78	34	-63	-54	124

Table S10. Music playback fMRI task - Main Effect of Task. Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.

Main Effect of Task		MNI coordinates			
Region Label (AAL3)	T-value	X	Y	Z	extent
L precentral gyrus	13.41	-27	-25	74	243
R temporal pole	11.70	54	15	-4	222
Vermis IV V	9.81	1	-48	-4	10
L postcentral gyrus	9.04	-49	-35	59	48
L superior temporal gyrus	8.52	-59	-30	14	126
L supplementary motor area	7.49	-7	0	74	54
Vermis VI	5.84	1	-75	-11	5

Table S11. Music playback fMRI task - Main Effect of Time. Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere. Highlighted peaks were later used for the visualisations (Figure 3.2.14B).

Main Effect of Time		MNI coordinates			
Region Label (AAL3)	F-value	X	Y	Z	extent
R postcentral gyrus	28.28	46	-28	47	714
R postcentral gyrus	21.49	49	-33	59	*
R postcentral gyrus	18.88	59	-13	34	*
R inferior parietal lobule	17.95	39	-50	52	*
R postcentral gyrus	17.73	49	-20	34	*
R supramarginal gyrus	16.13	54	-33	39	*
R precentral gyrus	15.11	39	-23	62	*
R superior parietal lobule	14.58	24	-53	57	*
R supramarginal gyrus	14.18	41	-38	44	*
R cerebellum crus I	19.84	39	-58	-41	116
R inferior frontal gyrus, pars triangularis	19.56	44	33	27	191
R inferior frontal gyrus, pars opercularis	18.83	41	5	34	70
L precuneus	18.78	-14	-68	34	40
L cerebellum VI	17.73	-34	-48	-26	48
L inferior parietal lobule	17.23	-47	-28	47	130
R inferior frontal gyrus, pars opercularis	17.18	54	10	24	28
R superior parietal lobule	17.18	14	-73	57	19
R middle frontal gyrus	15.99	36	18	52	31
L inferior temporal gyrus	15.71	-49	-53	-6	9
L inferior parietal lobule	15.51	-47	-48	59	13
R inferior frontal gyrus, pars orbitalis	15.39	29	33	-11	29
R cerebellum VI	15.27	31	-45	-29	29
L cerebellum crus I	15.08	-47	-63	-26	6
R superior frontal gyrus, medial segment	14.85	6	28	44	12
L hippocampus	14.80	-27	-35	-4	7
R superior frontal gyrus	14.77	31	10	59	29
R caudate nucleus	14.64	16	10	22	22
L cerebellum VI	14.55	-22	-53	-21	28
R lateral occipital cortex, superior division	14.26	26	-63	37	18
L superior parietal lobule	14.16	-24	-55	49	7
R cerebellum VIII	13.96	21	-60	-46	24
L inferior parietal lobule	13.83	-39	-60	57	9
L cerebellum VI	13.80	-27	-65	-29	8
L cerebellum crus I	13.61	-39	-63	-39	7
L precentral gyrus	13.40	-47	10	34	12
R precuneus	12.72	14	-65	34	10

** selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)*

Table S12. Music playback fMRI task - Novices vs Musicians. Local maxima separated by more than 8 mm. Regions were automatically labelled using the AAL3 atlas. X, Y, Z - Montreal Neurological Institute (MNI) coordinates in the left-right, anterior-posterior, and inferior-superior dimensions, respectively. R, L - right, left hemisphere.

	Novices > Musicians			MNI coordinates			
time-point	condition	Region Label (AAL3)	T-value	X	Y	Z	extent
TP_{onset}	bimanual (asymmetric)	L cerebellum VIII	5.76	-17	-63	-49	121
		L superior frontal gyrus	5.68	-24	-10	54	155
		R superior parietal gyrus	5.13	16	-60	59	252
		R precentral gyrus	4.87	26	-8	54	139
	bimanual (asymmetric > symmetric)	L cerebellum VIII	5.23	-19	-60	-54	116
		R superior frontal gyrus	5.15	16	-58	57	1061
		R precuneus	5.04	6	-70	52	*
		R inferior parietal gyrus	4.82	34	-55	54	*
		R postcentral gyrus	4.45	51	-28	52	*
		R superior frontal gyrus	4.88	24	3	62	271
		L superior parietal gyrus	4.73	-24	-60	52	236
	Musicians > Novices						
TP_{onset}	unimanual	R cerebellum II	6.00	44	-58	-46	123

** selected secondary peaks are listed because of a large extent of the cluster (>500 voxels)*

Bibliography

Abrams, Daniel A., Anjali Bhatara, Srikanth Ryali, Evan Balaban, Daniel J. Levitin, and Vinod Menon. 2011. "Decoding Temporal Structure in Music and Speech Relies on Shared Brain Resources but Elicits Different Fine-Scale Spatial Patterns." *Cerebral Cortex* 21 (7): 1507–18. https://doi.org/10.1093/cercor/bhq198.

Amad, Ali, Jade Seidman, Stephen B. Draper, Muriel M. K. Bruchhage, Ruth G. Lowry, James Wheeler, Andrew Robertson, Steven C. R. Williams, and Marcus S. Smith. 2017. "Motor Learning Induces Plasticity in the Resting Brain-Drumming Up a Connection." *Cerebral Cortex* 27 (3): 2010–21. https://doi.org/10.1093/cercor/bhw048.

Anwyl-Irvine, Alexander L., Jessica Massonnié, Adam Flitton, Natasha Kirkham, and Jo K. Evershed. 2020. "Gorilla in Our Midst: An Online Behavioral Experiment Builder." *Behavior Research Methods* 52 (1): 388–407. https://doi.org/10.3758/s13428-019-01237-x.

Aramaki, Yu, Rieko Osu, and Norihiro Sadato. 2010. "Resource-Demanding versus Cost-Effective Bimanual Interaction in the Brain." *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale* 203 (2): 407–18. https://doi.org/10.1007/s00221-010-2244-0.

Asano, Rie, Cedric Boeckx, and Uwe Seifert. 2021. "Hierarchical control as a shared neurocognitive mechanism for language and music." Cognition 216: 104847. https://doi.org/10.1016/j.cognition.2021.104847

Avants, B. B., C. L. Epstein, M. Grossman, and J. C. Gee. 2008. "Symmetric Diffeomorphic Image Registration with Cross-Correlation: Evaluating Automated Labeling of Elderly and Neurodegenerative Brain." *Medical Image Analysis* 12 (1): 26–41. https://doi.org/10.1016/j.media.2007.06.004.

Banaszkiewicz, Anna, Jacek Matuszewski, Łukasz Bola, Michał Szczepanik, Bartosz Kossowski, Paweł Rutkowski, Marcin Szwed, Karen Emmorey, Katarzyna Jednoróg, and Artur Marchewka. 2020. "Multimodal Imaging of Brain Reorganization in Hearing Late Learners of Sign Language." *Human Brain Mapping*, October. https://doi.org/10.1002/hbm.25229.

Bandettini, P. A., E. C. Wong, R. S. Hinks, R. S. Tikofsky, and J. S. Hyde. 1992. "Time Course EPI of Human Brain Function during Task Activation." *Magnetic Resonance in Medicine: Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine* 25 (2): 390–97. https://doi.org/10.1002/mrm.1910250220.

Bangert, Marc, Thomas Peschel, Gottfried Schlaug, Michael Rotte, Dieter Drescher, Hermann Hinrichs, Hans Jochen Heinze, and Eckart Altenmüller. 2006. "Shared Networks for Auditory and Motor Processing in Professional Pianists: Evidence from fMRI Conjunction." *NeuroImage* 30 (3): 917–26. https://doi.org/10.1016/j.neuroimage.2005.10.044.

Barrett, Karen Chan, Frederick Streeter Barrett, Patpong Jiradejvong, Summer K. Rankin, Andrew T. Landau, and Charles J. Limb. 2020. "Classical Creativity: A Functional Magnetic Resonance Imaging (fMRI) Investigation of Pianist and Improviser Gabriela Montero." *NeuroImage* 209 (April): 116496. https://doi.org/10.1016/j.neuroimage.2019.116496.

