18 Haptics

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18.1 Introduction

In the next two chapters, our focus will shift from the sense of hearing to the sense of touch. Actually, our interests are broader than the sense of touch (taction); they include the sense of body position and motion (kinesthesia) as well. Thus our discussion will cover sensors not only in the skin but also in the joints and muscles. Convenient for us, there does exist one word that may be used to refer to taction and kinesthesia together: *haptics*. These two chapters are about haptics, and especially the role of haptics in music production and perception.

Haptics is a very relevant topic in a book on psychoacoustics. There are many parallels between the studies of psychoacoustics and of haptics, since the two are neighboring branches of the more general field of psychophysics. But more important (given our interest in music), the haptic senses provide the second most important means for observing the behavior of a musical instrumentaudition is, of course, the primary means. The player of an instrument, besides hearing it, feels it. While audition carries meaning regarding the acoustical behavior of an instrument, haptics carries meaning regarding the mechanical behavior. This mechanical information is quite valuable to the process of playing or learning to play an instrument, as we shall see.

Take the trio of player, instrument, and listener depicted in figure 18.1. The player, on the left, manipulates the instrument, that is, exchanges mechanical energy with the instrument through one or more (perhaps transient) mechanical contacts. Note that mechanical information flows in both directions between player and instrument. The musical instrument converts this mechanical excitation into sound waves. The listener on the right senses and processes the sound waves to create a mental model of the musical instrument. Perhaps the listener even contemplates a musical idea expressed through the instrument by the player.

Previous chapters have concentrated on the perceptual processes taking place in the listener. We now turn our attention to the

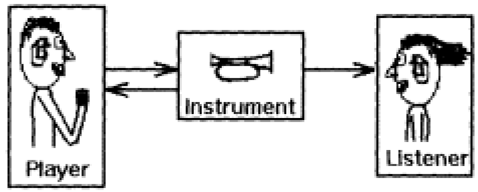

Figure 18.1
The components of musical interaction. A player and an instrument exchange mechanical information, and a listener receives acoustic information.

perceptual processes taking place in the player. In particular, what information regarding the acoustical behavior of the instrument can the player pick up by feeling for the mechanical behavior? After all, every instrument has both an acoustical and a mechanical response, and usually there is a relationship between the twodepending on the sound production physics of the instrument. The player forms a haptic impression of the instrument, much as the listener forms an acoustic impression. Moreover, an instrument's mechanical response may provide clues as to how to modify subsequent manipulations if the player desires a different sound.

Our study centers on the player's haptic senses and associated perceptual processes, but also encompasses the energetic interaction between player and instrument. The information available to the haptic senses is dependent on the player's actions, or how he/she exerts control over the instrument. Indeed, in mechanical interaction, the notion of sensation and control are closely coupled. For example, we shall see that whether haptic perception takes place during active manipulation or during passive stimulation has a large effect on the haptic impression formed. We will therefore delve into the topics of motor control and motor learning while considering the manipulation of musical instruments to make sounds.

Figure 18.1 is a general illustration. If we define music as sound that carries meaning, any device that produces sound under the control of a human player may be considered a musical instrument. Traditional *acoustic* instruments rely on mechanical excitation, in which case the player's control information comes encapsulated in the mechanical energy provided by the player through the mechanical contact. In *electronic* instruments, although production of the acoustical output is from an electrical energy source, modulation of the electrical-to-acoustical conversion is up to the player, and that modulation control is introduced through a mechanical contact. Certain electronic instruments fall outside this description: those that use noncontact transducers to pick up the player's control input. We are interested in the ways in which an understanding of haptics can be used to inform the process of designing electronic musical instruments, and to improve those designs.

The remainder of this chapter comprises a historical overview of the field of haptics and a discussion of the physiology of the haptic sensors. In addition to introducing the important figures in the field, the historical discussion will introduce and organize some subtle but significant concepts, such as the role of intentional movement in haptic sensation. The historical overview also leads into the discussion of sensor physiology, since many of the same subtle concepts must be brought to bear while discussing their function. Chapter 19 will take up the topics of motor control and motor learning.

