Chapter 14
Similarities Between Tinnitus and Pain

Aage R. Møller

Keypoints

1. Both pain and tinnitus have many different forms.
2. Tinnitus and central neuropathic pain are phantom sensations similar to the phantom limb symptoms that occur without any physical stimulation of sensory receptors.
3. Tinnitus and neuropathic pain are typical examples of "plasticity disorders" where the symptoms are caused by plastic changes that are not beneficial to an individual person.
4. Central neuropathic pain and tinnitus have no physical signs.
5. The severity of pain and tinnitus are difficult to assess quantitatively even under laboratory circumstances. Only the patients' own perception is a true measure of the severity of central pain and subjective tinnitus.
6. The perception of pain and tinnitus is affected by many factors such as actual circumstances, expectation, stress, and a person's emotional state.
7. Many forms of pain are best described as suffering; the same is the case for severe subjective tinnitus.
8. Pain and tinnitus can have strong emotional components, it often prevents or disturbs sleep, and it can interfere with or prevent intellectual work.
9. It is difficult to get reliable data on epidemiology of tinnitus and central neuropathic pain because of their subjective nature and large variability.
10. Activation of neural plasticity is involved in causing and maintaining central neuropathic pain and many forms of subjective tinnitus.
11. The nervous system is the site of the anomalies that cause central neuropathic pain and many forms of tinnitus. Both tinnitus and pain involve a cascade of neural structures.
12. The pathology of the nervous system in some forms of central neuropathic pain is stable in the pathologic state. It may be similar for some forms of tinnitus.
13. Pain that is perceived as escapable uses a different part of the periaquaductal gray than pain that is perceived as inescapable. It is not known if tinnitus also has such distinctions.
14. Severe tinnitus is often accompanied by hyperacusis (lowered tolerance to sounds); pain may be accompanied by allodynia (pain from normally innocuous touch of the skin) hyperpathia (exaggerated reaction to acute pain), and hypersensitivity (lowered threshold for painful stimulation).
15. Some forms of tinnitus and pain can be modulated by electrical stimulation of the skin.
16. Electrical stimulation of several cortical structures can modulate both pain and tinnitus.
17. The sympathetic nervous system can modulate pain and some forms of tinnitus.

Keywords Tinnitus • Pain • Central neuropathic pain • Hyperacusis • Allodynia

Abbreviations

DCN	Dorsal cochlear nucleus
NST	Nucleus of the tractus solitaries
PAG	Periaquaductal gray
TENS	Transderm electrical nerve stimulation
VCN	Ventral cochlear nucleus
WDR	Wide dynamic range neurons

A.R. Møller (✉)
The University of Texas at Dallas, School of Behavioral and Brain Sciences, GR 41, 800 W Campbell Rd, Richardson, TX 75080, USA
e-mail: amoller@utdallas.edu

A.R. Møller et al. (eds.), *Textbook of Tinnitus*,
DOI 10.1007/978-1-60761-145-5_14,

Introduction

It was Jürgen Tonndorf [1] who first drew attention to the similarities between tinnitus and pain. Other investigators have later elaborated on the many similarities between tinnitus and severe chronic pain (central neuropathic pain) [2–5]. Activation of neural plasticity is involved and both are examples of "plasticity diseases" [6]. Pain gets far more attention than tinnitus. The fifth edition of the Wall and Melzack's Textbook of Pain has over 1,200 pages; Weiner's Pain Management has over 1,500 pages. Textbooks devoted to tinnitus are essentially non-existent (this book is the first textbook on tinnitus). The research literature on pain is far greater than that on tinnitus; a search in PubMed came up with approximately 400,000 articles about pain vs. approximately 6,000 for tinnitus. Literature about hyperacusis and phonophobia is sparse.

Many forms of tinnitus have similarities with central neuropathic pain, in that activation of neural plasticity is involved in creating the symptoms. Central neuropathic pain is a particular condition where the symptoms are caused by abnormal activity in populations of neurons in the spinal cord and brain that occurs without signals from receptors in the body.

