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CHAPTER 10

Auditory Perception and Cognition

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The sound environment in which we live is extraordinarily rich. As we scurry about in our little animal lives, we perceive sound sources and the sequences of events they emit and must adapt our behavior accordingly. How do we extract and make use of the information available in this highly structured acoustic array?

Sounds arise in the environment from the mechanical excitation of bodies that are set into vibration. These bodies radiate some of their vibratory energy into the surrounding air (or water) through which this energy propagates, getting bounced off some objects and partially absorbed by different materials. The nature of the acoustic wave arising from a source depends on the mechanical properties both of that source and of the interaction with other objects that set it into vibration. Many of these excitatory actions are extended through time, and this allows a listener to pick up important information concerning both the source and the action through an analysis of the sequences of events produced. Further, most environments contain several vibrating structures, and the acoustic waves impending on the eardrums represent the sum of many sources, some near, others farther away.

To perceive what is happening in the environment and adjust its behavior appropriately to the sound sources present, a listening organism must be able to disentangle the acoustic information from the many sources and evaluate the properties of individual events or sequences of events arising from a given source. At a more cognitive level, it is also useful to process the temporal relations among events in more lengthy sequences to understand the nature of actions on objects that are extended in time and that may carry important cultural messages such as in speech and music for humans. Finally, in many cases, with so much going on, listening must be focused on a given source of sound. Furthermore, this focusing process must possess dynamic characteristics that are tuned to the temporal evolution of the source that is being tracked in order to understand its message.

Aspects of these complex areas are addressed in this chapter to give a nonexhaustive flavor for current work in auditory perception and cognition. We focus on auditory scene analysis, timbre and sound source perception, temporal pattern processing, and attentional processes in hearing and finish with a consideration of developmental issues concerning these areas. The reader may wish to consult several general texts for additional information and inspiration (Bregman, 1990; Handel, 1989; McAdams & Bigand, 1993; Warren, 1999, with an accompanying CD), as well as compact discs of audio demos (Bregman & Ahad, 1995; Deutsch, 1995; Houtsma, Rossing & Wagenaars, 1987).

AUDITORY SCENE ANALYSIS

It is useful for an organism to build a mental representation of the acoustic environment in terms of the behavior of sound sources (objects set into vibration by actions upon them) in order to be able to structure its behavior in relation to them. We can hear in the same room and at the same time the noise of someone typing on a keyboard, the sound of someone walking, and the speech of someone talking in the next room. From a phenomenological point of view, we hear all of these sounds as if they arrive independently at our ears without distortion or interference among them, unless, of course, one source is much more intense than the others, in which case it would mask them, making them inaudible or at least less audible.

The acoustic waves of all sources are combined linearly in the atmosphere, and the composite waveform is then analyzed as such by the peripheral auditory system (Figure 10.1; see Chap. 9, this volume). Sound events are not opaque like most visual objects are. The computational problem is thus to interpret the complex waveform as a combination of sound-producing events. This process is called *auditory scene analysis* (Bregman, 1990) by analogy with the analysis of a visual scene in terms of objects (see Chap. 5, this volume, for a comparison of how these two sensory systems have come to solve analogous problems). Contrary to vision, in which a contiguous array of stimulation of the sensory organ corresponds to an object (although this is not always the case, as with partially occluded or transparent objects), in hearing the stimulation is a distributed frequency array mapped onto the basilar membrane. For a complex sound arising from a given source, the auditory system must thus reunite the sound components coming from the same source that have previously been channeled into separate auditory nerve fibers on the basis of their frequency content. Further, it must separate the information coming from distinct sources that contain close frequencies that would stimulate the same auditory nerve fibers. This is the problem of *concurrent organization*. The problem of *sequential organization* concerns perceptually connecting (or binding) over time successive events emitted by the same source and segregating events

