The Guitar Player's Brain: A Functional Analysis by Gary R. Peterson

I'm no doctor, but thanks to my penchant for research, a rigorous self-determination, and the Internet, I now know more about neuroscience than the average sailor, boy scout, or algebraic topologist knows about knots. Plus, I've played the guitar since I was ten.

Your brain orchestrates your thinking and doing. It takes a symphony of electric-chemical interplay between countless brain cells for a person just to scratch an itch let alone play a musical instrument. Making music is largely a whole-brain task that entails sight, sound and touch, the cognitive processes of memory and planning, and fine motor skills, not to mention intuition, emotion, and aesthetics of music, all sharing brain resources with overlapping systems and redundancies aplenty. (This study also revealed an olfactory element but only because my guitar, a Gibson J-45, was brand new from the factory and the fragrance of rosewood, mahogany, and Sitka spruce is intoxicating no matter what tune I play.) I'll describe what my brain does when I play the guitar, then narrow it down to a single moment of maximum neural activity during my performance of Beethoven's *Für Elise*, a musical composition familiar to my ear but one I've never played before. It is a pure music example with no lyrics to get in the way, but the verbal "picture" I hope to convey will not be pretty like a portrait of the mysterious Elise (presuming she was attractive), but an abstract monograph more at a Jackson Pollack painting—somewhere between a state of mind and gross anatomy. Differentiation of otherwise homogeneous looking brain matter is found in the cytoarchitecture: the microscopic composition of varied brain cells by which scientists identify specific areas and their functions. The casual reader may want to bone up on the names of common brain parts plus be familiar with Brodmann Areas and standard terms e.g., lateral and medial. For reference, I used a transcription for guitar by Andrei Krylov (www.mkduzgoren.com) and, a bagatelle byproduct of this research, my solo rendition of *Für Elise* can be heard at: www.garypetersonart.com/music/fur-elise_rvb2.mp3

The auditory cortex in my temporal lobe gets busy whenever I perform or just listen to music, but the perception of sound does not make it music. There are neural dissociations between music and speech and song lyrics. Broca's area (or what we brainiacs call the left inferior frontal operculum) detects harmonic deviations common to both music and language. Melody and rhythm also entail separate subsystems. The right-lobe processes new melodies while familiar ones diffuse across temporal and frontal areas as part of a mental representation of the music. It's instructive to note that associated memories, or lyrics, can help a person work around brain damage to recognize a melody. Aphasics who can hardly speak, can still sing songs and vice versa. Furthermore, neural plasticity allows different areas of the brain to adapt to alternative tasks.

Memory is the embodiment of experience. With each neuron having thousands of receptors, the stimuli from any external event can spark new connections and form pathways, the unique configuration of which, in and of itself, embodies the event as a memory. Transforming *Für Elise* into a well-practiced piece will require three types of long-term memory: 1.) Semantic, meaning learned facts or beliefs; 2.) Episodic, or recall of events in time and place; and 3.) Procedural, the autonomous replay of a well-practiced routine. Semantic and episodic memories are processed by the hippocampus, a famously seahorse-ish looking extrusion (an *upside-down* seahorse, it seems to me) along the inner lip of the temporal lobe. Its molecular mechanisms turn short-term audio stimuli into permanent records. To say I know a song "by heart," really means I know it by hippocampus.