Subjective tinnitus and central neuropathic pain are phantom sensations where the sensations are not elicited by activation of receptors. Central neuropathic pain and some forms of tinnitus are symptoms with very few, if any, objective signs. Despite that, both central neuropathic pain [7] and severe tinnitus [8] can affect a person's entire life, the entire family, as well as social and working relationships. Both these disorders may prevent or disturb sleep and interfere with intellectual work. There are examples of people who like their work but retire because of tinnitus.

Other similarities include the lack of effective treatment, diverse etiology, and sparse knowledge about the anatomical and physiologic bases for these disorders. The treatments a patient with either one of these disorders may receive depend on the specialty of the physician they choose to consult, and the specific interest of the physician or surgeon. In only a few forms of central neuropathic pain and tinnitus can any underlying disease be found.

There are many forms of tinnitus and many forms of pain. Some common forms of pain such as headache and back pain can be managed by simple analgesics. No such general treatment is known for tinnitus. Peripheral neuropathic pain, migraine, and fibromyalgia are complex pain conditions that have less satisfactory treatments. Central neuropathic pain can often be managed by medication. Brain and spinal cord injuries can cause both pain and tinnitus that are difficult to treat.

A separate chapter (Chap. 15) describes the basic anatomy and physiology of pain. Here, we will discuss the similarities between some forms of subjective tinnitus and central neuropathic pain, both being phantom sensations, with activation of neural plasticity playing a central role in their cause. The similarities between treatment of pain and tinnitus are discussed in chapter 94.

Common Features of Subjective Tinnitus and Central Pain

Both central neuropathic pain [9, 10] and subjective tinnitus [11] have many different forms (see Chap. 2). Different forms of disorders with the same name cause difficulties in studying their pathologies and treatments. It would be more appropriate to consider both central and subjective tinnitus as groups of different disorders rather than a single disorder.

Most forms of subjective tinnitus and central neuropathic pain are phantom sensations, which mean that the symptoms are not caused by physical stimulation, but are similar to symptoms that occur after amputations. This is known as phantom limb syndrome, where pain and other sensations are felt as if coming from the limb that no longer exists [12]. The symptoms of many forms of tinnitus and central neuropathic pain are felt as coming from a different anatomical location than the actual pathology and physiological anomaly that cause the symptoms. The anatomical locations of the pathologies of most forms of central pain and most forms of tinnitus are in the brain, although the pain is often referred to a specific part of the body. This is well known from studies of central pain and it is also evident from some observations regarding tinnitus. Tinnitus is often referred to the ear, although tinnitus may occur in deaf people and after severance of the auditory nerve, thus similar to the pain that is felt as coming from an amputated leg. Neural plasticity activated by the absence of input from receptors in an amputated limb is the main cause of the phantom limb syndrome.

Some forms of tinnitus are caused by deprivation of auditory inputs as evidenced from the fact that tinnitus can be caused by middle ear disorders (see Chap. 34) and disappears when sound conduction to the ear is restored, either by treating the conductive pathology such as otosclerosis or by a hearing aid (see Chaps. 56 and 76) or cochlear implants (see Chap. 77). Many people get tinnitus when placed in a silent environment [13].

Neural plasticity plays an important role in creating central tinnitus and central pain, and activation of neural plasticity also plays a role in tinnitus that is caused by pathology in the ear and in acute pain caused by stimulation of nociceptors.

Both tinnitus and central neuropathic pain are examples of harmful effects of plastic changes, thus forms of "plasticity disorders" [6] caused by neural plasticity going awry. Activation of such maladaptive neural plasticity causes abnormal neural activity and re-routing of information. Activation of neural plasticity is involved in many forms of subjective tinnitus and central neuropathic pain as has been discussed in other parts of this book (see Chaps 10 and 15). The way plasticity is turned on is often unknown and probably more complex than what it is for creating phantom limb symptoms.

Both pain and tinnitus can cause suffering; that may be a different condition than tinnitus and pain that does not cause suffering. Tinnitus that causes suffering, or is "bothersome" [14], may activate other neural circuits than tinnitus that does not have these qualities. It has been shown that pain that is "escapable" and pain that is perceived as being "inescapable" activate different parts of a neural structure, the periaquaductal gray (PAG) [15], and different parts of the hypothalamus and midbrain [16].