Behzadi, Yashar, Khaled Restom, Joy Liau, and Thomas T. Liu. 2007. "A Component Based Noise Correction Method (CompCor) for BOLD and Perfusion Based fMRI." *NeuroImage* 37 (1): 90–101. https://doi.org/10.1016/j.neuroimage.2007.04.042.

Belfi, Amy M., Anna Kasdan, and Daniel Tranel. 2019. “Anomia for Musical Entities.” *Aphasiology* 33 (4): 382–404. https://doi.org/10.1080/02687038.2017.1409871.

Belfi, Amy M., and Daniel Tranel. 2014. “Impaired Naming of Famous Musical Melodies Is Associated with Left Temporal Polar Damage.” *Neuropsychology* 28 (3): 429–35. https://doi.org/10.1037/neu0000051.

Berlot, Eva, Nicola J. Popp, and Jörn Diedrichsen. 2020. “A Critical Re-Evaluation of fMRI Signatures of Motor Sequence Learning.” *eLife* 9 (May). https://doi.org/10.7554/eLife.55241.

Bermudez, Patrick, Jason P. Lerch, Alan C. Evans, and Robert J. Zatorre. 2009. “Neuroanatomical Correlates of Musicianship as Revealed by Cortical Thickness and Voxel-Based Morphometry.” *Cerebral Cortex* 19 (7): 1583–96. https://doi.org/10.1093/cercor/bhn196.

Bianchi, Federica, Jens Hjortkjær, Sébastien Santurette, Robert J. Zatorre, Hartwig R. Siebner, and Torsten Dau. 2017. “Subcortical and Cortical Correlates of Pitch Discrimination: Evidence for Two Levels of Neuroplasticity in Musicians.” *NeuroImage* 163 (July): 398–412. https://doi.org/10.1016/j.neuroimage.2017.07.057.

Bianco, R., B. P. Gold, A. P. Johnson, and V. B. Penhune. 2019. “Music Predictability and Liking Enhance Pupil Dilation and Promote Motor Learning in Non-Musicians.” *Scientific Reports* 9 (1): 17060. https://doi.org/10.1038/s41598-019-53510-w.

Bliss, T. V., and T. Lomo. 1973. “Long-Lasting Potentiation of Synaptic Transmission in the Dentate Area of the Anaesthetized Rabbit Following Stimulation of the Perforant Path.” *The Journal of Physiology* 232 (2): 331–56. https://doi.org/10.1113/jphysiol.1973.sp010273.

Botvinik-Nezer, Rotem, Felix Holzmeister, Colin F. Camerer, Anna Dreber, Juergen Huber, Magnus Johannesson, Michael Kirchler, et al. 2020. “Variability in the Analysis of a Single Neuroimaging Dataset by Many Teams.” *Nature* 582 (7810): 84–88. https://doi.org/10.1038/s41586-020-2314-9.

Brett, Matthew , Jean-Luc Anton, Romain Valabregue, Jean-Baptiste Poline. Region of interest analysis using an SPM toolbox [abstract] Presented at the 8th International Conference on Functional Mapping of the Human Brain, June 2-6, 2002, Sendai, Japan. Available on CD-ROM in NeuroImage, Vol 16, No 2.

Brown, Rachel M., Joyce L. Chen, Avrum Hollinger, Virginia B. Penhune, Caroline Palmer, and Robert J. Zatorre. 2013. “Repetition Suppression in Auditory-Motor Regions to Pitch and Temporal Structure in Music.” *Journal of Cognitive Neuroscience* 25 (2): 313–28. https://doi.org/10.1162/jocn_a_00322.

Brown, Rachel M., and Virginia B. Penhune. 2018. “Efficacy of Auditory versus Motor Learning for Skilled and Novice Performers.” *Journal of Cognitive Neuroscience* 30 (11): 1657–82. https://doi.org/10.1162/jocn_a_01309.

Burgoyne, Alexander P., Lauren Julius Harris, and David Z. Hambrick. 2019. “Predicting Piano Skill Acquisition in Beginners: The Role of General Intelligence, Music Aptitude, and Mindset.” *Intelligence* 76 (September): 101383. https://doi.org/10.1016/j.intell.2019.101383.

Caswell, Thomas A., Antony Lee, Elliott Sales de Andrade, Michael Droettboom, Tim Hoffmann, Jody Klymak, John Hunter, et al. 2023. *Matplotlib/matplotlib: REL: v3.7.1*. https://doi.org/10.5281/zenodo.7697899.

"CC BY 3.0 Deed." n.d. CC BY 3.0 Deed | Attribution 3.0 Unported. Accessed March 19, 2024. https://creativecommons.org/licenses/by/3.0/.

Chen, Joyce L., Virginia B. Penhune, and Robert J. Zatorre. 2009. "The Role of Auditory and Premotor Cortex in Sensorimotor Transformations." *Annals of the New York Academy of Sciences* 1169 (July): 15–34. https://doi.org/10.1111/j.1749-6632.2009.04556.x.

Chen, Joyce L., Charlotte Rae, and Kate E. Watkins. 2012. "Learning to Play a Melody: An fMRI Study Examining the Formation of Auditory-Motor Associations." *NeuroImage* 59 (2): 1200–1208. https://doi.org/10.1016/j.neuroimage.2011.08.012.

Che, Yuqing, Crescent Jicol, Chris Ashwin, and Karin Petrini. 2022. "An RCT Study Showing Few Weeks of Music Lessons Enhance Audio-Visual Temporal Processing." *Scientific Reports* 12 (1): 20087. https://doi.org/10.1038/s41598-022-23340-4.

Clemente, Ana, Manel Vila-Vidal, Marcus T. Pearce, Germán Aguiló, Guido Corradi, and Marcos Nadal. 2020. "A Set of 200 Musical Stimuli Varying in Balance, Contour, Symmetry, and Complexity: Behavioral and Computational Assessments." *Behavior Research Methods* 52 (4): 1491–1509. https://doi.org/10.3758/s13428-019-01329-8.

Correia, Ana Isabel, Margherita Vincenzi, Patrícia Vanzella, Ana P. Pinheiro, César F. Lima, and E. Glenn Schellenberg. 2021. "Can Musical Ability Be Tested Online?" *Behavior Research Methods*, August. https://doi.org/10.3758/s13428-021-01641-2.

Ding, Yue, Kathleen Gray, Alexander Forrence, Xiaoqin Wang, and Juan Huang. 2018. "A Behavioral Study on Tonal Working Memory in Musicians and Non-Musicians." *PloS One* 13 (8): e0201765. https://doi.org/10.1371/journal.pone.0201765.

Doyon, Julien, Pierre Bellec, Rhonda Amsel, Virginia Penhune, Oury Monchi, Julie Carrier, Stéphane Lehéricy, and Habib Benali. 2009. "Contributions of the Basal Ganglia and Functionally Related Brain Structures to Motor Learning." *Behavioural Brain Research* 199 (1): 61–75. https://doi.org/10.1016/j.bbr.2008.11.012.

Draganski, Bogdan, Christian Gaser, Volker Busch, Gerhard Schuierer, Ulrich Bogdahn, and Arne May. 2004. "Changes in Grey Matter Induced by Training Newly Honed Juggling Skills Show up as a Transient Feature on a Brain-Imaging Scan." *Nature* 427 (6972): 311–12. https://doi.org/10.1038/427311a.

D'Ausilio, A., E. Altenmüller, M. Olivetti Belardinelli, and M. Lotze. 2006. "Cross-Modal Plasticity of the Motor Cortex While Listening to a Rehearsed Musical Piece." *The European Journal of Neuroscience* 24 (3): 955–58. https://doi.org/10.1111/j.1460-9568.2006.04960.x.

Elmer, Stefan, Jürgen Hänggi, Martin Meyer, and Lutz Jäncke. 2013. "Increased Cortical Surface Area of the Left Planum Temporale in Musicians Facilitates the Categorization of Phonetic and Temporal Speech Sounds." *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior* 49 (10): 2812–21. https://doi.org/10.1016/j.cortex.2013.03.007.

Endestad, Tor, Rolf Inge Godøy, Markus Handal Sneve, Thomas Hagen, Agata Bochynska, and Bruno Laeng. 2020. "Mental Effort When Playing, Listening, and Imagining Music in One Pianist's Eyes and Brain." *Frontiers in Human Neuroscience* 14 (October): 576888. https://doi.org/10.3389/fnhum.2020.576888.