18.2 Historical Overview

18.2.1 Aristotle

Haptics as an academic discipline dates to the time of Aristotle. To Aristotle, touch was the most essential of the five senses. His treatise *De Anima* (On the Soul), which dates from 350 B.C., discusses each of the five senses in turn. He noted that possession of the sense of touch was the one feature that could be used to distinguish an animal from a plant or an inanimate object. While some animals cannot see or hear, all respond to touch. Aristotle noted the direct correlation between man's superior intelligence and his superior sense of touch. Moreover, when stimuli for the sense of touch are at their extreme, they cause damage to the being itself, whereas extremes of the other senses cause damage only to *well-being*.

Interestingly (in light of modern thought on haptics, reviewed below), there exists a thread tying together the sense of touch and the capacity for movement in Aristotle's work. To Aristotle, features are closely related to function. One may suitably classify an object by describing either its features or its function. Having identified the sense of touch as the distinguishing *feature* of animals, Aristotle associated touch with the accepted *functional* definition of animals: objects that move of their own volition.

Today the close link between motility and haptics is readily acknowledged, both because the mechanical senses are indispensable in the production of movement, and because movement is indispensable in the gathering of haptic information. We will return to this unbreakable link between feature and function, sensation and movement, many times in these chapters on haptics.

Two questions regarding haptics that interested Aristotle persist today. First, is skin the organ of touch or is the organ situated somewhere else, possibly deeper? Second, is touch a single sense or a group of senses? Aristotle provided answers to these questions that are surprisingly insightful, given that he had no knowledge of nervous system physiology. Aristotle maintained that skin is not the organ of touch but, rather, a medium, much as air can be considered the medium for hearing, sight, and smell. He cited the fact that one can feel through gloves, which can be explained only by their being an extension of the medium, the skin. In answer to the second question, Aristotle postulated the existence of more than a single touch sensor, noting that things tangible are marked by several *binarisms,* or pairs of contrasting qualities: hot/cold, hard/soft, wet/dry, and so on. There are many more binarisms in haptics than can be named for the other senses. Since man carries the medium for touch (skin) with his being, he is inclined to group the various binarisms into one sense. If man were to carry an envelope of air, he would tend to group sight, sound, and vision into one sense.

Aristotle was in fact correct from a physiological standpoint, for today we know there are several specialized tactile sense organs embedded in the dermis and epidermis (see section 18.3). With his answer to these questions, Aristotle effectively anticipated much current research on taction that aims to ascertain the mechanical filtering properties of the skin, that is, its transmission properties as a medium for mechanical energy. The question as to the organ of touch may be answered in various ways, depending on the standpoint of the researcher. Even Aristotle acknowledged that "We are unable clearly to detect in the case of touch what the single subject is which underlies the contrasted qualities and corresponds to sound in the case of hearing."

18.2.2 Denis Diderot

In 1749, Diderot (of *Encyclopedia* fame) published his "Letter on the Blind," a fascinating account of tactile perception in the congenitally blind. He laid the foundation for our understanding of *sensory* *substitution,* that one sense gains in power with use or loss of another. Modern neurological evidence also points to the plasticity of the brain: changes in cortical organization occur with changes in use or type of sensory stimulation. Diderot also wrote on the role of memory and the process of learning in touch, noting that an impression of form relies on retention of component sensations.

18.2.3 Ernst H. Weber

Weber introduced systematic experimental procedures to the study of haptics and the other senses, and is thus considered the founder of the field of psychophysics. His famous law, formulated while investigating cutaneous sensation, was reported in *The Sense of Touch* (1834). *Weber's law* states that one's ability to discriminate differences between a standard and a comparison is a function of the magnitude of the standard. For example, a larger difference is needed to discriminate between two weights when the standard weighs 100 grams than when the standard weighs 20 grams. Anticipating later work in haptics, Weber recognized the role of intentional movement in the perception of hardness and distance between objects.

