Music Beyond Sound: Weighing the Contributions of Touch, Sight, and Balance

Frank A. Russo

Address:
Department of Psychology
Ryerson University
350 Victoria Street
Toronto, ON M5B 2K3
Canada

Email:
russo@ryerson.ca

Although hearing is at the core of music for most listeners, not all of us experience music in the same way.

Ludwig van Beethoven suffered many hardships in his life, but the least known among them may be the persistent slivers he endured while handling wood. Yes, wood! Be it through clenching a wooden stick between his teeth or cutting the legs off of a grand piano, he is said to have developed resourceful methods that enabled him to feel mechanical vibrations of music in an effort to compensate for his failing sense of hearing (Wallace, 2018). Indeed, by all accounts, Beethoven was profoundly deaf by the time he composed his masterful ninth symphony. Stories of its debut in Vienna in 1824 suggest that Beethoven had to be turned around to see the rapturous applause of the audience.

The notion of *feeling* music continues to this day (Moore, 2019). Cities around the world host Deaf raves — giant parties where dancers feel the music through powerful subwoofers and bass shakers connected to floorboards. They also dance to the music, taking inspiration from visualizations that are projected onto large overhead screens. There is also a growing cadre of deaf musicians who are performing signed music (see bit.ly/37sQv4h). This music tends to be beat heavy, featuring lyrics delivered through sign language. Fueled in part by this cultural interest, researchers have begun to investigate the processes that enable deaf music and the ways in which auditory and nonauditory modalities combine to influence the experience of music for listeners of varying hearing ability.

Hearing the Music

In an article in *Acoustics Today* entitled "Does Sensory Modality Matter? Not for Speech Perception," Lawrence Rosenblum (2019) asks a question that can also

Figure 1. Sensory information from sound, touch, sight, and balance combine to influence the experience of music.
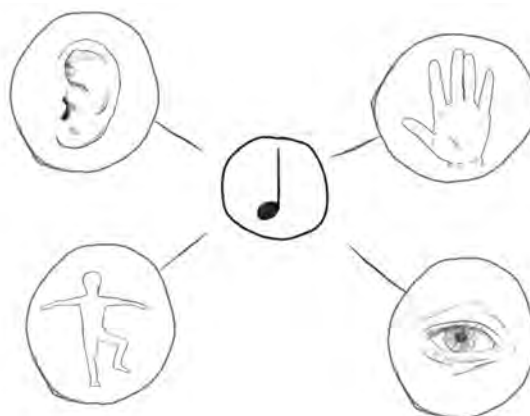
reasonably be asked of music. It would seem that music perception, like speech perception, is possible on the basis of sensory input that does not involve any sound (see **Figure 1**). However, before considering how the brain manages to process music by touch, sight, and balance, it is useful to first consider music in its conventional form, as a sound-based temporal art form, but to do so from the perspective of auditory cognitive neuroscience.

Sound waves produced by voices or instruments are collected in the outer ear, mechanically amplified in the middle ear, and transduced by sensory hair cells in the cochlea within the inner ear to produce neuroelectric activity. This neuroelectric activity is then transmitted by the auditory nerve to the brainstem and onto the thalamus, which in turn projects to the auditory cortex within the temporal lobe of the brain. The auditory cortex is the main cortical area involved in processing sensory information arising from music in normal-hearing listeners. At the core of the auditory cortex lies a "tonotopic map" wherein unique spatial positions correspond to unique frequency regions of sound input. Surrounding the core is a "belt area" and surrounding the belt lies the "parabelt." In a normal-hearing adult, the core will be activated by sound alone, whereas the belt and parabelt can be activated by sound as well as other forms of sensory input. **Figure 2** provides a macroperspective on the cortical modules and pathways beyond the auditory cortex that are believed to be involved in music perception (see article in *Acoustics Today* by Loui, 2019, for more on this subject).