Esteban, Oscar, Christopher J. Markiewicz, Ross W. Blair, Craig A. Moodie, A. Ilkay Isik, Asier Erramuzpe, James D. Kent, et al. 2019. "fMRIPrep: A Robust Preprocessing Pipeline for Functional MRI." *Nature Methods* 16 (1): 111–16. https://doi.org/10.1038/s41592-018-0235-4.

Esteban, Oscar, Christopher J. Markiewicz, Christopher Burns, Mathias Goncalves, Dorota Jarecka, Erik Ziegler, Shoshana Berleant, et al. 2021. *Nipy/nipype* (version 1.6.1). https://doi.org/10.5281/zenodo.5585697.

Esteban, Oscar, Christopher J. Markiewicz, Mathias Goncalves, Elizabeth DuPre, James D. Kent, Taylor Salo, Rastko Ciric, et al. 2021. *fMRIPrep: A Robust Preprocessing Pipeline for functionalMRI* (version 21.0.0.). https://doi.org/10.5281/zenodo.5781797.

Fonov, V. S., A. C. Evans, R. C. McKinstry, C. R. Almli, and D. L. Collins. 2009. “Unbiased Nonlinear Average Age-Appropriate Brain Templates from Birth to Adulthood.” *NeuroImage* 47 (July): S102. https://doi.org/10.1016/S1053-8119(09)70884-5.

Freitas, Carina, Enrica Manzato, Alessandra Burini, Margot J. Taylor, Jason P. Lerch, and Evdokia Anagnostou. 2018. “Neural Correlates of Familiarity in Music Listening: A Systematic Review and a Neuroimaging Meta-Analysis.” *Frontiers in Neuroscience* 12 (OCT): 686. https://doi.org/10.3389/fnins.2018.00686.

Friston, K. J., A. P. Holmes, K. J. Worsley, J-P Poline, C. D. Frith, and R. S. J. Frackowiak. 1994. “Statistical Parametric Maps in Functional Imaging: A General Linear Approach.” *Human Brain Mapping* 2 (4): 189–210. https://doi.org/10.1002/hbm.460020402.

Garrido, Marta I., James M. Kilner, Stefan J. Kiebel, Klaas E. Stephan, Torsten Baldeweg, and Karl J. Friston. 2009. “Repetition Suppression and Plasticity in the Human Brain.” *NeuroImage* 48 (1): 269–79. https://doi.org/10.1016/j.neuroimage.2009.06.034.

Garzón, Benjamín, Gunther Helms, Hampus Olsson, Claudio Brozzoli, Fredrik Ullén, Jörn Diedrichsen, and Martin Lövdén. 2023. “Cortical Changes during the Learning of Sequences of Simultaneous Finger Presses.” *Imaging Neuroscience* 1 (September): 1–26. https://doi.org/10.1162/imag_a_00016.

Gaser, Christian, and Gottfried Schlaug. 2003. “Gray Matter Differences between Musicians and Nonmusicians.” In *Annals of the New York Academy of Sciences*, 999:514–17. Wiley. https://doi.org/10.1196/annals.1284.062.

Georgi, Markus, Bruno Gingras, and Marcel Zentner. 2022. “The Tapping-PROMS: A Test for the Assessment of Sensorimotor Rhythmic Abilities.” *Frontiers in Psychology* 13: 862468. https://doi.org/10.3389/fpsyg.2022.862468.

Gorgolewski, Krzysztof, Christopher D. Burns, Cindee Madison, Dav Clark, Yaroslav O. Halchenko, Michael L. Waskom, and Satrajit S. Ghosh. 2011. “Nipype: A Flexible, Lightweight and Extensible Neuroimaging Data Processing Framework in Python.” *Frontiers in Neuroinformatics* 5 (August): 13. https://doi.org/10.3389/fninf.2011.00013.

Grafman, J. 2000. “Conceptualizing Functional Neuroplasticity.” *Journal of Communication Disorders* 33 (4): 345–55; quiz 355–56. https://doi.org/10.1016/s0021-9924(00)00030-7.

Greenberg, David M., Jean Decety, and Ilanit Gordon. 2021. “The Social Neuroscience of Music: Understanding the Social Brain through Human Song.” *The American Psychologist* 76 (7): 1172–85. https://doi.org/10.1037/amp0000819.

Greve, Douglas N., and Bruce Fischl. 2009. “Accurate and Robust Brain Image Alignment Using Boundary-Based Registration.” *NeuroImage* 48 (1): 63–72. https://doi.org/10.1016/j.neuroimage.2009.06.060.

Groussard, Mathilde, Fausto Viader, Brigitte Landeau, Béatrice Desgranges, Francis Eustache, and Hervé Platel. 2014. “The Effects of Musical Practice on Structural Plasticity: The Dynamics of Grey Matter Changes.” *Brain and Cognition* 90 (October): 174–80. https://doi.org/10.1016/j.bandc.2014.06.013.

Gut, Malgorzata, Andrzej Urbanik, Lars Forsberg, Marek Binder, Krystyna Rymarczyk, Barbara Sobiecka, Justyna Kozub, and Anna Grabowska. 2007. “Brain Correlates of Right-Handedness.” *Acta Neurobiologiae Experimentalis* 67 (1): 43–51. https://doi.org/10.55782/ane-2007-1631

Habermeyer, Benedikt, Marcus Herdener, Fabrizio Esposito, Caroline C. Hilti, Markus Klarhöfer, Francesco Di Salle, Stephan Wetzel, Klaus Scheffler, Katja Cattapan-Ludewig, and Erich Seifritz. 2009. “Neural Correlates of Pre-Attentive Processing of Pattern Deviance in Professional Musicians.” *Human Brain Mapping* 30 (11): 3736–47. https://doi.org/10.1002/hbm.20802.

Haslinger, Bernhard, Peter Erhard, Eckart Altenmüller, Andreas Hennenlotter, Markus Schwaiger, Helga Gräfin von Einsiedel, Ernst Rummeny, Bastian Conrad, and Andrés O. Ceballos-Baumann. 2004. “Reduced Recruitment of Motor Association Areas during Bimanual Coordination in Concert Pianists.” *Human Brain Mapping* 22 (3): 206–15. https://doi.org/10.1002/hbm.20028.

Hebb, D. O. 1949. *The Organization of Behavior; a Neuropsychological Theory*. Vol. 335. Oxford, England: Wiley. https://doi.org/10.4324/9781410612403.

Hebb, Donald O. 1947. “The Effects of Early Experience on Problem-Solving at Maturity.” *The American Psychologist* 2: 306–7. https://cir.nii.ac.jp/crid/1571698600613192832.

Herholz, Sibylle C., Bastiaan Boh, and Christo Pantev. 2011. “Musical Training Modulates Encoding of Higher-Order Regularities in the Auditory Cortex.” *The European Journal of Neuroscience* 34 (3): 524–29. https://doi.org/10.1111/j.1460-9568.2011.07775.x.

Herholz, Sibylle C., Emily B. J. Coffey, Christo Pantev, and Robert J. Zatorre. 2016. “Dissociation of Neural Networks for Predisposition and for Training-Related Plasticity in Auditory-Motor Learning.” *Cerebral Cortex* 26 (7): 3125–34. https://doi.org/10.1093/cercor/bhv138.

Herholz, Sibylle C., and Robert J. Zatorre. 2012. “Musical Training as a Framework for Brain Plasticity: Behavior, Function, and Structure.” *Neuron* 76 (3): 486–502. https://doi.org/10.1016/j.neuron.2012.10.011.

Herlin, Bastien, Vincent Navarro, and Sophie Dupont. 2021. “The Temporal Pole: From Anatomy to Function-A Literature Appraisal.” *Journal of Chemical Neuroanatomy* 113 (April): 101925. https://doi.org/10.1016/j.jchemneu.2021.101925.

Higham, Thomas, Laura Basell, Roger Jacobi, Rachel Wood, Christopher Bronk Ramsey, and Nicholas J. Conard. 2012. “Testing Models for the Beginnings of the Aurignacian and the Advent of Figurative Art and Music: The Radiocarbon Chronology of Geißenklösterle.” *Journal of Human Evolution* 62 (6): 664–76. https://doi.org/10.1016/j.jhevol.2012.03.003.

