

Literature Review

Tonal processing and musical imagery: the tonal chronotop of music

Marina Korsakova-Kreyn

Cognition and Neuroscience Doctoral Program

School of Behavioral and Brain Sciences

University of Texas at Dallas

Advisor: Dr. Walter Jay Dowling

2005

We can conceptualize the art of music as organization of some space governed by two unifying principles: musical “gravity” or tonal attraction and temporal (gross) structuring. The review presents the results of behavioral studies that give insight into primal auditory processing—for instance how our brains generate tonal schemata—and into processing of such complex musical constituent as a melodic contour. It also presents imaging and behavioral studies showing what regions of the brain are vital to music perception and how the brains of musicians differ from the brains of non-musicians. We speculate that a particular region of the cortex may be generally involved in pattern recognition notwithstanding the modality of the patterns, namely that the superior parietal lobule (BA7) is perhaps involved in both mental rotation and music perception.

Contents

1. Music as organization of some space
2. Pitch discrimination
3. Tonal schema
4. Melodic contour
5. Memory in music
6. Musicians' Brains
7. Gender and musicianship effect
8. Neuroanatomy of emotion
9. Music and spatial task performance
10. Mental Rotation in Visual and Acousmatic Space
11. Reference List

List of Plates

1. Tonal attraction
2. Hypothetical neuronal circuit for a periodicity analysis in the auditory brainstem
3. Three-D space with the coordinates of the attack time, spectral centroid, and spectral flux
4. Diatonic Scale expressed in the logarithmic curve
5. ‘Singularity’ in depiction of 3-D object
6. M. C. Escher, *Another World*
7. J. S. Bach, *Two-Part Invention in C* (fragment)
8. Patterns of activations of the neural substrates underlying the semantic and episodic components of music
9. Brain regions with gray matter differences between professional musicians, amateur musicians, and non-musicians
10. Results of the direct comparison between professional musicians and non-musicians using voxel-based morphometry (VBM)
11. Location of cerebellar gray matter effect
12. Smaller FA (fractional anisotropy) in the internal capsule and greater FA in the cerebellum in musicians as compared with non-musicians
13. PFC activity during source memory task in Young and Old-Low performing participants and in Old-High performing participants
14. Areas where functional anisotropy is significantly greater in musicians
15. Brain regions with significant hemispheric gray matter differences in a sample of 60 professional musicians

Music as organization of some space

Sounds have limitless suppleness and can be arranged into space of any configuration.

Father Pavel Florenskii [1]

The highest level of abstractness of the art of music gives to imagination vast freedom; in turn it demands creative efforts during listening. The directness with which art of music affects us—in Robert Zatorre’s words...*contacts our more primordial neurobiology* [2] —makes music a powerful communicator of universal concepts, which are conveyed to us by way of abstract immaterial structures we can neither touch nor see. In music we are dealing with a mental construct that can be imagined as some kind of a space. In describing music we commonly use words like ‘low’, ‘high’, and ‘architectonic’ that are indeed the proper characteristics of 3-D space. Moreover, in musicology music compositions are classified by their structure and their musical architectonics are carefully analyzed. The very names of some simple musical constituents—like an interval and a melodic contour—have strong suggestion of space-ness. In other words, the characteristics of a metric space are freely assigned to the temporal art of music. In one of his pioneering works on melodic contour (*the pattern of ups and downs of pitch*) [3] Jay Dowling wrote that “Many problems of visual pattern recognition find direct analogues in auditory pattern recognition” [4], [5].

Application of the spatial terminology seems at first to reflect merely a necessity to employ metaphors in teaching and in defining the highly abstract art of music.—Professional musicians in general do not think of music as organization of some space. In music, while listening to a stream of organized sounds, we first of all are involved in emotional resonance with the *logic of emotion* (in Susan Langer words) [6], or in the experience of a musical representation of a gesture (a concept by Roger Scruton) [7]. This spatial terminology, when combined with the jargon of physics, provides the effective metaphors to describe the fundamentals of organization of musical matter and the source of musical patterns. Thus we can say that musical patterns are born out of a tonal tension-resolution interplay. In the tonal force field, which is expressed in the

European musical tradition through the hierarchically organized Diatonic Scale, the tonal centers are analogous to the points of low ‘potential energy’, while other notes in the scale differ in their level of attraction toward the tonal center. For example, in the C-major scale the C is a tonal center toward which the B strongly gravitates. (Figure 1)

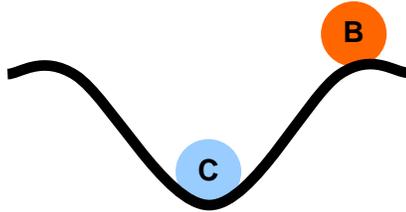


Figure 1: Tonal attraction

The tonal hierarchy creates a gradient of tonal attraction that can be compared to the force of gravity in the real world. The gradient is indeed a source of musical patterns. The tonal orientation does not generally involve a conscious registering of the tonal relationships: our perception follows intuitively a musical idea expressed through the logic of tonal arrangement that is unfolding in time. We identify the space of music as the tonal time-space or the tonal chronotop: the temporal structures of music are shaped by the tonal forces. The temporal and tonal patterns of the art of music are not independent modules working through parallel processing, but the intertwine parameters that together define musical thought, similar to how time and space each exists only in a presence of other.

When a single note sounds on its own, with no context, there is no tonality yet. Similar to how human societal structures are generated by interrelationships within a group of individuals, the manifestation of a tonal space requires a company of different sounds. The magic of music begins as soon as notes are connected into a melodic line. A single note on its own, without tonal relationships with other musical sounds, is just an acoustical signal, however complex it might be, but when a stream of musical sounds unfolds a musical thought, we find ourselves in a different domain: We transcend the acoustics and enter the acousmatic realm—the realm of listening. (As Scruton wrote, “Pythagoras is reputed to have lectured to his disciples from behind a screen, while they sat in silence attending to his words alone, and without a thought for the man who uttered

them. The Pythagoreans were therefore known, Iamblicus tells us, as *akousmatikoi*—those willing to hear. The term has been redeployed by Pierre Schaeffer, to describe the character of sound itself, when considered in the context of the musical experience. In listening, Schaeffer argues, we spontaneously detach the sound from the circumstances of its production.” [8]

As soon as a musical sound enters into relationship with other sounds, tonality springs up. Tonality is a system of relationship between musical sounds, which shape and keep musical objects together. A tonal center—the tonic—acts as reference point, as a center of attraction with a lowest level of energy.—In other words, it is the center of stability. Instinctively, we are ‘looping’ in our mind by constantly testing the tonal relationships in reference to the tonal center. As Dowling (2001) penned it, “The tonal hierarchy influences both expectancies and perceptual processing. The hierarchy imposes not only relative degree of stability, but also governs the tendencies of the less stable tones toward stable ones.” [9]. Somehow the analysis of these tonal relationships, which are defined by the gradient of tonal attraction, generates feelings of emotion and even cognition.

Pitch discrimination

The mechanism of pitch discrimination is unknown yet. Music processing begins with primary sound processing in the cochlea and then runs through the brain stem, midbrain nuclei, and cortical areas in both hemispheres. The cochlea performs spectral analysis in two ways:

1. through a specific tonotopic organization: definite locations on cochlea have hair cells that react to certain frequencies
2. when wave-like propagation of sound along cochlea ends up due to loss of energy at a certain location on cochlea (function of intensity of sound) and thus activates hair cells in this location.

These two ways of frequency discrimination seem non-compatible, particularly because of the second one, where frequency appears as dependent on intensity of sound. However, current model accepts this co-existence. Nerve fibers, that form auditory afferent pathways targeting various nuclei, seem to be rather specialized thus carrying the

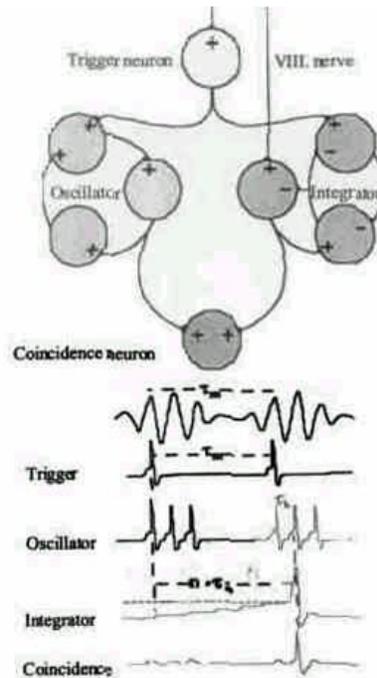
diverse information that is processed step by step in auditory nuclei, midbrain, inferior colliculi, medial geniculate nuclei, and primary auditory cortex. The information from the single fibers converges on various levels of signal processing. The temporal processing assesses the waveform and the complexity of the sound. This detection and processing are conducted by specialized neurons working in groups. The final processing is always part of multi-modal activity that places sounding patterns into the bigger picture of place and time. This frequency analysis is, most likely, quite precise [10], and it is our perceptive flexibility (Moller calls it the brain plasticity) [11] that allows adjustment of sounds within meaningful system of tonal relationships in music, for instance, placing an out of tune sound within a specific tonality.

Langner (1997) [12] hypothesized that the same neurons respond both to the fundamental tone frequency and frequencies of its harmonics. He wrote: “It is now well known that stimuli with harmonically related fundamental frequencies will elicit similar train of action potentials in the auditory nerve and in neurons in the brainstem.” His theory of correlation analysis in the auditory system explains “response properties of neurons in the auditory midbrain”. According to this theory “periodic signals are represented by synchronized neuronal activity and processed by neuronal circuits characterized by intrinsic oscillations, temporal integration, and coincidence detection. Neurons in the auditory midbrain act as coincidence detectors and transfer the temporal information into a rate code. Consequently, pitch is arranged topographically, orthogonal to the frequency map. The neuronal correlation theory is able to explain periodicity pitch, the perception of the missing fundamental and the pitch-shift effects.” (Figure 2.)

Langner emphasized the importance of a potentially dual role of the coincidence neurons: “In addition, a property of the temporal correlation mechanisms is that a coincidence neuron tuned to a particular fundamental frequency may also be activated by multiples of that frequency.” If this proposition is correct, than the consonant intervals—which are composed of the tones that have their strongest harmonics in common—are easier to process than dissonant intervals by virtue of requiring less energy for the processing. Perhaps, the energy gradient translates into a gradient of perceptual comfort on an elemental level. For example, the tones of the so-called Pythagorean intervals of the Octave, Fifth and Fourth—all of which are the consonant intervals—share their

strongest overtones. In other words, each of these intervals is formed by the strongest multiples of the fundamental frequency of a same tone. (Helmholtz, 1863; Deutsch

Gerald Langner: The Neuronal Correlation Analysis



$$\text{Periodicity equation: } \tau_c = \tau_m + \tau_k$$

Figure 2. A hypothetical neuronal circuit for a periodicity analysis in the auditory brainstem. It is assumed that the coincidence neuron is located in the ICC [central nucleus of the inferior colliculus] and that all other neurons of this circuit correspond to cells of the cochlear nucleus. The spike trains at the bottom of the figure indicate trigger, oscillator, and integrator responses synchronized to the signal envelope. As expressed by the periodicity equation, the delay due to the integration time of the integrator circuit must be compensated by the period of the signal for the coincidence unit to be activated. Therefore the integration time of the integrator is crucial for the best modulation frequency of the circuit. In addition, a more or less small delay is contributed by the oscillator. (Langner, 1997) [13]

The feeling for consonant and dissonant combinations of tones seems to be wired into the human brain very early: Infants as young as six months (Schellenberg & Trehub, 1996), [14] “show sensitivity to musical scales and respond preferentially to consonant,

as opposed to dissonant intervals”, since human cochlea is already formed at the end of second trimester and thus becomes available to music experience (in filtered version of sound). Consequently, “...the conformity of a melody to a diatonic scale ... appears to be detectable by virtually all listeners brought up in Western culture, even at an early age.” (Bartlett & Dowling, 1988) [15].

Studies show a relative specialization of the auditory cortices, such that those in the left hemisphere are specialized for processing rapidly changing temporal information (Liégeois-Chauvel et al, 1999) [16], and those on the right are specialized for spectral processing, (I. Peretz, 2001) [17]. In other words, the right hemisphere is responsible for temporal phase-lock (spectral) processing—that is for the fine pitch discrimination—which is necessary for music perception. In comparison, the left hemisphere is responsible for temporal processing that is important for the formant discrimination, which is necessary to vowel-recognition in language. Studies on amusia suggest “presence of early pressures for the normal development of neural networks that are dedicated to music” In a study on amusic patient Monica, Hyde & Peretz, (2004) [18] wrote that “Amusics have difficulty detecting changes in pitch that area smaller than 2 semitones (200 cents), whereas normal acuity is at least four times finer grained”. Therefore it is this roughness of spectral analysis that makes the difference in music perception: “congenital amusia is best understood as developmental disorder that arises from failures to encode pitch with sufficient resolution to allow acquisition of core knowledge regarding the pitch structure of music.”

In his article on *Neural specialization for tonal processing*, Robert Zatorre states that the right primary auditory area plays a special role not simply in discriminating one pitch from another, but in some aspect of organizing the sounds according to their pitch. [19]. — The inadequate spectral resolution compromises ability to perform what Leibniz famously called the “unconscious calculation” that underlies the music perception. [20]. A case report by Russell and Golfinos states that “Resection of the right hemisphere Heschl gyrus gliomas can result in deficits involving music comprehension”. [21]. Also, study on children and adolescence (Dennis & Hopyan, 2003) who had temporal lobectomy because of intractable epilepsy showed that “Left and right lobectomy groups discriminated rhythm equally well, but the right lobectomy group was poorer at

discriminating melodies.” [22]. Liegeois-Chauvel et al. (1999) noted selectivity of neurons in the right and left hemispheres. Neurons in the right auditory cortex were more sharply tuned to frequency than neurons in the homologous region of the left hemisphere. “... left auditory neurons were specifically sensitive to the temporal features of auditory information.” [16]. In a study by Liegeois-Chauvel et al (2001) intracerebral evoked potentials in pitch perception revealed a functional asymmetry of human auditory cortex. [23]. It showed that in the right hemisphere, “clear spectrally organized tonotopic maps were observed with distinct separations between different frequency-processing regions”, while in the left hemisphere the tonotopic organization was less evident.

In regard to the cognitive neuroscience of music perception, the studies on amusia (both on the congenital and lesion-caused) tell us convincingly that perception of the tonal hierarchy requires high sensitivity in a particular brain region (which seems to be an auditory equivalent of the 2-point sensory discrimination). Therefore, without the ability for differentiation of the fine *relational* pitch properties, which is necessary for perceiving the tonal hierarchy, the tonal field is not able to spring up and reveal the tonal patterns. One of Isabelle Peretz’ patients, I.R [24], who suffered brain damage, was not able to detect local pitch shifts that created dissonance in the musical selection when Mozart piano Concert in A was presented with the left-hand part of a score transposed a half-step in relation to original tonality while the right-hand part was played in the original tonality. This arrangement creates continuous presence of a half-step dissonance in each instance of hands playing together, (which makes a horrendous distortion of this harmonically clear and transparent music.) And yet I. R. was able to distinguish as ‘same’ or ‘different’ isolated tones across varying pitch distances and complexity. She had “normal appreciation of pitch but was “unable to perceive musical sequences.” [25] The amusic persons lack perception of the tonal relationships even when they have normal hearing in regard to language and the normal general intellectual and memory abilities. In Stewart & Walsh (2002) [26] study, *Congenital Amusia: All Songs Sound the Same*, the researchers found that the congenital amusics are not impaired in detecting a pitch change in speech. Sentences, presented as statements such as “He speaks French”, or questions such as “He speaks French?”, which differ only in the pitch direction of the final syllable, were easily discriminated. But “when these sentences were stripped of their linguistic

content and the same pitches were played, [participants] in the amusic group were considerably impaired”. Such a finding suggests that the pitch processing proceeds differently according to the context, depending on whether the context is musical or linguistic, even when the pitch information is identical in both cases. In this study, the musical impairment in amusics could not be explained on the basis of hearing impairment, because all the participants had, or grew up, with normal hearing. Moreover, all of them were raised in ‘musically normal’ families, and all had reached a high level of education. The research allows the authors to state that “Pitch processing is an ideal candidate for a musical ‘universal’ – an element of the musical system which is biologically hardwired from birth and independent of training and cultural effects”.

There is special case in pitch discrimination: the absolute pitch (AP), or perfect pitch, that is defined as the ability to produce or identify the pitch of a tone without reference to an external standard. The ability is rather rare “with an estimated incidence in our population of less than one in ten thousand.” [27]. According to Zatorre (2003) [28], the AP depends on both genetic factors and environment; it seems that there is a sensitive period during which a child can acquire the ability. The event related potentials revealed that listeners with AP “show an absent or reduced electrical scalp component that is thought to index the updating of working memory”. The explanation to this phenomenon is that people with AP keep absolute values of the pitches in their semantic memory. Therefore, “pitch representation requires encoding into working memory, but no updating once it is in memory.” Unlike individuals without AP whose listening requires “continuous maintenance of a sensory trace” [in other words, operates within tonal reference system], AP possessors apparently use their categorical representation of tones in such tasks”. Characteristically, individuals with AP exhibit left-ward asymmetry during pitch discrimination.