Rhythm is music's underlying meter of strong "down" beats and respondent "back" beats. The right temporal lobe handles the underlying meter while groupings—triplets, syncopation, hip-hop, etc.—are processed on the left. A strong motor component adds to the mental representation of rhythm. The cerebellum, a pleated bundle of nerves attached to the brain stem under the forebrain, is the hub of timing. The outer cerebellum times the taps while the inner region fine-tunes them. Procedural memories are encoded in the on/off configurations of the cerebellum's switch-like Purkinje cells (not completely unlike the perforations that inform a “player” piano). They in turn project to mirror cells in the motor cortex (a sideways swath across the top of the brain) fostering a predisposition for a “learned” behavior. The premotor cortex (PM) is active in new learning while the a supplementary motor area conducts well-practiced pieces. Procedural memory is like storing a melody in my fingers and it's cheaper than hiring a bass player. Finger memory “remembers” guitar licks but doesn't “know” the musical scales from which those notes emerge. The feed-forward structure of the cerebellum lends itself to so-called “supervised” learning. When I want to play a riff, an impulse from the PM signals my intention to the cerebellum which then returns its guesstimate of kinematic parameters—the trajectories and muscle forces required to finger the strings—which further signals the primary motor cortex. The cerebellum sets my hands in motion and then adjusts motor commands based on audio feedback. Surprisingly, atrophy in the anterior vermis of the cerebellum is associated with schizophrenia, an affliction that allegedly caused certain notable rock guitarists like Peter Green from the group Fleetwood Mac or Syd Barrett of Pink Floyd to drop out of the music scene prematurely.

Microscopically, Purkinje cells look like sea monkeys—kidding—they're more like tiny oak trees truncated at the ground line. If the trunk represents the cell body, then dendrites be like limbs and branches. Instead of the massive root system of a tree, each cell has but one long tap root, the output axon. Imagine these brain cells pressed and stacked flat with hundreds of thousands of climbing fibers running perpendicularly through them to feed information to receptors on their branches. Dense and uniform (the cerebellum harbors half of all the neurons in the brain), this cellular array is a calculator. It filters down data to a single decision—whether or not to output a signal from its axon to inform or enable a motor sequence. The sum total of firings affect the size and frequency of the action potentials relayed to the fingers. Disclaimer: As brain cells go, Purkinje cells are very large but if they were actually the size of oak trees, my head would be seventy-five miles wide.

Playing *Für Elise* involves an awkward hand maneuver after the main theme where—from a basic E chord position—I must quickly slide the left hand up to the seventh fret while my right hand plucks open strings (requiring no left-hand fingering) to facilitate a high-E harmonic with the little finger at the twelfth fret. This intuitive solution, switching hand positions prior to the stretch, is compliments of the basal ganglia (BG), a multipurpose cell structure in the mid-brain. Intuition is a strong suit of the BG, specifically the caudate nucleus which concocts fingering strategies.

Sheet music enlists alternate routes for encoding pitch in the brain. One is by associating the notes to names like do, re, mi, or A, B, C. Another is procedural memory where the notated pitch correlates to the guitar fret board. Visually, and conceptually, a complex musical passage is a “snapshot,” a vertical section view of the progression moving across a threshold like frames of a motion picture. The aperture of this view port is a three-beat wide frame of focus with the current beat being transitional from one to the next—chain-linked moments cobbled together on the work bench of short-term memory. Alternately, the second-nature quality of procedural memory lets me focus on a melody that is synchronized to, say, a “walking” bass line played automatically by my cerebellum-driven thumb. This parallel process compliments the single frame approach. I place mental benchmarks in *Für Elise* pointing where to toggle between these two modes as deciphered by the inferior frontal junction in my brain.