Hikosaka, Okihide, Kae Nakamura, Katsuyuki Sakai, and Hiroyuki Nakahara. 2002. “Central Mechanisms of Motor Skill Learning.” *Current Opinion in Neurobiology*. Elsevier Ltd. https://doi.org/10.1016/S0959-4388(02)00307-0.

Hofstetter, Shir, Wietske Zuiderbaan, Benedetta Heimler, Serge O. Dumoulin, and Amir Amedi. 2021. “Topographic Maps and Neural Tuning for Sensory Substitution Dimensions Learned in Adulthood in a Congenital Blind Subject.” *NeuroImage* 235 (July): 118029. https://doi.org/10.1016/j.neuroimage.2021.118029.

Honing, Henkjan. 2021. *Music Cognition: The Basics*. London: Routledge. https://doi.org/10.4324/9781003158301.

Ioannidis, John P. A. 2005. “Why Most Published Research Findings Are False.” *PLoS Medicine* 2 (8): e124. https://doi.org/10.1371/journal.pmed.0020124.

Ito, Yoshiki, Tomoyo Isoguchi Shiramatsu, Naoki Ishida, Karin Oshima, Kaho Magami, and Hirokazu Takahashi. 2022. “Spontaneous Beat Synchronization in Rats: Neural Dynamics and Motor Entrainment.” *Science Advances* 8 (45): eabo7019. https://doi.org/10.1126/sciadv.abo7019.

Jacini, Wantuir F. S., Gianna C. Cannonieri, Paula T. Fernandes, Leonardo Bonilha, Fernando Cendes, and Li M. Li. 2009. “Can Exercise Shape Your Brain? Cortical Differences Associated with Judo Practice.” *Journal of Science and Medicine in Sport / Sports Medicine Australia* 12 (6): 688–90. https://doi.org/10.1016/j.jsams.2008.11.004.

Jahn, Andrew. 2015. “Converting T-Maps to Z-Maps — Andy’s Brain Blog.” Andy’s Brain Blog. July 31, 2015. https://www.andysbrainblog.com/andysbrainblog/2015/07/converting-t-maps-to-z-maps.html.

James, Clara E., Mathias S. Oechslin, Dimitri Van De Ville, Claude Alain Hauert, Céline Descloux, and François Lazeyras. 2014. “Musical Training Intensity Yields Opposite Effects on Grey Matter Density in Cognitive versus Sensorimotor Networks.” *Brain Structure & Function* 219 (1): 353–66. https://doi.org/10.1007/s00429-013-0504-z.

James, William. 1890. *The Principles of Psychology*. Henry Holt and Co. https://doi.org/10.1037/10538-000

Jäncke, Lutz, N. Jon Shah, and Michael Peters. 2000. “Cortical Activations in Primary and Secondary Motor Areas during Complex Bimanual Movements in Professional Piano Players.” *NeuroImage* 11 (5, Supplement): S867. https://doi.org/10.1016/S1053-8119(00)91795-6.

Jaschke, Artur C. 2023. *Mind the Music: On Improvisation, Music and the Brain*. Hetmoet-Menard.

Jenkinson, Mark, Peter Bannister, Michael Brady, and Stephen Smith. 2002. “Improved Optimization for the Robust and Accurate Linear Registration and Motion Correction of Brain Images.” *NeuroImage* 17 (2): 825–41. https://doi.org/10.1016/s1053-8119(02)91132-8.

Jenkinson, M., and S. Smith. 2001. “A Global Optimisation Method for Robust Affine Registration of Brain Images.” *Medical Image Analysis* 5 (2): 143–56. https://doi.org/10.1016/s1361-8415(01)00036-6.

Johnson, Julene K., Chiung-Chih Chang, Simona M. Brambati, Raffaella Migliaccio, Maria Luisa Gorno-Tempini, Bruce L. Miller, and Petr Janata. 2011. “Music Recognition in Frontotemporal Lobar Degeneration and Alzheimer Disease.” *Cognitive and Behavioral Neurology: Official Journal of the Society for Behavioral and Cognitive Neurology* 24 (2): 74–84. https://doi.org/10.1097/WNN.0b013e31821de326.

Jünemann, Kristin, Damien Marie, Florian Worschech, Daniel S. Scholz, Frédéric Grouiller, Matthias Kliegel, Dimitri Van De Ville et al. 2022. "Six months of piano training in healthy elderly stabilizes white matter microstructure in the fornix, compared to an active control group." Frontiers in aging neuroscience 14: 817889. https://doi.org/10.3389/fnagi.2022.817889

Jünemann, Kristin, Anna Engels, Damien Marie, Florian Worschech, Daniel S. Scholz, Frédéric Grouiller, Matthias Kliegel, et al. 2023. "Increased Functional Connectivity in the Right Dorsal Auditory Stream after a Full Year of Piano Training in Healthy Older Adults." *Scientific Reports* 13 (1): 19993. https://doi.org/10.1038/s41598-023-46513-1.

Karpati, Falisha J., Chiara Giacosa, Nicholas E. V. Foster, Virginia B. Penhune, and Krista L. Hyde. 2017. "Dance and Music Share Gray Matter Structural Correlates." *Brain Research* 1657 (February): 62–73. https://doi.org/10.1016/j.brainres.2016.11.029.

Kawashima, R., P. E. Roland, and B. T. O'Sullivan. 1994. "Fields in Human Motor Areas Involved in Preparation for Reaching, Actual Reaching, and Visuomotor Learning: A Positron Emission Tomography Study." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 14 (6): 3462–74. https://doi.org/10.1523/JNEUROSCI.14-06-03462.1994.

Kleber, Boris, Anthony G. Zeitouni, Anders Friberg, and Robert J. Zatorre. 2013. "Experience-Dependent Modulation of Feedback Integration during Singing: Role of the Right Anterior Insula." *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 33 (14): 6070–80. https://doi.org/10.1523/JNEUROSCI.4418-12.2013.

Koelsch, Stefan. 2005. "Neural Substrates of Processing Syntax and Semantics in Music." *Current Opinion in Neurobiology* 15 (2): 207–12. https://doi.org/10.1016/j.conb.2005.03.005.

Konorski, Jerzy. 1948. *Conditioned Reflexes and Neuron Organization*. Vol. 267. New York, NY, US: Cambridge University Press. https://psycnet.apa.org/fulltext/1950-03074-000.pdf.

Krishnan, Saloni, César F. Lima, Samuel Evans, Sinead Chen, Stella Guldner, Harry Yeff, Tom Manly, and Sophie K. Scott. 2018. "Beatboxers and Guitarists Engage Sensorimotor Regions Selectively When Listening to the Instruments They Can Play." *Cerebral Cortex* 28 (11): 4063–79. https://doi.org/10.1093/cercor/bhy208.

Kuchenbuch, Anja, Evangelos Paraskevopoulos, Sibylle C. Herholz, and Christo Pantev. 2014. "Audio-Tactile Integration and the Influence of Musical Training." Edited by Claude Alain. *PloS One* 9 (1): e85743. https://doi.org/10.1371/journal.pone.0085743.

Kuper, Clara, Jacek Matuszewski, Anna Banaszkiewicz, Łukasz Bola, Michał Szczepanik, Małgorzata Draps, Przemysław Kordos, Marcin Szwed, Katarzyna Jednoróg, and Artur Marchewka. 2021. "Functional Reorganization of the Reading Network in the Course of Foreign Language Acquisition." *NeuroImage* 226 (February): 117544. https://doi.org/10.1016/j.neuroimage.2020.117544.

Kwong, K. K., J. W. Belliveau, D. A. Chesler, I. E. Goldberg, R. M. Weisskoff, B. P. Poncelet, D. N. Kennedy, B. E. Hoppel, M. S. Cohen, and R. Turner. 1992. "Dynamic Magnetic Resonance Imaging of Human Brain Activity during Primary Sensory Stimulation." *Proceedings of the National Academy of Sciences of the United States of America* 89 (12): 5675–79. https://doi.org/10.1073/pnas.89.12.5675.

Lahav, Amir, Elliot Saltzman, and Gottfried Schlaug. 2007. “Action Representation of Sound: Audiomotor Recognition Network While Listening to Newly Acquired Actions.” *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 27 (2): 308–14. https://doi.org/10.1523/JNEUROSCI.4822-06.2007.