18.2.4 David Katz

In 1925, David Katz published his influential book *Der Aufbau der Tastwelt (The World of Touch)*. He was interested in bringing the sense of touch back into prominence, since psychological research in vision and audition had already outstripped haptics research. Although Katz was certainly influenced by the work of his contemporaries who were laying the foundations of Gestalt psychology, he was more concerned with texture and ground than form and figure. Rather than simplicity of the internal response, he was interested in the correspondence of the internal response with the external stimulus. But, consistent with Gestalt thinking, he held that sensations themselves are irrelevant. Rather, the invariants of the object are obtained over time, and an internal impression is formed that is quite isolated from the sensory input.

Katz was particularly interested in the role of movement in haptic perception. Resting your hand against a surface, you may feel that it is flat, but until there is relative movement between your fingertips and the surface, you will not be able to discern its texture. Only with movement do objects "come into view" to the haptic senses. With movement, touch becomes more effective than vision at discerning certain types of texture.

In part to emphasize the importance of movement, Katz proposed that vibration be added as a fifth sensory component of touch. The accepted four at that time were those proposed by Max von Frey in 1894: pressure, warmth, cold, and pain. Katz noted that the pressure sense adapts or dies away without change in stimulus, whereas vibration persists. For example, one does not notice clothes against the body, yet motion of cloth past a fingertip can stimulate the vibration sense indefinitely. Indeed, Katz treated vibratory sensitivity as separate from and superior to pressure sensitivity. Vibration was not simply oscillating pressure. He paired vibration with hearing as dynamic senses, whereas pressure and vision he associated with stationary qualities.

Katz noted that the pressure sense can be excluded by holding a stick, or stylus, between the teeth and moving it across some material: vibrations are still produced and accurate judgments can be made as to the material "touched." Katz's experiments with styli further suggest that touch is a *far sense,* like vision and hearing, contrary to our tendency to assume that it requires direct impression on the skin by an object. Vibration of the earth (felt in our feet) may signal the imminent approach of a train or a herd of wild buffalo. In a real sense, a tool becomes an extension of one's body; the sensory site moves out to the tool tip. These comments further underline the claim that understanding haptics has important implications for the effective use and design of tools (including musical instruments).

Arguably, Katz's most important contribution to haptics research was on the subject of active and passive touch. When a subject is allowed to independently direct the movements of his/her hand, he/ she is able to make a much more detailed report of surface texture than when the object is moved under his/her passive fingertips. Rather boldly, and with much foresight, Katz proposed an altogether different kind of organ for the sense of touch: the hand. By identifying the hand as the seat of haptic perception, he emphasized the role of intentional movement. He essentially coupled the performatory function of the hand to its perceptual function. By naming an organ that includes muscles, joints, and skin, he coupled the kinesthetic sense to the tactile. In certain instances, he claimed, two hands may be considered the organ of touch just as two eyes may be considered the organ of vision.

18.2.5 Geza Revesz

Revesz was particularly interested in the development of haptic perception in the blind, and especially the coding of spatial information. According to Revesz, haptic recognition of objects is not immediate, as it is in vision, but requires constructive processing of sequentially acquired information. In haptics, the construction of the whole is a cognitive process that follows perception of parts. Revesz emphasized the spatial nature of haptics and its possibilities for apprehending an object from all sides. His theories and experiments with blind persons have had important implications for the development of aids for the blind, such as tactile maps. Perspective cues, which work so well in drawings presented to the eyes (lines vanishing to the horizon, as shown in figure 3.2; occlusion; and background fading), do not work well in raised-line drawings presented to the hands. Recognition of three-dimensional models of objects with the hands, in contrast, is very good.