Peripheral processes can contribute to the initiation of chronic neuropathic pain as well as many forms of tinnitus. Peripheral and central sensitization have been shown to play an important role in the creation of hyperactivity that is the cause of central neuropathic pain [9, 10]. The same is probably the case for tinnitus, although it has not been studied to the same extent as pain [17]. The fact that different mechanisms can initiate processes that result in changes in the central nervous system that cause many forms of tinnitus may explain some of the differences in the symptoms that patients experience [9, 18]. The same is the case for central pain.

Another similarity between tinnitus and pain is that the severity of these disorders cannot be substantiated by objective tests. Even health care professionals may sometimes misjudge the severity of these diseases. Individuals with tinnitus as well as individuals with pain have no attributes of illness and therefore do not attract much attention and sympathy. Relatives and friends may doubt the seriousness of their diseases. In the absence of objective test results, health professionals may even sometimes think that their patients may be malingering. This makes both tinnitus and central pain disorders some of the most challenging disorders for clinicians.

Prevalence of Central Pain and Tinnitus

One of the problems in getting reliable epidemiologic data is similar for pain and tinnitus, namely that the definition of the severity varies among individuals with these conditions. These problems are greater for central neuropathic pain than other neuropathic pain conditions, and it is greater for tinnitus than for other hearing disorders, such as hearing loss from exposure to noise (see Chap. 37), which have been studied extensively as has age-related hearing loss (presbycusis) (see Chap. 36). No reliable information about the epidemiology of central neuropathic pain is available, nor is the prevalence of other chronic pain conditions such as peripheral neuropathic pain that commonly occurs in individuals with diabetes neuropathy completely known [18, 19].

The prevalence of chronic neuropathic pain may be greater than commonly assumed and its prevalence is likely to increase in the future. This is very similar to tinnitus, where the prevalence seems to increase. The prevalence of both central pain and tinnitus increases after middle age, which means that age-related changes add to the factors that cause tinnitus and pain (see Chap. 36).

Tinnitus is estimated to effect 13–20% of the overall population of the United States [20]. These complaints, often associated with hearing loss, increase with age to 27–34% of the population older than 70 years reporting significant tinnitus [21]. Twenty percent to 45% of tinnitus sufferers also have hyperacusis; a few individuals only have hyperacusis [22] (see also Chap. 5).

One reason for the increased incidence of tinnitus is the increased occurrence of head injuries (see Chap. 67), which also is associated with pain conditions. From 10 to 30% of people with spinal cord injuries have central

pain. Individuals with head injuries often have central pain and tinnitus [23, 24] (see Chap. 67). After strokes, 1–8% have central pain [19, 25].

The prevalence of post-surgical neuropathic pain has been estimated to be 2–3% of the population in the developed world [18]. This problem is poorly recognized. Equally poorly recognized is postoperative tinnitus. It occurs often after surgical removal of vestibular schwannoma where the concerns are about preserving facial function and hearing, which has improved after introduction of intraoperative neurophysiologic monitoring [26]. However, little is known about how to reduce the risk of tinnitus.

Neuroanatomical Similarities Between Tinnitus and Pain

The neuroanatomy of hearing and pain has many similarities. The neural pathways for acute pain have similarities with the classical and non-classical ascending auditory pathways. The medial tract of the spinothalamic system may be regarded as the non-classical pathways of the somatosensory system (see Chap. 15). The fibers of the lateral spinothalamic tract terminate in neurons in the ventral thalamus corresponding to the classical pathway, whereas the medial spinothalamic tract terminates in the dorsal and medial thalamus and thus resembles the non-classical pathways of other sensory systems. The lateral spinothalamic tract provides information about the location of the pain and the medial tract provides information about the nature of the pain (see Chap. 15).

The medial and dorsal thalamus have subcortical connections to several regions of the brain, such as the limbic system, and the neurons in the cortical projections of the dorsal thalamus bypass the primary somatosensory cortex. These neurons terminate directly on neurons in the secondary and association cortices while the classical pathways project to primary cortices.

Functional Similarities Between Pain and Tinnitus

Tinnitus has similarities with several characteristics of central neuropathic pain. Repeating painful stimulations causes increasing intensity of pain, known as the "wind up" phenomenon [27]. When a noxious stimulation is repeated at a short interval, the pain from the second presentation feels stronger. This is thus a form of abnormal temporal integration of painful stimulation. In other studies, it has been shown that temporal integration of pain signals is different in individuals with signs of neuropathic pain and individuals without central neuropathic pain [28].