Lanczos, C. 1964. “Evaluation of Noisy Data.” *Journal of the Society for Industrial and Applied Mathematics Series B Numerical Analysis* 1 (1): 76–85. https://doi.org/10.1137/0701007.

Lappe, C., S. C. Herholz, L. J. Trainor, and C. Pantev. 2008. “Cortical Plasticity Induced by Short-Term Unimodal and Multimodal Musical Training.” *Journal of Neuroscience* 28 (39): 9632–39. https://doi.org/10.1523/JNEUROSCI.2254-08.2008.

Lee, Seung Hyun, Sang Hyeon Jin, and Jinung An. 2019. “The Difference in Cortical Activation Pattern for Complex Motor Skills: A Functional near- Infrared Spectroscopy Study.” *Scientific Reports* 9 (1): 14066. https://doi.org/10.1038/s41598-019-50644-9.

Lester, Michael, and J. Boley. 2007. “The Effects of Latency on Live Sound Monitoring.” https://www.semanticscholar.org/paper/be7dacc915505dad360084592725b859cd440e36.

Levenshtein, Vladimir I., and Others. 1966. “Binary Codes Capable of Correcting Deletions, Insertions, and Reversals.” In *Soviet Physics Doklady*, 10:707–10. Soviet Union. https://nymity.ch/sybilhunting/pdf/Levenshtein1966a.pdf.

Li, Chiang-Shan Ray, Cong Huang, R. Todd Constable, and Rajita Sinha. 2006. “Imaging Response Inhibition in a Stop-Signal Task: Neural Correlates Independent of Signal Monitoring and Post-Response Processing.” *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 26 (1): 186–92. https://doi.org/10.1523/JNEUROSCI.3741-05.2006.

Li, Qiongling, Xuetong Wang, Shaoyi Wang, Yachao Yongqi Xie, Xinwei Li, Yachao Yongqi Xie, and Shuyu Li. 2018. “Musical Training Induces Functional and Structural Auditory-Motor Network Plasticity in Young Adults.” *Human Brain Mapping* 39 (5): 2098–2110. https://doi.org/10.1002/hbm.23989.

Limb, Charles J. 2006. “Structural and Functional Neural Correlates of Music Perception.” *The Anatomical Record. Part A, Discoveries in Molecular, Cellular, and Evolutionary Biology* 288A (4): 435–46. https://doi.org/10.1002/ar.a.20316.

Limb, Charles J., Stefan Kemeny, Eric B. Ortigoza, Sherin Rouhani, and Allen R. Braun. 2006. “Left Hemispheric Lateralization of Brain Activity during Passive Rhythm Perception in Musicians.” *The Anatomical Record. Part A, Discoveries in Molecular, Cellular, and Evolutionary Biology* 288A (4): 382–89. https://doi.org/10.1002/ar.a.20298.

Lisman, John, Katherine Cooper, Megha Sehgal, and Alcino J. Silva. 2018. “Memory Formation Depends on Both Synapse-Specific Modifications of Synaptic Strength and Cell-Specific Increases in Excitability.” *Nature Neuroscience* 21 (3): 309–14. https://doi.org/10.1038/s41593-018-0076-6.

Lister, Jennifer J., Elizabeth M. Hudak, Ross Andel, and Jerri D. Edwards. 2023. “The Effects of Piano Training on Auditory Processing, Cognition, and Everyday Function.” *Journal of Cognitive Enhancement* 7 (1): 97–111. https://doi.org/10.1007/s41465-023-00256-z.

Logothetis, Nikos K. 2008. “What We Can Do and What We Cannot Do with fMRI.” *Nature* 453 (7197): 869–78. https://doi.org/10.1038/nature06976

Logothetis, N. K., J. Pauls, M. Augath, T. Trinath, and A. Oeltermann. 2001. “Neurophysiological Investigation of the Basis of the fMRI Signal.” *Nature* 412 (6843): 150–57. https://doi.org/10.1038/35084005.

Maess, B., S. Koelsch, T. C. Gunter, and A. D. Friederici. 2001. “Musical Syntax Is Processed in Broca’s Area: An MEG Study.” *Nature Neuroscience* 4 (5): 540–45. https://doi.org/10.1038/87502.

Maguire, E. A., D. G. Gadian, I. S. Johnsrude, C. D. Good, J. Ashburner, R. S. Frackowiak, and C. D. Frith. 2000. “Navigation-Related Structural Change in the Hippocampi of Taxi Drivers.” *Proceedings of the National Academy of Sciences of the United States of America* 97 (8): 4398–4403. https://doi.org/10.1073/pnas.070039597.

Makin, Tamar R., and John W. Krakauer. 2023. “Against Cortical Reorganisation.” *eLife* 12 (November). https://doi.org/10.7554/eLife.84716.

Makin, Tamar R., and Jean-Jacques Orban de Xivry. 2019. “Ten Common Statistical Mistakes to Watch out for When Writing or Reviewing a Manuscript.” *eLife* 8 (October). https://doi.org/10.7554/eLife.48175.

Ma, Liangsuo, Binquan Wang, Shalini Narayana, Eliot Hazeltine, Xiying Chen, Donald A. Robin, Peter T. Fox, and Jinhu Xiong. 2010. “Changes in Regional Activity Are Accompanied with Changes in Inter-Regional Connectivity during 4 Weeks Motor Learning.” *Brain Research* 1318 (March): 64–76. https://doi.org/10.1016/j.brainres.2009.12.073.

Manzano, Örjan de, Karen L. Kuckelkorn, Karin Ström, and Fredrik Ullén. 2020. “Action-Perception Coupling and Near Transfer: Listening to Melodies after Piano Practice Triggers Sequence-Specific Representations in the Auditory-Motor Network.” *Cerebral Cortex* 30 (10): 5193–5203. https://doi.org/10.1093/cercor/bhaa018.

Marek, Scott, Brenden Tervo-Clemmens, Finnegan J. Calabro, David F. Montez, Benjamin P. Kay, Alexander S. Hatoum, Meghan Rose Donohue, et al. 2022. “Publisher Correction: Reproducible Brain-Wide Association Studies Require Thousands of Individuals.” *Nature* 605 (7911): E11. https://doi.org/10.1038/s41586-022-04692-3.

Matsuda, Tadamitsu, Shu Watanabe, Hironobu Kuruma, Yoshiyuki Murakami, Rui Watanabe, and Atsushi Senou. 2009. “A Comparison of Three Bimanual Coordinations: An fMRI Study.” *Journal of Physical Therapy Science* 21 (1): 85–92. https://doi.org/10.1589/jpts.21.85.

Matuszewski, Jacek, Bartosz Kossowski, Łukasz Bola, Anna Banaszkiewicz, Małgorzata Paplińska, Lucien Gyger, Ferath Kherif, et al. 2021. “Brain Plasticity Dynamics during Tactile Braille Learning in Sighted Subjects: Multi-Contrast MRI Approach.” *NeuroImage* 227 (December): 117613. https://doi.org/10.1016/j.neuroimage.2020.117613.

McFarquhar, Martyn. 2019. “Modeling Group-Level Repeated Measurements of Neuroimaging Data Using the Univariate General Linear Model.” *Frontiers in Neuroscience* 13 (April): 352. https://doi.org/10.3389/fnins.2019.00352.

Mehr, Samuel A., Max M. Krasnow, Gregory A. Bryant, and Edward H. Hagen. 2020. “Origins of Music in Credible Signaling.” *The Behavioral and Brain Sciences*. https://doi.org/10.1017/S0140525X20000345.

Molendowska, Malwina, Jacek Matuszewski, Bartosz Kossowski, Łukasz Bola, Anna Banaszkiewicz, Małgorzata Paplińska, Katarzyna Jednoróg, Bogdan Draganski, and Artur Marchewka. 2021. “Temporal Dynamics of Brain White Matter Plasticity in Sighted Subjects during Tactile Braille Learning: A Longitudinal Diffusion Tensor Imaging Study.” *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 41 (33): 7076–85. https://doi.org/10.1523/JNEUROSCI.2242-20.2021.

Molina-Luna, Katiuska, Benjamin Hertler, Manuel M. Buitrago, and Andreas R. Luft. 2008. “Motor Learning Transiently Changes Cortical Somatotopy.” *NeuroImage* 40 (4): 1748–54. https://doi.org/10.1016/j.neuroimage.2007.11.018.