18.2.6 James Gibson

Gibson contributed in subtle but important ways to the field of psychophysics, and haptics in particular. He was interested in fostering a more ecological approach to research in sensory processes and perception, an approach that takes into account all properties of an environment that may have relevance to a person with particular intentions within that environment. He argued that perceptual psychologists should study recognition of objects rather than such "intellectual" processes as memory or imagination, or such low-level phenomena as stimulus response. Gibson proposed that perception is not simply a process of information-gathering by the senses and subsequent processing by perceptual centers, but the result of a hierarchical perceptual system whose function depends on active participation by the perceiver. For example, the visual system includes not only the eyes and visual cortex but also the active eye muscles, the actively positioned head, and even the mobile body. The haptic system, in addition to the tactile and kinesthetic sensors and somatosensory cortex, includes the active muscles of the arms, hands, and fingers.

Gibson, like Katz, stressed the importance of intentional movement in haptic perception. He preferred to think of active touch as a separate sense. Even when a subject has no intention of manipulating an object, he/she will choose to run his/her fingers over the object when left to his/her own devices. Certainly the fingertips are to the haptic sense as the fovea centralis is to the visual sense: an area with a high concentration of sensors, and thus particular acuity. The fingers may be moved to place the highest concentration of sensors on the area of interest. Movement may be used to produce vibration and transient stimuli, which we know to be important from the experiments of Katz.

Gibson pointed to yet another reason for exploratory movement of the hand: to "isolate invariants" in the flux of incoming sensory information. Just as the image of an object maintains identity as it moves across the retina, or the sound of an instrument maintains identity as its changing pitch moves the stimulus across the basilar membrane, so an object maintains its identity as its depression moves across the skin. The identity even persists as the object is moved to less sensitive areas of the arm, and it is felt to maintain a fixed position in space as the arm glides by it. These facts, central to Gestalt theory, were underlined by Gibson and used as a further basis for understanding active touch. The exploratory movements are used to produce known changes in the stimulus flux while monitoring patterns that remain self-consistent. Thus, active touch is used to test object identity hypothesesin Gibson's words, to "isolate the invariants." Remember from chapter 3 that common fate is a very strong principle for grouping, according to Gestalt theorists, and certainly it seems plausible that a subject will choose to exploit common fate when given the opportunity to do so.

Gibson also demonstrated that a subject passively presented with a haptic stimulus will describe an object in subjective terms, noting the sensations on the hand. By contrast, a subject who is allowed to explore actively will tend to report object properties and object identity. Under active exploration, he/she will tend to *externalize* the object, or ascribe percepts to the object in the external world. For example, when a violin bow is placed on the palm of a subject's passive hand, he/she will report the sensations of contact on the skin, whereas a subject who is allowed to actively explore will readily identify the object and report object properties rather than describe sensations. Furthermore, when a string is bowed, the contact is experienced at the bow hairs and not in the hand.

If we were to attempt to extend Gibson's ideas regarding active touch and active ocular scanning to audition, the question arises: What is active listening? What is the fovea of the ear? Although we cannot move our pinnae like a cat, we certainly can move our head to modify auditory stimuli to our ears. But one could also argue that there exists a kind of internal auditory fovea, or mechanism for choosing a direction in which to concentrate attention. If you concentrate your attention on a particular area in your environment, you will notice more auditory sources in that area. Alternatively, certain pitch or timbre ranges can be singled out with concentration.

18.2.7 The Present

Today the field of haptics has many proponents in academe and industry. After having been taken for granted in perceptual psychology, and considered subservient to vision and audition for so long, haptics is finally enjoying a resurgence of interest.

From our present vantage point in history, we can identify reasons for the earlier lack of research interest in haptics. Certainly the haptic senses are more complex than the auditory or the visual, in that their function is coupled to movement and active participation by the subject. And further, the availability of an experimental apparatus for psychophysical study in haptics has been lacking until nowsomething that corresponds to the computer screen for vision and the loudspeaker or headphones for audition. That apparatus is called the *haptic interface*. It is a specially engineered device that, in response to motions imparted by a human user, can impart reaction forces. The reaction forces are produced by motors under computer control. A haptic interface is a human-computer interface device like a mouse and a monitor screen. Unlike a mouse or computer monitor, however, a haptic interface is simultaneously used for information input and output. Through a haptic interface, human subjects may explore virtual objects. Since the virtual objects are computer-programmable, properties of these objects can be varied more easily than can those of real-world objects.