One of the important characteristic of musical sounds is timbre, the color of a sound. Takeuchi & Hulse (1993) made an interesting suggestion that timbral memory can be involved during pitch identification by those with absolute pitch. [29]. McAdams et al (1995) [30], by using a set of synthesized sounds that imitated instruments of a symphony orchestra, found a three-dimensional timbre space in which Attack Time (the Dimension 1) reflects the time it takes the energy envelope to go from perceptual threshold to its

maximum; Spectral Centroid (Dimension 2) is a measure of the relative presence of high-frequency versus low-frequency spectrum; and Spectral Flux (Dimension 3) is a measure of how much the spectral envelope changes over the duration of a tone. (Figure 3)

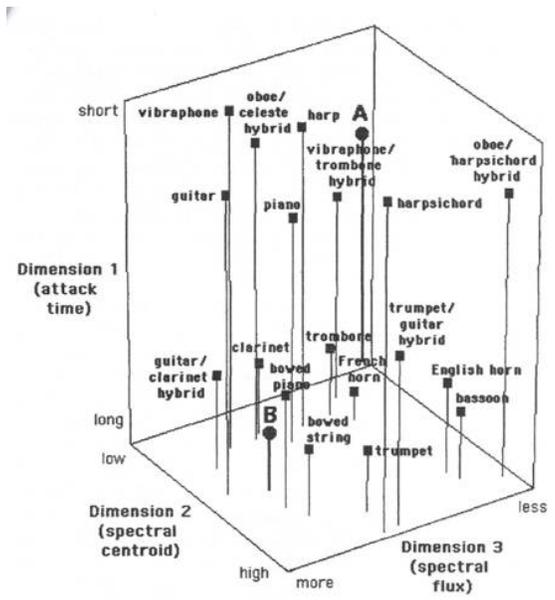


Figure 3. Three-D space with the coordinates of the attack time, spectral centroid, and spectral flux. (McAdams et al, 1995) [30].

Menon et al (2002) [31] fMRI study showed that the timbre-related information is processed in both the left and right hemispheres. The statistical analysis revealed that “timbre-related differences in activation were detected only in mid sections of the STG [superior temporal gyrus], STS [superior temporal sulcus], and adjoining insular cortex. The authors were particularly intrigued by asymmetry of the activation: “left temporal lobe activations were significantly posterior to right temporal activations, suggesting a functional asymmetry in the left and right temporal lobe regions involved in timbre processing.” They suggested that the asymmetry perhaps indicates that “same acoustical cues involved in perception of musical timbre may also be involved in processing linguistic cues”, by providing “a more complete set of acoustical correlates for vowel identity than do formants.” While research by Liegeois-Chauvel et al., (1999) suggested that the left superior temporal gyrus may be involved in differentiating voiced and unvoiced consonants. [16]

Tonal schema

The historic evolution of the language of harmony in music—that was necessitated by modulation—had several important consequences in regard to pitch-relationship sensitivity. First of all, the evolution led to re-tuning the keyboard instruments towards closer and closer versions of the Equal Temperament, which aimed to provide the universality of 12 half-tones of the Diatonic Scale and away from the Just Intonation scale that was based on the overtone series. The equalization of relationships between the 12 half-tones of the Diatonic Scale was the only way to achieve freedom of modulation (the moving from one key to another). In terms of the tonal gravitation, the modulation is a process of moving from one tonal ‘solar system’ to another. The Equally Tempered Diatonic Scale has elegance of mathematical expression and presents an instance of homothetic (gnomonic) growth: the Diatonic Scale is repeated every seven notes and these notes’ frequencies increase in the logarithmic relation. (Figure 4) M.Ghyka, in his *The Geometry of Art and Life*, wrote that “The logarithmic spiral is the only plane curve in which two arcs are always “similar” to each other, varying in dimensions but not in shape...” [32] This property has important role in living growth.

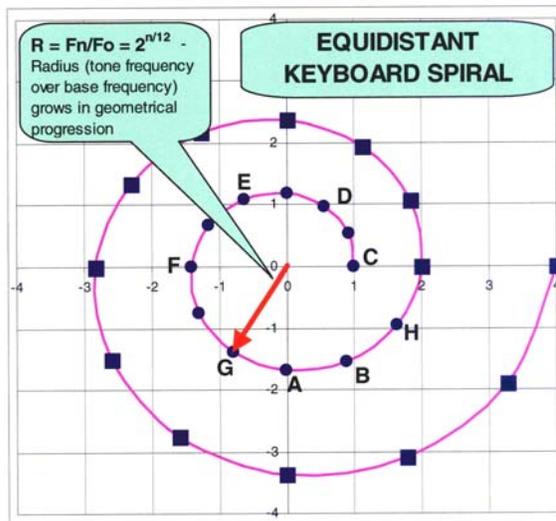


Figure 4: Diatonic Scale expressed in the logarithmic curve

The Just Intonation system of tuning is based on the Octave (2/1), the pure Fifth (3/2), and the pure major Third (5/4), while the Equal Temperament “means division of the octave into an equal number of parts, specifically 12 semitones, each of which has the ration of $12\sqrt{2}$ ”. [33] The history of keyboard instruments’ tuning might be generalized as a global case of brain plasticity. It is plausible that modern tuning, agreeable to the present-day musicians’ ears, would be torturous to music professionals few centuries ago. We can only guess how unpleasant was the Equal Temperament to the auditory perception of those 17th century musicians like the famous theoretic of music Zarlino Giozeffo—a teacher of Vincenzo Galilei—who espoused the “sweet” purity of Just Temperament. [34]. And while Barbour believed that the equal Temperament became a desirable practice already in the 16th century [35], knowledgeable modern piano tuners use the Historical Temperaments: They are trying to salvage as much as possible from the Just Intonation scale. [36]. To emphasize the most important aspect of the Just Intonation scale, Dowling (1981) uses a beautiful term of the “psychophysical scale” that values the precisions of intonation over the “constancy of relationships of intervals across octaves”. [37]. Moreover, it seems that present-day listeners, at least those who grew up within the European cultural tradition, intuitively ‘dress’ a solo melody with implied harmonies. It means that the logic of musical development cues the implicit harmonization response, (Holleran *et al.* 1995; Bigand, 1993). [38], [39]. It is difficult to say with certainty how much the implicit harmonization differs qualitatively today from what it used to be in the past, but it is probable that our vocabulary of accompanying harmonies evolved in parallel with the evolution of the harmonic language.

In the European musical tradition, the foundation of the immensely rich language of harmony can be reduced to, and laconically presented through, just three chords: the triads on the First, Fourth, and Fifth steps of the Diatonic scale; everything else is a derivative. Because the sequence is based on the notes that form the Pythagorean favorites, (the intervals of the Fourth and Fifth, where the Fourth is actually an inverted form of the Fifth), it brings us back to the subject of harmonic series and its importance for the formation of the tonal force field. Jordan calls the “diatonic hierarchy of tonal functions ... an active cognitive mechanism in the perception of musical tones”, (here,

the word *function* is used in physico-mathematical terms and refers to the gradient of the tonal attraction.) [40].

Music perception operates within innate constraints; the most common scales are built on 5-7 pitches per octave, which agrees with the Joseph Jacobs' measure known as the *memory span*: seven, plus or minus two.[41]. Dowling et al (1986) wrote that "Virtually every culture in the world has a least one systematic pattern for the organization of pitch classes that repeats from octave to octave." [42]. A study by Jordan & Shepard (1987) [43] is directly related to the problem of inborn wiring for sensitivity to musical scales and degree of tolerance toward deviations from the sensitivity. For example, Jordan & Shepard used 'stretched' variant of the Diatonic Scale to probe responses on seven notes of the scale. The stretching, distributed evenly between 12 half-tones of the scale, made the scale 100 cents larger (C – C#). The experiment supported the authors' hypothesis that the perception of tones is mediated by the tonal schema. This template (schema) experiment can be seen as a witty illustration to the 'elasticity' of our brain in creating a system of reference. The authors wrote that "the perception and memory of tones is mediated by a tonal schema [that] behaves as semi-rigid structure with respect to the log-frequency continuum, although it may be subject to some small degree of stretching or compression to accommodate tonal sequences that are stretched or compressed in pitch". Notably, the semi-rigid schema, "when brought into register with incoming tones, also assigns musically significant tonal functions (tonic, dominant, median, leading tone)". The authors of the study noted the Major Diatonic Scale congruence and the symmetry that manifests itself during shifting of n-number of half-tones in either direction. However, this description fits just one kind of the Western diatonic system: the Equal Temperament system. The following quote from Jordan & Shepard (1987) [43] is particularly relevant to my current research on quasi-spatial characteristics of the tonal chronotop: "Perceptual schemas, which have long been recognized to be important in visual perception and cognition, appear to be of equal importance in the perception of musical tones. Moreover, just as the mental representation of structure preserving transformations evidently underlines the comparison of visual objects, as in the phenomenon called mental rotation, the mental representation of structure-preserving transformations (in this case, of the tonal template)

underlie the comparison of auditory objects.” To me, our ongoing experiment with melodic contour transformations—when melodies are bent and mirrored in the tonal field—seems to be a stronger analogue to the Shepard & Metzler [44] experiment than one that suggested by the tonal-template method. Tempering a perceptual musical schema is akin to tempering properties of a space; like for example tempering with a 3-D space—where the Fifth Euclidean postulate reigns—in such a way that the parallel lines would allow to cross. However, in the classical Shepard & Meltzer [44] experiment, rotation of the 3-D objects happens within the stable Euclidian space. A melodic contour can be thought of as an aural analog of an object in 3-D space; we can say that musical components within European classical tradition inhabit musical space with the fixed tonal schema. In our experiment on Mental Rotation in Visual and Acousmatic Space the melodic contours and their transforms are treated as ‘objects’ that inhabit such space of the fixed tonal schema. I prefer to call the space of music the tonal chronotop for a reason that the intertwined existence of temporal and tonal organization of music is as organic to the objects that inhabit the tonal space as the unity of skeleton and flesh is organic to a living form.

There is an essential difference in my understanding of the idea of an object-rotation in the auditory space and the approach expressed by Shepard & Cooper (1982) [45] in their important book, *Mental Images and Their Transformations*, where the authors suggested a study case that would look upon the auditory rotation in terms of physical sources of varying in timbre sounds within the Cartesian coordinates. The Shepard & Cooper approach concerns first of all a perception of an auditory signal in a 3-D space and thus is limited to field of acoustics. In other words, this approach does not reach cognitive level of object-recognition that had been presented in the Shepard & Meltzer mental rotation model.

Melodic contour: thinking of visual analogues

Altogether, the Shepard & Jordan study (1987) on tonal schema can be viewed as an important follow up to a problem posed by Dowling (1971) [42], who suggested that “visual pattern recognition find direct analogues in auditory pattern recognition” and poses a question, “What distortions of detail leave the patterns recognizable, and what are

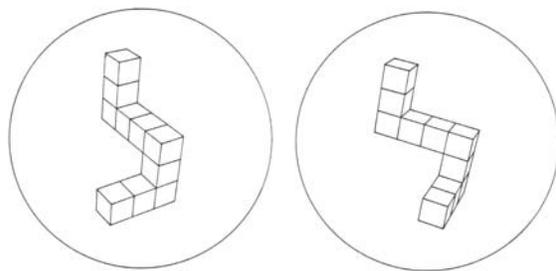
the effects of various changes of orientation of shape on recognition?" [46]. Shepard & Cooper (1982) listed types of the apparent [visual] transformation: "a translation, a rotation, as dilation (i.e., a uniform expansion or contraction), or some combination of these (as well, under some circumstances, as a reflection)". Each of these properties of the visual objects' transformations has an analogue in the domain of classical music, namely in the polyphonic music. A musical theme in a Fugue can be transposed (translated), bent by the tonal forces (as if presented under different angle), reflected, augmented and diminished (dilated) through change of time-values, or have some combination of these types of transformation. In other words, within the tonal chronotop of music the polyphonic compositions display patterns that can be understood as analogous to the visual objects' transformation. For example, such melodic transformation as musical dilation is perceptually an easy task when a uniform expansion or contraction of a musical theme is presented 'as it is', out-of-context. Yet it could be a formidable task when it is woven into a polyphonic composition. As for inversion and retrograde inversion in music, and the difficulty in comprehending these transformations, they provide a great illustration to the idea of the fundamental difference between visual object-perception done 'at once' and the process, stretched in time sequentially of the perception of a musical form that always arrives element by element along the Arrow of Time.

The idea of the tremendous qualitative difference between the acoustic and the acousmatic realm was forcefully expressed and thoroughly illustrated by the British philosopher (and writer and composer) Rodger Scruton in his *The Aesthetics of Music*: "There is no real space of sounds; but there is a phenomenal space of tones. It is modeled on the phenomenal space of everyday perception – the space in terms of which we orient ourselves. It had 'up' and 'down', height and depth; its single dimension is understood not only geometrically but also in terms of effort and motion, attraction and repulsion, heaviness and lightness. It is permeated by a phenomenal gravity, to the law of which all the tones are subjects, and against which they must strive if they are to move at all." [47]. Scruton's logic clearly follows the Gestalt approach, which emphasizes that in music a whole is not merely a sum of its parts but a product of complex interrelationships among the parts. A musical sound apart from any comparison with other musical sounds, can be

understood as an acoustical signal, which is easy to characterize by its physical features of amplitude (intensity), frequency, spectral and temporal envelopes (timbre), and duration. However, when we move to perception of a melody, the major interest is directed towards an idea expressed by musical means. Dowling (1991), to accentuate the fluidity of the tonal space wrote that, "...when the listener's point of view shifts in the tonal space, the pitch categories it represents change their values." [48].

Dowling's studies on melodic contour opened the venue towards treating temporal objects of music as an analogue of visual objects. The idea of a melodic contour and its transformation implicitly supposes, first of all, the existence of a certain space where the very transformations happen, and, secondly, implies that this space—the tonal chronotop—possesses certain characteristics that make the transformations possible. Characteristically, Krumhansl (1990) noticed that "Support for Gestalt laws of perceptual organization comes primarily from visual examples." [49] Janata et al (2002) wrote that "In contrast to categories of common visual objects that differ in their spatial features, musical keys are abstract constructs that share core properties. The internal relationships among the pitches defining a key are the same in each key, thereby facilitating the transposition of musical themes from one key to another." [50].

In commenting on the mental rotation experiment [45], Shepard discusses problems arising from apparent distortion of object's proportions in drawings—for



instance, the 'singularity', the visible fusion of the lines depicting 3-D object—that makes recognition of an object more difficult: It takes time to figure out that the distortion of an object's proportions is due to an angle of rotation, (Figure 5.)

Figure 5: Example of the 'singularity', (Shepard & Meltzer, 1971), [43]

In visual perception, it is our instinctive ability to interpret the available information and to reconstruct a model of the world in such a way that it fits the fundamental ideas of the space and time that performs the feat of perception. For instance, we intuitively understand true proportion in foreshortening; that is, we easily solve distance relationships when geometric perspective is concerned. [1] Similarly, a

melodic object can be recognized irrespective of the absolute size of the musical intervals between its ‘point’-tones. Dowling (1987) found that “...subjects were able only to recognize the melodic contour when so transformed [turned upside down, backward, or both] and not the exact interval sizes.” [51]. He also wrote that “what people store in memory when they hear a tune is more abstract than a literal copy.” [52] Grasping a melodic contour is a first response to a melodic line in music perception: Dowling’s studies on melodic contour showed that contour is a “dominant factor in immediate recognition memory for brief, novel, isochronous melodies.” [53].



Figure 6: M.C. Escher, *Another World*

The Shepard-Meltzer [44] mental rotation experiment aimed to find a correlation between angle of rotation and time it takes to make a decision on a congruence task. A rotated object might appear at first sight as if its proportions are distorted (Figure 6.) Similarly, in music a melodic contour can be heard as ‘bent’ by the tonal forces. If system of tonal reference (schemata) can be compared to a quasi-Cartesian system of coordinates that dictates geometrical perspective, a ‘bent’ melodic contour would be like something that is ‘seen’ from a different coordinate system (or from a different angle in the same system). [54] Shift of a melody within a key is one of the ways to reshape the contour.

Stretching and compressing intervals of a contour makes the contour appear as being ‘bent’. Perhaps, there is even an analog of angle of rotation in music. For instance, depending on pitch composition, shifting a melody along the scale might give relatively mild synergetic impression of changing ‘color’ of a melodic contour. For example, playing a theme (1) from the *Two-Part Invention in C* by J. S. Bach (Figure 7) from the A (2) instead of the C converts the melody from major to minor, while when played from the G (3) the melody remains in major. But when the same melody is played from the E (4), the contour’s transformation goes beyond changing the mode and gives an impression of ‘bent’ melodic contour.