Molnar-Szakacs, Istvan, and Lucina Q. Uddin. 2022. “Anterior Insula as a Gatekeeper of Executive Control.” *Neuroscience and Biobehavioral Reviews* 139 (August): 104736. https://doi.org/10.1016/j.neubiorev.2022.104736.

Mukamel, Roy, Hagar Gelbard, Amos Arieli, Uri Hasson, Itzhak Fried, and Rafael Malach. 2005. “Coupling between Neuronal Firing, Field Potentials, and FMRI in Human Auditory Cortex.” *Science* 309 (5736): 951–54. https://doi.org/10.1126/science.1110913.

Münte, Thomas F., Eckart Altenmüller, and Lutz Jäncke. 2002. “The Musician’s Brain as a Model of Neuroplasticity.” *Nature Reviews. Neuroscience* 3 (6): 473–78. https://doi.org/10.1038/nrn843.

Nettl, Bruno. 2015. *The Study of Ethnomusicology: Thirty-Three Discussions*. Third edition. Springfield: University of Illinois Press.

Neves, Leonor, Ana Isabel Correia, São Luís Castro, Daniel Martins, and César F. Lima. 2022. “Does Music Training Enhance Auditory and Linguistic Processing? A Systematic Review and Meta-Analysis of Behavioral and Brain Evidence.” *Neuroscience and Biobehavioral Reviews* 140 (July): 104777. https://doi.org/10.1016/j.neubiorev.2022.104777.

Nichols, Thomas. 2007. “Easythresh_conj.” University of Oxford. https://warwick.ac.uk/fac/sci/statistics/staff/academic-research/nichols/scripts/fsl/easythresh_conj.sh.

Nichols, Thomas, Matthew Brett, Jesper Andersson, Tor Wager, and Jean-Baptiste Poline. 2005. “Valid Conjunction Inference with the Minimum Statistic.” *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2004.12.005.

Oechslin, Mathias S., Dimitri Van De Ville, François Lazeyras, Claude-Alain Alain Hauert, Clara E. James, Dimitri Van De Ville, François Lazeyras, et al. 2013. “Degree of Musical Expertise Modulates Higher Order Brain Functioning.” *Cerebral Cortex* 23 (9): 2213–24. https://doi.org/10.1093/cercor/bhs206.

Ogawa, S., and T. M. Lee. 1990. “Magnetic Resonance Imaging of Blood Vessels at High Fields: In Vivo and in Vitro Measurements and Image Simulation.” *Magnetic Resonance in Medicine: Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine* 16 (1): 9–18. https://doi.org/10.1002/mrm.1910160103.

Ogawa, S., T. M. Lee, A. R. Kay, and D. W. Tank. 1990. “Brain Magnetic Resonance Imaging with Contrast Dependent on Blood Oxygenation.” *Proceedings of the National Academy of Sciences of the United States of America* 87 (24): 9868–72. https://doi.org/10.1073/pnas.87.24.9868.

Ogawa, S., T. M. Lee, A. S. Nayak, and P. Glynn. 1990. “Oxygenation-Sensitive Contrast in Magnetic Resonance Image of Rodent Brain at High Magnetic Fields.” *Magnetic Resonance in Medicine: Official Journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine* 14 (1): 68–78. https://doi.org/10.1002/mrm.1910140108.

Ohnishi, T. 2001. “Functional Anatomy of Musical Perception in Musicians.” *Cerebral Cortex* 11 (8): 754–60. https://doi.org/10.1093/cercor/11.8.754.

Olszewska, Alicja M., Dawid Droździel, Maciej Gaca, Agnieszka Kulesza, Wojciech Obrębski, Jakub Kowalewski, Agnieszka Widlarz, Artur Marchewka, and Aleksandra M. Herman. 2023. “Unlocking the Musical Brain: A Proof-of-Concept Study on Playing the Piano in MRI Scanner with Naturalistic Stimuli.” *Heliyon*, July, e17877. https://doi.org/10.1016/j.heliyon.2023.e17877.

Olszewska, Alicja M., Maciej Gaca, Aleksandra M. Herman, Katarzyna Jednoróg, and Artur Marchewka. 2021. “How Musical Training Shapes the Adult Brain: Predispositions and Neuroplasticity.” *Frontiers in Neuroscience* 15 (March): 630829. https://doi.org/10.3389/fnins.2021.630829.

Pando-Naude, Victor, Agata Patyczek, Leonardo Bonetti, and Peter Vuust. 2021. “An ALE Meta-Analytic Review of Top-down and Bottom-up Processing of Music in the Brain.” *Scientific Reports* 11 (1): 20813. https://doi.org/10.1038/s41598-021-00139-3.

Papadaki, Eleftheria. 2023. “Experience-Dependent Plasticity in the Auditory Domain: Effects of Expertise and Training on Functional Brain Organization.” Freie Universität Berlin. https://doi.org/10.17169/REFUBIUM-42045.

Paraskevopoulos, Evangelos, Anja Kuchenbuch, Sibylle C. Herholz, and Christo Pantev. 2012. “Evidence for Training-Induced Plasticity in Multisensory Brain Structures: An MEG Study.” Edited by Ramesh Balasubramaniam. *PloS One* 7 (5): e36534. https://doi.org/10.1371/journal.pone.0036534.

Pasupathy, Anitha, and Earl K. Miller. 2005. “Different Time Courses of Learning-Related Activity in the Prefrontal Cortex and Striatum.” *Nature* 433 (7028): 873–76. https://doi.org/10.1038/nature03287.

Peelle, Jonathan E. 2014. “Methodological Challenges and Solutions in Auditory Functional Magnetic Resonance Imaging.” *Frontiers in Neuroscience* 8 (August): 253. https://doi.org/10.3389/fnins.2014.00253.

Penhune, Virginia B. 2022. “Understanding Sensitive Period Effects in Musical Training.” In *Sensitive Periods of Brain Development and Preventive Interventions*, edited by Susan L. Andersen, 167–88. Cham: Springer International Publishing. https://doi.org/10.1007/7854_2021_250.

Penhune, Virginia B., and Christopher J. Steele. 2012. “Parallel Contributions of Cerebellar, Striatal and M1 Mechanisms to Motor Sequence Learning.” *Behavioural Brain Research* 226 (2): 579–91. https://doi.org/10.1016/j.bbr.2011.09.044.

Pfordresher, Peter Q., James T. Mantell, Steven Brown, Robert Zivadinov, and Jennifer L. Cox. 2014. “Brain Responses to Altered Auditory Feedback during Musical Keyboard Production: An fMRI Study.” *Brain Research* 1556 (March): 28–37. https://doi.org/10.1016/j.brainres.2014.02.004.

Poldrack, Russell A., Chris I. Baker, Joke Durnez, Krzysztof J. Gorgolewski, Paul M. Matthews, Marcus R. Munafò, Thomas E. Nichols, Jean-Baptiste Poline, Edward Vul, and Tal Yarkoni. 2017. "Scanning the Horizon: Towards Transparent and Reproducible Neuroimaging Research." *Nature Reviews. Neuroscience* 18 (2): 115–26. https://doi.org/10.1038/nrn.2016.167.

Poldrack, Russell A., Jeanette A. Mumford, and Thomas E. Nichols. 2011. *Handbook of Functional MRI Data Analysis*. Cambridge University Press.

Rae, Charlotte L., Laura E. Hughes, Chelan Weaver, Michael C. Anderson, and James B. Rowe. 2014. "Selection and Stopping in Voluntary Action: A Meta-Analysis and Combined fMRI Study." *NeuroImage* 86 (February): 381–91. https://doi.org/10.1016/j.neuroimage.2013.10.012.

Ramon y Cajal, Santiago. 1894. "The Croonian lecture.—La Fine Structure Des Centres Nerveux." *Proceedings of the Royal Society of London* 55 (331-335): 444–68. https://doi.org/10.1098/rspl.1894.0063.

Rauschecker, Josef P. 2011. "An Expanded Role for the Dorsal Auditory Pathway in Sensorimotor Control and Integration." *Hearing Research* 271 (1-2): 16–25. https://doi.org/10.1016/j.heares.2010.09.001.

R Core Team. 2020. "R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing." Vienna, Austria. 2020. https://www.r-project.org/index.html.

