2005

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Neuron, Vol. 47, 9–12, July 7, 2005, Copyright ©2005 by Elsevier Inc. DOI 10.1016/j.neuron.2005.06.013

Mental Concerts: Musical Imagery and Auditory Cortex

Minireview

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Most people intuitively understand what it means to "hear a tune in your head." Converging evidence now indicates that auditory cortical areas can be recruited even in the absence of sound and that this corresponds to the phenomenological experience of imagining music. We discuss these findings as well as some methodological challenges. We also consider the role of core versus belt areas in musical imagery, the relation between auditory and motor systems during imagery of music performance, and practical implications of this research.

Cognitive neuroscientists are faced with a seemingly daunting task: understanding how the brain enables us to experience our rich inner world of thoughts, feelings, and images. The subjectivity involved in these internal processes provides a particular challenge because scientific methods require one to measure verifiable, observable events. One domain in which this problem has played out is mental imagery. Although behaviorists in their heyday insisted that imagery was off limits because of its obscure, subjective nature, clever cognitivists demonstrated early on that reliable behavioral measures could be obtained that served as indices of what was going on inside the mind. Shepard's classic demonstration of mental rotation (Shepard and Metzler, 1971) serves as an excellent example of how an overt measurement (response time to judge the orientation of a letter) can provide evidence of a covert mental process. In other words, one infers the existence of a process based on observing some effect caused by that process; in this respect, cognitive approaches are not so different from physics or other sciences in which the objects of study (neutrinos, black holes, or whatever) are simply not accessible.

Recent Advances in the Study of Musical Imagery

Imagery is not exclusively visual, as anyone can attest to who has ever been annoyed by some advertising jingle playing relentlessly in his or her mind. On a more exalted level, composers such as Beethoven or Smetana, who became deaf later in their lives, nonetheless were able to compose magnificent music, presumably because they were able to conjure up musical images solely internally. Many researchers have concentrated on understanding musical imagery in particular partly because of the ubiquity and vividness of imagined music. So what enables us to produce these "mental concerts"? What are the psychological and neural mechanisms associated with these processes?

A handful of studies have now been carried out on this topic using a variety of techniques, including, magneto-encephalography (Schürmann et al., 2002), positron emission tomography (Halpern and Zatorre, 1999; Zatorre et al., 1996), and functional MRI (Halpern et al., 2004; Kraemer et al., 2005; Yoo et al., 2001), as well as behavioral lesion measures (Zatorre and Halpern, 1993), which provide better evidence of causality than do functional measures. These diverse studies converge on one principal finding: that neural activity in auditory cortex can occur in the absence of sound (Figure 1) and that this activity likely mediates the phenomenological experience of imagining music. Beyond this basic understanding, however, much remains to be understood, including the relative contributions of primary versus secondary auditory regions in each hemisphere, the participation of the frontal cortex to the imagery process, and the role of musical training in development of musical imagery. Before discussing these substantive questions, however, we turn our attention briefly to methodological issues.

Methodological Problems and Solutions

The problem of measuring internal phenomena might appear to have finally found a solution with functional imaging techniques, since one can observe the underlying neural activity more directly, rather than inferring its presence. Yet, we are still left with the conceptual problem of knowing what is being measured. Thus, merely placing subjects in a scanner and asking them to imagine some music, for instance, simply will not do, because one will have no evidence that the desired mental activity was actually taking place. Neural activity can still be measured under these circumstances, but it may well be related to other processes than the one intended. One good solution to this problem involves behavioral indices, such that an overt response is measured that either depends on or correlates with the imagined event. For instance, if we ask people to imagine the first four notes of Beethoven's Fifth Symphony and they correctly and consistently judge that the fourth note is lower than the third, then we have objective evidence that an internal representation containing pitch information has been accessed (Halpern, 1988). In the context of neuroimaging, such tasks have the disadvantage that they carry a lot of cognitive overhead in the form of attentional, working memory, and response demands; but these can be accounted for with appropriate control conditions. Simpler tasks, such as imagining the continuation of a known musical selection (Kraemer et al., 2005) can also be useful. But in such tasks there is less control over the success with which imagery may be achieved at any given moment, absent a behavioral correlate, such as the time taken for the continuation, matched against the length of the excerpt. Using fMRI poses special problems because of the loud acoustical artifact produced by echo-planar imaging, which itself results in a large auditory cortical response. The interactions between this response and