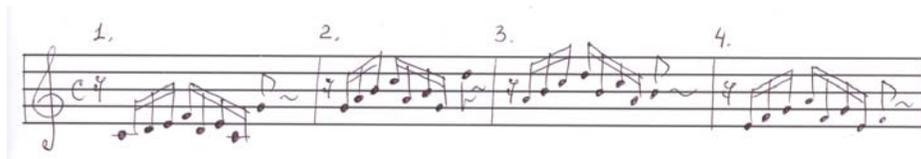


Figure 7: J. S. Bach, *Two-Part Invention in C*: the invention theme in C major when played from C (1), in major when played from G (2), in a minor when played from A (3), a bent theme when played from E (4).

There is another interesting phenomenon in music perception that invites thinking of visual analogues. Dowling (1981) wrote that “Tonal imitations in others keys are confused with transpositions to the degree that their keys are similar to that of the original. The more remote is the key, the less the confusion.” [54]. The transposition into a distant key dissociates a melodic contour from the shared tones of an original key and allows the melody to appear as ‘same’ but on a distance, similar to how a spatial translation is indeed a relocation of an object in such a way that all object’s points are moved along parallel lines, which leaves the shape undistorted. The task of recognizing a visual object as the ‘same but on a distance’ is apparently so simple that Shepard & Cooper does not include it into their list of possible transformations [45]

Bartlett & Dowling (1980) [55] reasoned that “modal scale is temporarily anchored to a specific pitch level, thus representing what we are calling a key. The mode-key schema governs expectations for the pitches of subsequent notes in the melody. The occurrence of a new pitch is disruptive only if it violates the schematic representation of the key. Thus it should not be the occurrence of new notes per se that causes the

impression of dissimilarity but rather the occurrence of notes foreign to the mode-key schema.” While simple shift of a melody along the diatonic scale can generate very different responses depending on a pitch composition of a melody, some of the contour transpositions can predictably produce less drastic results than others. For example, “moderate distance in pitch level and shared pitches” defined choice of target comparison stimuli in Dowling (1987) study *Scale and Contour: Two Components of a Theory of Memory for Melodies*. [56]. Bartlett & Dowling (1980) expressed the view that “key-distance effects reflect musical schemata that are to some degree culture specific but acquired early in life”. [57]. The results of this experiment made authors conclude that “...the invariance across such wide range of age and experience raises the possibility that key-distance effects result from the processing of auditory information in memory in ways that have little to do with music.” Bartlett & Dowling explained the key-distance effect in terms of “repeated and nonrepeated pitches, that is, the greater the number of new pitches in a comparison stimulus, the more different it sounds, and the lower probability of a response of *same*.” As Dowling (1981) pointed “The listener’s strategy leads him to stay within the original key whenever it is possible”. [54]. In other words, our perception seeks for defining points to perform effectively a pattern-recognition task within a given system of reference or system of coordinates.

Memory in music

The tonal schema is generated by tonal relationships among musical sounds. The simplest building blocks of music are musical intervals: a sequence of musical intervals forms a melody. A behavioral study by Dowling & Bartlett (1981) showed that while interval information is more difficult to encode than a melodic contour into short-term memory, it is retained better than a contour in a long-term memory. — “Contour information, though easily extracted, may be rapidly forgotten...while interval information ... is apparently retained with high efficiency in long-term memory.” [57] And though the multi-faceted processing of music and memory consolidation “proceeds automatically”(Dowling et. al 2001) [55], perhaps it is the important role of intoning—which is indispensable for drawing out an emotional response to a musical idea encased into a melodic contour—that makes intervallic information so vital on a long run.

A positron emission tomography (PET) study by Zatorre et al (1994), revealed that listening to melodies, as opposed to noise bursts, activated the right superior temporal gyrus, while a musical memory task, requiring listeners to compare the pitches of the first and last notes of a melody, additionally activated an area in frontal cortex of the right hemisphere. [19] The authors wrote that "The results also indicate a complementary hemispheric specialization in right-hemisphere belt cortical areas for spectral processing. The data provide a unifying framework to explain hemispheric asymmetries in processing speech and tonal patterns. We propose that differences exist in the temporal and spectral resolution of corresponding fields in the two hemispheres, and that they may be related to anatomical hemispheric asymmetries in myelination and spacing of cortical columns." In an fMRI study by Gaab et al (2003) [59] the participants performed a simple task of comparing last two tones in a sequence of sine-wave tones. (The task obviously did not focus on any aesthetical properties of the sound sequences.) The strongest response (signal change) came from the planum temporale—a representative anatomical region for the secondary auditory cortex. Contrary to the Zatorre et al (1994) [19] findings, the Gaab et al fMRI study found that the left hemisphere activation was stronger and slower in decaying.

The Platel et al. (1997) [60] PET study on six males aimed to explore cerebral structures involved in the appreciation of music. Same auditory material was used to investigate the brain activation patterns on familiarity, attention, to pitch, attention to rhythm, and attention to timbre tasks. A between-task comparison showed the increased left hemisphere activations for familiarity (BA 47), pitch tasks (BA 18/19) and rhythm (BA 44/46), and the increased right hemisphere activations for the timbre task. The authors found the pattern activation for the pitch task "the most unexpected" and contradicting "previous experimental work on melodic perception" performed and interpreted by Zatorre. [19]

Janata et al (2002) [50] suggested that the rostromedial prefrontal cortex is the likely brain substrate for the tonal encoding. In their experiment, musically experienced listeners performed two perceptual tasks—detection of timbre change or tonality change—during three sessions separated by one week. On each trial, the participants heard a melody that systematically modulated through all 24 keys. On the timbre task the

listeners were asked to say whether they heard a note played by a flute instead of the standard clarinet timbre. On the tonality task they were asked to say whether there were notes that violated the local tonality. Thus the participants heard the same melody but performed different analysis. The tasks activated several regions in the temporal, parietal, frontal, and limbic lobes as well as the thalamus and cerebellum. The most extensive and consistent was bilateral activation of the superior temporal gyrus (STG), with greater activation in the right hemisphere. Both the task and the tonality regressors correlated significantly and consistently with activity in the rostromedial prefrontal cortex, primarily in the rostral and ventral reaches of the superior frontal gyrus (SFG). The authors supposed that this region might be a site of a ‘tonality map’ because of “the consistent modulation of this area in all of our listeners”. They suggested that “the tonal contexts are maintained in cortical regions predisposed to mediating interactions between sensory, cognitive, and affective information”, and that the medial prefrontal cortex is a “nexus for such functions”. And while the authors suggested that distribution of keys in the tonality map appears in an organized manner (torus-like), they wrote that this topography of tonality is dynamic and “selectivity rearranged itself across scanning sessions”.

Ohnishi et al’s (2001) [61] research on functional anatomy of music perception was conducted with real music—the Italian Concerto by J. S. Bach. They found that listening produced a rightward temporal cortical activation (BA 21, 22) in non-musicians and leftward activation in the homologous areas in musicians. The authors think that “increasing musical sophistication should cause a shift of musical processing, or at least music perception, from right to the left hemisphere.” Moreover, they accept the possibility that “music training not only changes the regions involved in musical perception, but may also change how the music is perceived.”

In a PET study Hervé Platel et al. (2003) [62] researchers used familiar and non-familiar melodies to investigate differences in the brain activation that would identify neural substrates for semantic and episodic memory in music processing. They proposed that musical semantic memory is a memory for well-known excerpts that can be retrieved without temporal and spatial circumstances of encounter, involving “musical lexicon, separate from a verbal lexicon, even though strong links certainly exists between them”.

To my opinion, the existence of such a strong links between musical lexicon and

verbal lexicon is doubtful, and hence this definition of musical semantic memory lacks strength. Like language, music has phrasal boundaries. However, unlike language music does not have semantic certainty of words. An intensive theoretical research on such strong links, particularly by Fred Lerdahl and Ray Jackendoff, did not produce conclusions in support to the direct similarity. It seems that the closest links between music and language are the presence of feeling of a closure (rhythmic and tonal) and an 'intonational envelope', which brings life to both speech and music. Symptomatically, Fred Lerdahl's contribution to a collection of articles comprising *The Cognitive Neuroscience of Music* (2003) was an analysis of Robert Frost's poem [63]

John C. M. Brust wrote in *Music and the Neurologist: a Historical Perspective* [64], "...active retention of pitch requires interaction of right frontal and right temporal cortices." In other words, whatever memory activation is involved, it cannot avoid employing primary neural substrates responsible for cognitive processing of organizational principles of music. However implicit tonal processing in music might be, it belongs to a higher cognitive level than simple pitch discrimination. Moreover, music—as sequence of sounding patterns organized in time—has a strong temporal aspect: in terms of duration.—A melody can be compared with a proverb, not with a word. The temporal constraint places music perception on a different plane when compared to visual images and even to language; while the rhythmicity in poetry and the sense-dictated grouping in prose are function of time, music differs from them in having a rigorous tempo constraint. Music is called the universal language. Here are strong indirect parallels between music and spoken language: phrasing, rhythm, feeling of closure, and 'breathing' that punctuates phrasing. Yet, the direct comparison of music and language does not work for a simple reason that music does not name things. As Aniruddh Patel put it, "Observations ... suggest that overlap in linguistic and musical syntax is not on a level of representation." [65] In speech, same words can present different meaning depending on how they are pronounced, how they are intoned. The melodic line of speech emphasizes a sense of what exactly a speaker wants to say. Artistic expressiveness of music has its strength in the meaning 'behind' words: in an implicit sense of intention. Music is an interesting case for a philosopher because music is able to deliver a concept non-verbally, thus refuting an idea that we think by words. In

comparison with language, music does not possess certainty of symbolic representation—there is no semantic values in the art of music—consequently, music does not have rules of syntactic organization. There are no verbs, nouns, and qualifiers and thus no relationships of kind ‘who did what to whom’ that really give meaning to the word ‘syntax’. Musical concepts—these outrageously non-verbal constructs evidently accessible to the many—are delivered to the listeners by way of the intonational envelope. It is the same carrier that makes us trust the words of some people and doubt other; the intonational information delivers to us the intuitively felt feeling of a psychological state. Perhaps this intonational sensitivity is what kept the art of music on an evolutionary road: A sharpened ear for intonation helps reading of intentions – this can be an evolutionary advantage. Apart from nobility of the art of music that grants us more than pleasure of harmonious sounds but the insight into the very metaphysical essence of being a human, music perhaps is the great adaptational tool of finessing one’s sense of others’ intentions. More than simple communication, music is about intuition.

Intonation is the soul of interpretation, and, like in a spoken language what is said in music depends on how it is intoned. The musical text gives only an approximation of a composer’s thought; it is artist’s personality that steps forward in interpreting the text. Lerdahl reflects on the “intonational phrase, which conveys the melody of speech.” [63] Leos Janacek wrote a following touching tribute to the eloquence of music: “...Sounds, the intonation of human speech, indeed of every living being, had for me the deepest truth.” [66]

Besson and Schon (2001) [67] argue for a possible separate long-term memory subsystem between language and music: Their event-related brain potential study showed differential effect for semantic processing when subjects focus their attention only to the lyrics or to the music of opera excerpts. Brust (2003) wrote that “Left lobotomy resulted in impaired recognition of words alone, and right lobotomy resulted in impaired recognition of tunes alone, but either left or right lobotomy resulted in impaired recognition of melody combined with words. [68] (See also Patel et al, 1998, on processing prosody and music.) [69]. Peretz, (2003) [69] wrote that “the evidence points to the existence of at least two distinct processing modules: one for music and one for speech.” However, the specialization does not preclude the possibility of music and

language sharing certain neural substrate. Samson et al (2001) suggested that “If the left temporal cortex is dominant for fine grained time-related processing of language, it seems plausible to hypothesize that it would also be important for such temporal processing in music.” [70] Recent study by Grandjean et al (2005) found that the right superior temporal sulcus showed increased activation specifically for angry prosody as compared to neutral prosody. [71] Moreover, there exists a difference of opinion on what came first: music or language. “Darwin believed that musical ‘calling system’ evolved into speech, whereas Herbert Spencer believed that music evolved as a stylized form of speech” [64] Houser and McDermott (2003), whose theoretical perspective on the musical faculty was, in their words, in part inspired by Noam Chomsky’s analysis of language, wrote that music is “at least superficially similar to language”. [72] They presented the following explanation to the music faculty: “Human and nonhuman animals ...encode emotional information in their vocalization and have perceptual systems that are designed to respond appropriately to such signals. Given the evolutionary ancestry, our music faculty may well have co-opted this mechanism for use in music, even if it did not evolve for this function.” The authors’ logic thus follows Darwin’s understanding of the role of vocalization in natural selection. This view is in collision with Pinker’s opinion that “as far as biological cause and effect concerned, music is useless.” [73]

Going back to the Platel et al. (2003) [62] study on memory for music, the statistical analysis of imaging data showed that activation of episodic memory produced bilateral activation of the middle and superior frontal gyri and precuneus (more on the right side), while activation of semantic memory produced bilateral activation of the medial and orbital frontal cortex, the left angular gyrus, and mostly left anterior part of the middle temporal gyri. According to the design, the “semantic task” was supposed to involve incidental encoding of the stimuli, which then were to be recalled in the subsequent episodic task. In the two control tasks, one task contained only familiar melodies, and another contained only non-familiar melodies. Comparing the semantic task with control tasks showed left-side lateralization. Comparing the episodic and control task showed right-side lateralization. The results of this study were in agreement with Tulving’s HERA model, which is based on functional asymmetry in favor of the left brain hemisphere for semantic memory search and the right hemisphere for episodic

retrieval. (Concerning visual and verbal memory, the HERA model (Tulving et al., 1994) ascribes to the left prefrontal cortex a preferential role in the encoding processes of episodic material and the recall of semantic information, while ascribes a preferential role the right prefrontal cortex in the recall of episodic information.) [74]. However Habib et al (2003) proposed that both hemispheres are involved in episodic memory. [75] Moreover, there are new evidences that do not agree with the most important aspect of the HERA model—the left hemisphere dominance for semantic memory search in language. For example, Taylor & Regard (2003) stated that “Far from mere supportive tasks, the right hemisphere appears to be functionally dominant for some aspects of language processing (e.g., pictographic reading, metaphor appreciation, and other semantic functions.) [76] It is worth noting that the hemispheric asymmetry of the Tulving’s HERA model was demonstrated in studies where stimuli were of verbal nature; in other words, what Platel et al (2003) identifies as “semantic” is not what Tulving means as semantic.

In their study on music memory, Halpern & Zatorre (1999) [77] claimed that musical semantic memory primarily engages right-side regions. To investigate the nature of mental imagery, they searched for physiological evidence of possibility of imagery and perception sharing actual neural structures. The authors wrote: “To the extend that brain areas known to be associated with sensory processing are active during imagery tasks, we may conclude that brain efficiently uses similar areas both to process information initially, as well as to reactivate it for further processing.” They defined imagery as “perceiving of object when the object is no longer available.” In this research the participants were presented with stimuli that were exclusively musical (the experimenters tried to minimize the involvement of verbal processing structures in the left hemisphere): 15 target melodies and 15 sequences with randomly permuted tones from the target melodies. The stimuli were grouped into melodic themes, cue sequences, and control sequences. The familiar tunes were grouped by their duration: short, medium, and long. This manipulation enabled authors to measure the time taken to imagine the tune; the end point of each tune coincided with the phrase ending. Three conditions were tested during scanning: Cue/Image, Control/Image, and Control

1. Cue/Image condition: listening to first few notes of a familiar tune and imagining the continuation. – Involves working memory and imagery, as well as retrieval from semantic memory
2. Control/Image: listen to a novel tune and then re-imagine it. – Involves working memory and imagery, but not retrieval from semantic memory
3. Control condition: simple listening and then pressing a button at the end of each stimulus. – Involves working memory

The Cue/Image–Control subtraction was intended to capture processes involved into musical imagery. It showed a significant activation within the right inferior frontal gyrus (BA 10/47); in the right frontal cortex (BA 45) and its counterpart in the left but with less level of significance, as well as a bilateral activation of the middle frontal gyrus (BA 46). The only left-side frontal lobe activation was in BA 44. In addition, right superior temporal cortex (BA 9) and the right inferior temporal cortex (BA 19) were activated as well; activation was also found in the SMA (supplemental motor area).

Cue/Image–Control/Image subtraction was intended to separate processing components associated with retrieval of familiar melodies from semantic memory. Activation was shown in the inferior frontal gyrus (BA 10/47), BA 45/46 bilaterally with greater activation on the right, the right STG (BA 6), right inferior temporal gyrus, and in the right thalamus. The authors concluded that these findings “implicate a right inferior frontal/thalamic network in melodic semantic retrieval. There was no activation in the SMA. To the authors, this was sign of the SMA importance in the generation of an auditory image but not in the retrieval task. The authors also accepted an alternative interpretation that the retrieval component in the imagery task may have contained some episodic retrieval.