Reuter, Martin, H. Diana Rosas, and Bruce Fischl. 2010. "Highly accurate inverse consistent registration: a robust approach." Neuroimage 53, no. 4 : 1181-1196. https://doi.org/10.1016/j.neuroimage.2010.07.020

Román-Caballero, Rafael, and Juan Lupiáñez. 2022. "Suggestive but Not Conclusive: An Independent Meta-Analysis on the Auditory Benefits of Learning to Play a Musical Instrument. Commentary on Neves et Al. (2022)." *Neuroscience and Biobehavioral Reviews* 142 (November): 104916. https://doi.org/10.1016/j.neubiorev.2022.104916.

Rosenzweig, M. R., E. L. Bennett, and D. Krech. 1964. "CEREBRAL EFFECTS OF ENVIRONMENTAL COMPLEXITY AND TRAINING AMONG ADULT RATS." *Journal of Comparative and Physiological Psychology* 57 (June): 438–39. https://doi.org/10.1037/h0046387.

Saarikallio, Suvi, and Margarida Baltazar. 2018. "Music as a Forum for Social-Emotional Health." In *Music and Public Health: A Nordic Perspective*, edited by Lars Ole Bonde and Töres Theorell, 101–13. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-76240-1_7.

Sato, Kanako, Eiji Kirino, and Shoji Tanaka. 2015. "A Voxel-Based Morphometry Study of the Brain of University Students Majoring in Music and Nonmusic Disciplines." *Behavioural Neurology* 2015: 1–9. https://doi.org/10.1155/2015/274919.

Schellenberg, E. Glenn, and César F. Lima. 2024. "Music Training and Nonmusical Abilities." *Annual Review of Psychology* 75 (January): 87–128. https://doi.org/10.1146/annurev-psych-032323-051354.

Schlaug, Gottfried. 2015. "Musicians and Music Making as a Model for the Study of Brain Plasticity." *Progress in Brain Research* 217 (February): 37–55. https://doi.org/10.1016/bs.pbr.2014.11.020.

Schlaug, Gottfried, Lutz Jäncke, Yanxiong Huang, Jochen F. Staiger, and Helmuth Steinmetz. 1995. “Increased Corpus Callosum Size in Musicians.” *Neuropsychologia* 33 (8): 1047–55. https://doi.org/10.1016/0028-3932(95)00045-5.

Schmithorst, Vincent J. 2005. “Separate Cortical Networks Involved in Music Perception: Preliminary Functional MRI Evidence for Modularity of Music Processing.” *NeuroImage* 25 (2): 444–51. https://doi.org/10.1016/j.neuroimage.2004.12.006.

Schneider, Brett, Jonah Heskje, Joel Bruss, Daniel Tranel, and Amy M. Belfi. 2018. “The Left Temporal Pole Is a Convergence Region Mediating the Relation between Names and Semantic Knowledge for Unique Entities: Further Evidence from a ‘Recognition-from-Name’ Study in Neurological Patients.” *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior* 109 (December): 14–24. https://doi.org/10.1016/j.cortex.2018.08.026.

Schneider, Peter, Vanessa Sluming, Neil Roberts, Stefan Bleeck, and André Rupp. 2005. “Structural, Functional, and Perceptual Differences in Heschl’s Gyrus and Musical Instrument Preference.” *Annals of the New York Academy of Sciences* 1060 (December): 387–94. https://doi.org/10.1196/annals.1360.033.

Schwarzbauer, Christian, Matt H. Davis, Jennifer M. Rodd, and Ingrid Johnsrude. 2006. “Interleaved Silent Steady State (ISSS) Imaging: A New Sparse Imaging Method Applied to Auditory fMRI.” *NeuroImage* 29 (3): 774–82. https://doi.org/10.1016/j.neuroimage.2005.08.025.

Segado, Melanie, Robert J. Zatorre, and Virginia B. Penhune. 2021. “Effector-Independent Brain Network for Auditory-Motor Integration: fMRI Evidence from Singing and Cello Playing.” *NeuroImage* 237 (August): 118128. https://doi.org/10.1016/j.neuroimage.2021.118128.

Seung, Yunhee, Jeong-Sug Kyong, Sung-Ho Woo, Byeong-Taek Lee, and Kyoung-Min Lee. 2005. “Brain Activation during Music Listening in Individuals with or without Prior Music Training.” *Neuroscience Research* 52 (4): 323–29. https://doi.org/10.1016/j.neures.2005.04.011.

Shannon, Claude Elwood. 1949. "Communication in the presence of noise." Proceedings of the IRE 37, no. 1 (1949): 10-21. https://doi.org/10.1109%2Fjrproc.1949.232969

Siuda-Krzywicka, Katarzyna, Łukasz Bola, Małgorzata Paplińska, Ewa Sumera, Katarzyna Jednoróg, Artur Marchewka, Magdalena W. Śliwińska, Amir Amedi, and Marcin Szwed. 2016. “Massive Cortical Reorganization in Sighted Braille Readers.” *eLife* 5 (MARCH2016): e10762. https://doi.org/10.7554/eLife.10762.

Smith, Stephen M., Mark Jenkinson, Mark W. Woolrich, Christian F. Beckmann, Timothy E. J. Behrens, Heidi Johansen-Berg, Peter R. Bannister, et al. 2004. “Advances in Functional and Structural MR Image Analysis and Implementation as FSL.” *NeuroImage* 23 Suppl 1: S208–19. https://doi.org/10.1016/j.neuroimage.2004.07.051.

Spunt, Bob. 2016. *Bspmview: Formal Release for Archiving on Zenodo*. Zenodo. https://doi.org/10.5281/zenodo.595175.

Szucs, Denes, and John Pa Ioannidis. 2020. “Sample Size Evolution in Neuroimaging Research: An Evaluation of Highly-Cited Studies (1990-2012) and of Latest Practices (2017-2018) in High-Impact Journals.” *NeuroImage* 221 (November): 117164. https://doi.org/10.1016/j.neuroimage.2020.117164.

Takahashi, Hirokazu, Akihiro Funamizu, Yusuke Mitsumori, Hidekazu Kose, and Ryohei Kanzaki. 2010. “Progressive Plasticity of Auditory Cortex during Appetitive Operant Conditioning.” *Bio Systems* 101 (1): 37–41. https://doi.org/10.1016/j.biosystems.2010.04.003.

Tanzi, E. 1893. “I Fatti E La Induzioni Nell ’Odierna Istologia Del Sistema Nervoso.” *Sperimentale Di Freniatria E Medicine Legale Della Alienazioni Mentali* 19:419–72. [aTJS]

Tardif, Christine Lucas, Claudine Joëlle Gauthier, Christopher John Steele, Pierre-Louis Bazin, Andreas Schäfer, Alexander Schaefer, Robert Turner, and Arno Villringer. 2016. “Advanced MRI Techniques to Improve Our Understanding of Experience-Induced Neuroplasticity.” *NeuroImage* 131 (May): 55–72. https://doi.org/10.1016/j.neuroimage.2015.08.047.

Tarr, Bronwyn, Jacques Launay, and Robin I. M. Dunbar. 2014. “Music and Social Bonding: ‘Self-Other’ Merging and Neurohormonal Mechanisms.” *Frontiers in Psychology* 5 (September): 1096. https://doi.org/10.3389/fpsyg.2014.01096.

Tavor, Ido, Rotem Botvinik-Nezer, Michal Bernstein-Eliav, Galia Tsarfaty, and Yaniv Assaf. 2019. “Short-Term Plasticity Following Motor Sequence Learning Revealed by Diffusion Magnetic Resonance Imaging.” *Human Brain Mapping* 14 (September): 208. https://doi.org/10.1002/hbm.24814.

Tinaz, Sule, Kiran Para, Ana Vives-Rodriguez, Valeria Martinez-Kaigi, Keerthana Nalamada, Mine Sezgin, Dustin Scheinost, Michelle Hampson, Elan D. Louis, and R. Todd Constable. 2018. “Insula as the Interface Between Body Awareness and Movement: A Neurofeedback-Guided Kinesthetic Motor Imagery Study in Parkinson’s Disease.” *Frontiers in Human Neuroscience* 12 (December): 496. https://doi.org/10.3389/fnhum.2018.00496.