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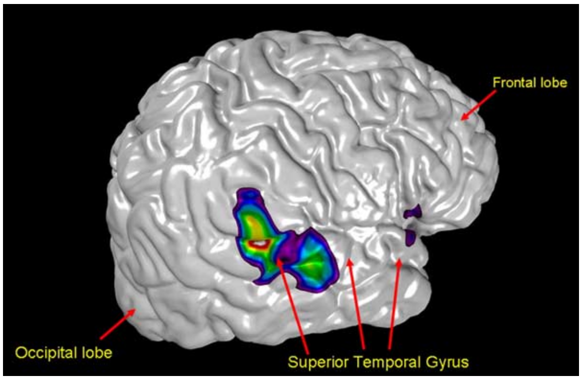

Figure 1. Lateral View of Right Cerebral Hemisphere Illustrating Area of Hemodynamic Increase, in Color, during an Auditory Imagery Task

Although the task is performed in silence, activation is observed within auditory cortex in the posterior aspect of the superior temporal gyrus. Data reanalyzed from Halpern et al., 2004.

the one related to the formation of auditory imagery makes interpretation difficult, particularly when the hemodynamic response functions between imagined and perceived events overlap (Kraemer et al., 2005). This problem can be mitigated, however, by using sparse sampling or other noise abatement strategies.

What Role Does Auditory Cortex Play in Imagery?

Despite these technical difficulties, most imagery studies have indeed succeeded in demonstrating that the auditory cortex responds even in the absence of sound and that this response tends to co-occur with subjective reports of imagining music. But does the primary, or core auditory cortex, participate in musical imagery? A similar question exists in the field of visual imagery, but there is now substantial evidence that primary visual cortex can be recruited by certain tasks (Kosslyn and Thompson, 2003). The literature in musical imagery to date is still uncertain on this point. Most prior studies do agree that activation in secondary, or belt, auditory cortex is reliably found (Figure 1). Although some authors have reported activation in primary cortex, the precise location of core areas can be difficult to determine because of the intersubject variability of these structures; furthermore, because of partial volume effects, what may appear to be activity in primary regions may actually represent spillover from adjacent nonprimary zones. The most critical variable, however, is likely to be the task demands, as they have proven to be in the visual domain. It is premature to anticipate what auditory imagery tasks might reliably elicit primary activation, given the very small number of studies carried out so far and the small subset of those that have even sought to verify the precise location of the activation.

An additional point that many of these studies address concerns the lateralization of the response; once again, task demands and also the nature of the stimuli to be imagined likely play a role. For instance, bilateral activation has been observed when familiar songs with lyrics are used, most likely because there is imagery of both the sung text and the musical component (Zatorre et al., 1996). But when instrumental music is used (Halpern et al., 2004), the pattern tends to shift toward activation in the right auditory cortex, in accord with the important role of these structures in processing pitch information (Zatorre et al., 2002). The recent study by Kraemer et al. (2005) did show left auditory cortex activation even with nonverbal materials, but the degree of activity on the right, if any, was not reported, leaving this question still open.

Assuming we can agree that auditory cortical activity underlies the experience of imagery, the question still remains, how does the auditory cortex become active in the first place? The most likely explanation is that top-down mechanisms are involved in reactivating neural traces that are somehow encoded in sensory cortex. Long ago, Penfield observed that electrical stimulation of the exposed surface of sensory cortical areas (Figure 2) could result in the patient reporting illusory visual or auditory percepts (Penfield and Perot, 1963). The artificial electrical input from an electrode results in a hallucinatory rather than an imagery experience, but presumably under normal circumstances there is a signal coming from elsewhere that accesses the sensory information in auditory cortex. It is most likely that interactions between frontal cortical areas and auditory cortex are the way that imagery is instantiated. There is a tight anatomical connectivity between these regions, and most studies that report whole-brain data involving the generation of an auditory image find frontal cortex to be an important component (Halpern and Zatorre, 1999). Thus, when one wants to conjure up a song in one's mind, frontal-based retrieval mechanisms might be called upon; at the same time, feedback signals from auditory cortex could be important in distinguishing between imagery and a real sound coming from the environment. Indeed, Griffiths (2000) proposed that a breakdown in this system might be responsible for the musical hallucinations that he observed in people with acquired deafness. It is notable that this study found no evidence for primary auditory cortex activation, making suspect any argument linking primary cortex activation with stronger phenomenology of imagined sounds.