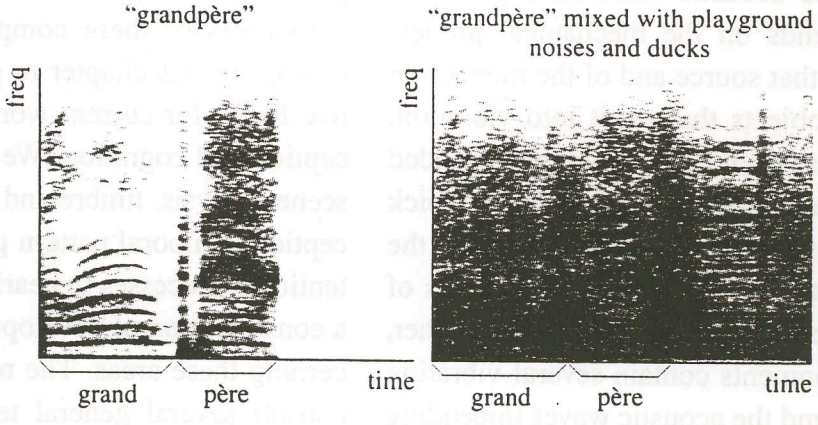


Figure 10.1 Spectrogram of (a) a target sound—the word *grandpère* ("grandfather" in French)—and (b) the target sound embedded in a noisy environment (a children's playground with voices and ducks). NOTE: A spectrogram represents time on the horizontal axis and frequency on the vertical axis. The level at a given frequency is coded by the darkness of the spectrographic trace. Note that in many places in the mixture panel, the frequency information of the target sound is strongly overlapped by that of the noisy environment. In particular, the horizontal lines representing harmonic frequency components of the target word become intermingled with those of other voices in the mixture.

coming from independent sources in order to follow the message of only one source at a time.

This section examines the mechanisms that are brought into play by the auditory system to analyze the acoustic events and the behavior over time of sound sources. The ultimate goal of such a system would be to segregate perceptually actions that occur simultaneously; to detect new actions in the environment; to follow actions on a given object over time; to compute the properties of sources to feed into categorization, recognition, identification, and comprehension processes; and to use knowledge of derived attributes to track and extract sources and messages. We consider in order the processes involved in auditory event formation (concurrent grouping), the distinction of new event arrival from change of an ongoing event, auditory stream formation (sequential grouping), the interaction of concurrent and sequential grouping factors, the problem posed by the transparency of auditory events, and, finally, the role of schema-based processes in auditory organization.

Auditory Event Formation (Concurrent Grouping)

The processes of concurrent organization result either in the *perceptual fusion* or *grouping* of components of the auditory sensory representation into a single auditory event or in their *perceptual segregation* into two or more distinct events that overlap in time. The nature of these components of the sensory representation depends on the dual coding scheme in the auditory periphery. On the one hand, different parts of the acoustic frequency spectrum are represented in separate anatomical locations at many levels of the auditory system, a representation that is called tonotopic (see Chap. 9, this volume). On the other hand, even within a small frequency range in which all the acoustic information is carried by a small number of adjacent auditory nerve fibers, different periodicities in the stimulating waveform can be discerned on the basis of the temporal pattern of neural discharges that are time-locked to the stimulating waveform (see Chap. 9, this volume). The term *auditory event* refers to the unity and limited temporal extent that are experienced when, for example, a single sound source is set into vibration by a time-limited action on it. Some authors use the term *auditory objects,* but we prefer to distinguish objects (as vibrating physical sources) from perceptual events. A single source can produce a series of events.

A relatively small number of acoustic cues appear to signal either common behavior among acoustic components (usually arising from a single source) or incoherent behavior between components arising from distinct sources. The relative contribution of a given cue for scene analysis, however, depends on the perceptual task in which the listener is engaged: Some cues are more effective in signaling grouping for one attribute, such as identifying the pitch or vowel quality of a sound, than for another attribute, such as judging its position in space. Furthermore, some cues are more resistant than are others to environmental transformations of the acoustic waves originating from a vibrating object (reflections, reverberation, filtering by selective absorption, etc.).

Candidate cues for increasing segregation of concurrent sounds include inharmonicity, irregularity of spacing of frequency components, asynchrony of onset or offset of components, incoherence of change over time of level and frequency of components, and differences in spatial position.