A few similar studies have been done regarding temporal integration of sound in individuals with tinnitus [29], but animal experiments indicate that strong sound stimulation changes the temporal integration in the inferior colliculus as assessed using evoked potential techniques [30].

Sensitization and Modulation of Pain and Tinnitus

It is well known that peripheral and central sensitization can play important roles in creation of pain. Together with re-organization of neural circuits, this is regarded as the cause of central neuropathic pain. Evidence is accumulating that similar processes affecting the auditory system may play important roles in some forms of tinnitus.

Peripheral Sensitization

There are several ways in which peripheral sensitization of receptors in the body and the ear can contribute to pain and tinnitus. One way is through activation of the sympathetic nervous system, which can cause sympathetic nerve fibers that terminate near receptors to secrete norepinephrine, which increases the sensitivity of the receptors. Epinephrine secreting nerve fibers have been identified near receptors in the skin and close to the receptors (hair cells) in the cochlea [31]. Thus, the fact that sympathectomy is an effective treatment for tinnitus when it is a symptom of Ménière's disease [32] indicates that the sympathetic nervous system is involved in at least the kind of tinnitus that occurs in Ménière's disease.

The sympathetic nervous system may even activate the receptors without external stimulation, so they send information to the nervous system similar to when

normal stimulation of the receptors occurs with physical stimuli. The most extreme of such sympathetically induced pain is reflex sympathetic dystrophy (RSD), now known as complex regional pain syndrome type I [33].

Central Sensitization

Certain kinds of neurons in the dorsal horn of the spinal cord (and the trigeminal nucleus), known as the wide dynamic range (WDR) neurons, are believed to have important roles in central sensitization of pain circuits ([9, 34, 35], see also [36]). Activation of neural plasticity that can change synaptic efficacy also plays an important factor in creating the abnormal states of the neural circuits in the dorsal horn associated with central pain [37] (see Chap. 15).

Activation of neural plasticity in the neural circuits of the dorsal horn is important because it can change the excitability of neurons (central sensitization) and re-route information by making dormant synapses become active [38]. Also, it can make synapses that are normally active become dormant.

It has been hypothesized that reorganization of the neural circuits in the spinal cord plays an important role for creation and maintaining central neuropathic pain. Doubell has proposed that the pain circuits in the dorsal horn of the spinal cord (and the trigeminal nucleus) can operate in four main different states [34] (see Chap. 15).

Similar hypotheses may apply to some forms of tinnitus, but hypotheses about the pathology of tinnitus are less uniform and less detailed. Studies in animals in which tinnitus conditions were induced by deprivation of input to the auditory system [39] or by overstimulation [40] have shown evidence that some neurons in the inferior colliculus have the ability to change their function in a similar way as the WDR neurons.

Interaction Between Sensory Systems

The old concept that certain functions of the brain are done in specific parts of the brain has gradually been eroded. It has become more and more evident that considerable interaction between many systems in the brain and the spinal cord occurs normally, as well as in diseases where certain interactions have adverse and harmful effects. It was earlier regarded as an axiom that the information from the different sense organs was processed in specific and separate parts of the brain.

Anatomical Aspects

We have discussed in Chap. 10 how somatosensory signals can interfere with hearing when the non-classical auditory pathways are active such as it is in children [41] and in some individuals with tinnitus [42]. This can occur in two different ways. One way is through connections that neurons in the dorsal column nuclei and the trigeminal nucleus make with neurons in the dorsal cochlear nucleus (DCN) [43–45] (see Chap. 9). The other way is through activation of the non-classical ascending auditory pathways, which receive input from other senses through connections to the inferior colliculus [46] (see Chap. 8).

Physiologic Signs of Cross-Modal Interaction

Certain anomalies of sensory systems in individuals with central pain have similarities with anomalies that occur in connection with some forms of tinnitus. One such anomaly is cross-modal sensory interaction, which means that the perception of one sensory modality can be affected by stimulation of another sense.