Auditory versus Motor Imagery

Motor imagery is the imagination of the kinesthetics involved in actual movement and has been examined for both simple tapping sequences and complex musical routines. One methodological challenge in examining brain activations in motor imagery is to insure that no actual movements have occurred, which can be accomplished via EMG monitoring. Motor imagery for nonauditory-associated movements sometimes results in activation of M1 and often activates secondary motor areas, such as SMA (Naito et al., 2002). Thus it should not be surprising that musicians can evoke motor imagery for their instrument during imagined playing. For instance, Langheim et al. (2002) asked string players to play or imagine playing a familiar piece; the times taken to play and imagine the pieces were highly correlated. These authors found a number of areas to be active in frontal lobes, cerebellum, parietal lobe, and SMA, but not M1 during imagined playing compared to rest.

In many musical situations, sound is associated with

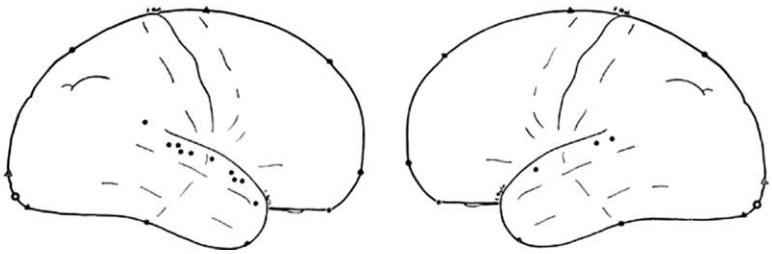

Figure 2. Regions of the Exposed Cortical Surface, Marked with Dots, which Resulted in a Hallucinatory Experience of Hearing Music Upon Electrical Stimulation

Modified from Penfield and Perot, 1963.

movement. Instrumentalists make extensive arm, finger, and sometimes foot movements in the course of producing their instrument's voice. Singers use complex movements of the vocal apparatus to produce songs, especially if they are putting words to those songs. Given the behavioral and neural evidence for people being able to imagine musical movements, is there evidence that auditory and motor imagery may be integrated in the brain? Hickok et al. (2003) found that area Spt (parietal-temporal boundary) responded to both imagined auditory (both speech and music) and covertly produced sequences in a similar fashion. In perhaps a stronger test of this integration, Haueisen and Knösche (2001) found that pianists showed activation in primary motor regions corresponding to the finger that would have produced a given note, even when they were merely listening to pieces they knew how to perform. Conversely, Haslinger et al. (2005) observed activation in several auditory areas when musicians watched a silent video of someone fingering piano keys. Thus, despite a rather different circuitry, imagery of related musical sounds and movement can be integrated. This corresponds to reports from musicians that they can "hear" their instrument during mental practice.

Cross-Modal Interactions

Processing in one sensory modality can affect processing in another, either by increasing or suppressing activity; similar interactions also appear to occur if one or both tasks are based not on perceptual, but on imagined information. Langheim et al. (2002) found that imagining musical performances suppressed activity in the auditory regions, although they suggested that it may have been related to suppression of scanner noise. Halpern et al. (2004) also found that a visual imagery task suppressed activity in right secondary auditory cortex (which was active in imagery for musical timbre) to levels below that seen with a silent baseline. As noise was not a factor given the sparse sampling technique used, it seems that cross-modal interactions may operate similarly in auditory imagery as they do in the processing of actual sound.

Implications

Musical imagery is important to musicians, so an understanding of its neural basis may help us understand aspects of expertise as well as provide some useful information for music educators. For instance, brass, wind, string players, and singers imagine the pitch of an upcoming entrance to facilitate tuning. Conductors and arrangers who study scores in silence also must imagine pitches, as well as timbre, rhythm, and other musical attributes. Highben and Palmer (2004) asked pianists to learn an unfamiliar piece, under normal conditions or when they could not hear their own playing. Players who tested high on an aural skills battery were least disturbed in learning the piece without auditory feedback, suggesting that their auditory imagery skills were adding in the necessary auditory experience to facilitate learning. Humphreys (1986) reported that training in auditory imagery improved harmony skills in children.