Control/Image–Control subtraction isolated activity associated with imagery in the absence of any semantic component. No activation in the inferior frontal areas or temporal cortex, but SMA activation was increased as well as activation of left-sided frontal cortical sites.

Cue/Image–Control/Image and Control/Image–Control subtractions were analyzed as Image Generation vs. Retrieval comparison. The Cue/Image–Control/Image subtraction isolated retrieval of melodies from semantic memory, and it showed right

STG activation together with predominantly right inferior frontal cortical activation. The Control/Image–Control subtraction focused on image generation without a retrieval component; it showed activation in the SMA and in several left frontal areas. Taken together, these two substations show an activity pattern similar to that seen in the Cue/Image–Control subtraction. (Figure 8)

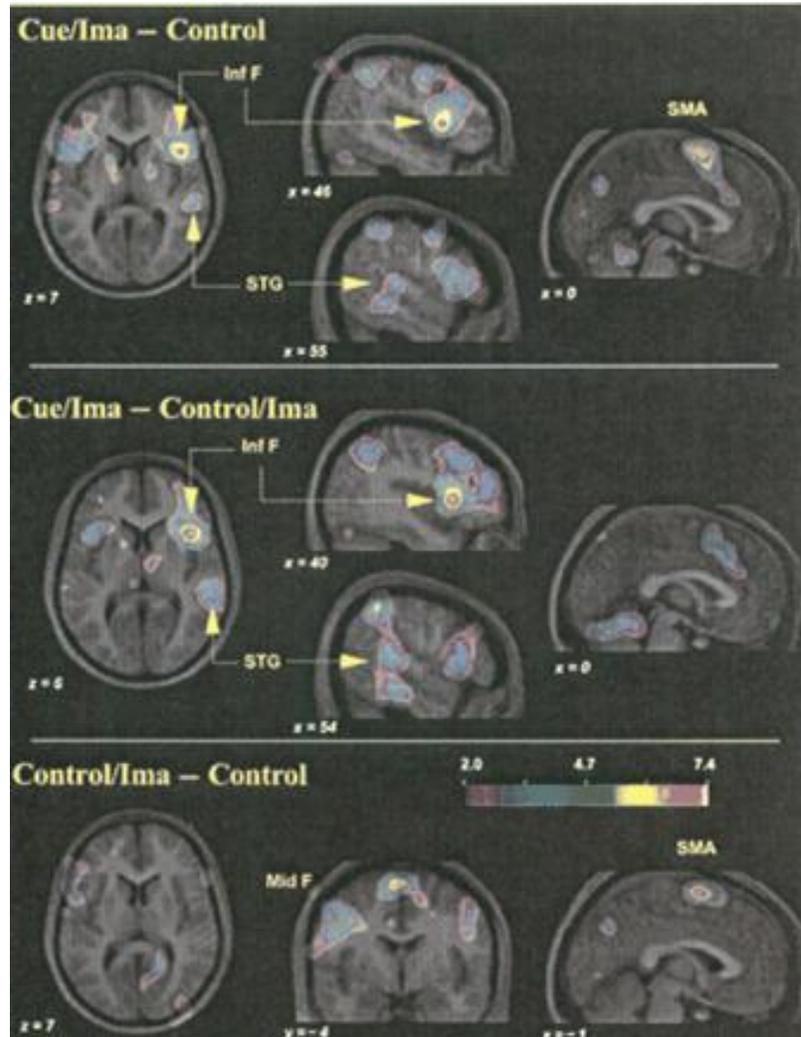


Figure 8: Patterns of activations of the neural substrates underlying the semantic and episodic components of music (Halpern & Zatorre, 1999) [77]

The authors noted that their findings suggested that the imagery task may have entailed some degree of episodic retrieval....”it is possible that some of the activity in the right frontal region may reflect subjects’ retrieval of an episodic memory trace associated with recalling at what point in the melody they were supposed to stop. Nevertheless, the major aspect ...should be the semantic component, since the cue sequence only presented

in the first few notes, and the rest of the tune is stored in long-term memory” Results of Cue/Image–Control subtraction gave the principal finding of this study that confirm the authors’ predictions that activity in the right auditory association cortex, together with supplemental motor cortex, accompanies musical imagery. Breaking the task into two components allowed to find that when imagery had entailed retrieval from musical semantic memory (Cue/Image–Control/Image), it led to activity in a right inferior frontal region and bilaterally in the middle frontal areas (more significant on the right side), together with right auditory association areas in superior temporal gyrus. When imagery did not require semantic retrieval (Control/Image–Control), left frontal areas and SMA were recruited.

There is conflicting evidence on the role of the SMA in generation of an auditory image. Some researchers believe that SMA is important for ‘singing to oneself’ during the imagery task. Halpern (2003) that “...parts of the cortex specialized for processing actual sound are also recruited to process imagined sound.” [78] However, other studies point toward more universal presence of SMA activation in the music processing: Graham (2004) [79] found consistent SMA activation during meter-rhythm tasks that did not include any vocalization.

Only associative cortical regions, not primary sensory regions, were active in the imagery task: no activation in primary auditory cortex was shown in music imagery task. This pattern of activation supports the hypothesis of cortical perceptual areas ability to mediate internally generated information. The study is in accord with previous findings that mechanisms within the right hemisphere are specialized for processing tonal patterns. Moreover, Halpern & Zatorre results show that the right-hemisphere specialization extends beyond perceptual analysis to encompass complex tonal imagery processes. The authors noted two surprising aspects of the Control/Imagery–Control subtraction. The first was an absence of the right STG activation, which was explained by the short duration of the stimuli. The second aspect was activation in several left frontal sites. The authors reasoned that the areas activated in the left frontal lobe are related to working memory: imagined stimuli were novel. They also concluded that the SMA is involved in motor processes relevant for auditory image generation, irrespective of the familiarity of the stimuli. Similarly, Patel (2003) mentioned that “we found evidence for strong

functional coupling between left posterior hemisphere and right hemisphere regions during the perception of melody-like sequences”. [80] In an event-related brain potentials (ERPs) study by Peretz (1990) [81] “brain waves elicited by chords with unexpected notes revealed two ERP effects: an early right-hemispheric preponderant-anterior negativity, which was taken to reflect the violation of sound expectancy; and late bilateral-frontal negativity. The late negativity was larger compared to in-key chords and taken to reflect the higher degree of integration needed for unexpected chords.” The results showed that “the amplitudes of both early and late negativities were found to be sensitive to the degree of musical expectancy induced by the preceding harmonic context, and to the probability for deviant acoustic events.”

A fundamental principle of memory holds that encoding and retrieval processes are strongly interdependent (Nyberg et al 2000) [82] An imaging study by Warrier & Zatorre (2004) [83] found that the right anterior auditory cortical areas were implicated in “making pitch judgments relative to tones that were heard previously” and that “the auditory association areas located on the anterior portion of the superior temporal gyrus, an area with connections to frontal regions implicated in working memory, could be involved in holding and integrating tonal information”. In this study, the participants were asked to make pitch judgments on complex tones that could differ in fundamental frequency and/or spectral shape (that is pitch and timbre). To perform this task it is necessary to extract the fundamental frequencies from both sets of harmonics and compare them. (Perceptual constancy is the ability to recognize things as being the same under different conditions. For example, pitch constancy is necessary to hear that a flute and a piano are both playing middle C.) It appears that placing a tone within the context of a melody enhances the pitch perception of that tone by establishing a reference point from which to judge pitch. When the fundamental frequency component was removed from each tone, patients with right temporal lobe lesions that included Heschl’s gyrus were impaired on music perception.

The participants were thirty six patients with temporal lobe excisions for relief of pharmacologically intractable epilepsy: eighteen of them with the temporal lobe excisions on the left (LB) and another eighteen – on the right (RL), and twelve control participants. All resections in the patients included the amygdala, uncus and anterior temporal lobe in

one hemisphere. There were two test conditions. In the isolated context condition, each trial consisted of two tones presented with an inter-stimulus interval (ISI) of 100 ms. The second tone was either same or 35c or 52c higher than the first tone. In the melodic context condition, the task was to determine whether the last note of a melody was in tune; the stimuli were well known tunes like “Oh, Susanna,” “The Blue Danube.” Each melody was presented in one of the spectral shapes. The results show that in the isolated context (pitch condition), the overall scores were highest in the + 52c condition, in which patients with the RL scored significantly lower than controls in both +35c and +52c conditions.

In the melodic context (timbre condition) all groups showed improvement; however the RL improved significantly less than the control group. The authors concluded that “the deficit seen in the RT group can be attributed to the excision of the anterior areas of the temporal lobe, excised in all RT patients. This implies that anterior portions of the auditory cortex are involved in making “pitch judgments relative to tones that were heard previously.” The anterior portion of the superior temporal gyrus (STG) contains auditory areas with connections to the superior temporal sulcus and to the frontal and paralimbic areas that have connections with dorsolateral and inferior frontal regions. The dorsolateral and inferior frontal regions areas are known to be involved in working memory. Studies with patients suffering brain damage point towards importance of the anterior and superior portion of the STG. For example, Peretz (1996) [84] wrote about patient C.N. with bilateral temporal lesions who was unable to memorize new tunes and did not show a priming affect; the latter suggests abolished access to encoding specific to music. Heschl’s gyrus (HG) showed the same activity on melodic and random sequences and when pitches did not change. However, the anterior portion of the right superior temporal gyrus, in addition to the right temporal superior temporal sulcus, was more active during changes of pitch. The data from this study support the view that the Heschl’s gyrus is involved in short-term pitch processing, and that auditory regions outside the Heschl’s gyrus are responsible for longer-term pitch processing involving comparisons across sequences of tones. As for the detected cerebellar activation, it is known that the lateral cerebellum is involved into timing, for instance, in response to reproduction of intricate rhythms. Penhune et al (1998) wrote that the cerebellum

“provides the necessary circuitry for the sensory system to extract temporal information” [85]. Parsons (2003) provided fascinating data that implicates cerebellum in music perception: “As a group...patients with pancerebellar degeneration...show strong impaired pitch discrimination...proportional to the severity of their pancerebellar ataxia,” [86] and Griffiths (2003) [87] wrote that while processing simple note-sequences and note-duration “activates network that is distinct from the primary auditory cortex” and that highly significant activation was demonstrated in both lobes of cerebellum along with bilateral activation in the posterior superior temporal planum in the region of the planum temporale, and in both frontal opercula [rightward]. Studies by Ivry et al (1989) [88] and Lanmgheim et al (2001) [89] also implicate the cerebellum in music processing. Volumetric imaging studies by Schlaug (2003) [90] showed that professional musicians (males) have larger cerebellum than non-musicians: the relative volume difference is about 5%. And Hutchinson et al (2003) [91] found that “lifelong intensity of practice” positively correlated with “relative cerebellar volume in the male musician group.”

The fMRI research by Lanmgheim et al. (2001) [89] investigated process of musical cognition during imagined musical performance (IMP) that excluded a direct involvement of sensorimotor and auditory components of active music making. The investigators used blood oxygenation level-dependant (BOLD) fMRI during imagined performing, listening, and motor task. The study was arranged in four interleaved blocks of rest and musical performance, each 30-second long, thus creating a 4-minutes period. Participants’ eyes were closed at all time; before switching task, participants tapped upon the ankle. For each imagined performance task, musicians were asked imagine their musical selection from measure one, in order to avoid mental searching in time. The participating musicians—two violinists, one pianist, and three cellists—practiced their musical selections during the weeks prior to participation in the study. By mapping the blood oxygenation level-dependent fMRI activation response to imagined performance in the experienced musicians, the researches found consistent activation in the supplementary motor and premotor areas, right superior parietal lobule (BA 7), bilateral lateral cerebellum, bilateral mid-frontal gyri, right superior (B 6) and inferior frontal gyri (BA 45/47). Imagined musical performance showed greatest activation in the superior parietal lobule (BA 7) “that has been implicated in encoding/retrieval and complex

cognitive processing tasks such as working memory and selective attention.” Also, when compared to a rest-task, IMP generated relative decrease in activity in the right precuneus (BA 18/31), right superior temporal gyrus (BA 22), and right middle temporal gyrus (BA 21). The motor cortex activation was absent during IMP. The data suggest that imagined musical performance is not tightly tied to the primary sensory-motor and auditory regions, and that there are integrating cortical pathways that combine temporal- and pitch-related information in performance. These pathways create a network that involves the prefrontal cortex, parietal cortex, and the lateral cerebellum; they coordinate the spatial and temporal components of musical performance and function independently of the sensory-motor and auditory cortices. Instead of the sensory-motor and auditory cortices, the premotor and supplementary motor areas appeared active during IMP. In comparison, the spatial activation of supplemental motor area was smaller during fingertapping, which is a very simple task. Itoh et al, 2001, found that in musicians, during piano performance, “unilateral supplementary motor area activation was correlated to motion of the corresponding contralateral hand.” [92]

Musicians’ Brains

It has been known long before the ‘imaging era’ that the brains of musicians differ from the brains of non-musicians because of a larger corpus callosum, a sign that points towards a greater bi-laterality of the musicians’ brains. With the advent of imaging technology the brains of musicians invited special interest because professional musicians present a strong case for the brain plasticity. Schlaug (2001) wrote that “the musician is apparently an ideal model to investigate functional and structural adaptation of the motor and auditory system.” [93] Mastering a musical instrument requires years of consistent practicing to develop and maintain a high level of dexterity. Moreover, conceptualizing a complex musical composition most likely generates a special way of thinking. The structural differences that have been found up to date between brains of musicians and non-musicians suggest different ways of cognition. The difficult question is whether the structural differences between musicians and non-musicians are the result of nature or nurture.

A behavioral study by Brandler & Rammsayer (2003) [94] investigated differences in psychometric performance between musicians and non-musicians. The participants—35 adult musicians and 35 non-musicians—were tested on different aspects of primary mental abilities: verbal comprehension, word fluency, space, closure, perceptual speed, reasoning, number and memory. Both groups were matched for sex, age, and formal academic education. A correlation analyses of the data suggested different relations among aspects of intelligence for musicians and non-musicians, which led the authors to conclude that the differences between the two groups “are suggestive of different conception of intelligence of reasoning.” The mean scores showed that the non-musicians preformed better on series, classification, matrices and topology, while musicians had higher performance on verbal memory. After performing a correlation analyses, the researchers completed Principal Component Analysis (PCA)—separately for musicians and non-musicians—“to further analyze the dimensional structure of intelligence.” For the musician group, the first factor was characterized by verbal comprehension, space, perceptual speed and number. The second factor was associated with reasoning ability: it showed high negative loadings for all four reasoning tests, which was interpreted as demonstration of lack of reasoning in musicians. The non-musician group PCA yielded one factor, eigenvalue=4.28 that accounted for 32.91 % of the variance; all mental tests had positive loadings on this factor. In the authors’ opinion the mental tests in the non-musician group indicated a stronger source of shared variance, while results of the musicians’ group indicated a more diversified structure of mental abilities. The authors interpreted the results as a reflection of a less analytical and more intuitive way of thinking by musicians and suggested that the musicians’ group presented “right-hemisphere cognitive style that is associated with musical talent.” In authors’ opinion, having as dominant the ‘emotional brain’ (right-hemisphere) “impairs reasoning performance.” They also think that in addition to the innate differences, the extensive training leads to “cortical reorganization” in the left hemisphere that gives advantage of a better verbal memory. The most interesting part of the paper concerns fundamental explanation of the differences in the mental abilities of musicians and non-musicians: The authors think that the poor reasoning is the price that the musicians pay for their innate talent. Yet, there are points to contradict this verdict. First of all, musicians have a

particular kind of education that generally does not favor science and the scientific way of reasoning in general. Also, being an excellent musician does not mean being a professional musician: Alexander Borodin, Max Planck, Albert Einstein and a legion of others demonstrated formidable reasoning abilities despite great fondness for and proficiency in music.

Imaging study by Schlaug (2001) [90] found that musicians, as compared to non-musicians, have the significantly larger anterior part of the corpus callosum. Moreover, among the musicians the larger anterior corpus callosum was found in those who began music studies earlier as compared to both those who began later, as well as controls. The anterior part of the corpus callosum contains many fibers from frontal motor-related regions and prefrontal regions. Thompson et al (2005) [94] wrote that “callosal development may be an activity-dependent process.”