It has been known for a long time that acute pain sensations elicited by stimulation of pain receptors can be modulated by stimulation of nerve fibers, which innervate receptors that mediate innocuous sensory stimuli (touch, etc.). This is a normal phenomenon involving Aβ fibers in the spinal cord, which have inhibitory influence on cells that receive nocuous input from pain receptors (Fig. 14.1). This fact is used in treatment of pain, using electrical stimulation of the skin. This method is in routine use under the name of transderm electrical nerve stimulation (TENS) [47], and it has shown effectiveness for acute pain [48] as well as central pain [49]. It relies of stimulation of large sensory fibers, which can have an inhibitory influence on pain cells in the spinal cord and activate neural plasticity and thereby is effective in reducing pain not caused by activation of pain receptors (central neuropathic pain).

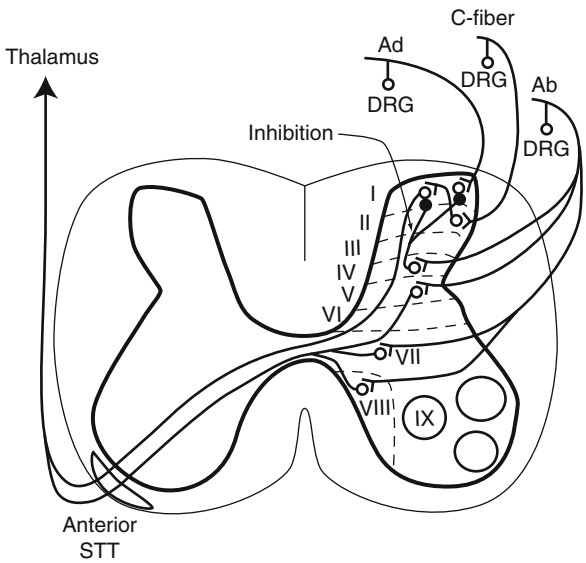

Fig. 14.1 Schematic illustration of the connections through which innocuous sensory input mediated by large myelinated (Aβ) fibers can inhibit pain neurons in lamina I that receive noxious input from Aδ fiber and C fibers via interneurons and which give rise to axons of the STT. Reproduced from: Møller AR (2006) Neural plasticity and disorders of the nervous system. Cambridge: Cambridge University Press, with permission by Cambridge University Press [9]

Modulation of tinnitus by activation of the somatosensory system [50, 51] has been demonstrated by electrical stimulation of the median nerve at the wrist [42], manipulation of neck muscles [52, 53], from temporomandibular problems [54, 55], and from changing one's gaze [50, 56, 57]. Functional imaging studies indicate that gaze-evoked tinnitus is caused by neural activity associated with eye movements that enters the auditory system [58]. These effects seem to be mediated through cross-modal interaction between the auditory system and the somatosensory system.

The anatomical and physiologic bases for these interactions are not as well known as the modulation of pain by somatosensory stimulation. Electrical stimulation of the skin around the ears can modulate tinnitus in some individuals [59] (see Chap. 91), and there are two different theories to explain this. One hypothesis states that sensory cells in these areas of the skin activate axons that become parts of dorsal spinal root C_2, which terminate on cells in the brainstem [60] (DCN and VCN) (See Chap. 9). Some of the axons from these cells terminate on cells in the dorsal cochlear nucleus (DCN) [43, 61]. Other studies have implicated the DCN in some forms of tinnitus [62, 63] (see Chap. 8).

The other way that somatic stimulation can affect the auditory system is through the non-classical ascending auditory pathways [64]. The non-classical auditory pathways receive input not only from the ear but also from other sensory systems such as the somatosensory system [45, 46] (see Chap. 8).

A different kind of interaction on pain [65] and possibly tinnitus is that from the vagus nerve. Earlier, little attention was paid to the vagus nerve; the focus has been on the motor functions of the vagus nerve. However, approximately 80% of the nerve fibers are afferent fibers. The discovery that electrical stimulation of the vagus nerve could treat epilepsy renewed the attention to the vagus nerve. Electrical stimulation of the vagus nerve is an approved treatment for epilepsy in the US [66] and is in clinical use for controlling epileptic seizures. Electrical stimulation has also been used for treatment of depression.