A neuroimaging study by Zatorre and Belin (2001) revealed that responses to the local temporal features of sound (i.e., those with relevance for rhythm) were biased toward processing in the left hemisphere of the brain. In contrast, responses to the spectral features of sound (i.e., those with relevance for pitch and timbre) were biased toward processing in the right hemisphere. Consistent with these observations from neuroimaging studies are accounts from studies of patients experiencing unilateral brain damage. Patients with damage in the left hemisphere tend to show impairments in their ability to discriminate rhythms relative to neurotypical controls (Peretz, 1990). In contrast, patients with damage to the right hemisphere tend to require larger pitch differences to make pitch discriminations (Milner, 1962), show a weaker ability to discriminate pitch direction (Johnsrude et al., 2000), and degraded sensitivity to the global pitch contour (i.e., whether a melody is rising or falling; Peretz, 1990).

The beat is an aspect of rhythm that is intuitive but challenging to define on the basis of physical features alone. Nevertheless, following the beat is considered to be essential for music production as well as perception. Almost all humans possess the ability to follow the beat, including many of those who are "tone deaf" (Hyde and Peretz, 2003). This ability is thought to be primarily served by a dorsal pathway connecting sensory and motor areas of the cortex. This same dorsal pathway is thought to be involved in perceiving emotion in music (McGarry et al., 2015), learning a new piece of music by ear (Lahav et al., 2007), and in the type of feedback monitoring

*Figure 2. A sagittal view of the human brain featuring modules and pathways that are believed to be involved in the perception of music. The front of the brain is to the **left**.*
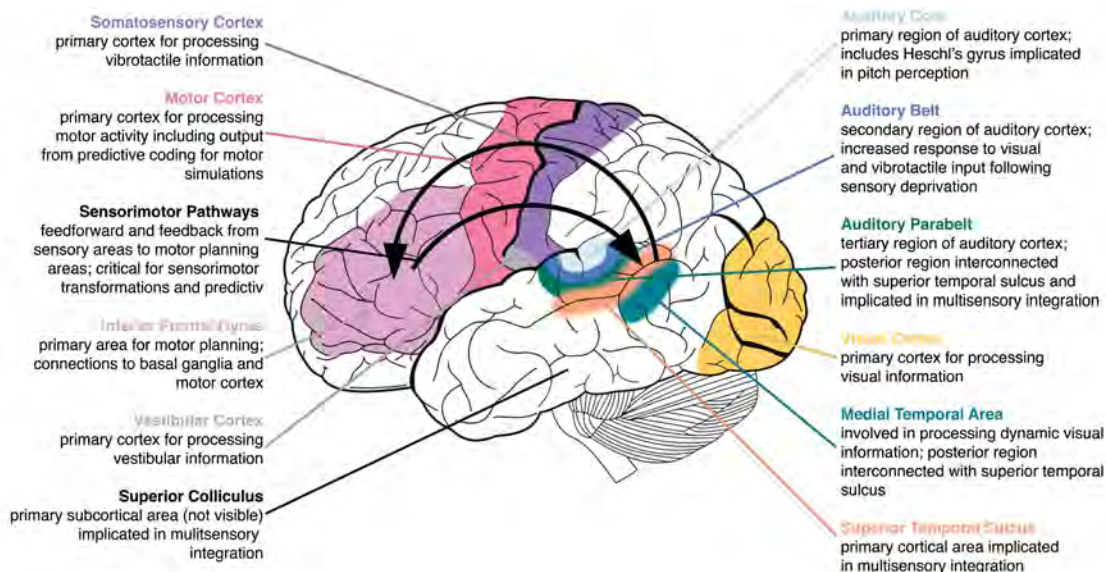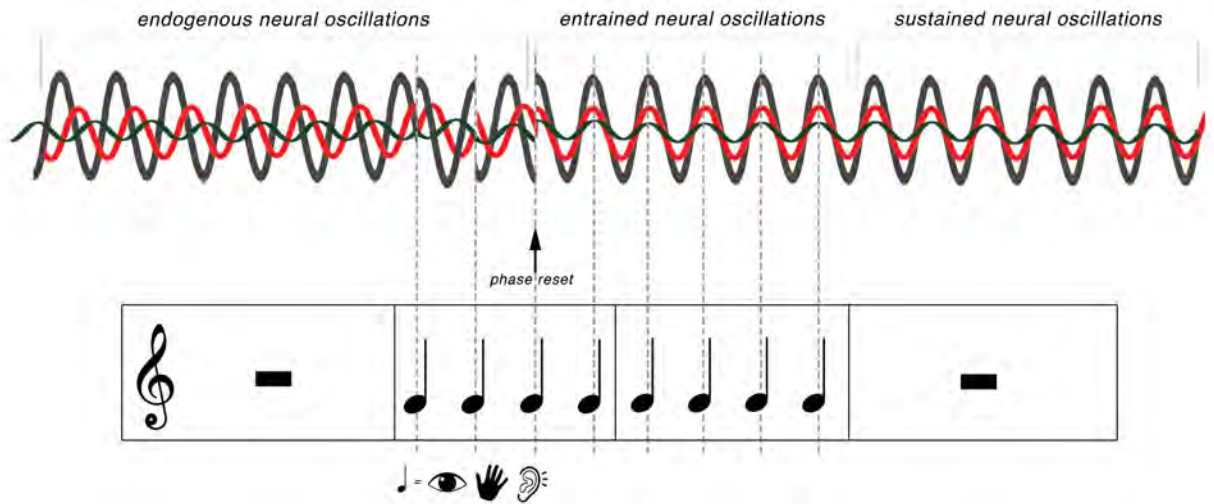
Figure 3. A schematic model of neural entrainment. Endogenous neural oscillations (see text for details) experience a phase reset following a sequence of regularly spaced salient events (e.g., beats in music). These events tend to be heard but they can also arise from vision and touch. After a phase reset, the synchronized oscillations are considered to be entrained. The neural entrainment continues through a rest in the music (i.e., it persists after the sensory stimulation ends).