Current leaders in haptics research include Roberta Klatzky and Susan Lederman, who are often cited for their work on *exploratory procedures,* motor patterns that are used by subjects to ascertain certain object properties. For example, when asked about an object's texture, subjects will glide or rub their fingers over the object, whereas when asked about shape, they will follow contours with fingertips or enclose the object between their hands. It seems that certain patterns of movement maximize the availability of certain information. Klatzky and Lederman have also conducted experiments on the recognition of object representations that have demonstrated poor apprehension of form in two dimensions but good apprehension in three dimensions. The work of Klatzky and Lederman is providing the empirical evidence to back up the ideas of Katz, Revesz, and Gibson on active touch.

Many open questions remain in haptics. We are still not sure if we have an answer to the question that Aristotle raised: What is to haptics as sound is to hearing and color is to seeing? As is apparent from experiments with active and passive touch, the notion of haptic sensation cannot be divorced from the notion of manipulation. Furthermore, the spatial and temporal sensitivity of the haptic sensors is not fully understood. Much research, especially using haptic interfaces, will likely lead to new results. As never before, psychologists and mechanical engineers are collaborating to understand human haptic perception. Results in the field have important implications for virtual reality: the effective design of virtual objects that can be touched through a haptic interface requires a thorough understanding of what is salient to the haptic senses. Furthermore, the design of electronic musical instruments requires research into such topics as active and passive touch and sensory equivalence.

18.3 The Sensors

As we have seen, the designation of the *organ* of touch is a subject open to debate. The gathering of haptic information involves the integration of many faculties, one of which is movement production. The description of the haptic sensors by themselves, however, can be laid out neatly. In this case we may stop our investigation at the level of nerve impulses, and avoid raising questions about higher-level perceptual processes. The following are some of the research techniques that have produced the present knowledge of the haptic sensors.

Knowledge about the structure and function of the various nerve endings that convert thermal or mechanical stimuli into impulses is the product of recent histological (anatomical) and physiological research. Knowledge is still limited, however, because the receptor structures are difficult to isolate from the skin. But perhaps isolation from the skin is counterproductive, since the mechanical properties of the skin and the mechanical integration of sensor and skin largely determine the function of each sensor. A second research technique for haptics is mechanical modeling and simulation of the sensors and skin. Noting that mechanical modeling of the cochlea has contributed to auditory research, haptics researchers hope to gain an understanding of mechanical energy transduction through skin and sensor structures by observing the behavior of models (a much simpler venture than histological observation). A third important technique is microneurography, in which nerve impulses emanating from a single sensor are monitored by using a tiny tungsten fiber inserted into a nerve bundle while various mechanical stimuli are presented to the corresponding site on the skin. In this manner, the receptive field and the response characteristics of a particular receptor type may be mapped out.

If we look beyond the nerve impulses and attempt to find associations between particular receptor types and reported sensations, results are a bit more sketchy. There do not appear to be any clear delineations by sensor type of the haptic percepts. Probably the most promising technique used to associate sensors with sensations is microneurography performed on alert human subjects. While a particular mechanical stimulus is presented to the skin, neural responses are recorded and the subject is asked to report sensations. Alternatively, the nerve fiber may be stimulated electrically with a tungsten fiber. In that case, the subject typically reports the same tactile sensation, localized to the same site where the sensor was stimulated mechanically. Such subject responses may be used to confirm a correspondance between mechanical stimulus, recorded nerve signal, and percept.

In the next sections, the sensors located in the skin (cutaneous sensors) and those located in the muscles, tendons, and joints are described. Very roughly, the cutaneous sensors mediate the tactile senses, and the sensors in the muscles, tendons, and joints mediate the kinesthetic senses. This distinction is rough, however. For example, the skin moves when joints move.