Gazer & Schlaug’s (2003) [95] MRI study presents a comprehensive overview of the structural differences between musicians and non-musicians. This study’s findings suggest that musicians have their special way of performing the motor, auditory, and somatosensory tasks. The findings have two interpretations: either we observe a direct result of years of intensive music practicing, or this special anatomy is a pre-requisite for advanced skills demanded by the art of music. The participant of this study were 80 men aged 18-40: 40 non-musicians, 20 professional pianists (at least 1 hour daily practice), and 20 amateur pianists. The researchers used voxel-based morphometry (VBM) that deals with local composition of brain tissue. First, images were spatially normalized to a standardized anatomical space, gray and white matter were extracted from the normalized images, and then differences in local volume of gray and white matter were analyzed across the whole brain. (Figure 9) After that the images were analyzed on regionally specific differences, voxel by voxel *t*-test was used to identify differences on white and gray matter between musicians, non-musicians, and amateur musicians. Three-level gradation was assigned (arbitrarily): musicians - 1, non-musicians - 0, amateur musicians - 0.5. The analysis included only homogeneous voxels to avoid edge effect around white matter–gray matter border. All statistical images were thresholded at $p < 0.05$ and corrected for multiple comparisons: only clusters with a minimum of 225 voxels reported. The results show that the musicians, as compared with the non-musicians, have

greater gray matter volume in perirolandic regions bilaterally: in motor and somatosensory areas (B 4, 5); premotor areas (B 6); anterior superior parietal areas (B 5, 7); inferior temporal gyrus (B 20) (Figure 10). Additional positive correlations were seen in the left cerebellum (Figure 11), the left Heschl’s gyrus (B 41), (when the spatial threshold was lowered to 225-190 voxels, the positive correlation became bilateral), and left inferior frontal gyrus (B46).

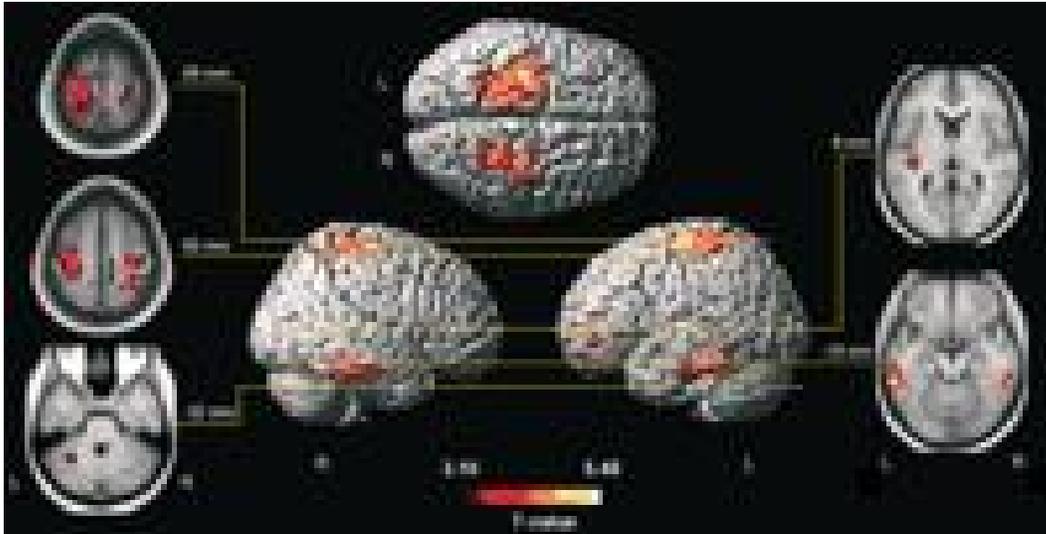


Figure 9: Brain regions with gray matter differences between professional musicians, amateur musicians, and non-musicians. The axial slices show the overlay of the results onto the average of all 80 anatomical images. (Gazer & Schlaug, 2003) [95]

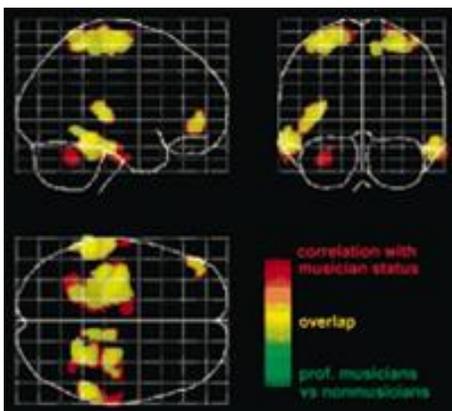


Figure 10: Results of the direct comparison between professional musicians and non-musicians (green), the correlation with musician status (red), and the overlap between two results (yellow—as a mixture of green and red). (Gazer & Schlaug, 2003) [95]



Figure 11: Location of cerebellar gray matter effect (Gazer & Schlaug, 2003) [95]

The researchers reasoned that in musicians the left Heschl's gyrus (B 41) has structural differences associated with ways musicians listen to musical sounds. The superior parietal region plays important role in integrating multi-modal sensory information—visual (“where”), auditory, somatosensory—and has intense reciprocal connections with the premotor cortex. There was no correlation found between white matter volume and musician status. Surprisingly, the study found differences neither in the planum temporale nor in the corpus callosum. Additionally, a comparative analysis of available data from previously done anatomical and functional MRI studies on 51 classically trained, professional musicians and 39 non-musicians showed that the musicians differ significantly from the non-musicians by having an increased left-sided asymmetry of the planum temporale. In author's words, in musicians “asymmetry of dominance of certain homologue structures can have functional implications.”

Schlaug (2001) [90] found that all participants—AP musicians, non-AP musicians, and non-musicians—showed a pronounced activation of the left-sided superior temporal lobe in the phonemes vs. control task comparison; similar activations were seen in the tones condition for the AP musicians. However, the non-AP musicians, as well as the non-musicians, showed either symmetric or right-sided activation of the superior temporal lobe in the tones task. The author hypothesized that musicians with Absolute Pitch (AP) would perceive tones as well as phonemes categorically, while non-AP subjects would only perceive phonemes categorically but not musical tones: “the left planum temporale, or, more generally, the left superior temporal lobe, might be the mediator for a very specific kind of perception, categorical perception, which may underlie absolute pitch perception. Also, AP musicians showed a distinct activity more posterior in the left posterior superior temporal lobe than in the non-musicians. An ongoing longitudinal study on a large group of children (Schlaug et al, 2003) aims to investigate an effect of music training on developing brain [96].

A relatively new method of fractional anisotropy (FA) allows us to detect the white matter organization on a microstructural level, which is not readily assessable by other means *in vivo*. The fractional anisotropy indicates the degree of directionality of water diffusion and has a range from a zero, in the case of completely isotropic diffusion, to one, in the case of completely anisotropic diffusion. In white matter, water diffuses more easily along axons than perpendicular to them, and increased organization of white matter tracks is reflected in increased FA values. The highest FA values are found in the internal capsule, where many parallel fibers in a tight space require a high degree of organization. Schmithorst & Wilke's (2002) [97] diffusion tensor imaging study was conducted on six non-musicians and five musicians with at least 10 years of musical training. The study found significant changes in FA values between those with musical training since childhood and non-musicians: Musicians displayed significantly less FA in the corona radiata and the internal capsule, which was interpreted as the effects of intensive motor training. This investigation showed smaller functional anisotropy in the internal capsule and greater FA in the cerebellum in musicians as compared with non-musicians. (Figure 12) It is known that during normal development, as an individual grows, fractional anisotropy increases in the corona radiata and the internal capsule. The FA increase apparently reflects the normal development of motor control, particularly the control of fine movements of fingers. Yet in musicians FA decreases in the corona radiata. This seems particularly intriguing when presented along with the facts that string players have greater cortical representation of the left hand (that is a hand which fingers perform feats of virtuosity) [98, 99], and that professional pianists showed significantly weaker hemodynamic response in the cerebellum in response to motor tasks in Koeneke et al's (2004) [100] fMRI study. In other words, the primary motor areas exhibit a lesser degree of involvement in musicians than in non-musicians. In regard to the string players, the finding shows that the greater cortical representation is not necessarily a sign of greater white matter organization. As for the weaker response of the primary motor areas in the professional pianists, it might suggest that professional pianists have different brain pathways for the incredibly complex motor tasks that are the norm in serious piano performing. Both the cerebellum and striatum are necessary for the learning of the fine movements that are repetitive and temporally accurate. The authors think that extensive

musical training produces “automated movement” circuits of the striatum and cerebellum, which cause changes in white matter anatomy. (The cerebellar function includes maintaining equilibrium, coordinating muscle action in both stereotyped movement (e.g., gait) and non-stereotyped movement, and synchronization of muscles that act as a group.)

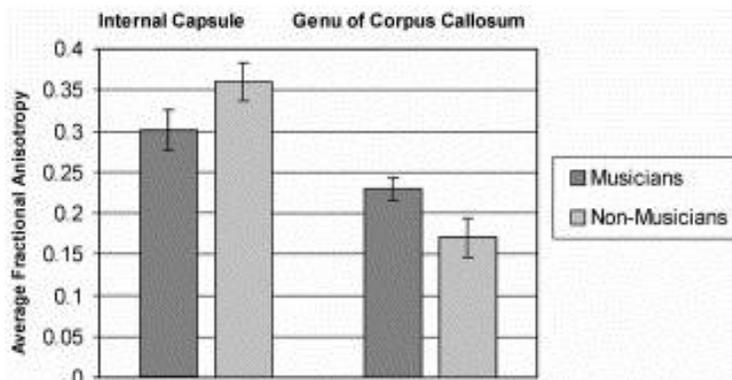


Figure 12: Smaller Functional Anisotropy in the internal capsule and greater FA in the cerebellum in musicians as compared with non-musicians. (Schmithorst et al, 2002) [97]

Perhaps what authors called the “automated movement” circuits indicate an economical way of performing various everyday tasks without heavy involvement of energy-expensive higher neural activity. It is possible that the professional musicians develop strings of quasi-reflexes that support the dexterity of the motor memory. (It actually could be detrimental to a musician to analyze these series of movements consciously.) Music making weaves highly complex series of movement while producing sound structures that are rich intellectually and emotionally. This is the result of the “concerted neural activity in a widely distributed cortical space.” (Haxby et al, 2001) [98]

The differences in white matter organization revealed re-organization of the white matter in response to the very well learned complex motor tasks. In experienced musicians the cerebellum and striatum assume the task of supporting the repetitive and highly complex series of movements of musical performance. The elemental motor programs become assembled into a time-series of movements that then are redirected by the corticospinal tract (corona radiata and internal capsule) to the cerebellum and striatum. The weaker hemodynamic response to motor tasks in musicians reminds us of

diminished activation of the amygdala in response to danger when ways to escape the danger had become acquired.

Researches on FA provide additional data on differences in corpus callosum between musicians and non-musicians. The Schmithorst & Wilke (2002) [101] FA study outlines the presence of significantly greater fractional anisotropy in the corpus callosum, (Figure 13), which was explained as the result of cognitive processes involved in music study. The authors conclude that “intensive musical training leads to distinct changes in white matter architecture.”

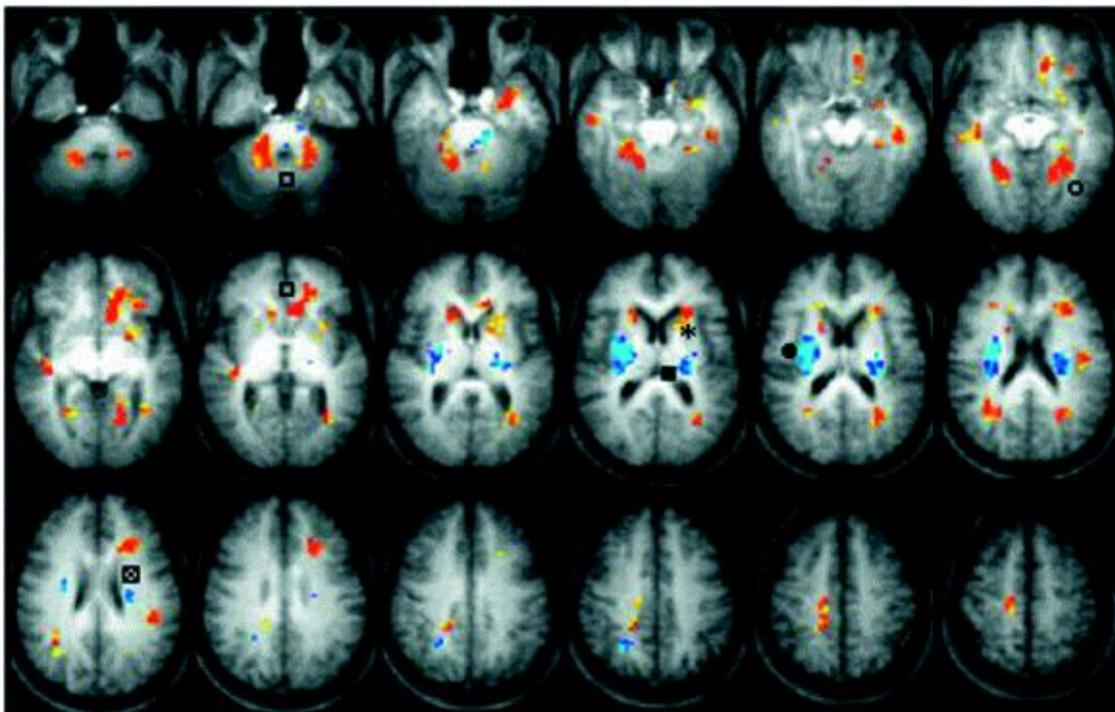


Figure 13: Areas where FA is significantly greater (red): cerebellum, left and right inferior longitudinal fasciculi, corpus callosum, and the left and right caudate and putamen. Areas where FA is significantly smaller (blue): thalamus, right external capsule/clastrum, left and right internal capsule and corona radiate (Schmithorst et al, 2002) [101].

Schlaug et al (1995) [102] inform us that the differences in the corpus callosum are especially pronounced among musicians who began training before the age of seven: their corpus callosum is 10-15% thicker than in non-musicians. The researchers suggest that because frontal cortical areas are involved into recognition and recollection of

familiar musical sounds, it leads toward increase in the callosal fibers that connect these areas. Perhaps, the increase in bilaterality helps the hemispheric functioning synergistically. Recently Compton et al (2005) [103] showed that “...individuals with more efficient interhemispheric communication displayed superior performance on cognitive tasks” and suggested that it is the utilization of the resources of both hemispheres that makes the cognitive performance better. A PET study by Cabeza et al (2002) [104] revealed that older adults who performed well on a memory task showed increased bilaterality of brain activity. The finding supports the “compensation hypothesis of age-related hemispheric asymmetry reduction.” While the young and low-performing older adults both demonstrated lateral activity in the right anterior prefrontal cortex, the high-performing adults showed bilateral activation (Figure 14). The authors suggested that the “additional contralateral activity ... compensated age-related memory decline by reorganizing memory networks.” It is tempting to think that music making helps keeping the brain in good shape by increasing the bilaterality.

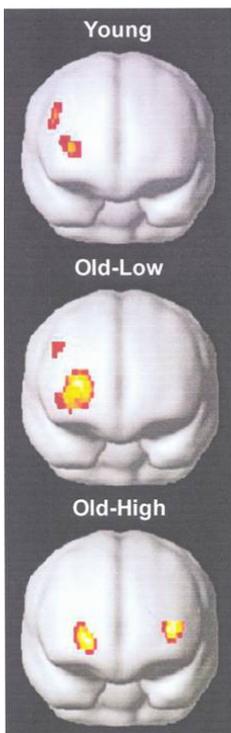


Figure 14: PFC activity during source memory task was right-lateralized in Young and Old-Low performing participants but bilateral in Old-High performing participants (Cabeza et al, 2002) [102]

The Schmithorst & Wilke’s (2002) [97] comparative study on functional anisotropy in the brains of musicians and non-musicians emphasizes importance of the subgenual region of the PFC for emotional states: This region is connected with

amygdala, the lateral hypothalamus, the nucleus accumbens, the noradrenergic, serotonergic, and the dopaminergic systems of the brain stem. The researchers wrote that “emotional perception of music develops early in childhood,” which perhaps speaks for the brain that leans toward greater emotional sensitivity genetically. Besides stimulating fine finger movements and touch, music-making aids to the development of auditory sensitivity, imagination, and the discipline of timing. In regard to the brain’s hemispheric bilaterality, it seems that consistent music training—which demands multi-modal integration—helps brain maturation by developing greater emotional and tactile sensitivity and abstract thinking.

Differences in processing music between musicians and non-musicians begin on a level of non-melodic pitch memory. Gaab & Schlaug’s (2003) [105] fMRI study demonstrated that in the sparse temporal sampling “musicians showed more right temporal and supramarginal gyrus activation while non-musicians had more right primary and left secondary auditory cortex activation.” They explained the difference as a consequence of musical training in musicians who use brain regions specialized in short-term memory while non-musicians rely more on brain regions that are important for pitch discrimination.