Tustison, Nicholas J., Brian B. Avants, Philip A. Cook, Yuanjie Zheng, Alexander Egan, Paul A. Yushkevich, and James C. Gee. 2010. “N4ITK: Improved N3 Bias Correction.” *IEEE Transactions on Medical Imaging* 29 (6): 1310–20. https://doi.org/10.1109/TMI.2010.2046908.

Vallat, Raphael. 2018. “Pingouin: Statistics in Python.” *J. Open Source Softw.* 3 (31): 1026.

Van Rossum, Guido, and Fred L. Drake. 2009. *Python 3 Reference Manual: (Python Documentation Manual Part 2)*. CreateSpace Independent Publishing Platform.

Vaquero, Lucía, Neus Ramos-Escobar, Clément François, Virginia Penhune, and Antoni Rodríguez-Fornells. 2018. “White-Matter Structural Connectivity Predicts Short-Term Melody and Rhythm Learning in Non-Musicians.” *NeuroImage* 181 (November): 252–62. https://doi.org/10.1016/j.neuroimage.2018.06.054.

Viola, Erica, Marco Martorana, Chiara Airoldi, Cristina Meini, Daniele Ceriotti, Marta De Vito, Damiano De Ambrosi, and Fabrizio Faggiano. 2023. “The Role of Music in Promoting Health and Wellbeing: A Systematic Review and Meta-Analysis.” *European Journal of Public Health* 33 (4): 738–45. https://doi.org/10.1093/eurpub/ckad063.

Wallentin, Mikkel, Andreas Højlund Nielsen, Morten Friis-Olivarius, Christian Vuust, and Peter Vuust. 2010. "The Musical Ear Test, a New Reliable Test for Measuring Musical Competence." *Learning and Individual Differences* 20 (3): 188–96. https://doi.org/10.1016/j.lindif.2010.02.004.

Waskom, Michael. 2021. "Seaborn: Statistical Data Visualization." *Journal of Open Source Software* 6 (60): 3021. https://doi.org/10.21105/joss.03021.

Wenger, Elisabeth, Claudio Brozzoli, Ulman Lindenberger, and Martin Lövdén. 2017. "Expansion and Renormalization of Human Brain Structure During Skill Acquisition." *Trends in Cognitive Sciences* 21 (12): 930–39. https://doi.org/10.1016/j.tics.2017.09.008.

Westlin, Christiana, Jordan E. Theriault, Yuta Katsumi, Alfonso Nieto-Castanon, Aaron Kucyi, Sebastian F. Ruf, Sarah M. Brown, et al. 2023. "Improving the Study of Brain-Behavior Relationships by Revisiting Basic Assumptions." *Trends in Cognitive Sciences* 27 (3): 246–57. https://doi.org/10.1016/j.tics.2022.12.015.

Wollman, Indiana, Virginia Penhune, Melanie Segado, Thibaut Carpentier, and Robert J. Zatorre. 2018. "Neural Network Retuning and Neural Predictors of Learning Success Associated with Cello Training." *Proceedings of the National Academy of Sciences of the United States of America* 115 (26): E6056–64. https://doi.org/10.1073/pnas.1721414115.

Worschech, Florian, Clara E. James, Kristin Jünemann, Christopher Sinke, Tillmann H. C. Krüger, Daniel S. Scholz, Matthias Kliegel, Damien Marie, and Eckart Altenmüller. 2023. "Fine Motor Control Improves in Older Adults after One Year of Piano Lessons: Analysis of Individual Development and Its Coupling with Cognition and Brain Structure." *The European Journal of Neuroscience*, May. https://doi.org/10.1111/ejn.16031.

Yotsumoto, Yuko, Takeo Watanabe, and Yuka Sasaki. 2008. "Different Dynamics of Performance and Brain Activation in the Time Course of Perceptual Learning." *Neuron* 57 (6): 827–33. https://doi.org/10.1016/j.neuron.2008.02.034.

Zatorre, Robert J., Joyce L. Chen, and Virginia B. Penhune. 2007. "When the Brain Plays Music: Auditory-Motor Interactions in Music Perception and Production." *Nature Reviews. Neuroscience* 8 (7): 547–58. https://doi.org/10.1038/nrn2152.

Zeta-Jones, Catherine, Susan Misner, Denise Faye, Deidre Goodwin, Ekaterina Chtchelkanova, and Mýa. 2022. *Cell Block Tango. Chicago: Music from the Miramax Motion Picture*. Sony Music Entertainment Inc.

Zhang, Y., M. Brady, and S. Smith. 2001. "Segmentation of Brain MR Images through a Hidden Markov Random Field Model and the Expectation-Maximization Algorithm." *IEEE Transactions on Medical Imaging* 20 (1): 45–57. https://doi.org/10.1109/42.906424.

Publications of the PhD Candidate

* **Olszewska, Alicja M.,** Gaca, M., Droździel, D., Widlarz, A., Herman, A. M., & Marchewka, A. 2024. Understanding functional brain reorganization for naturalistic piano playing in novice pianists. Journal of Neuroscience Research, 102(2), e25312. https://doi.org/10.1002/jnr.25312

Herman, Aleksandra M., **Olszewska, A.M.,** Gaca, M., Droździel, D., & Marchewka, A. 2023. Interoception and the musical brain: Evidence from cross-sectional and longitudinal behavioral and resting-state fMRI study. Psychophysiology, 60(12), e14402. https://doi.org/10.1111/psyp.14402

* **Olszewska, Alicja M.,** Droździel, D., Gaca, M., Kulesza, A., Obrębski, W., Kowalewski, J., Widlarz, A., Marchewka A. & Herman, A. M. 2023. Unlocking the musical brain: A proof-of-concept study on playing the piano in MRI scanner with naturalistic stimuli. Heliyon, 9(7). https://doi.org/10.1016/j.heliyon.2023.e17877

* **Olszewska, Alicja M.,** Gaca, M., Herman, A. M., Jednoróg, K., & Marchewka, A. 2021. How musical training shapes the adult brain: Predispositions and neuroplasticity. Frontiers in Neuroscience, 15, 630829. https://doi.org/10.3389/fnins.2021.630829

Kowal, Marta, Sorokowski, P., Sorokowska, A., Lebuda, I., Groyecka-Bernard, A., Białek, M., Kowalska, K., Wojtycka, L**., Olszewska, A.M.** & Karwowski, M. 2020. Dread in academia–how COVID-19 affects science and scientists. Anthropological Review, 83(4), pp.387-394. https://doi.org/10.2478/anre-2020-0028

Wang, Jing, Phi, X. A., Greuter, M. J., **Daszczuk, A. M.°**, Feenstra, T. L., Pijnappel, R. M., Vermeulen, K.M., Buls, N., Houssami, N., Lu, W., & de Bock, G. H. 2020. The cost-effectiveness of digital breast tomosynthesis in a population breast cancer screening program. European Radiology, 30, 5437-5445.8 https://doi.org/10.1007/s00330-020-06812-x

Wang, Jing, **Daszczuk, A. M.°,** Greuter, M.J., Feenstra, T.L., Pijnappel, R.M., Vermeulen, K.M., Buls, N. & De Bock, G.H. 2018. Early health technology assessment of digital breast tomosynthesis in national breast cancer screening. European Journal of Cancer, 92, pp.S89-S90.

Daszczuk, Alicja M. †°, Koleva-Kolarova, Rositsa G. †, de Jonge, C., Hantash, M.K.A., Zhan, Z.Z., Postema, E.J., Feenstra, T.L., Pijnappel, R.M., Greuter, M.J. & De Bock, G.H. 2018. A modelling study to evaluate the costs and effects of lowering the starting age of population breast cancer screening. Maturitas, 109, pp.81-88. https://doi.org/10.1016/j.maturitas.2017.12.009

Daszczuk, Alicja M. †°, Dessalegne, Y. †, Drenth, I. †, Hendriks, E., Jo, E. †, van Lente, T. †, Oldebesten, A. †, Parrish, J. †, Poljakova, W. †, Purwanto, A.A. † & van Raaphorst, R. † (2014). Bacillus subtilis biosensor engineered to assess meat spoilage. ACS Synthetic Biology, 3(12), pp.999-1002. https://doi.org/10.1021/sb5000252

* Publications included in this dissertation

† - shared first authorship, ° - published under the maiden name of the PhD Candidate