The research described above can also help illuminate how musicians use mental practice. This skill involves imagery in several modalities: visual (pianists "see" their hands on the keyboard), motor/kinesthetic (they "feel" the keyboard and finger motions), as well as auditory. Experimental evidence bearing on the neural processes involved is still quite limited, but Pascual-Leone (2003) has demonstrated that mental practice improves performance, albeit not to the level of real practice. However, changes over time in the size of the cortical representation of the motor cortex were similar for real and imagined practice. Given the existence of cross-modal interactions, we may eventually be in a better position to explain when and how these imagined experiences will actually benefit musicians and thus be able to optimize practice regimes for individuals as well as add to the literature on neuroplasticity in response to expert training.

We have attempted here to argue that well-considered behavioral methods combined with convergent neuroimaging and other techniques can successfully externalize the particularly covert process of musical auditory imagery. This research allows us to gain insight into one of the more inaccessible aspects of cognition, and thereby provides us with valuable information concerning the neural underpinnings of abstract mental processes. Clinical or educational applications pertaining to these highest levels of cognitive function will emerge only to the extent that we can rigorously link brain mechanisms to mental processes; we would argue that the future of cognitive neuroscience will depend on expanding just this sort of knowledge.

Selected Reading

Griffiths, T.D. (2000). Brain *123*, 2065–2076.

Halpern, A.R. (1988). J. Exp. Psychol. Learn. Mem. Cogn. *14*, 434–443.

Halpern, A.R., and Zatorre, R.J. (1999). Cereb. Cortex *9*, 697–704.

Halpern, A.R., Zatorre, R.J., Bouffard, M., and Johnson, J.A. (2004). Neuropsychologia *42*, 1281–1292.

Haslinger, B., Erhard, P., Altenmüller, E., Schroeder, U., Boecker, H., and Ceballos-Baumann, A.O. (2005). J. Cogn. Neurosci. *17*, 282–293.

Haueisen, J., and Knösche, T. (2001). J. Cogn. Neurosci. *13*, 786–792.

Hickok, G., Buchsbaum, B., Humphries, C., and Muftuler, T. (2003). J. Cogn. Neurosci. *15*, 673–682.

Highben, Z., and Palmer, C. (2004). Bulletin of the Council for Research in Music Education *159*, 58–65.

Humphreys, J.T. (1986). Journal of Research in Music Education *34*, 192–199.

Kosslyn, S.M., and Thompson, W.L. (2003). Psychol. Bull. *129*, 723–746.

Kraemer, D.J.M., Macrae, C.N., Green, A.E., and Kelley, W.M. (2005). Nature *434*, 158.

Langheim, F.J., Callicott, J.H., Mattay, V.S., Duyn, J.H., and Weinberger, D.R. (2002). Neuroimage *16*, 901–908.

Naito, E., Kochiyama, T., Kitada, R., Nakamura, S., Matsumura, M., Yonekura, Y., and Sadato, N. (2002). J. Neurosci. *22*, 3683–3691.

Pascual-Leone, A. (2003). In The Cognitive Neuroscience of Music, I. Peretz and R. Zatorre, eds. (Oxford: Oxford University Press), pp. 396–412.

Penfield, W., and Perot, P. (1963). Brain *86*, 595–696.

Schürmann, M., Raija, T., Fujikia, N., and Hari, R. (2002). Neuroimage *16*, 434–440.

Shepard, R.N., and Metzler, J. (1971). Science *171*, 791–793.

Yoo, S.-S., Lee, C.U., and Choi, B.G. (2001). Neuroreport *12*, 3045–3049.

Zatorre, R.J., and Halpern, A.R. (1993). Neuropsychologia *31*, 221–232.

Zatorre, R.J., Halpern, A.R., Perry, D.W., Meyer, E., and Evans, A.C. (1996). J. Cogn. Neurosci. *8*, 29–46.

Zatorre, R.J., Belin, P., and Penhune, V.B. (2002). Trends Cogn. Sci. *6*, 37–46.