Electrical stimulation of the left vagus nerve has been shown to suppress some forms of pain [65] (see Chap. 94), and research is now aimed at other applications such as treatment of depression and control of severe tinnitus.

Afferent vagus nerve fibers terminate in the nucleus of the tractus solitaries (NST), which connect to many parts of the brain. The vagus nerve supplies cholinergic input to many structures in ways that have similarities to that of the basal nucleus of Meynert, which provides arousal and promote cortical plasticity [67, 68].

Central neuropathic pain is often associated with allodynia (pain from light touch stimulation). This may be similar to the rarely reported perception of sound by rubbing the skin, such as by a towel.

References

1. Tonndorf J (1987) The analogy between tinnitus and pain: a suggestion for a physiological basis of chronic tinnitus. Hear Res 28:271–5.
2. Møller AR (1997) Similarities between chronic pain and Tinnitus. Am J Otol 18:577–85.
3. Møller AR (2000) Similarities between severe tinnitus and chronic pain. J Amer Acad Audiol 11:115–24.
4. Folmer RL, SE Griest and WH Martin (2001) Chronic tinnitus as phantom auditory pain. Otolaryngol Head Neck Surg 124:394–400.
5. Bartels H, MJ Staal and FW Albers (2007) Tinnitus and neural plasticity of the brain. Otol Neurotol 28:178–84.
6. Møller AR (2008) Neural Plasticity: for Good and Bad. Progress of Theoretical Physics Supplement No 173:48–65.