Harmonicity

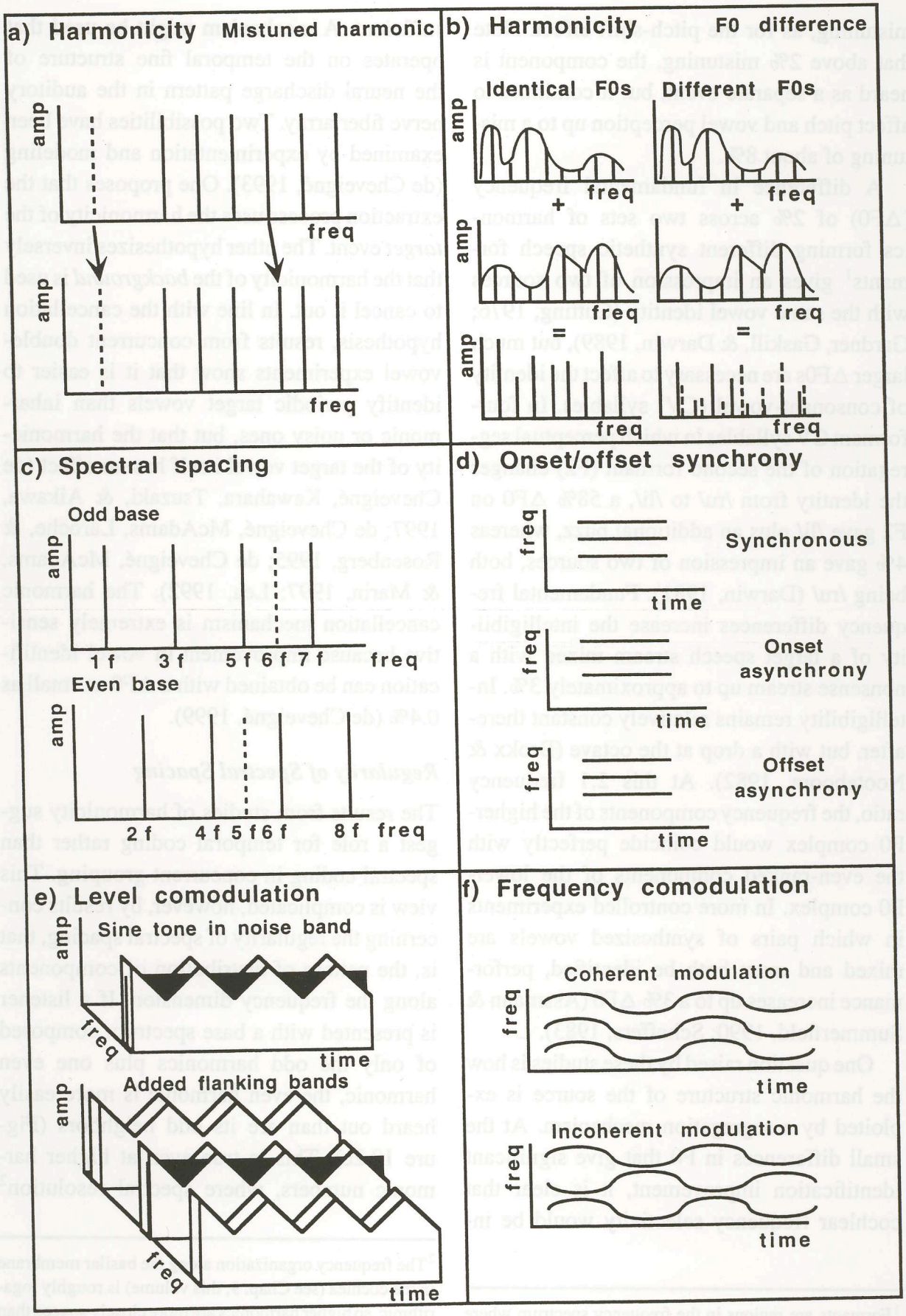
In the environment two unrelated sounds rarely have frequency components that line up such that each frequency is an integer multiple

of the fundamental frequency (F0), which is called a harmonic series. It is even less likely that they will maintain this relation with changes in frequency over time. A mechanism that is sensitive to deviations from harmonicity and groups components having harmonic relations could be useful for grouping acoustic components across the spectrum that arise from a single source and for segregating those that arise from distinct sources.

Two main classes of stimuli have been used to study the role of harmonicity in concurrent grouping: harmonic complexes with a single component mistuned from its purely harmonic relation and complexes composed of two or more sets of harmonic components with a difference in fundamental frequency (Figures 10.2a–b).