Gender and musicianship effect

When Luders et al (2004) [106] analyzed hemispheric gray matter differences within a group of 60 professional male-musicians, their analysis revealed extensive rightward gray matter asymmetries in the frontal and prefrontal lobe, the superior temporal lobe, the posterior parts of the inferior and medial temporal gyrus, and the temporal pole. (Figure 15) In addition, more focal rightward gray matter asymmetries were detected in the superior parts of the pre- and postcentral gyrus, the inferior and superior parietal lobe, the cuneus, cingulate, and lingual gyrus, as well as the orbital and medial occipital gyrus. The researchers suggested that the hemispheric asymmetry of the caudate nucleus, which is connected with secondary auditory areas, is directly related to presence of AP. The study showed a “significantly increased leftward gray matter asymmetry in the anterior part of planum temporale region in male AP musicians.” Janata et al. (2002) reported that the auditory cortex in professional musicians is 130% denser

than in non-musicians. [50] Also, Luders et al (2004) [106] found significantly increased leftward gray matter asymmetry in male-musicians in a region posterior to the central sulcus. This finding gives support to the results of an imaging study by Sadato et al (2000) [107] that discovered that on a tactile discrimination task females showed bilateral activation of premotor cortices while males showed an asymmetric activation. In regard to “unusually pronounced rightward gray matter asymmetries in musicians” the researchers reasoned that size of the precentral gyrus may be a consequence of consistent practice in instrumentalists.

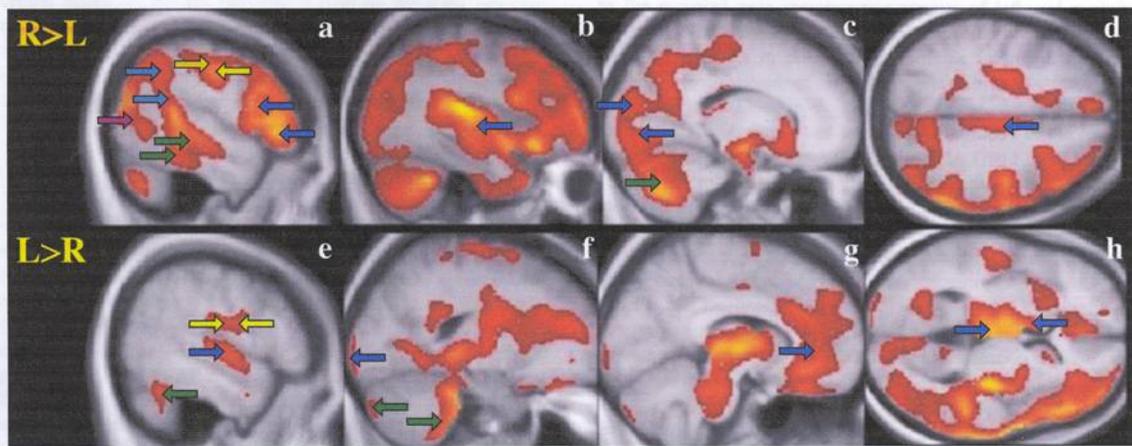


Figure 15: Brain regions with significant hemispheric gray matter differences in a sample of 60 professional musicians. Rightward asymmetries (R>L): the frontal and prefrontal lobe, the mesial superior temporal lobe, posterior parts of the inferior and medial temporal gyrus, superior parts of the pre- and postcentral gyrus, inferior and superior parietal lobe, cuneus and lingual gyrus, cingulated gyrus, medial occipital gyrus, some regions of cerebellum. Leftward symmetries (L>R): superior temporal gyrus including Heschl’s gyrus and anterior portion of planum temporale, inferior parts of pre- and postcentral gyrus, mesial frontal lobe, thalamus and caudate nucleus, occipital pole, and cerebellum. (Luders et al, 2004) [106]

Other regions showing rightward asymmetry are the fronto-temporal network responsible for the auditory-motor mapping tasks and the superior parietal lobe. As in their other studies [108, 109], Schlaug and colleagues found “a significant musicianship effect in corpus callosum size [in male-musicians] while females did not show a

significant effect.” There was also a “dominant rightward asymmetry in most of the cerebellum.” The cerebellum, which contains about 70 percent of the brain's neurons, was found to be about 5 percent larger in professional musicians than non-musicians. [90] The authors wrote that “specific hemispheric differences in musicians could reflect the innate ability to become a professional musician or acquire exceptional skills like AP.” Yet Schlaug believes that “Musicians are not just born with these differences [in gray matter].”

Gaab et al's (2003) [110] fMRI study employed a pitch memory task to investigate possible differences in hemispheric processing between males and females. The study showed that male subjects had greater leftward lateralized activations in anterior and posterior perisylvian regions and a greater cerebellar activation than females. However, even while the activation patterns differed, it was not translated into behavioral performance differences between the males and females. The data showed that males rely more on left lateralized hemispheric processing even for basic pitch tasks. Hassler (1991) [111] found, remarkably, that “composers of both sexes were physiologically highly androgynous.” The tendency was explained as a result of associated with creativity testosterone level, which “minimized sex differences.”[112]

A comparative study on gender effect, Good et al 2001, [113] performed a voxel-based morphometric analysis of 465 normal adult human brains. The study concluded that there are morphometric, histological, and time-of-the-month-related differences between the brains of women and men. The study found global asymmetry—common to all groups—in the left occipital, right frontal and right temporal lobes. Mean grey matter volume was significantly greater in men and the percentage of total intracranial volume was also significantly greater in men. Regionally, males showed a significantly increased grey matter volume bilaterally in the amygdala, hippocampus, entorhinal, perirhinal cortex, and in the anterior lobes of cerebellum, and left anterior superior temporal gyrus. In homosexual men the interstitial nuclei of anterior hypothalamus were smaller. In comparison, females showed a significantly increased grey matter volume in the right middle temporal, lateral orbital and left parahippocampal gyri, in the left transverse temporal (Heschl's gyrus = B 41) and both inferior frontal gyri, in the right planum temporale, and within the right inferior parietal and cingulate gyri. There was also

increased grey matter volume in the banks of the superior temporal sulcus and in the banks of both central sulci. Females have significantly increased grey matter concentration extensively and relatively symmetrically in the frontal, posterior temporal and parietal cortical mantle, parahippocampal gyri, adjacent to the caudate head and within the banks of the cingulate and calcarine sulci.

There was white matter asymmetry adjacent to the areas of grey matter asymmetry. There was a significant interaction of sex with asymmetry: with increased leftward asymmetry adjacent to Heschl's gyrus and, globally, a mean white matter volume was significantly greater in men. Men have significantly increased white matter extending into the internal capsule (temporal stem), and a significantly increased white matter concentration bilaterally in the anterior temporal and posterior frontal lobes. Females have a significantly increased white matter volume bilaterally in posterior frontal lobes and in the left temporal stem/optic radiation. To the researchers' surprise, they found no interaction of handedness with asymmetry in the regions previously described as affected (left posterior temporal lobe, central sulci, left occipital lobe). The grey-white matter absolute volume ratio and fractional volume ratio were the same for both genders.

Neuroanatomy of emotion

Davidson and Irwin (1999) [114] identified the prefrontal cortex (PFC) and the amygdala as "two key components" in the neural network responsible for emotion and affective style. The prefrontal cortex is important for planning and executing goal-directed behavior and for short-term memory. The PFC is also a part of circuitry that implements both positive and negative affects: medial PFC (B 10/32 and B 24/25) produce greater activation during emotional conditions as compared to neutral control conditions, while different areas of PFC respond to either positive or negative stimuli or both. There was a significant decrease in the right superior PFC blood flow during induced states of happiness. Generally, being depressed is viewed as a disease; yet, abnormal placidity and imperturbability are not perceived as impediments. Damasio (2003), presents in pragmatic terms of neuroscience Spinoza's idea that conscious

striving for joy and inner peace is our true spiritual goal that improves our chances for a healthy and happy life and hence for a longevity. [115].

The amygdala is known to be important for the perception and production of certain negative emotions and for aversive learning. [116, 117, 118] Electrophysiological measures and PET show greater activation in the right side of the brain during the production of negative affect, and left-side activation during the production of positive affect. Observations show that the majority of patients who have damage to the left dorsolateral PFC are more likely to develop depression than patients with damage to the right dorsolateral PFC. This has been interpreted as evidence of disruption in the cortical real estate that contributes to positive affect: Depression thus is explained as a consequence of deficit in positive affect. The data show that an increase in glucose metabolism is proportional to severity of depression: easing of depression coincides with recovering of normal blood flow in the amygdala.

Emotions represent a subconscious assessment of stimuli: It seems that the dopamine system is essential to the creation of positive affect. Along with the prefrontal cortex and amygdala there are other regions involved in emotion processing: the ventral striatum, anterior cingulate and insular cortex. The anterior cingulate cortex (ACC) seems to be a site of attentional processing. The insular cortex showed activation in response to diverse stimulation, which was interpreted as a sign of visceral representation in this cortical region. In comparison to positive affect, detection of negative affect has the advantage of a quicker reaction, because registering negative information is essential to survival. Danger of any kind elicits a fast and clear response, which generally works even before adverse information reaches level of conscious consideration. The imaging data shows that the amygdala is the superstar of negative affect, while the ventral striatum — and particularly the nucleus accumbens—is essential to generating positive feeling. Our brains, in fact our whole body, spend more energy and time on processing negative information than on processing positive information. The explanation is most likely within the same concept of primacy of survival that translates into allocation better resources to processing of any threatening stimulus than to non-threatening ones. In psychology this is known as a “negativity bias,” the definition that has its roots in Walter Cannon’s concept of “emergency response to flight or fight.” [119]

This innate greater attentiveness to negative stimuli may perhaps explain why in the fine arts some ideas dominate over others. When thinking of the art of music, one cannot fail to notice that images of sadness, tragedy and melancholy prevail over expression of joy or light-heartedness. Moreover, it is not just a sheer number of compositions expressing sadness but the depth and subtleties of representation of sorrow and anxiety that separate this kind of music from a ‘happy’ one. Indeed, great music gives listener a spiritual gift of cathartic experience. Possibly in music we encounter the same universal principle of the greater attentiveness to negative stimuli that quietly governs our general state of mind in everyday life.

Music and spatial task performance

The Mozart Effect

Rauscher et al (1994) described the Mozart Effect as “transitory increase of certain visuo-spatial scores following listening to a particular Mozart sonata”. [120] The original study, Rauscher et al (1993) [121], examined how 10-minutes listening to Mozart’ Sonata for Two Pianos in D, K 448 affected the spatial IQ of 36 psychology students. The investigation revealed 8-9 points higher score among those who listened to Mozart as compared to those who spent 10 minutes either in silence or listening to taped self-hypnosis instructions. The facilitation effect lasted 10-15 minutes. The Mozart Effect was found in a replicated study (Rauscher et al, 1993), which had music by Philip Glass and a “highly rhythmic dance piece” as a control to the Mozart’s Sonata. [122] The research on adults has been followed by studies on children. An 8-month-long study by Rauscher et al (1993) [123] of 37 preschoolers aged from 3 years to almost 5 years, 22 of whom received musical instructions and 15 did not, showed that musically trained children “had significantly higher scores on visuo-spatial task.” The authors concluded that, unlike in adults, music training can provide long-term facilitation in children, particularly in very young children “in whom cortex is still maturing”. However, other researchers found that “the Mozart Effect is difficult to replicate” (Schellenberg, 2004.) A study by Thompson et al (2001) found that the short-term effect of listening to Mozart on spatial abilities is “artifact of arousal and mood” and depends on personal preferences; a preferred stimulus could be a lovely piece of music for some and an interesting story for

others. A Sarnthein et al (1997) [127] EEG study on Mozart Effect showed “presence of right frontal and left temporo-parietal coherent activity induced by listening to Mozart which carried over into the spatial-temporal tasks in three of our seven subjects”. Since the effect was present in less than the half of the participants the study provides seemingly unconvincing results.

Mental Rotation in Visual and Acousmatic Space

Our behavioral study, Dowling & Korsakova-Kreyn, 2005, *Mental Rotation in Visual and Acousmatic Space*, is aimed to find a correlation between music perception and visuo-spatial processing. The study’s experimental paradigm treats melodic contours as objects within the tonal chronotop. The experiment combines two tasks: auditory and visual. The auditory part presents melodies in its standard and altered form. The melodic transformations that were used in the experiment belong to the standard polyphonic technique’s transformations and can be metaphorically explained as the auditory analogues of object-rotation in 3D space. The visuo-spatial task in our experiment was a simplified replica of the classic Shepard & Meltzer (1971) experiment on mental rotation. By selecting these tasks, we reasoned that in both of them the brain is involved in pattern-recognition, and that perhaps our higher mental functioning is less tied to a modality of patterns than it is commonly accepted: In other words, perhaps the brain reads both music and spatial information as a signal-distribution within system of reference, even if the nature of signal-distribution is different. Our hypothesis is that notwithstanding difference in modality there is perhaps the same neural substrate responsible for processing both musical patterns (that exist within hierarchically organized tonal space) and visuo-spatial patterns (that exist within 3D space shaped by the force field of the gravity). Our behavioral study is also as a preparatory stage for the imaging (MRI) investigation that would compare cortical activation during music perception and visuo-spatial task.

Shepard & Meltzer [44] classic experiment on mental rotation had supported a hypothesis that amount of time to make a judgment on congruency of two 3D objects, which are rotated in reference to each other, depends on an angle of rotation. With development of imaging technology, the mental rotation task was investigated from the

point of view of functional neuroanatomy. Alivastos (1992) [128] proposed that the process of mental rotation has three main steps: (i) visual perception of both objects, (ii) mental rotation of the object, and (iii) decision whether or not both objects are identical.” He identifies the occipital lobe as “primarily responsible for visual processing”; the parietal cortex, mainly its right superior parietal lobule, as responsible for the spatial processing; and the prefrontal cortex as a whole ”for holding the relevant information with necessary updates and finally yielding the decision”.

It is known from studies on functional neuroanatomy that the parietal lobes interpret sensory information from the rest of the body and control body movement. [129, 120, 131, 132] The parietal lobes combine impressions of form, texture, and weight into general perception: they store spatial memories that enable people to orient themselves in space (know where they are) and to maintain a sense of direction (know where they are going). The main function of the parietal lobe is to processing of somatosensory information such as touch, vibration, pain and position sense (proprioception). The right parietal lobe is concerned with spatial awareness and the ability to carry out and understands spatial relationships. The superior parietal lobe is responsible for spatial processing and visual guidance of hands, fingers, eyes, limbs, and head. It allows us to localize objects around and directing movement in space as well as detecting stimuli in space. The inferior parietal lobe is involved in spatial cognition, such as reading and arithmetic and creating visual maps: The parietal lobes influence mathematical and language skills, which are controlled more specifically by adjacent areas of the temporal lobes. For example, Silk et al (2002) [133] found in their fMRI study on mental rotation processing in mathematically gifted adolescent boys that mental rotation produces bilateral activation in the parietal lobes both in those with average mathematical abilities and in mathematically gifted “though to different levels.” Damage to the anterior parietal lobe can lead to impaired sense of position, high sensory thresholds, decreased sensitivity to both two-point touch and double simultaneous touch, to astereognosia (can’t tell what things are by feeling them) and anautotopagnosia (inability to localize or name body parts – usually on the left side), to asymbolia for pain (absence of normal reaction to pain), and asomatognosia (loss of knowledge or sense of one’s own body). Damage to the posterior parietal lobe leads to troubles with spatial processing, to poor visual guidance of hands,

fingers, eyes, and limbs, head, poor tactile recognition, and with directing movement in space.

