Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Issue: *The Neurosciences and Music IV: Learning and Memory*

The multisensory brain and its ability to learn music

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Playing a musical instrument requires a complex skill set that depends on the brain's ability to quickly integrate information from multiple senses. It has been well documented that intensive musical training alters brain structure and function within and across multisensory brain regions, supporting the experience-dependent plasticity model. Here, we argue that this experience-dependent plasticity occurs because of the multisensory nature of the brain and may be an important contributing factor to musical learning. This review highlights key multisensory regions within the brain and discusses their role in the context of music learning and rehabilitation.

Keywords: brain; multisensory; learning; music

Introduction

We live in a multisensory world, and as a result, the brain is equipped with many multisensory areas. Traditionally, the brain was thought to contain several modality-specific, or unisensory, regions that could receive input from one of the primary senses. However, with advancing research it has become clear that many of the unisensory brain regions are actually multisensory in nature. For example, visual and somatosensory inputs have been observed in the auditory cortex,[1–12] auditory and somatosensory inputs have been observed in the visual cortex,[13–17] and visual and auditory inputs have been observed in the somatosensory cortex.[18,19] Therefore, the brain is composed of several multisensory regions, making it possible to handle the sensory challenges of our multisensory world.

The human brain depends highly on sensory input. When a sensory signal is received, receptor organs create neural impulses that are sent along unisensory pathways into subcortical and cortical structures. Typically, when the signals reach the cortex they remain unisensory. However, there are specialized areas within the brain that integrate and store information from different sensory modalities. These multisensory brain areas receive inputs through several unisensory cortical pathways, including auditory, visual, and somatosensory circuits.[20]

Musical training and the multisensory brain

Multisensory brain regions are shaped by specialized sensory experiences. One example of a specialized sensory experience is the process of learning to play a musical instrument. Initially, musical training takes advantage of the innate multisensory capabilities of the brain; however, as skillful expertise develops, further plasticity and neural specificity occurs. Previous studies have shown structural and functional brain differences in auditory,[21–24] sensorimotor,[25–27] and multimodal integration areas[26,28–30] in musicians compared to nonmusicians. Later in the review, we will argue that it is indeed the multimodal integration areas that play an advantageous role in music learning, performance, and rehabilitation.

In addition, brain plasticity seems to be highly sensitive to the multisensory conditions under which training was obtained. For instance, it has been shown that trained violin players have increased somatosensory representation of their left hand,[25] trained trumpet players have enhanced interactions between auditory and somatosensory inputs to the lips,[31] and trained pianists have increased activation in presupplementary motor cortex and lateral dorsal premotor cortex.[32] Taken together, these studies show that musical training can result in plasticity-induced cortical changes to further optimize the multisensory demands required for music performance.

Is there an advantage to having multisensory regions in the brain?

When multiple senses are stimulated at the same time, termed multimodal, the result can be advantageous. For example, when a violinist is playing, you can not only hear the music, but can also see the violinist bowing against the strings. Because these stimuli (i.e., sound/sight of violin) originate from the same event, the resultant combination is synergistic and can significantly exceed the response from either sensory input alone or their arithmetic sum.[33–40] Often, the neural responses can exceed the sum of the responses to each sense alone by approximately 1,000%.[36,41] This type of additive neural response derived from multisensory regions is beneficial for learning music and may be a key factor for the effective use of music in physical rehabilitation.

Multisensory cortical brain regions associated with music learning

Although the brain contains a vast amount of multisensory areas, several distinct cortical brain regions have been particularly implicated in the music domain. These regions mainly include the superior temporal sulcus (STS), the intraparietal sulcus (IPS), and the prefrontal cortex (PFC). As we discuss each brain region, we will first introduce the multisensory nature of the region and then highlight its role in the context of music learning and performance.

STS

The STS is the sulcus separating the superior temporal gyrus from the middle temporal gyrus in the temporal lobe. Studies have shown that approximately 36–38%[42,43] of the anterior STS neurons and 12% of the caudal STS neurons are multimodal.[44] Barraclough *et al.*[45] have shown that the same STS neurons that code the sight of actions can also code the sound of those actions. They found that 23% of neurons responsive to the sight of an action were also responsive to the sound of that action.[45] Thus, neurons in the STS seem to form multisensory representations of observed actions.

Functional magnetic resonance imaging (fMRI) studies have shown activation of the STS during various musical tasks, such as the processing of melody,[46] pitch,[47] and timbre changes,[48] perception of musical chords,[49] recognition of musical memories,[50] and during singing.[50] This region seems to be activated by the fine structures evident within musical pieces.

IPS

The IPS is located on the lateral surface of the parietal lobe and is thought to be related to perceptual-motor coordination. Three subareas within the IPS are involved in multisensory integration. These areas include the lateral intraparietal region, which receives sensory signals for eye positioning and auditory signals;[51] the ventral intraparietal region, which contains neurons that can respond to visual, auditory, somatosensory, and vestibular to create bimodal and trimodal receptive fields;[52–55] and the temporoparietal junction, which is thought to contain many multimodal representations of space.[56]

Schulze *et al.*[57] found large IPS activation during auditory working memory in musicians compared to nonmusicians. Another study by Lahav *et al.*[58] has shown activation in the IPS[59] during motionless listening to a rehearsed musical piece five days after learning. IPS activation has also been shown during temporal reversal of a melody—where musicians were presented with the first few notes of a familiar tune, or its title, followed by a string of notes in a reversed order. These studies implicate the IPS as a brain area involved in auditory memory circuitry—a crucial component for music learning.