Listeners report hearing out a single, mistuned harmonic component from the rest of the complex tone if its harmonic rank is low and the mistuning is around 2% of its nominal frequency (Moore, Peters, & Glasberg, 1985). If mistuning is sufficient, listeners can match the pitch of the segregated harmonic, but this ability deteriorates at component frequencies above approximately 2000 Hz, where temporal information in the neural discharge pattern is no longer reliably related to waveform periodicities (Hartmann, McAdams, & Smith, 1990). A mistuned harmonic can also affect the virtual pitch (see Chap. 11, this volume) of the whole complex, pulling it in the direction of mistuning. This pitch shift increases for mistunings up to 3% and then decreases beyond that, virtually disappearing beyond about 8% (Hartmann, 1988; Hartmann et al., 1990; Moore, Glasberg, & Peters, 1985). This relation between mistuning and pitch shift suggests a harmonic-template model with a tolerance function on the harmonic sieve (Duifhuis, Willems, & Sluyter, 1982) or a time-domain autocoincidence processor (de Cheveigné, 1993) with a temporal margin of error. Harmonic mistuning can also affect vowel perception by influencing whether the component frequency is integrated into the computation of the spectral envelope that determines the vowel identity (Darwin & Gardner, 1986). By progressively mistuning this harmonic, a change in vowel percept has been recorded up to about 8%

Figure 10.2 Stimuli used to test concurrent grouping cues.
NOTE: a) Harmonicity tested with the mistuned harmonic paradigm. A harmonic stimulus without the fundamental frequency still gives a pitch at that frequency (dashed line). A shift of at least 2% but no more than 8% in the frequency of the fourth harmonic causes the harmonic to be heard separately but still contributes to a shift in the pitch of the complex sound. b) Harmonicity tested with the concurrent vowel paradigm. In the left column two vowels (indicated by the spectral envelopes with formant peaks) have the same fundamental frequency (F0). The resulting spectrum is the sum of the two, and the new spectral envelope does not correspond to either of the vowels, making them difficult to identify separately. In the right column, the F0 of one of the vowels is shifted, and two separate groups of harmonics are represented in the periodicity information in the auditory nerve, making the vowels more easily distinguished. c) Spectral spacing. An even harmonic in an odd-harmonic base, or vice versa, is easier to hear out than are the harmonics of the base. d) Onset/offset asynchrony. When harmonics start synchronously, they are fused perceptually into a single perceptual event. An asynchrony of the onset of at least 30–50 ms makes the harmonic easier to hear out. An asynchrony of the offset has a relatively weak effect on hearing out the harmonic. e) Level comodulation (comodulation masking release). The amplitude envelopes of a sine tone (black) and a narrow band noise with a modulating envelope (white) are shown. The masking threshold of the sine tone in the noise is measured. When flanking noise bands with amplitude envelopes identical to that of the on-signal band are added, the masked threshold of the sine tone decreases by about 3 dB. f) Frequency comodulation. A set of harmonics that are coherently modulated in frequency (with a sinusoidal vibrato in this example) are heard as a single event. Making the modulation incoherent on one


a) Harmonicity
Mistuned harmonic
amp
freq
amp
freq
b) Harmonicity
F0 difference
Identical F0s
Different F0s
amp
freq
+
freq
+
amp
freq
freq
=
=
amp
freq
freq
c) Spectral spacing
Odd base
amp
1 f
3 f
5 f
6 f
7 f
freq
Even base
amp
2 f
4 f
5 f
6 f
8 f
freq
d) Onset/offset synchrony
freq
Synchronous
time
freq
Onset
asynchrony
time
freq
Offset
asynchrony
time
e) Level comodulation
Sine tone in noise band
amp
freq
time
Added flanking bands
amp
freq
time
f) Frequency comodulation
Coherent modulation
freq
time
Incoherent modulation
freq
time

mistuning, as for the pitch-shift effect. Note that above 2% mistuning, the component is heard as a separate event, but it continues to affect pitch and vowel perception up to a mistuning of about 8%.

A difference in fundamental frequency (ΔF0) of 2% across two sets of harmonics forming different synthetic speech formants[1] gives an impression of two sources with the same vowel identity (Cutting, 1976; Gardner, Gaskill, & Darwin, 1989), but much larger ΔF0s are necessary to affect the identity of consonant-vowel (CV) syllables. In four-formant CV syllables in which perceptual segregation of the second formant (F2) changes the identity from /ru/ to /li/, a 58% ΔF0 on F2 gave /li/ plus an additional buzz, whereas 4% gave an impression of two sources, both being /ru/ (Darwin, 1981). Fundamental frequency differences increase the intelligibility of a target speech stream mixed with a nonsense stream up to approximately 3%. Intelligibility remains relatively constant thereafter, but with a drop at the octave (Brokx & Nooteboom, 1982). At this 2:1 frequency ratio, the frequency components of the higher-F0 complex would coincide perfectly with the even-ranked components of the lower-F0 complex. In more controlled experiments in which pairs of synthesized vowels are mixed and must both be identified, performance increases up to a 3% ΔF0 (Assmann & Summerfield, 1990; Scheffers, 1983).