Harris & Miniussi's (2003) [134] TMS study found that "the right superior parietal lobe plays an essential role in mental rotation, consistent with its involvement in a variety of visuospatial and visuomotor transformations." The researchers explained TMS (transcranial magnetic stimulation) as "method of delivering electrical stimulation through the intact scalp by inducing a rapidly changing magnetic field at the scalp. This produces synchronous activity in a subpopulation of neurons located under the stimulating coil, with the net result of disrupting any pattern of activity that was occurring at the time of the stimulation." When rTMS (repetitive TMS) was applied to B7 (superior parietal lobule), the disrupting of neural activity interfered with task performance. "In contrast, stimulation of the left superior parietal lobe did not reliably affect mental rotation performance at any time points". Passini et al (2000) [135] presented neurophysiological evidence that lesions to the right parietal lobe impair mental rotation abilities. A comprehensive review by Ark (2002) [136] of studies on mental rotation stated that "the main components of performing a mental rotation include but are not limited to: parietal areas, some frontal components, some occipital, some temporal and more specific premotor, somatomotor and basal ganglia (some of these areas overlap). Different mental rotation stimuli elicit different responses. Mental rotation activates multiple spatial representation and, perhaps, neuronal motor system." Jordan et al (2001) are more categorical in their assessment: "The superior parietal region seems to play a major role in the multiple spatial representations of visual objects." [137] While Richter et al (1997) [138] suggested that the inferior parietal area has a similar pattern of activation to the superior parietal area, Kosslyn et al (1998) claimed that the use of motor and premotor areas during mental rotation tasks is related to the stimuli used in the experiment. – ... "a person will mentally use the right hand to rotate the object." [139] (Also Julian et al, 2000) [140]. Vingerhoets et al. (2001) wrote that "motor processes may, at least to some degree, be an inherent part of every mental rotation." [140] Jordan et al's (2001) [137] fMRI study found that "decision time increases with degree of separation" in the mental rotation task. Interestingly, the study also found that cortical activation—in the bi-lateral regions in the superior and inferior parietal lobe—was

similarly present during all three mental rotation tasks: classical 3-D cube figures, pairs of letters, and pairs of abstract figures. The authors of the study wrote that they did not find expected “strong between-hemisphere differences with regard to parietal activations...both hemispheres are more or less equivalently involved in the mental rotation task.” In this study participants included eight females and one male; perhaps the bilaterality of activation reflected a greater number of women than men in the study.— Voyer et al (1995) analysis of sex differences in spatial abilities show that males perform better on mental rotation tasks than females. [142]

Recalling experience-related hemispheric dominance changes found in research in music perception [61], a study by Corballis (1997) showed that “the functional lateralization of mental processes is modulated by the skill level of performing the mental rotation task. With increasing practice there is a shift from a right hemisphere advantage to a left hemisphere advantage.” [143] While Corballis found that the left hemisphere is more strongly involved in mental rotation of more complex stimuli, Carpenter et al (2000) showed “more parietal activation for spatial position versus more inferior temporal activation for patterns.” [144]

Recent imaging studies suggest that the parietal lobe is an integral part of a neural lateral prefrontal–parietal cortices circuit that is critical in cognition. An fMRI study by Choi et al (2005) [145] demonstrated that greater activity of the superior parietal cortex was correlated with superior general intelligence ($r = .71- .81$). The authors of the study wrote that “these results suggest that the superior parietal area in the fronto-parietal network may play a crucial role in supporting superior general intelligence”.

A PET study by Bushara et al (1999) found that “the hierarchical organization of the auditory system extends beyond the temporal lobe to include areas in the posterior parietal and prefrontal regions specialized in auditory spatial processing.” [146] The fMRI research by Frederick et al. (2001) [147] revealed that imagined musical performance “consistently activated supplementary motor and premotor areas, right superior parietal lobule, right inferior frontal gyrus, bilateral mid-frontal gyri, and bilateral lateral cerebellum...These data implicate an associative network independent of primary sensorimotor and auditory activity.” The most intriguing results of this investigation concern the superior parietal lobule activation (B 7): the imagined musical

performance showed greatest activation in the superior parietal lobule “that has been implicated in encoding/retrieval and complex cognitive processing tasks such as working memory and selective attention.” The superior parietal lobule carries out some of the "background computations" necessary for making movements in space. To organize such movements, it is necessary to assemble input from a variety of sensory systems to create a map of space and to compute a trajectory by which a body part can reach its target. Altenmüller & Bangert wrote that “it seems just plausible if the efference copy of the ongoing action is coded acoustically rather than kinesthetically”. [148]

Since musical forms possess a definite kind of architectonics, the perception of which demands orientation in the acousmatic space of music—that is within a certain reference system—it is logical to suggest that perhaps activation of the parietal lobes reflects ‘reading’ and assessing patterns within this tonal/temporal system of reference—in other words, involves orientation in a such system of reference. To understand a complex musical structure requires a high level of expertise that provides for compressing mentally the temporal structures of music into quasi-spatial forms. Pylyshin (1981) [149] remarked that in regard to music “...the word *hear*, taken in the sense of having an auditory-like imagined experience, need not to entail anything about the duration of that experience.” He quotes Mozart who said about imaging musical composition: “Nor do I hear in my imagination, the parts successively, but I hear them, as it were, all at once.” In other words, highly trained musicians have ability to transcend the temporal nature of a musical composition and imagine musical form in a quasi-spatial manner, as if embracing it at a glance—at once. It is even possible that this process of time compression in music is indeed a standard way of perceiving any musical structure. Since in music we are dealing with temporal sound patterns shaped within the tonal reference system, following the patterns is not only based on a continuous mental looping between incoming tones and the already established reference tone, but also presumes gradual mental assembling of a musical structure in terms of functional harmony and phrasing. Perceiving a musical composition means maintaining its structure as a whole—or, more realistically, a more-less complete fragment of the overall structure that is nearest in time.

There are a number of behavioral and brain imaging studies suggesting that musicians process both music perception and visuo-spatial tasks differently from non-musicians. An EEG study on mental rotation by Bhattacharya et al (2001) [150] revealed that musicians demonstrate different patterns of brain activation during mental rotation task than non-musicians: “Musicians showed higher degree of synchronization between frontal cortex and right parietal cortex than non-musicians. Left hemispheric dominance in the degree of phase synchronization, stronger in the posterior right parietal and occipital regions, was observed in musicians.” In another research by Bhattacharya et al. (2001) it was found that while listening to different pieces of music musicians showed “significantly higher degree of interdependency...over multiple cortical areas.” [151]. Gaser & Schlaug (2003) [95], in their MRI study on structural differences between the brains of musicians and non-musicians, emphasized that “the finding in the superior parietal region is of particular interest considering the existing literature on visual-spatial processing differences in groups of subjects with and without musical training. This region is known to play an important role in integrating multimodal sensory information (e.g., visual, auditory, and somatosensory) and providing guidance for motor operations through intense reciprocal connections with the premotor cortex. Both functions are of enormous importance to the performing musicians. In addition, the superior parietal lobe was also found to play an important role in sight-reading, a musical task that depends on the fast integration of multimodal sensory information and motor preparation. Throughout their entire musical life, musicians repetitively practice this visual-spatial-to-motor transformation by reading musical notation and translating it into motor plans accompanied by simultaneous auditory feedback that aids the matching of the visual patterns to the motor program.”

Conclusion

Pattern perception in music operates within the tonal chronotope that is within a reference space with coordinates of time and tonal attraction. The characteristics of a metric space are freely assigned to the temporal art of music: spatial terminology, mixed with the terminology physics helps to describe the basics of music. Music offers us sound structures that carry universal concepts in a most abstract way. While there are strong

indirect parallels between music and spoken language—phrasing, rhythm, feeling of closure, and 'breathing' that punctuates phrasing—music does not possess either certainty of symbolic representation or semantic values and syntactic organization similar to that of the language. In music we are dealing with temporal sound patterns stretched in time within the tonal reference system, yet highly trained musicians think of musical composition not in terms of duration but in a quasi-spatial manner. Polyphonic technique in particular points toward such quasi-spatial thinking: a musical theme in a polyphonic composition undergoes transformations that can be compared with transformations of a visual object in the 3-D space.

Behavioral and imaging studies show that musicians differ from non-musicians: those individuals who study music consistently from childhood develop a particular way of reasoning and show structural changes in the brain, among them the structural differences in the superior parietal region. The parietal lobes interpret sensory information and are concerned with the ability to carry out and understand spatial relationships. There are a number of behavioral and brain imaging studies suggesting that musicians process both music perception and visuo-spatial tasks differently from non-musicians. I hypothesize that perhaps the brain reads both music and spatial information as a signal-distribution within system of reference notwithstanding the modality of the signal.

Reference List:

1. P. A. Florenskii, Analiz prostranstvennosti i vremeny v izobrazitelnom iscusstve, 1925, [*Analysis of space-ness and time in fine arts*], Moscow: Progress, 1993, pg. 63
2. R. Zatorre, 2005, Music, the food of neuroscience? *Nature*, 434: 312-315
3. M. W. Andrews, W. J. Dowling, 1991, The development of Perception of Interlayed Melodies and Control of Auditory Attention, *Music Perception*, 8 (4) 349-368
4. W. J. Dowling, 1971, Recognition of inversions of melodies and melodic contours, *Perception and Psychophysics*, 9 (3B): 348–349
5. W. J. Dowling, 1972, Recognition of melodic transformations: Inversion, retrograde, and retrograde inversion, *Perception and Psychophysics*, 12 (50): 417-421
6. S. Langer, *Philosophy in a New Key: A Study in the Symbolism of Reason, Rite and Art* Cambridge, Mass: Harvard University Press, 1957.
7. R. Scruton, *The Aesthetics of Music*, New York: Oxford University Press, 1997
8. R. Scruton, *The Aesthetics of Music*, New York: Oxford University Press, 1997, pg. 2
9. W. J. Dowling, Perception of Music, *Blackwell Handbook of Perception*, 2001, Chapter Fifteen, pg. 487
10. J.O. Nordmark, *Foundation of Modern Auditory Theory*, J. V. Tobias, ed. Academic Press, 1970, Chapter 2
11. A. R. Moller, *Hearing: Its Physiology and Pathophysiology*, Academic Press, 2000
12. G. Langner, 1998, Neuronal Periodicity Coding and Pitch Effects, Zoological Institute, Technical University of Darmstadt, Germany, Plenum Press
13. G. Langner, 1997, Temporal Processing of Pitch in the Auditory System, *Journal of New Music Research*, 1997
14. E. G. Schellenberg, S. E. Trehub, 1996, Natural music intervals. Evidence from infant listeners, *Psychological Science*, 7.272-277
15. J.C. Bartlett, W. J. Dowling, Scale Structure and Similarity of Melodies, 1988, *Music Perception*, Vol. 5, No. 3, 285-314 Pg. 285
16. C. Liégeois-Chauvel, J. B. de Graaf, V. Laguitton, P. Chauvel, 1999, Specialization of Left Auditory Cortex for Speech Perception in Man Depends on Temporal Coding, *Cerebral Cortex*, Vol. 9, No. 5, 484-496

17. I. Peretz (2001), Brain Specialization for Music: New Evidence from Congenial Amusia, *Annals of New York Academy of Sciences*, 930:153-165
18. K. L. Hyde, I. Peretz, 2004, Brains That Are out of Tune but in Time, *Psychological Science*, 15:356-360
19. R. J. Zatorre, A. C. Evans, E. Meyer, 1994, Neural mechanisms underlying melodic perception and memory for pitch. *Journal of Neuroscience*, 14:1908-1919
20. Leibniz G.W., *Principles of Nature and Grace, in Philosophical Essays*, tr. and ed. R. Ariew and D. Garber, Indianapolis: Hackett Publishing Co., 1989, pg. 212.
21. S. M. Russell, J. G. Golfinos, Amusia following resection of a Heschl gyrus glioma. Case report, 1998, *Journal of Neurosurgery*, 98 (5):1109-1112.
22. M. Dennis, T. Hopyan, 2001, Rhythm and Melody in Children and Adolescents after Left or Right Temporal Lobectomy, *Brain and Cognition*, Vol. 47 (3):461-469.
23. C. Liegeois-Chauvel, K. Giraud, J.-M. Badier, P. Marquis, P. Chauvel, 2001, Intracerebral Evoked Potentials in Pitch Perception Reveal a Functional Asymmetry of Human Auditory Cortex, *Annals of the New York Academy of Sciences* 930:117-132
24. I. Peretz, A.J. Blood, V. Penhune, R. J. Zatorre, 2001, Cortical deafness to dissonance, *Brain*, Vol. 124, No. 5, 928-940
25. T. D. Griffiths, The Neural Processing of Complex Sounds, *The Cognitive Neuroscience of Music*, 2003, pg. 173
26. L. Stewart, V. Walsh, 2002, Congenital Amusia: All Songs Sound the Same, *Current Biology*, 12 (12):R420-421
27. D. Deutsch, 1999, Tone Language Speakers Possess Absolute Pitch, *Acoustical Society of America 138th Meeting Lay Language Papers*, Columbus, Ohio
28. R. Zatorre, 2003, Absolute Pitch: a model for understanding the influence of genes and development on neural and cognitive function, *Nature Neuroscience*, 6(7):692-695.
30. A. H. Takeuchi, S. H. Hulse, 1993, Absolute Pitch, *Psychological Bulletin*, 113 (2): 345-36
31. S. McAdams, S. Winsberg, S. Dnnadiou, G. De Soete, J. Krimphoff, 1995, Perceptual scaling of synthesized musical timbres: Common dimensions, specificities, and latent subject classes. *Psychological Research*, 58: 177-192
32. M. Ghyka, *The Geometry of Art and Life*, Dover Publication, 1977, pg. 91

33. V. Menon, D. J. Levitin, B. K. Smith, A. Lembke, B. D. Krasnov, D. Glazer, G. H. Glover, and S. McAdams, 2002, Neural Correlates of Timbre Change in Harmonic Sounds, *NeuroImage* 17, 1742-1754.
34. J. M. Barbour, 1932, *Tuning and temperament: A Historical Survey*, Dover Publications, Inc.
35. J. James, *The Music of the Spheres: Music, Science, and the Natural Order of The Universe*, Grove Press, 1993, pg. 90).
36. S. Becker, An Essay on the History of Tuning—Part IX, *Piano Technicians Journal*, 41 (1998), 31-34.
37. W. J. Dowling, 1981, Musical Scales and Psychological Scales: Their Psychological Reality, *Cross-Cultural Perspectives on Music*, ed. Robert Flack and Timothy Rice, University of Toronto Press, Pg. 24.
38. E. Bigand, 1993, Perceiving musical stability: the effect of tonal structure, rhythm and musical expertise. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 808-18
39. S. Holleran, M. Jones, D. Butler, 1995, Perceived Implied Harmony, *Journal of Experimental Psychology*, 21 (3): 737-753
40. D. S. Jordan, 1987, Influence of the diatonic tonal hierarchy at microtonal intervals, *Perception and Psychophysics*, 41 (6): 482-488
41. I. Neath, A. Surprenant, 2003, *Human Memory: An Introduction to research, data, and Theory*, Wadsworth, pg. 47
42. W. J. Dowling, D. L. Harwood, *Music cognition*, 1986, New York: Academy Press
43. D.S. Jordan and R. N. Shepard, 1987, Tonal schemas: Evidence obtained by probing distorted musical scales, *Perception and Psychophysics*, 41 (6), 489-504
44. R. Shepard & J. Meltzer, 1971, Mental rotations of three-dimensional objects. *Science* 171: 701-3
45. R.N. Shepard, L. A. Cooper, Mental Images and Their Transformations, *A Bradford Book*, 1982, pg. 319
46. W. J. Dowling, 1971, Recognition of inversions of melodies and melodic contours, *Perception and Psychophysics*, Vol. 9 (3B): 348–349
47. R. Scruton, *The Aesthetics of Music*, New York: Oxford University Press, 1997, pg.75

48. W. J. Dowling, Pitch Structure, *Representing Musical Structure*, 1991, Academic Press, pg. 43
49. C. L. Krumhansl, *Cognitive Foundations of Musical Pitch*, 1990, Oxford University Press, Pg. 153
50. P. Janata, J. L. Birk, J. D. Van Horn, M. Léman, B. Tillmann, J. Bharucha, 2002, The Cortical Topography of Tonal structures Underlying Western Music, *Science* 298: 2167-2170
51. W. J. Dowling, 1987, Scale and Contour: Two Components of a Theory of Memory for Melodies, *Psychological Review*, 85 (4): 341-354.
52. W. J. Dowling, 1981, Mental Structures Through Which Music is Perceived, *Documentary report of the Ann Arbor Symposium*, pg. 147
53. W. J. Dowling, Melodic and Rhythmic Contour in Perception and Memory, Chapter XI in W. J. Dowling, A. Barbey, L. Adams, *Music, Mind, and Science*, 1999, Seoul National University Press, pg. 172
54. W. J. Dowling, 1981, Music, Meaning and Use, *Psychology and the Arts*, edited by David O'Hare, Humanities Press, pg. 189
55. J.C. Bartlett, W. J. Dowling, 1980, Recognition of Transposed Melodies: A Key-Distance Effect in Developmental Perspective, *Journal of Experimental Psychology*, 6 (3): 501-515, pg. 514
56. W. J. Dowling, 1987, Scale and Contour: Two Components of a Theory of Memory for Melodies, *Psychological Review*, 85 (4): 341-354.
57. W. J. Dowling, J. C. Bartlett, 1981, The importance of interval information in long-term memory for melodies. *Psychomusicology*, 1/1, 30-49
58. W. J. Dowling, B. Tillman, D. F. Ayers, 2001, Memory and the Experience of Hearing Music, *Music Perception*, 19 (2): 249-276
59. N. Gaab, C. Gazer, T. Zaehle, L. Jancke, and G. Schlaug, 2003, Functional anatomy of pitch memory—an fMRI study with sparse temporal sampling, *Neuroimage*, 19 (4): 1417-1426
60. H. Platel, C. Price, J.C. Baron, R. Wise, J. Lambert, R.S. Frackowiak, B. Lechevalier, F. Eustache, 1997, The structural components of music perception, A functional anatomical study, *Brain*, 120(2): 229-243

61. T. Ohnishi, H. Matsuda, T. Asada, M. Aruga, M. Hirakata, M. Nishikawa, A. Katoh, E. Imabayashi, 2001, Functional Anatomy of Musical Perception in Musicians, *Cerebral Cortex*, 11(8): 754-760

62. H. Platel, J.-C. Baron, B. Desgranges, F. Bernard, and F. Eustache Semantic and episodic memory of music are subserved by distinct neural networks, *Neuroimage*, 20 (2003) 244-256

63. F. Lerdahl, The Sounds of Poetry Viewed as Music, *The Cognitive Neuroscience of Music*, 2003, ed. I. Peretz and R. J. Zatorre, Oxford University Press, pg. 414

Nature's first green is gold,
Her hardest hue to hold.
Her early leaf's a flower;
But only so an hour.
The leaf subsides to leaf.
So Eden sank to grief.
So down go down to day.
Nothing gold can stay.