required for expert music performance, particularly in continuous pitch instruments like the voice or violin (Loui, 2015).

Let us define the beat here as a pattern of *perceptual* accents that occur at equally spaced time intervals across a rhythmic sequence. It is important to note that by invoking the notion of a perceptual accent, the beat is ultimately a psychological construct (London, 2012). There are several reasons for considering the beat in this manner. First, the perceptual accents need not be physically prominent (i.e., louder or longer). Second, the beats of a rhythm do not always coincide with events of a rhythm. Third, the feeling of the beat can persist even after the music stops.

A neurocognitive view of beat perception suggests that the beat emerges from the entrainment of endogenous (i.e., internally generated) neural oscillations. This process, referred to as *neural entrainment*, is depicted in **Figure 3**. The starting point for understanding neural entrainment is noting that it is well-known that neurons exhibit endogenous oscillatory activity, regardless of whether or not these neurons are part of a system that is currently "online." These neural oscillations exhibit their own frequency and phase characteristics. However, after an observer perceives a few regularly spaced perceptually salient events, a phase reset may occur wherein the endogenous oscillations that are of a similar frequency to the frequency of the perceptually salient events become phase aligned (Obleser et al., 2017). At this point, the neural oscillations are said to be entrained. Remarkably, this entrainment of neural oscillations

will continue to be sustained even after a beat has stopped. Open questions in this subtopic of rhythm research include the extent to which this neural entrainment persists and the extent to which it is possible to entrain to rhythms that are presented through nonauditory modalities (Iversen et al., 2015).