PFC

The PFC plays a role in temporal integration and receives projections from both the auditory and visual cortices.[60–62] This widespread connectivity makes the PFC a prime location for multisensory integration. This region has been of particular interest in the past 15 years with the discovery of mirror neurons. A mirror neuron is a type of neuron that discharges both when an individual performs an action and when they observe another individual performing a similar action.[63,64] Mirror neurons likely play a large role in music integration and learning. Buccino *et al.*[65] scanned nonmusicians during the following tasks: guitar chords being played, a pause after the model observation, execution of the observed chords, and then rest. They found that the basic circuit underlying imitation learning consisted of the IPL, posterior aspect of the inferior frontal gyrus, and the mirror neurons in PFC.[65]

Leaver *et al.*[66] examined the predictive or "anticipatory imagery" of music at various stages using fMRI. They found that anticipatory imagery in silence for highly familiar music activated rostral prefrontal cortex and premotor areas. Not only is the prefrontal cortex important for musical prediction, it is also activated during error correction during musical performance.[67] In addition, the prefrontal cortex has been shown to be activated in pitch processing,[68,69] temporal modulations in rhythmic stimuli,[70] musical chord violations,[71] recognition of tonal structures,[72] and emotional responses to music.[73,74] It is clear that the prefrontal cortex is a necessity for music because planning, execution, and emotion are all vital aspects for a successful musical performance.

The three multisensory regions discussed previously are crucial for musical training and performance. For example, music is not attained by merely activating the motor cortex to press down a piano key with your finger; it requires the fine structure and specificity afforded by multisensory regions. A musical piece must contain pitch, timing, and timbre, which are all housed in these multisensory brain regions. We hypothesize that music requires more than an integrated sensorimotor system; it requires an integrated multisensory system. A prime model for this hypothesis is a nonmusician, who may have a well-intact sensorimotor system but still lacks the fine structure of a good musician. It may be, in fact, that these nonmusicians have abnormal neuronal structure, characterized by reduced gray matter volume or impaired white matter connectivity in the three multisensory regions discussed previously. Future studies are encouraged to examine this hypothesis in more detail.

Implications for music learning

Is the multisensory learning environment (e.g., vision, audition, and touch) indeed beneficial in the initial process of learning to play a musical instrument? The usage of nonmusicians as study subjects can provide investigators with a unique experimental model to answer this question. For example, Eldridge *et al.*[75] examined the effect of unisensory versus multisensory feedback on the ability to code and recognize pitch information. In this study, two groups of nonmusicians were trained to play a piano piece by ear. One group received uninterrupted audiovisual feedback, whereas the other group could hear but not see their hands on the keyboard (audio alone). This study found that multimodal stimulation increased learning and encouraged the use of audiovisual (rather than audio or visual alone) in learning new skills.[75] Similarly, Pantev *et al.*[76] found that multimodal sensorimotor-auditory training in nonmusicians resulted in greater plastic changes in auditory cortex than auditory training alone. Music is a multimodal experience and when one of the modalities is occluded—it can come at the cost of learning. Thus, when it comes to music learning, receiving feedback from multiple senses is probably better than receiving feedback from one.

Although this review focuses primarily on cortical multisensory regions in the context of music learning, there are also several subcortical processes that are attributed to musical training (for a review, see Ref. 77). Kraus *et al.*[78] point to pitch, timbre, and timing as having subcortical populations that can be enhanced through musical training. Similarly, other studies have shown that musicians have been shown to have enhanced electrophysiological responses to melodic contour and interval information[79] and enhanced evoked potentials in response to pitch changes during speech processing[80–82] in the auditory brainstem. As the focus on subcortical structures in musical training increases, it will likely reveal vast multisensory regions and cortico–subcortical connectivity that further integrate and evolve during musical training.

Implications for rehabilitation

Music is often a highly motivating and pleasurable form of therapy that can have global benefits on the brain (for review, see Ref. 83). Previous studies have shown that rapid plastic adaptation because of music performance is not restricted to motor areas but also incorporates auditory and auditory-sensorimotor circuitry.[84–86] Thus, the multisensory nature of music making and listening concurrently stimulates multiple systems within the brain. This type of multimodal stimulation is believed to facilitate crosstalk and connectivity between key regions of the brain, which may be particularly beneficial for neurologically impaired patients.

Schneider *et al.*[86] provided 20 stroke patients with a musical training program (15×/3 weeks) and compared them to 20 stroke patients who did not receive the program. They found that the stroke patients who received the musical training program had significant improvements in speed, precision, and smoothness of movements, as well as in everyday activities compared to the control group. The reason music is so powerful is because it requires integration of multisensory and motor inputs as well as the precise monitoring of the resultant motor performance by multiple feedback mechanisms.[87] Therefore, if all possible connections and networks are being targeted, not only does the likelihood for rehabilitation increase, but the ability to create new connections through experience-dependent plasticity also increases.

The engagement of multiple multisensory and motor regions activated by playing music can have beneficial effects on the physiological and psychological health of individuals.[83] In addition, playing music in rehabilitation can improve attention,[88–90] emotion,[91] cognition,[92] behavior,[93,94] and communication[95] skills (for a review on this topic, see Ref. 83). It is clear that the use of music for neurologically impaired patients is a favorable clinical option.

Conclusion

These multisensory areas enable musicians to integrate complex sensory inputs and the resultant motor outputs necessary to play music. This paper argues that the use of multisensory feedback during musical training should be highly preferred because of the vast interconnectivity within and between multisensory areas, which allows for music-induced brain plasticity to occur. This plasticity may be particularly important for neurologically impaired patients. Thus, the implementation of multisensory music-based therapies in physical rehabilitation should be further encouraged.

Conflicts of interest

The authors declare no conflicts of interest.

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