To say the cochlea in my ear projects a range of sound frequencies to my primary auditory cortex is like me saying that to be a movie star I'd first take Route 66 to California—an over-simplification. No, the pathway between cochlea and cortex is complex enough to fill an atlas. It involves bushy, octopus, and stellate cells in the thalamus, colliculus, olivary, and medial geniculate nucleus (which separates musical properties from sound by Fourier analysis, the math that taunted me in college). One becomes aware of sound only after it reaches the brain's cortex. The left temporal lobe (of a right-handed person) is a linguistic conduit with Wernicke's area at the back interpreting language (including emotional tone), and Broca's area up front fabricating speech both written and spoken. Pure music tones, on the other hand, are mostly processed on the right side of the brain—even if I'm not listening but merely hearing it. Music sparks activity mostly in my right lateral sulcus, or Sylvian fissure, above the temporal lobes. The top ledge of that cerebral side flap is Heschl's gyrus, one of several graduated tone maps that sorts out musical pitch. Towards the back is where tonal complexions and spectral modulations (fuzz-tones, wah-wahs, speech etc.) are processed independently of pitch. Without this timbre-analyzer, the dulcet overtones of my J-45 acoustic guitar could well be played on door buzzers or a slide-whistle and I wouldn't know the difference. Beyond that area, the visual cortex correlates sheet music to auditory pitch. Even if my ears didn't perceive the sound, I could conceive the tones by the mathematical ratios signified by the musical notation. Beethoven was stone deaf when he wrote his Ninth Symphony but he could "hear" perfectly what he had written.

The neighboring secondary auditory cortex is part of the so-called phonologic loop that sub-vocally rehearses melodies or, sans lyrics, the purely frequency driven tonotopic loop takes a right-lobe route to working memory, where the musical stimulus is maintained on-line short-term to relate one element to a later one. Working memory improves by increasing short-term storage capacity, like a parking lot with ample space between cars so an attendant need not move several cars to drive away in another. (Einstein's brain had ample parking in key areas.) Still, when the work load is high, as with part two in *Für Elise*, frontal areas can also dial up an extra half watt's worth of energy to power through the computations.

Which brain regions light up on both the first "walk-through" of a new musical piece as well as a well-learned version? Memories are retrieved via separate paths and not simply by reversal of electrical polarity along the original trace. The insula, deep in the lateral sulcus, monitors the replay so that I don't confuse a memory for the real event. After intuition is baked into a memory by the hippocampus (which, frankly, looks more like Van Gogh's ear than a seahorse to me), the basal ganglia can hang fire, ditto the orbital frontal areas active in the guessing game of learning but not in the knowing surety of planning. If I were improvising, as in jazz music, the lateral frontal cortex would shift its activity to the medial region, foregoing conscious planning in favor of an "in the zone" or "don't think, just do" functionality. However, this tune is "learned" via right channels and may output through the left temporal and frontal regions, including the premotor cortex, while the parietal cortex throttles back and the retrosplenial cortex deep in the posterior cingulate cortex—an envelope of spindle cells between the primitive inner brain and the highly evolved neocortex—cues up Brodmann Area 5 after I'm done sight-reading. Heschl's gyrus may be the only area active during both learning and playing modes. Otherwise, Elise is a familiar face wearing a different expression.

Each hand, the plucking right hand and the pinching left, has motor controls on opposite sides of the brain from them. Mental practice activates the same circuits (but doesn't build muscles or callouses).

Guitar students recruit more neural tissue in motor areas, or use it more efficiently, than most other instrumentalists. Changes also occur in the cerebellum and corpus callosum, the bridge between left and right hemispheres. Cortical representations of the left hand fingers (especially the little finger) are larger in guitarists' brains; The right hand, not so much. (The adage, “Right hand motion, left hand emotion” is poetic but nebulous.) However, with practice, guitar playing results in a reduction rather than an increase in activity in the motor cortex as it reorganizes itself with fewer neurons but new firing patterns and connectivity to serve new objectives and strategies. Auditory areas responding to tones are twenty-five percent greater though, especially to one's own instrument. Playing the guitar is trickier than a piano where music is laid-out in black and white. A pianist merely pokes the correct keys whereas a guitarist must yank, squeeze, cajole and finesse clear and proper tones from an obscure matrix of strings and frets. This requires more strength, precision, flexibility and coordination than pushing piano keys, although a piano offers more tones to juggle at one's pressure-sensitive fingertips. Given the importance of manual dexterity in general, that little homunculus embedded in the brain of even a non-musical human has oversize hands.