Feeling the Music

Because all sound arises from mechanical vibration, one might expect that music should be perceptible on the basis of mechanical vibration on the skin (see the example with a cello in **Figure 4**). Like the sensory hair cells that exist in the cochlea of the inner ear, mechanoreceptors found in the dermis layer of the skin are responsible for the transduction of vibrotactile stimuli. Four classes of mechanoreceptors have been identified that are sensitive to vibrotactile input (Bolanowski et al., 1988). Each class has its own characteristic frequency and frequency range. Because of these physiology foundations, there appears to be some capacity to represent the spectral properties of a vibrotactile stimulus even at the level of the skin.

Georg von Békésy, the Nobel Laureate biophysicist who has arguably had the most lasting impact on auditory research (see acousticstoday.org/7302-2 for a short biography), conducted a series of experiments that involved mechanically stimulating skin on the forearm to assess different models of cochlear function (von Békésy and Wever, 1960). These particular experiments led him to conclude that the frequency response corresponding to the place of maximal excitation in a traveling wave was sharpened through a

process of inhibition, wherein activity from neighboring receptor areas was dampened. However, it is important to note that despite the similarities across modalities in regard to frequency-tuned mechanoreceptors and inhibition, pitch discrimination thresholds obtained with vibrotactile stimuli tend to be about five times greater than those obtained with auditory stimuli (Verrillo, 1992).

Detection thresholds for vibrotactile stimuli show a peak sensitivity around 250 Hz, exhibiting a sharp decline below 100 Hz and above 1,000 Hz (Verillo, 1992). Sensitivity has also been found to increase as a function of the number of mechanoreceptors that are stimulated (Morioka and Griffin, 2005). The number of mechanoreceptors stimulated will be influenced by the type of skin and the contact area between the source of vibrotactile stimulation and the skin. Mechanoreceptor density is higher in smooth areas of the skin (e.g., palms of the hands), which leads to higher overall sensitivity in smooth skin compared with hairy skin (Verrillo and Bolanowski, 1986). A commensurate, albeit speculative, point to make about sensitivity to vibrotactile stimulation in smooth skin is that observers may experience annoyance sooner over smooth skin because of its heightened sensitivity.

Several studies have investigated the ability to discriminate timbre on the basis of vibrotactile stimulation alone. Russo et al. (2012) found that both deaf and hearing observers were able to accurately distinguish instrument timbres on the basis of vibrotactile input. Deaf and hearing participants were also able to distinguish timbre on the basis of vibrotactile input when stimuli consisted of synthetic tones that differed only with respect to spectral tilt — whether the envelope was weighted toward low or high frequencies. Based on these findings, Russo et al. (2012) proposed that the vibrotactile perception of timbre involves the cortical integration of activity across the frequency-tuned mechanoreceptors. The relative activity across channels would allow for perceptual coding of the spectral shape in the same way that has been proposed for the critical bands in the auditory system (Makous et al., 1995). It would only take two such channels to allow for the coding of spectral tilt. Moreover, a follow-up study revealed that deaf participants are able to discriminate sung vowels and that the extent of difference in the spectral tilt between pairs strongly predicted their discriminability (Ammirante et al., 2013).

In addition to the role of vibrotactile stimulation in perception of music, it seems that vibrotactile feedback arising

Figure 4. Pitch, timbre, and rhythm can be perceived on the basis of touch alone.

during music performance provides valuable information about timbre that may be used by the performer (Marshall and Wanderley, 2011). Perhaps, not surprisingly, the perception of sound quality as evaluated by the performer has been shown to be positively influenced by microvibrations as feedback from the strings that can be felt through the keys (Fontana et al., 2017). The ability to incorporate vibrotactile feedback in performance is further supported by the observation that vibrotactile detection thresholds are reduced when stimulation arises from actively touching a vibrating surface compared with receiving the vibration on a stationary hand (Papetti et al., 2017).