18.3.1 The Cutaneous Sensors

The cutaneous sensors include free nerve endings and a number of specialized nerve endings responsible for transducing warmth, cold, pain, and mechanical energy.

Thermal Sensors

Since the fingers are generally warmer than environmental objects, thermal conductivity plays a large role in thermal sensitivity. The rate at which heat is conducted away from the fingers will determine why a metal object feels colder than a glass object, and a glass object feels colder than a wooden object, even though all three objects are at room temperature before contact. It has long been known that there are separate cold and warmth sensors, for certain sites on the skin are sensitive to cold and certain sites to warmth. This can be shown with a simple temperature-controlled metal probe placed at various sites on the skin. The punctilious nature of the each of the cutaneous sensors must be taken into acount when designing stimuli for psychophysical experiments.

Mechanoreceptors

Let us concentrate our study on the four distinct structures, called the mechanoreceptors, responsible for transducing mechanical energy. Individually, they are known as Meissner's corpuscles, Ruffini endings, Merkel's disks, and the Pacinian corpuscles. These sensors lie at various depths in the dermal tissue or at the dermal-epidermal interface, as shown in figure 18.2. In addition to the morphology of the sensors themselves, it is interesting to note that each is integrated into its surrounding tissue in a unique fashion. For example, Meissner's corpuscules are loosely encased at their base and connected with fibrils on top, while the Ruffini endings are tightly integrated all around. Differences in their integration into surrounding tissue presumably have to do with differentiation in function.

The neural response to all four mechanoreceptors dies out if the mechanical stimulus (usually a motion input) is discontinued. Relative movement is required between skin and object in order to sense aspects like texture. Microneurography studies show that the firings of two types of mechanoreceptors die out quickly and are called rapidly adapting (RA), while the firings of the remaining two last longer and are called slowly adapting (SA). Today it is believed that Pacinian corpuscles and Meissner's corpuscles are the rapidly adapting units, and Ruffini endings and Merkel's disks are the slowly adapting units.

Another means to classify the sensors is by receptive field. Generally, the sensors that are located deeper in the skin have larger sensitive areas. It appears that the Pacinian corpuscles are the vibration sensors. They are capable of sensing vibrations well into the audio range. The Ruffini endings respond most vigorously to skin stretch. Table 18.1 shows some characteristics of the four types of mechanoreceptors.

Table 18.1 Field of sensitivity, frequency range, and supposed sensed parameter, by receptor type

RECEPTOR	FIELD	TYPE	FREQUENCY RANGE	SENSED PARAMETER
Meissner	3-4 mm	FAI	10-60 Hz	skin stretch
Merkel	3-4 mm	SAI	DC-30 Hz	compressive stretch (curvature)
Pacinian	>20 mm	FAII	50-1000 Hz	vibration
Ruffini	>10 mm	SAII	DC-15 Hz	directional skin stretch