The motor cortex has three areas of functionality. The primary motor cortex (MC) coordinates the movement of muscle groups rather than individual muscles. Secondly, the premotor cortex (PM) plans those moves by a consensus of inputs from environmental and contextual perceptions, then provides the will and impetus for MC to pull my finger, so to speak. Thirdly, the supplementary motor area (SMA) might lift a script from the cerebellum's library of stock algorithms, or solicit episodic memories elsewhere (hint: starts with hippo, looks like horse) to inform the fingers. SMA makes quick adjustments to muscle force and trajectory. Those forces are manifest in the firing frequency of the neurons.

Scores of different molecules called neurotransmitters include two basic flavors: Glutamate electrically charges excitatory neurons such as pyramidal cells, and GABA (gamma-Aminobutyric acid) prompts inhibitory types like Purkinje cells that function by decreasing firing rates. Pyramidal neurons play a big role in a guitarist's brain, being prevalent throughout including layer V of the premotor cortex to actuate grasping motions in the hand, with axons projecting directly to the spine for fine motor control of the fingers. PM also contains mirror cells aplenty, helpful to someone learning to play a tune from an instructor or a YouTube video, and also for playing “air guitar” along with Van Halen. Intercommunication between brain parts is ultimately electrical in nature. In a nutshell (and brain cell), ion channels in the cell walls are blocked by amino acids at receptor cites (synapses) that selectively allow charged molecules to pass, thus controlling the flow of electrical signals by depolarizing action potentials in the differing voltages of sodium and potassium on opposite sides of the cell membrane. This activity underlies all of our thoughts, feelings and actions—more evidence that reality, and guitar playing, is a chemical reaction.

Low-frequency brain waves—Alpha, Beta, et al—arise from the sum total of all my neural activity. Among these, Theta waves help spur the hippocampus and corral short-term impressions into long-term memory banks by riding those galloping waves while I sleep. Gamma waves serve as a standard of measure when extracting information found in the differences between wave properties (think broadcast radio) of neural spike trains output from any group of brains cells that stimulate other attuned cells throughout the cortex. Brain waves can correlate mathematically to sound waves in music, occasionally causing the phonological loop to harbor “ear worms,” those insidious tunes that get stuck in one's head when nothing else is going on.

Music's abstract internal representation separates signal from noise but ignores superficial features such as loudness and reverberation. Listeners don't have to remember every detail of music to get its “gist.” Still, audio imagery can integrate certain formal qualities of sound, both surface and structural, in a stored representation. If music imagery were like architectural drawings, plans and elevations etc., then it might include the auditory equivalent of a perspective rendering. Every picture tells a story worth a thousand words, as the sayings conjoin, but then pure music is perceptual, not semantic; it doesn’t convey meaning unless by association (or lyrics). Music memory is modality-specific, detecting things such the Dorian mode or a twelve-bar blues structure. Conjunctive neurons link modal aspects from all associative cortices, forming a statistical representation: a prototypical memory.

When I play the guitar, I hear the music from the inside out. Sight, sound, and touch integrate with premotor activity in my brain just before the impulses are sent to the my fingers and before any feedback reaches my ears. Furthermore, my view of the guitar is upside down. I see the front of my guitar from over the top making it the default position of the eye-centered egocentric map represented in the precuneus of my brain's parietal lobe. This lends an omniscient aspect to my subjective viewpoint: It's as much outside-in as it is inside-out. My posterior parietal cortex codifies the relationship between my fingers, frets, and guitar strings independently from my eyes via my sense of touch coupled to the sound of my guitar. This internal representation is provided by neural projections from the somatosensory cortex just across the central divide from the motor cortex. This proprioceptive feedback informs my fingers to impart the proper pressure, tension, posture, muting, tremolo etc. to the guitar strings for, say, a B-flat chord—and that's just the left hand! The right hand makes that chord an arpeggio. The precuneus, Brodmann Areas 23 and 31, dorsolateral PMC, and the SMA contribute to the finger movements based on continuously updated comparisons between BA5 and the stable body image. The visual input solicited by BA7 enjoins this touchy-feely data, hand “sight” and finger “memory,” in BA5 from where it can project directly to the cerebellum via those excitable little granule cells in cortical layer IV. I'd like to thank them all by name: Thanks, Chet...thanks, Lightnin'...Joni...