Several lines of evidence exist to suggest that touch can influence our perception of rhythm. In one study, researchers asked deaf and hearing participants to synchronize their movements to a vibrotactile beat that was delivered through a vibrating platform on which the participants were asked to stand (Tranchant et al., 2017). The synchronization of movements was achieved by attempting to bounce in time with the beat. Hearing participants were asked to perform an additional task in which they were asked to synchronize their bounces to the same beat when it was delivered through sound alone. The results showed that most participants were able to bounce to a vibrotactile beat. However, for hearing participants, synchronization performance was better in the auditory condition, presumably due to the years of experience they had amassed tapping or dancing to music. The study did not, however, consider individual differences such as formal dance training or the extent of experience in moving to music.

Empirical evidence for synchronization to a beat has also been found using vibrotactile stimulation applied to the fin-

gertip (Brochard et al., 2008), toe (Müller et al., 2008), and back (Ammirante et al., 2016). In the case of a simple beat like that produced by a metronome (isochronous), synchronization is equivalent for vibrotactile and auditory presentations, at least under some presentation conditions. For example, Müller et al. (2008) found that the ability to tap to the beat was comparable when the vibrotactile stimulation was applied to the fingertip, but performance dropped when the stimulation was applied to the toe. Ammirante et al. (2016) found that synchronization ability was equivalent when the input stimulus was sound or vibrotactile stimulation on the back, but only if the area of stimulation on the back was large. In the same study, synchronization ability was found to be superior for auditory stimulation when the rhythms were more complex than a metronome. Again, this effect may be related to the vast experience amassed with moving to music presented as sound. Along these same lines, Lauzon et al. (2020) found that the ability to detect asynchronies in a rhythm were superior when the rhythm was presented by auditory compared with vibrotactile stimulation.

Vibrotactile stimuli have been shown to activate belt areas of the auditory cortex bilaterally (Schürmann et al., 2006). The extent of auditory activations observed in deaf participants is more widespread than that observed in normal-hearing participants (Auer et al., 2007), likely due to rewiring in the brain that follows a period of sensory deprivation. One question resulting from this work is whether activation of auditory areas by vibrotactile stimuli is direct or whether the auditory activation arises indirectly as a result of projections from touch areas.

Using magnetoencephalography, Caetano and Jousmäki (2006) were able to track the time course of activations corresponding to different sensory cortices. Normal-hearing participants were presented with vibrotactile stimulation at 200 Hz delivered to the fingertips. An initial response was observed in the primary touch (somatosensory) cortex, peaking at around 60 ms poststimulus, followed by transient responses in auditory cortex between 100 and 200 ms. Finally, a sustained response was observed in the auditory cortex between 200 and 700 ms. These findings suggest that in normal-hearing listeners, at least, auditory representations of vibrotactile stimuli are made possible by a causal processing chain that starts in the somatosensory cortex that then feeds forward into the auditory cortex.

Facing the Music
A melodic interval is produced when two notes are played in succession. Larger melodic intervals involve a greater pitch
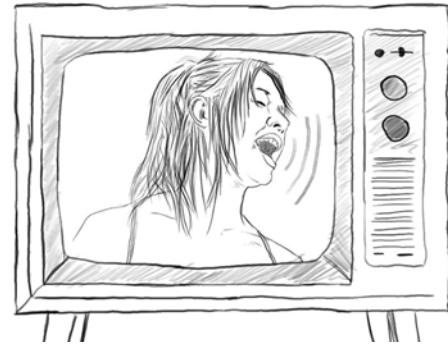

Figure 5. Movements of the head, eyebrows, and mouth in a vocal performance provide reliable information about melodic interval size.

distance between notes. Several studies have shown that observers can detect the size of a sung melodic interval on the basis of visual observation of the performer's head and face. When silent videos of sung melodic intervals are presented to observers, they are able to accurately scale their relative size (Thompson and Russo, 2007). This ability does not appear to require music or vocal training, which argues against an explanation based on long-term memory and further suggests that some aspects of the visual information provide reliable cues for judging interval size. Video-based tracking has supported this interpretation, revealing that larger intervals tend to possess more head movement, eyebrow raising, and mouth opening. The influence of visual information on the perception of size in sung melodic intervals persists even when videos are converted into point-light displays in which the dynamic information is retained through a matrix of dots while eliminating static visual cues (Abel et al., 2016).