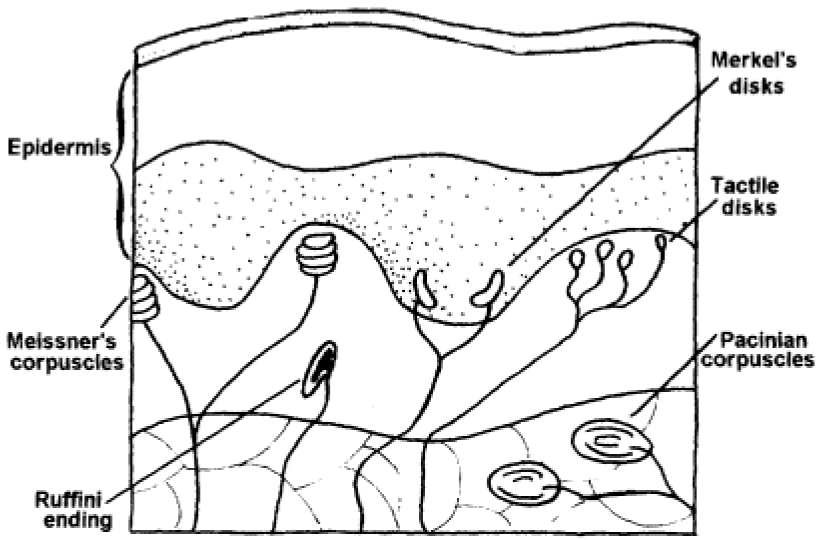

Figure 18.2
A schematic section of human skin, showing the mechanoreceptors. (Drawing courtesy of Jon Forsyth.)

The concentration of the cutaneous sensors varies a great deal over the body. The concentration in the thumb, forefinger, and lips is quite high, while on the torso it is relatively low. There are about 17,000 sensors on each handand 15,000 receptors in each cochlea, and 130,000,000 receptors in each eye. The entire body surface is mapped through neural connections to the somatosensory cortex, which lies on the top surface of the brain, running from ear to ear. The sensory homunculus shown in figure 18.3 has each body part sized according to its amount of associated gray matter, and thus has oversized lips, hands, and fingers.

Figure 18.3
Mapping of the surface of the body to the somatosensory cortex by means of the sensory homunculus. (Drawing courtesy of Jon Forsyth.)

18.3.2 The Kinesthetic Sensors

To complete our picture of the suite of sensors that mediate the haptic sensations, there remain the kinesthetic sensors: muscle spindles in the muscles and Golgi organs in the tendons.

The muscle spindles are instrumented fibers among the bundles that make up a muscle body. Muscle spindles consist of so-called alpha fibers wrapped around flower sprays that lie on the surface of the muscle fiber. The spindles are thought to mediate muscle stretch, rate of change of stretch, and perhaps effort. They are particularly interesting sensors because they involve both efferent (from the brain) and afferent (to the brain) nerves (recall the efferent and afferent nerves in the cochlea, discussed in chapter 1). As with the efferent connections in the cochlea, the efferent connections to the muscle spindles are thought to facilitate active gain control (signals from the brain to the muscle spindles can act to suppress signals coming back to the brain). Efferent signals perhaps cause the muscle fiber around which the afferent fibers are wrapped to tense up independently of the other fibers of the muscle, and thus change spindle sensitivity.

The Golgi organs in the tendons are thought to mediate tendon tension. Pacinian corpuscles are also found in the joints, and are thought to pick up vibration associated with the energy of impacts transmitted through the skeleton. The Golgi organs have little to do with proprioception (sensations of position), according to recent findings. Instead, the muscle spindles are thought to be responsible for proprioception and kinesthesia.

18.3.3 Efference Copy

Efference copy is yet another means of acquiring kinesthetic information. Efference copy refers to the idea that one part of the brain can be made aware of the motion of a limb by receiving a copy of the efferent signal issuing from the motor command center of the brain. Thus, even if the muscle spindles, skin stretch sensors, and Golgi organs associated with a particular limb fail to fire, the perceptual centers tracking that limb would be aware of motion because they would have received a copy of the outgoing motion command. One good demonstration of efference copy was first pointed out by Helmholtz. It presumes the existence of a visual perceptual center processing the information coming from the eye in such a way as to keep the perceived environment from moving relative to the body. The perceptual center must account for movement of the image across the retina as the eye moves relative to the environment. By efference copy, this visual perception center receives a copy of the commands given to the eye muscles, thereby knows where the eye is, and can compensate smoothly for the eye movement. If the eye is moved by some other means, say, by gently pressing on the side of the eyeball with a finger, there is a motion of the eyeball for which there is no efference copy, and the perception of the environment moves. Efference copy, then, is a kind of sense without a sensor.