7. Closs SJ, V Staples, I Reid et al (2009) The impact of neuropathic pain on relationships. J Adv Nurs 65:402–11.
8. Shipton E (2008) Post-surgical neuropathic pain. ANZ J Surg 78:548–55.
9. Møller AR (2006) Neural plasticity and disorders of the nervous system. Cambridge: Cambridge University Press, with permission by Cambridge University Press.
10. McMahon SB and M Koltzenburg, eds. Wall and Melzak's Textbook of Pain. 5th ed. 2006, Elsevier, Churchill, Livingstone: Amsterdam.
11. Langguth B, G Hajak, T Kleinjung et al (2007) Tinnitus: pathophysiology and treatment, progress in brain research. Prog Brain Res 166:1–542.
12. Jastreboff PJ (1990) Phantom auditory perception (tinnitus): mechanisms of generation and perception. Neurosci Res 8:221–54.
13. Tucker DA, SL Phillips, RA Ruth et al (2005) The effect of silence on tinnitus perception. Otolaryngol Head Neck Surg 132:20–4.
14. Gerken GM, PS Hesse and JJ Wiorkowski (2001) Auditory evoked responses in control subjects and in patients with problem tinnitus. Hear Res 157:52–64.
15. Keay KA, CI Clement, A Depaulis et al (2001) Different representations of inescapable noxious stimuli in the periaqueductal gray and upper cervical spinal cord of freely moving rats. Neurosci Lett 313:17–20.
16. Lumb BM (2002) Inescapable and escapable pain is represented in distinct hypothalamic-midbrain circuits: specific roles of Ad- and C-nociceptors. Exp Physiol 87:281–86.
17. Zenner HP, M Pfister and N Birbaumer (2006) Tinnitus sensitization: sensory and psychophysiological aspects of a new pathway of acquired centralization of chronic tinnitus. Otol Neurotol 27:1054–63.
18. Dworkin RH (2002) An overview of neuropathic pain: syndromes, symptoms, signs, and several mechanisms. Clin J Pain 18:343–9.
19. Schwartzman RJ, J Grothusen, TR Kiefer et al (2001) Neuropathic central pain: epidemiology, etiology, and treatment options. Arch Neurol. 58:1547–50.
20. Coles RAA and SA Sook (1998) Hyperacusis and phonophobia in hyperacusic and nonhyperacusic subjects. Br J Audiol 22:228.
21. Ruth R and JI Hall, (1999) Patterns of audiologic findings for tinnitus patients, in Proceedings Sixth International Tinnitus Seminar, J Hazell, Editor. The Tinnitus and Hyperacusis Center: London. 442–5.
22. Hamill-Ruth RJ, RA Ruth, DC Castain et al (2000) Mangement of Tinnitus and Hyperacusis using a Multidiciplinary Pain Model. Am Pain Soc Bull.
23. Dimberg E and T Burns (2005) Management of common neurologic conditions in sports. Clin Sports Med 24:637–62.
24. Nölle C, I Todt, R Seidl et al (2004) Pathophysiological changes of the central auditory pathway after blunt trauma of the head. J Neurotrauma 21:251–8.
25. Häusler R and R Levine (2000) Auditory dysfunction in stroke. Acta Otolaryngol 120:689–703.
26. Møller AR (2006) Intraoperative Neurophysiologic Monitoring, 2nd Edition. Totowa, New Jersey: Humana Press Inc.
27. Herrero JF, JM Laird and JA Lopez-Garcia (2000) Wind-up of spinal cord neurones and pain sensation: much ado about something? Prog Neurobiol 61:169–203.
28. Møller AR and T Pinkerton (1997) Temporal integration of pain from electrical stimulation of the skin. Neurol Res 19:481–8.
29. Quaranta A, V Sallustio and A Scaringi, (1999) Cochlear function in ears with vestibular schwannomas., in Third International Conference on Acoustic Neurinoma and other CPA Tumors, M Sanna et al, Editors. Monduzzi Editore: Rome, Italy. 43–50.
30. Szczepaniak WS and AR Møller (1996) Effects of (−)-baclofen, clonazepam, and diazepam on tone exposure-induced hyperexcitability of the inferior colliculus in the rat: possible therapeutic implications for pharmacological management of tinnitus and hyperacusis. Hear Res 97:46–53.
31. Densert O (1974) Adrenergic innervation in the rabbit cochlea. Acta Otolaryngol. (Stockh.) 78:345–56.
32. Passe EG (1951) Sympathectomy in relation to Ménière's disease, nerve deafness and tinnitus. A report of 110 cases. Proc Roy Soc Med 44:760–72.
33. Baron R, (2006) Complex regional pain syndromes, in Wall and Melzack's Textbook of Pain, SB McMahon and M Koltzenburg, Editors. Elsevier: Amsterdam. 1011–27.
34. Doubell TP, RJ Mannion and CJ Woolf, (1999) The dorsal horn: state-dependent sensory processing, plasticity and the generation of pain, in Handbook of Pain, PD Wall and R Melzack, Editors. Churchill Livingstone: Edinburgh. 165–81.
35. Price DD, S Long and C Huitt (1992) Sensory testing of pathophysiological mechanisms of pain in patients with reflex sympathetic dystrophy. Pain 49:163–73.
36. Brodal A (2004) The central nervous system third edition. New York: Oxford University Press.
37. Dubner R and AI Basbaum, (1994) Spinal dorsal horn plasticity following tissue or nerve injury, in Textbook of Pain, PD Wall and R Melzack, Editors. Edinburgh: Churchill Livinstone. 225–41.
38. Wall PD (1977) The presence of ineffective synapses and circumstances which unmask them. Phil. Trans. Royal Soc. (Lond.) 278:361–72.
39. Gerken GM, SS Saunders and RE Paul (1984) Hypersensitivity to electrical stimulation of auditory nuclei follows hearing loss in cats. Hear Res 13:249–60.
40. Szczepaniak WS and AR Møller (1996) Evidence of neuronal plasticity within the inferior colliculus after noise exposure: a study of evoked potentials in the rat. Electroenceph Clin Neurophysiol 100:158–64.
41. Møller AR and P Rollins (2002) The non-classical auditory system is active in children but not in adults. Neurosci Lett 319:41–4.
42. Møller AR, MB Møller and M Yokota (1992) Some forms of tinnitus may involve the extralemniscal auditory pathway. Laryngoscope 102: 1165–71.
43. Kanold PO and ED Young (2001) Proprioceptive information from the pinna provides somatosensory input to cat dorsal cochlear nucleus. J Neurosci 21:7848–58.
44. Zhou J and S Shore (2004) Projections from the trigeminal nuclear complex to the cochlear nuclei: a retrograde and anterograde tracing study in the guinea pig. J Neurosci Res 78:901–7.
45. Dehmel S, YL Cui and SE Shore (2008) Cross-modal interactions of auditory and somatic inputs in the brainstem and midbrain and their imbalance in tinnitus and deafness. Am J Audiol 17:S193–209.