Sight can influence the perceived size of sung melodic intervals even when the sound is present (Thompson et al., 2010). The mouth area may be particularly important in this visual effect (see **Figure 5**). In one study involving audiovisual presentations of sung intervals, the signal-to-noise ratio (SNR) in the audio channel was manipulated across conditions. As the SNR of the sung melodic intervals decreased, the extent to which participants directed their gaze toward the mouth increased (Russo et al., 2011). However, the visual influence on auditory judgments has been found to be reduced for participants with a young onset of musical training (Abel et al., 2016). One interpretation of this latter finding is that early-trained musicians possess a stronger audiomotor representation of sung melodic intervals. This enhancement in motor representation may allow these early-trained musicians to rely less heavily on sight when presented with audiovisual input.

The mechanism that my group has proposed as underpinning the visual contributions to melodic pitch perception involves feedforward and feedback connections along a dorsal stream connecting the sensory and motor areas. Feedforward connections from sensory areas to motor areas provide input that enable an internal motor simulation of what is being perceived. Motor areas feedback information about biological movement that can be compared with the incoming sensory information (Kilner et al., 2007). In the case of individuals who are hard of hearing, there may also be an additional contribution that stems from visual activation of the auditory cortex, particularly in the belt areas (Finney, 2001; Good et al., 2014). Research in animal models suggests that the belt areas of the auditory cortex undergo profound plastic changes following a period of auditory deprivation, which leads in some cases to enhanced visual processing.

The effects of vision are also invoked in the perception of musical timbre. In a musical extension of the well-known "McGurk effect," Saldaña and Rosenblum (1993) presented participants with audiovisual recordings of cello tones where bowing and plucking information was manipulated across channels. So, for example, observers were presented with an audiovisual recording in which the audio channel consisted of plucking and the visual channel consisted of bowing. The results revealed that plucking sounds were more likely to be heard as bowing when accompanied by the sight of bowing. These results were interpreted as evidence consistent with an automatic internal motor simulation. The authors further presume that the simulation may be driven by auditory or visual information.

A number of visual contributions to rhythm perception have been established (Schutz, 2008). For example, Rosenblum and Fowler (1991) recorded handclaps of varying intensity. Participants were presented with audiovisual pairings of the handclaps that were congruent (from recordings of similar intensity) or incongruent (from recordings of different intensity). Results revealed that the visual information had a systematic influence on loudness judgments despite the instruction to focus on auditory information only. Visual information can also influence the perceived duration of a performed note. To study this phenomenon, Schutz and Lipscomb (2007) utilized audiovisual recordings of marimba notes performed using "long" (i.e., exaggerated) and "short" gestures. Much like Rosenblum and Fowler (1991), visual channels were recombined to form congruent and incongruent pairings. In this example, the auditory channel had no effect on judgments even though the participants were asked to focus their judg-

ments on the auditory channel. However, the visual channel has a consistent effect on the perceived duration such that long gestures lengthened the perceived duration of notes and short gestures shortened them. In a follow-up study, the visual channel was replaced with a point-light rendering of the performer's movement. Results showed that the visual effect on judgments remained, which suggests that the visual effect is based on the dynamics of visual movement (Schutz and Kubovy, 2009).