One question raised by these studies is how the harmonic structure of the source is exploited by a segregation mechanism. At the small differences in F0 that give significant identification improvement, it is clear that cochlear frequency selectivity would be insufficient. A mechanism might be used that operates on the temporal fine structure of the neural discharge pattern in the auditory nerve fiber array. Two possibilities have been examined by experimentation and modeling (de Cheveigné, 1993). One proposes that the extraction process uses the harmonicity of the *target* event. The other hypothesizes inversely that the harmonicity of the *background* is used to cancel it out. In line with the cancellation hypothesis, results from concurrent double-vowel experiments show that it is easier to identify periodic target vowels than inharmonic or noisy ones, but that the harmonicity of the target vowel itself has no effect (de Cheveigné, Kawahara, Tsuzaki, & Aikawa, 1997; de Cheveigné, McAdams, Laroche, & Rosenberg, 1995; de Cheveigné, McAdams, & Marin, 1997; Lea, 1992). The harmonic cancellation mechanism is extremely sensitive because improvement in vowel identification can be obtained with a ΔF0 as small as 0.4% (de Cheveigné, 1999).

Regularity of Spectral Spacing

The results from studies of harmonicity suggest a role for temporal coding rather than spectral coding in concurrent grouping. This view is complicated, however, by results concerning the regularity of spectral spacing, that is, the pattern of distribution of components along the frequency dimension. If a listener is presented with a base spectrum composed of only the odd harmonics plus one even harmonic, the even harmonic is more easily heard out than are its odd neighbors (Figure 10.2c). This is true even at higher harmonic numbers, where spectral resolution[2]

[1] Formants are regions in the frequency spectrum where the energy is higher than in adjacent regions. They are due to the resonance properties of the vocal tract and determine many aspects of consonant and vowel identity (see Chap. 12, this volume).

[2] The frequency organization along the basilar membrane in the cochlea (see Chap. 9, this volume) is roughly logarithmic, so higher harmonics are more closely spaced than are lower harmonics. At sufficiently high ranks, adjacent harmonics no longer stimulate separate populations of auditory nerve fibers and are thus "unresolved" in the tonotopic representation.

is reduced. Note that the even harmonic surrounded by odd harmonics would be less resolved on the basilar membrane than would either of its neighbors. Contrary to the ΔF0 cue, harmonic sieve and autocoincidence models cannot account for these results (Roberts & Bregman, 1991). Nor does the underlying mechanism involve a cross-channel comparison of the amplitude modulation envelope in the output of the auditory filter bank, because minimizing the modulation depth or perturbing the modulation pattern by adding noise does not markedly reduce the difference in hearing out even and odd harmonics (Roberts & Bailey, 1993). However, perturbing the regularity of the base spectrum by adding extraneous components or removing components reduces the perceptual "popout" of even harmonics (Roberts & Bailey, 1996), confirming the spectral pattern hypothesis.

Onset and Offset Asynchrony

Unrelated sounds seldom start or stop at exactly the same time. Therefore, the auditory system assumes that synchronous components are part of the same sound or were caused by the same environmental event. Furthermore, the auditory system is extremely sensitive to small asynchronies in analyzing the auditory scene. A single frequency component in a complex tone becomes audible on its own with an asynchrony as small as 35 ms (Rasch, 1978). Onset asynchronies are more effective than offset asynchronies are in creating segregation (Figure 10.2d; Dannenbring & Bregman, 1976; Zera & Green, 1993). When a component is made asynchronous, it also contributes less to the perceptual properties computed from the rest of the complex. For example, a 30-ms asynchrony can affect timbre judgments (Bregman & Pinker, 1978). Making a critical frequency component that affects the estimation of a vowel sound's spectral envelope asynchronous by 40 ms changes the vowel identity (Darwin, 1984). Furthermore, the asynchrony effect is abolished if the asynchronous portion of the component (i.e., the part that precedes the onset of the vowel complex) is grouped with another set of components that are synchronous with it alone and that have a common F0 that is different from that of the vowel. This result suggests that it is indeed a grouping effect, not the result of adaptation (Darwin & Sutherland, 1984).