Reading music is neurally distinct from reading words and numerals. A musical reading disorder can be isolated to playing, singing, or musical memory. Left hemispheric lesions cause music alexia wherein music becomes meaningless dots, stems, and squiggles. Meanwhile, the familiar two-note motif in *Für Elise* recurs in various duration from three to six repetitions. In the longest stanza, I looked away from the sheet music and at my left ring finger tapping the alternating D# and E notes while I counted the prescribed six beats before continuing the main theme. As a visual guide, that was more helpful than following the written notes with my eyes. BA7 in the visual cortex is active either way, but with the reinforcement of watching my fingers do the maneuver, I can now close my eyes and play that passage by touch and tone thanks to BA5 because somatosensory neurons can “hear” better than they can “see.” To wit, the half-step up from A to B-flat in measure 73 of *Für Elise* doesn't look like much on paper but musically it amounts to a tectonic shift from the recurrent theme that precedes it.

Music is a relative, not absolute, phenomenon. Our ears—-attuned to Western music (Hemisphere and honky-tonk)—-perceive a central tone, or key, as a basis for all harmonic relationships between twelve equally spaced pitch frequencies, in a hierarchy of pleasing mathematical ratios, the simpler, the better. Persons with Absolute Pitch may have a differing brain anatomy, but an area of the right frontal cortex is more active in most musicians, like me, without AP. *Für Elise* is written in the key of A-minor, one whole step higher than my original guess. I relearned it in Am but I was pleased to find that my ear had perceived the relationship of certain critical tones correctly, relatively speaking. The consonant (i.e. pleasant) chordal harmonies of simple sound frequency ratios involve neural networks outside of the main auditory cortex whereas Heschl's gyrus, surprisingly, shows more activity for dissonant chords (of which there aren't many in *Für Elise*). Deviations from harmonic expectations cause sparks in the inferior frontal operculum, but it's unclear at what stage in auditory processing that dissonance is computed in the brain. A distinction between sensory and musical dissonance would suggest auditory constraints versus learned associations. Either way, I find that harmonic dissonance is an acquired taste, a pleasurable one. To wit the chord culminating at the opening of Bach's *Toccata and Fugue in D-minor*, or the final lingering organ chord in The Animals' classic rock rendition of *House Of The Rising Sun*. Both have spine tingling good dissonance, the first one resolving itself contextually while the latter desists in a backwash of silence. And speaking of acquired tastes, the gustatory cortex—last stop for stimuli from the tongue's taste buds—is located directly across from Heschl's gyrus.

Piecing together the final rendition of *Für Elise* populates my short-term memory with impressions from the immediate and distant past, pattern matching the neural signature—the impedance-friendly brain circuitry of a memory trace—much like harmonic vibes sympathizing with its resonant frequency. Working memory is where I assemble those short-term mental objects into something useful. Dorsolateral prefrontal cortex, a region keen on inductive reasoning and intention, is very active during this central executive command function. The broadly distributed neuroanatomy underlying this theoretical construct of working memory coordinates the interplay between process and storage. The mental objects include guitar strings, tone segments, and musical notation, represented in the precuneus and projected to the phonological loop, chiming in from the rostral superior auditory cortex. Sight-reading this musical passage (my memory of it being largely associative) entails the narrow focus of the eyeball with its high visual acuity concentrated in the small fovea centralis of the retina, toggling between single focus and multitask modes mapped to adjacent areas in my occipital lobe (to receptive fields of the ventral stream for extra credit). Yet, while episodic and procedural memory may work in tandem, "you can lead a horse to water, but you can't make it play Handel," that is, you can't force the cerebellum to remember, only enable it. The cerebellum is not hardwired for conscious access except through associated memories and musical notation. They can provide detours around any mental blocks. That's why it's prudent to write things down! or at least make mental notes. Engaging the right medial frontal gyrus projects to the left inferior parietal lobe for an account of what's going on in the cerebellum. The mere act of writing or otherwise re-imagining the music saves the core memory on parallel pathways. A bank teller recently asked me for my account number but due to my sole use of a computer for access, I couldn't recall the number without first tapping an imaginary keyboard.