Robert Frost

64. J. C. M. Brust, Music and the Neurologist: a Historical Perspective, *The Cognitive Neuroscience of Music*, 2003, ed. I. Peretz and R.J. Zatorre, Oxford University Press, pg. 187

65. A. D. Patel, 2003, Language, music, syntax and the brain, *Nature Neuroscience*, 6(7): 673-681

66. J. Pearl, 2001, Music and Language: Parallels and Divergences, CaPC Lecture Series, UCSB

67. M. Besson, D. Schon, 2001, Comparison between language and music, *The Biological Foundations of Music*, Annals of New York Academy of Science, 930:232-58

68. A. D. Patel, M. Tramo, I. Peretz, R. Labrecque, 1998, *Processing prosodic and musical patterns: a neurophysiological investigation*. Brain and Language, 61, 123-144

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

70. S. Samson, N. Ehrle, M. Baulac, 2001, Cerebral Substrates for Musical Temporal Processes, *Annals of the New York Academy of Sciences*, 930:166-178

71. D. Grandjean, D. Sander, G. Pourtois, S. Schwartz, M. L. Seghier, K.R. Scherer, P. Vuilleumier, 2005, The voices of wrath: brain responses to angry prosody in meaningless speech, *Nature Neuroscience*, 8 (2): 125-146
72. M. D. Hauser, J. McDermott, The evolution of music faculty; a comparative perspective, *Nature Neuroscience*, 6 (7): 663-668
73. S. Pinker, *The Language Instinct*, 1994, New York: HarperCollins
74. E. Tulving, S. Kapur, F. I. M. Craik, M. Moscovitch, S. Houle, 1994, Hemispheric encoding/retrieval asymmetry in episodic memory: Positron emission tomography findings, *Proceedings of National Academy of Sciences (USA)*, 91:2016–2020
75. R.Habib, L. Nyberg and E. Tulving, 2003, Hemispheric asymmetries of memory: the HERA model revisited, *Trends in Cognitive Sciences*, 7(6):241-2458
76. K.I. Taylor, M. Regard, 2003, Language in the right cerebral hemisphere: Contributions from reading studies, *News in Physiological Sciences*, 18: 257-61.
77. A. R. Halpern, R. Zatorre, 1999, When That Tune Runs Through Your Head: A PET Investigation of Auditory Imagery for Familiar Melodies, *Cerebral Cortex*, 9 (7): 697-704
78. A. R. Halpern, Cerebral Substrate of Musical Imagery, *The Cognitive Neuroscience of Music*, 2003, ed. Isabelle Peretz and Robert J. Zatorre, Oxford University Press, pg. 271
79. J. Graham, 2004, Poster Presentation at the Summer Institute in Cognition and Neuroscience, Dartmouth College
80. A. D. Patel, A new approach to the cognitive neuroscience of melody, *The Cognitive Neuroscience of Music*, 2003, ed. I. Peretz and R.J. Zatorre, Oxford University Press, pg. 341
81. I. Peretz, Processing of local and global musical information by unilateral brain-damaged patients, 1990, *Brain*, 113(4): 1185-1205
82. L. Nyberg, R.Habib, A. R. McIntosh, and E. Tulving, 2000, Reactivation of encoding-related brain activity during memory retrieval, *Proceedings of National Academy of Sciences (U S A)* 97(20):11120–11124
83. C. M. Warrier, R. J. Zatorre, 2004, Right temporal cortex is critical for utilization of melodic contextual cues in pitch constancy task, *Brain*, 27 (7):1616-1625
84. I. Peretz, 1996, Can we lose memory for music? A case of music agnosia in a nonmusician. *Journal of Cognitive Neuroscience*, 8: 481–9683.

85. V. B. Penhune, R. J. Zatorre, A. C. Evans, 1998, Cerebellar Contribution to Motor Timing: A PET Study of Auditory and Visual Rhythm Reproduction, *The Journal of Cognitive Neuroscience*, 10:752-765
86. L. M. Parsons, 2001, *Exploring the functional neuroanatomy of music performance, perception, and comprehension*, *Annals of the New York Academy of Science*, 930: 211-231.
87. T. D. Griffiths, The neural processing of complex sounds, *The Cognitive Neuroscience of Music*, 2003, ed. I. Peretz and R.J. Zatorre, Oxford University Press, pg. 174
88. R. B. Ivry, S. W. Keele, 1989, Timing functions of the cerebellum, *Journal of Cognitive Neuroscience*, 1, 136-152
89. F. J. P. Lanmghem, J. H. Callicot, V. S. Mattay, J. H. Duyn, D.R. Weinberger, 2001, Cortical Systems Associated with Covert Music Rehearsal, *Neuroimage* 16, 901-908
90. G. Schlaug, 2001, The Brain of Musicians: A Model for Functional and Structural Adaptation, *Annals New York Academy of Sciences* 930:281-299
91. S. Hutchinson, L. H.-L. Lee, N. Gaab, G. Schlaug, 2003, Cerebellar Volume of Musicians, *Cerebral Cortex*, 13(9): 943-949
92. K. Itoh, Y. Fujii, K. Suzuki, T. Nakada, 2001, Asymmetry of parietal lobe activation during piano performance: a high field functional magnetic resonance imaging study, *Neuroscience Letters*, 309(1):41-4.
93. S. Brandler, T. H. Rammsayer, 2003, Differences in mental abilities between musicians and non-musicians, *Psychology of Music* 31(2):123-138
94. P.M. Thompson, K. L. Narr, R. E. Blanton, A. W. Toga, 2005, Mapping structural Alterations of the Corpus Callosum during Brain Development and Degeneration, *Proceedings of NATO ASI on the Corpus Callosum*, Kluwer Academic Press, [in press]
95. C. Gazer and G. Schlaug, 2003, Brain Structures Differ Between Musicians and Non-Musicians, *The Journal of Neuroscience*, October 23(27):9240-9245
96. G. Schlaug, E. Winner, A. Norton, K. Overy, 2003, Effect of Music Training on Children, *Poster at Society for Neuroscience*, New Orleans
97. V. J. Schmithorst & M. Wilke, 2002, Differences in white matter architecture between musicians and non-musicians: a diffusion tensor imaging study, *Neuroscience Letters* 321:57-60

98. T. Elbert, C. Pantev, C. Wienbruch, B. Rockstroh, E. Taub, 1995, Increased Cortical Representation of the Fingers of the Left Hand in String Players, *Science*, 270 (5234): 305-307
99. I. Hashimoto, A. Suzuki, T. Kimura, Y. Iguchi, M. Tanosaki, R. Takino, Y. Haruta, M. Taira, 2004, Is there training-dependent reorganization of digit representation in area 3b of string players? *Clinical Neurophysiology* 114(2):435-447
100. S. Koeneke, K. Lutz, T. Wustenberg, L. Jancke, 2004, Long-Term training affects cerebellar processing in skilled keyboard players, *Neuroreport* 15(8):1279-1282
101. V. J. Schmithorst, M. Wilke., B. J. Darzinski., S. K. Hilland, 2002, Correlation of white matter diffusivity and anisotropy with age during childhood and adolescence: a cross-sectional diffusion-tensor MR imaging study, *Radiology*, 222 (1): 212-218
102. G. Schlaug, L. Jancke, Y. Huang, J.F. Staiger and H. Steinmetz, 1995, Increased corpus callosum size in musicians. *Neuropsychologia* 33 (8): 1047-1055
103. R. J. Compton, K. Feigenson, B. Ebendorf, 2005, Efficiency of Interhemispheric Interaction Predicts Cognitive Performance, *A Supplement of the Journal of Cognitive Neuroscience, Cognitive Neuroscience Society Annual Meeting 2005*
104. R. Cabeza, N. D. Anderson, J. K. Locantore, A. R. McIntosh, 2002, aging Gracefully: Compensatory Brain Activity in High-Performing Older Adults, *NeuroImage* 17: 1394-1402
105. N. Gaab, G. Schlaug, 2003, The effect of musicianship on pitch memory in performance matched groups. *Neuroreport*. 14(18):2291-2295
106. E. Luders, C. Gazer, L. Jancke, G. Schlaug, 2004, A voxel-based approach to gray matter asymmetries, *NeuroImage*
107. N. Sadato, V. Ibanez, M. P. Deiber, M. Hallett, 2000, Gender differences in premotor activity during active tactile discrimination. *Neuroimage* 11: 532-530
108. D. J. Lee, Y. Chen, G. Schlaug, 2003, Corpus callosum: musician and gender effects. *Neuroreport* 14: 205-209
109. S. Hutchinson, L. H. L. Lee, N. Gaab, G. Schlaug, 2003, Cerebellar volume: gender and musicianship effects. *Cerebral Cortex* 13: 943-949
110. N. Gaab, J. P. Kennan, G. Schlaug, 2003, The Effects of Gender on the Neural Substrates of Pitch Memory, *Journal of Cognitive Neuroscience*. 2003:15:810-820
111. M. Hassler, 1991, Testosterone and artistic talents, *The International Journal of Neuroscience* 56 (1-4): 25

112. M. Hassler, E. Nieschlag, 1991, Salivary testosterone and creative musical behavior in adolescent males and females. *Developmental Neuropsychology* 7: 504
113. C. D. Good, I. Johnstrude, J. Ashburner, R. N. Henson, K. J. Friston, R. S. Frackowiak RS, 2001, Cerebral asymmetry and effects of sex and handedness on brain structure: a voxel-based morphometric analysis of 465 normal adult human brains. *Neuroimage* 14: 685-700
114. R. J. Davidson, W. Irwin, 1999, The functional neuroanatomy of emotion and affective style, *Trends in Cognitive Sciences*, 3(1):11-21
115. A. Damasio, 2003, *Looking for Spinoza: Joy, Sorrow, and the Feeling Brain*, Harcourt
116. J. E. LeDoux, 1996, *The Emotional Brain*, New York, Simon and Schuster
117. J. E. LeDoux, 2002, *Synaptic Self*, New York, Viking
118. R. J. Davidson, Anxiety and Affective Style: Role of Prefrontal Cortex and Amigdala, 2002, *Biological Psychiatry*, 51:68-80
119. J. T. Cacioppo, G. G. Berntson, J. T. Larsen, K. M. Poehlmann, T. A. Ito, The psychophysiology of emotion, editors: M. Lewis, R. J. M. Haviland-Jones, *The handbook of emotions*, 2002, New York: Guilford Press
120. F. H. Rauscher, G. L. Shaw, K. N. Ky, 1994, APA 102nd Annual Convention.
121. F. H. Rauscher, G. L. Shaw, K. N. Ky, 1993, Music and spatial task performance, *Nature*, 365: 611
122. F. H. Rauscher, G. L. Shaw, K. N. Ky, 1993, Listening to Music Enhance Spatial Task Performance Design and Procedure, *Neuroscience Letters*, 185: 44-47
123. F. H. Rauscher, G. L. Shaw, L. J. Levine, E. L. Wright, 1993, Pilot study indicates music training of three-year-old enhances specific spatial reasoning skills. *Paper for Economic Summit of NAMM*, 1993
125. R. N. Shepard and S. Chipman, 1970, Second-order isomorphism of internal representations: Shapes of states, *Cognitive Psychology*, 1:1-17
126. E. G. Schellenberg, 2004, *Psychological Science*, 15(8): 511-514
127. W. F. Thompson, E. G. Schellenberg, G. Husain, 2001, *Psychological Science*, 12(3): 248-251.

127. J. Sarnthein, A Von Stein, P. Rappelsberger, H. Petsche, F. H. Rauscher, G. L. Shaw, 1997, Persistent patterns of brain activity: An EEG study of the positive effect of music on spatial-temporal reasoning, *Neurological Research* Vol.19, Issue 2, 107-116
128. B. Alivastos, 1992, The role of the frontal cortex in the use of advance information in a mental rotation paradigm, *Neuropsychology*, 30: 145-159
129. *Neuroscience*, 2001, ed. D. Purves, Sinauer Associates
130. *Principles of Neural Science*, 2001, ed. E. R. Kandel, J. H. Schwartz, T. M. Jessel, McGraw-Hill
131. *The Cognitive Neuroscience III*, 2004, ed. M. S. Gazzaniga, MIT
132. J. Nolte, *The Human Brain*, 2002, Mosby
133. T J Silk, M W O'Boyle, D Vaughan, A Syngeniotis, R Cunnington, A Puce and G F Egan, 2002, Proceedings of the 12th Australasian Psychophysiology Conference
134. I. M. Harris and C. Miniussi, 2003, Parietal Lobe Contribution to Mental Rotation demonstrated with rTMS, *Journal of Cognitive Neuroscience* 2003, 15:3, 315-323
135. R. Passini, C. Rainville, M. Habib, 2000, Spatio-cognitive deficits in right parietal lesion and its impact on wayfinding: A case study. *Neurocase*, 6: 245-257
136. W. S. Ark, 2002, Neuroimaging Studies Give New Insight to Mental Rotation, *Proceedings of the 35th Hawaii International Conference on System Sciences – 2002*
137. K. Jordan, H.-J. Heinze, K. Lutz, M. Kanowski, L. Jancke, 2001, Cortical Activation during the Mental Rotation of Different Visual Objects, *Neuroimage* 13: 143-52
138. W. Richter, K. Ugurbili, A. Georgopoulos, S.-G. Kim, 1997, Time resolved MRI of mental rotation, 1997, *Neuroreport* 8: 3697-3702
139. S. M. Kosslyn, G. J. Digirolamo, W. L. Thompson, N. M. Alpert, 1998, Mental rotation of objects versus hands: neural mechanisms revealed by PET, *Psychophysiology*, 35: 54-58
140. G.G. Julian P. Keenan, S. M. Kosslyn, A. Pascual-Leone, 2000, Transcranial Magnetic Stimulation of Primary Motor Cortex Affects mental Rotation, *Cerebral Cortex* 10:175-180
141. G. Vingerhoets, P. Santen, K. Van Laere, P. Lahorte, R. A. Dierckz, J. De Reuck, 2001, Regional brain activity during different paradigms of mental rotation in healthy volunteers: A positron emission tomography study, *NeuroImage* 13, 381-391.

142. D. Voyer, S. Voyer, M. P. Bryden, 1995, Magnitude of Sex Differences in Spatial Abilities: A Meta-Analysis and Consideration of Critical Variable, *Psychological Bulletin*. Vol. 117 (2): 250-270
143. C. Corballis, Mental rotation and the right hemisphere, 1997, *Brain and Language* 57:100–121
144. P. A. Carpenter, M. A. Just and E. D Reichle, 2000, Working memory and executive function: evidence from neuroimaging, *Current Opinion in Neurobiology*, 10: 195-199
145. Y. Y. Choi, S. H. Cho, J-H, Chae, K. Kim, K. H. Lee, 2005, A Supplement of the *Journal of Cognitive Neuroscience*, *CNS Annual Meeting Program -- 2005*
146. K. O. Bushara, R. A. Weeks, K. Ishii, M. J. Catalan, B. Tian, J. P. Rauschecker, M. Hallett, 1999, Modality-specific frontal and parietal areas for auditory and visual spatial localization in humans. *Nature Neuroscience* 2(8): 759-766
147. Frederick J. P. Lanmgheim, Joseph H. Callicot, Venkata S. Mattay, Jeff H. Duyn, Daniel R. Weinberger, 2001, Cortical Systems Associated with Covert Music Rehearsal, *Neuroimage* 16: 901-908
148. E. O. Altenmüller, M. W. Bangert, Audio-sensory-motor integration as a prerequisite for musical expertise, Hanover University of Music and Drama, web source.
149. Z. W. Pylyshin, *Imagery*, 1981, N. Block, editor, A Bradford Book, The MIT Press
- 150.. J. Bhattacharya, H. Petsche, U. Feldmann, B. Rescher, 2001, EEG gamma-band phase synchronization between posterior and frontal cortex during mental rotation in humans, *Neuroscience Letters* 311: 29-32
151. J. Bhattacharya, H. Petsche, E. Pereda, 2001, Interdependencies on the spontaneous EEG while listening to music, *International Journal of Psychophysiology* 42: 287 – 301
152. G. Schlaug, E. Winner, A. Norton, 2005, The Effects of Music Training on Children's Brain and Cognitive Development, A Supplement of the *Journal of Cognitive Neuroscience*, *Cognitive Neuroscience Society Annual Meeting – 2005*