18.4 Interlude: The Haptic Senses in Musical Performance

Musical instruments, by design, vibrate so as to produce sound. But they also vibrate so as to produce haptic sensations. Take, for example, the vibrations of the left-hand finger of a cellist during note onset, as shown in the spectrogram of figure 18.4. Comparison of the vibration frequencies with the data from table 18.1 reveals that certain vibrations will indeed be apparent to the player through the haptic senses. In general, the onsets of notes are particularly rich in low-frequency energy, and thus are candidates for haptic events. Almost all instruments produce mechanical vibration in the 10-1000 Hz range during such note changes, even when the note fundamental is well above 1000 Hz.

Let us make some conjectures about what kind of information is carried by the vibrations felt by a player in his/her fingers, palms, or lips. How can a player make use of haptic information?

A brass instrument player can feel the register jumps in the horn at the embouchure (the mouthpiece). Changes in the pressure or air

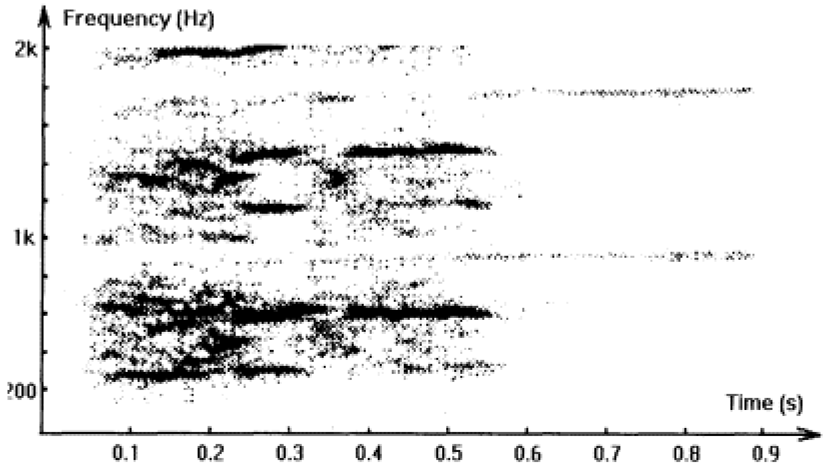

Figure 18.4
Vibration spectrum on the finger of the left hand of a cellist during a note onset. Broadband transients persist for about 0.5 second before a stable note at 880 Hz settles in. (Courtesy of Chris Chafe, CCRMA.)

flow rate through the embouchure during register jumps or note changes are also apparent to sensors in the vocal tract and even the diaphragm. It seems likely that brass players use these haptic cues to determine if the note is properly settled and stable in the instrument, as shown by Perry Cook (1996).

A string bass player can actually tune the instrument to a nearby instrument in the bass section of an orchestra by haptically monitoring the vibrations in his/her instrument. This rather specialized technique becomes useful when the sounds of low and long unison tones are masked to the ears by the sounds of the rest of the orchestra. It does not depend on frequency discrimination of the haptic sensors, since, as we have learned, vibrotactile frequency discrimination is poor. Instead, the bass player will monitor beats in the vibration amplitude that arise in the body of the instrument as it vibrates with its own note and, through air and floor conduction, with the note of an adjacent bass. (Recall the discussion in chapter 5 on how sums of slightly mistuned sine waves exhibit beating.)

From your own musical experience, whatever your instrument, you can probably identify a number of aspects in which the feel of your instrument provides information valuable to your expressive goals. It is hard to imagine playing an instrument successfully with numb fingers or lips. You probably have strong opinions about the make and model of your instrument that are based not only on the tone but also on the feel. For example, if you are a pianist, you appreciate the feel and control of a well-regulated action.

These comments regarding the utility of haptic feedback to a musician's artistic goals bring up another point. We have been speaking mainly about the haptic sensory system as one that supports awareness of the environment, but haptics also play a large role in the process of manipulating that environment. After all, playing a musical instrument is not simply a sensory process, it is a manipulation process. Does the feel of an instrument have anything to do with the ease with which it is played, the ease with which it may be learned, and ultimately its expressive potential? In the next chapter, we will investigate the role of haptics in playing or learning to play a musical instrument.

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