Music can express and induce emotions, but recognition of emotional tone is independent of the basic structure of music. It is neurally isolable from the intellect and is in contrast to the appreciation of aesthetics—the feeling of indifference for the content, but a reverence for the formal qualities of music or art and even delight in the precarious balance of details—which, FYI, shows up in the ACC and BA9 of PFC. Major and minor musical modes can convey happiness or sadness, as can tempo, but are not essential for recognizing a melody. Tickling ancient neural substrates, moody music entails neocortical cognition (the outer cortex being the most recent and highly developed part of the brain) and subcortical affectations. Emotions being cortically relayed to the limbic, or primitive, brain structures suggests how we should feel before we actually do (a nod to James-Lang theory in psychology). This increases blood flow in the mid-brain's ventral striatum (home of the nucleus accumbens—headquarters for all things emotional), the insula, and orbitofrontal cortex, all regions implicated with reward and motivation and the production of dopamine, the neurotransmitter of choice for the feel-good gang, plus new motor learning to boot. Emotions bolster the neural engram in the pleasure centers. Beethoven baked some emotion into *Für Elise* when he composed it, but as emotional charges go, this piece is no fork in the toaster. So, without any need for the amygdala—the almond shaped mood nodule next door to the hippocampus—to bore and stroke this musical memory trace, it defers to its neighbor, Seabiscuit. Still, it is my job as a guitarist to interpret and convey any empathetic properties, so I must first detect and decipher them in my supramarginal cortex. To test its efficacy, I withdrew to my home library with my guitar and played *Für Elise* for my wife, Elizabeth, coincidentally, a school teacher, who said, politely, “That's nice,” which is code for, “These report cards aren't going to write themselves.” That says something about empathy or perhaps my tenuous musical abilities. If sometimes I prefer the music of J. S. Bach over Beethoven's, it's because Johann's music, though passionate, seems to reflect a more intellectual, logical character compared to Ludwig's temperamental disposition. That could just be the Baroque left side of my brain scuffling with the Romantic right. The bottom line is that good music can make me cry, but generally not while I'm playing the guitar.

I've determined that the moment entailing the widest range of brain activity during any of my guitar recitals of *Für Elise* was the point at which, midst all else, I diverted my eyes from the written manuscript (measure 15) to watch my fingers tapping a string on the fret board while counting off six-beats. Areas of neural activity included the frontal and prefrontal lobes for executive command of working memory, the parietal lobe to map my fingers onto the guitar, premotor cortex providing the will and impulse, anterior cingulate to help focus attention, detect errors, and lend an aesthetic buzz to the transmission, the occipital lobe to see whatever my eyeballs are looking at, the cerebellum for automated finger routines, and, of course, the auditory (temporal) cortex including the nearby insula for a sense of self as I hear the music from the inside-out! This fanciful schematic includes a math loop in the left hemisphere for rhythm, and on the right for tempo and simple arithmetic. This snapshot merely suggests the extent of interrelationships between countless neural networks involved in the learning, storing, retrieval, integration and performance of a musical composition, a spectrum of activity encompassing the whole brain in, at least, a Rube Goldberg-grade amalgamation of serial and parallel processes right down to the superior colliculus for steering my eyeballs. With practice, I'm confident that new neural projections and the strength of those synaptic connections can grow prolifically in this guitar-player's brain.

–GRP