46. Aitkin LM (1986) The auditory midbrain, structure and function in the central auditory pathway. Clifton, NJ: Humana Press.
47. Willer JC (1988) Relieving effect of TENS on painful muscle contraction produced by an impairment of reciprocal innervation: an electrophysiological analysis. Pain 32:271–4.
48. Rakel B and R Frantz (2003) Effectiveness of transcutaneous electrical nerve stimulation on postoperative pain with movement. J Pain Symptom Manage 4:455–64.
49. Cooney WP (1997) Electrical stimulation and the treatment of complex regional pain syndromes of the upper extremity. Hand Clin. 13.
50. Cacace AT, JP Cousins, SM Parnes et al (1999) Cutaneous-evoked tinnitus. II: review of neuroanatomical, physiological and functional imaging studies. Audiol Neurotol 4:258–68.
51. Cacace AT, JP Cousins, SM Parnes et al (1999) Cutaneous-evoked tinnitus. I: phenomenology, psychophysics and functional imaging. Audiol. Neurotol 4:247–57.
52. Levine RA, EC Nam, Y Oron et al, (2007) Evidence for a tinnitus subgroup responsive to somatosensory based treatment modalities, in Tinnitus: Pathophysiology and Treatment, Progress in Brain Research, B Langguth et al, Editors. Elsevier: Amsterdam. 195–207.
53. Levine RA, M Abel and H Cheng (2003) CNS somatosensory-auditory interactions elicit or modulate tinnitus. Exp Brain Res 153:643–8.
54. Upton LG and SJ Wijeyesakere (2004) The incidence of tinnitus in people with disorders of the temporomandibular joint. Int Tinnitus J 10:174–6.
55. Morgan DH (1973) Temporomandbular joint surgery. Correction of pain, tinnitus, and vertigo. Den Radiogr Photogr 46:27–46.
56. Coad ML, AH Lockwood, RJ Salvi et al (2001) Characteristics of patients with gaze-evoked tinnitus. Otol Neurotol 22:650–4.
57. Cacace AT, TJ Lovely, DJ McFarland et al (1994) Anomalous cross-modal plasticity following posterior fossa surgery: some speculations on gaze-evoked tinnitus. Hear Res 81:22–32.
58. Lockwood AH, DS Wack, RF Burkard et al (2001) The functional anatomy of gaze-evoked tinnitus and sustained lateral gaze. Neurology 56:472–80.
59. Shulman A, J Tonndorf and B Goldstein (1985) Electrical tinnitus control. Acta Otolaryngol 99:318–25.
60. Zhan X, T Pongstaporn and DK Ryugo (2006) Projections of the second cervical dorsal root ganglion to the cochlear nucleus in rats. J Comp Neurol 496:335–48.
61. Young ED, I Nelken and RA Conley (1995) Somatosensory effects on neurons in dorsal cochlear nucleus. J Neurophysiol 73:743–65.
62. Kaltenbach JA (2000) Neurophysiologic mechanisms of tinnitus. J Am Acad Audiol 11:125–37.
63. Kaltenbach JA (2007) The dorsal cochlear nucleus as a contributor to tinnitus: mechanisms underlying the induction of hyperactivity, in Tinnitus: Pathophysiology and Treatment, Progress in Brain Research, B Langguth et al, Editors. Elevier: Amsterdam. 89–106.
64. Møller AR (2006) Hearing: Anatomy, physiology, and disorders of the auditory system, 2nd Ed. Amsterdam: Academic Press.
65. Kirchner A, F Birklein, H Stefan et al (2000) Left vagus nerve stimulation suppresses experimentally induced pain. Neurology 55:1167–71.
66. Groves DA and VJ Brown (2005) Vagal nerve stimulation: a review of its applications and potential mechanisms that mediate its clinical effects. Neurosci Biobehav Rev 29:493–500.
67. Weinberger NM, R Javid and B Lepan (1993) Long-term retention of learning-induced receptive-field plasticity. Proc Nat Acad Sci 90:2394–8.
68. Kilgard MP and MM Merzenich (1998) Plasticity of temporal information processing in the primary auditory cortex. Nature Neurosci 1:727–31.