Some evidence suggests that the ability to synchronize with a rhythm (i.e., tap along or dance in time) depends on the nature of the visual stimulus. Although discrete visual stimuli (e.g., flashes) have been found to be inferior to auditory tones (Patel et al., 2005), continuous visual stimuli (e.g., a bouncing ball) lead to near comparable synchronization performance (Iversen et al., 2015). Neuroimaging studies have demonstrated that continuous visual stimuli give rise to greater activation of the putamen (a brain area that is strongly implicated in beat perception) than do discrete visual stimuli, approaching levels of activation obtained with auditory beeps (Grahn, 2012). This finding suggests that the ability to synchronize to metrical structure is not simply contingent on the channel of sensory input but also on the nature of stimulus presentation. Although discrete events are optimal with auditory stimuli, continuous events lead to better outcomes with visual stimuli. Some evidence suggests that deaf individuals possess some advantage in tracking visual rhythms (Iversen et al., 2015). Referring back to **Figure 2**, the strength of direct visual input to auditory-motor pathways is likely enhanced in deaf individuals.

Getting the Balance Right
Both passive and active head movements are capable of stimulating the vestibular system that is involved with the sense of balance (Cullen and Roy, 2004). With the possible exception of classical music performances, it is common to see people moving their heads while listening to music. As such, it would seem that vestibular stimulation is commonplace during music listening (see **Figure 6**). Moreover, given that the vestibular cortex is extensively connected with other sensory cortices, it stands to reason that there are ample opportunities for multisensory integration in music that involve the vestibular system.

Phillips-Silver and Trainor (2005) assessed the contribution of the vestibular system to multisensory rhythm using an ambiguous auditory rhythm (see tinyurl.com/wwry2qu for an auditory example). These rhythms can be heard in duple or triple form, that is to say, recurring patterns of two beats (as in a march) or three beats (as in a waltz). The rhythms

Figure 6. Vestibular information has an influence over rhythm perception.

were presented to infants while they were bounced on every second or every third beat. On the basis of a head-turn preference procedure, researchers were able to conclude that when the infants were bounced on every second beat, they were coding the ambiguous rhythm in duple form and when they were bounced on every third beat, they coded the rhythm in triple form (see tinyurl.com/wwry2qu for an audio example). A follow-up experiment in the same study showed that blindfolding infants mitigated but did not eliminate the effect, which confirms that the contribution to rhythm perception was at least partially influenced by the vestibular system.

These effects of auditory-vestibular integration appear to persist into adulthood. In one study, adults were trained to bounce in duple or triple time while listening to an ambiguous rhythm. A subsequent listening test revealed that adults were more likely to identify an auditory version of the rhythm with accented beats that matched their bouncing experience as more similar than a version whose accents did not match (Phillips-Silver and Trainor, 2007).

Going Forward

This article has reviewed evidence to suggest that our perception of music involves more than just sound. Although the majority of hearing individuals will focus on sound as the core of music experience, it would seem that a more inclusive and nuanced consideration of music is possible when taking a multisensory perspective involving the integration of sensory inputs from touch, sight, and balance. There is growing interest in the experience of music by deaf and hard-of-hearing

individuals. Indeed, the majority of individuals in the deaf community report engagement in musical activities (Darrow, 1993). It would be worthwhile for future research to consider multisensory presentations of musical stimuli that minimize differences in perception across listeners of varying hearing ability. In addition, given the multisensory contributions to music, it would seem that it is quite possible to train aspects of music listening using a combination of auditory and nonauditory inputs. Future research should consider which individuals would benefit most from multisensory approaches to training (Glick and Sharma, 2017).

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BioSketch

Frank Russo is a professor of psychology and the Natural Sciences and Engineering Research Council (NSERC)-Sonova Senior Industrial Research Chair in Auditory Cognitive Neuroscience at Ryerson University in Toronto, ON, Canada. His research program focuses on the neurocognitive and social aspects of music, speech, and hearing. Frank has received career awards from the Ontario Ministry of Research and Innovation, the Canadian Society for Brain, Behavior and Cognitive Science, and the International Commission of Acoustics. He is a Fellow of the Canadian Psychological Association and Massey College and is a past president of the Canadian Acoustical Association.

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