The effect of a mistuned component on the pitch of the complex (discussed earlier) is increasingly reduced for asynchronies from 80 to 300 ms (Darwin & Ciocca, 1992). This latter effect is weakened if another component groups with a preceding portion of the asynchronous component (Ciocca & Darwin, 1993). Note that in these results the asynchronies necessary to affect pitch perception are much greater than are those that affect vowel perception (Hukin & Darwin, 1995a).

Coherence of Change in Level

From Gestalt principles such as common fate (see Chap. 5, this volume), one might expect that common direction of change in level would be a cue for grouping components together; inversely, independent change would signal that segregation was appropriate. The evidence that this factor is a grouping cue, however, is rather weak. In experiments by Hall and colleagues (e.g., Hall, Grose, & Mendoza, 1995), a phenomenon called *comodulation masking release* is created by placing a narrow-band noise masker centered on a target frequency component (sine tone) that is to be detected (Figure 10.2e). The masked threshold of the tone is measured in the presence of the noise. Then, noise bands with similar or different amplitude envelopes are placed in more distant frequency regions. The presence of similar envelopes (i.e., comodulation) makes it possible to detect the tone in the noise at a level of about 3 dB lower

than in their absence. The masking seems to be released to some extent by the presence of comodulation on the distant noise bands. Some authors have attributed this phenomenon to the grouping of the noise bands into a single auditory image that then allows the noise centered on the tone to be interpreted as part of a different source, thus making detection of the tone easier (Bregman, 1990, chap. 3). Others, however, consider either that cross-channel detection of the amplitude envelope simply gives a cue to the auditory system concerning when the masking noise should be in a level dip, or that the flanking maskers suppress the on-signal masker (Hall et al., 1995; McFadden & Wright, 1987).

Coherence of Change in Frequency

For sustained complex sounds that vary in frequency, there is a tendency for all frequencies to change synchronously and to maintain the frequency ratios. As such, one might imagine that frequency modulation coherence would be an important cue in source grouping (Figure 10.2f). The effects of frequency modulation incoherence may have two origins: within-channel cues and cross-channel cues. Within-channel cues would result from the interactions of unresolved components that changed frequency incoherently over time, creating variations in beating or roughness in particular auditory channels. They could signal the presence of more than one source. Such cues are detectable for both harmonic and inharmonic stimuli (McAdams & Marin, 1990) but are easier to detect for the former because of the reliability of within-channel cues for periodic sounds. Frequency modulation coherence is not, however, detectable across auditory channels (i.e., in distant frequency regions) above and beyond the mistuning from harmonicity that they create (Carlyon, 1991, 1992, 1994). Although frequency modulation increases vowel prominence when the $\Delta F0$ is already large, there is no difference between coherent and incoherent modulation across the harmonics of several vowels either on vowel prominence (McAdams, 1989) or on vowel identification (Summerfield & Culling, 1992). However, frequency modulation can help group together frequency components for computing pitch. In a mistuned harmonic stimulus, shifts in the perceived pitch of the harmonic complex continue to occur at greater mistunings when all components are modulated coherently than when they are unmodulated (Darwin, Ciocca, & Sandell, 1994).

Spatial Position

It was thought early on that different spatial positions should give rise to binaural cues that could be used to segregate temporally and spectrally overlapping sound events. Although work on speech comprehension in noisy environments (e.g., Cherry's 1953 "cocktail party effect") emphasized spatial cues to allow listeners to ignore irrelevant sources, the evidence in support of such cues for grouping is in fact quite weak. An interaural time difference (ITD) is clearly a powerful cue for direction (see Chap. 9, this volume), but it is remarkably ineffective as a cue for grouping simultaneous components that compose a particular source (Culling & Summerfield, 1995; Hukin & Darwin, 1995b).

The other principal grouping cues generally override spatial cues. For example, the detection of changes in ITD on sine components across two successive stimulus intervals is similar when they are presented in isolation or embedded within an inharmonic complex. However, detection performance is much worse when they are embedded within a harmonic complex; thus harmonicity overrides spatial incoherence (Buell & Hafter, 1991). Furthermore, mistuning a component can affect its lateralization (Hill & Darwin, 1996), suggesting that grouping takes place on

the basis of harmonicity, and only *then* is the spatial position computed on the basis of the lateralization cues for the set of components that have been grouped together (Darwin & Ciocca, 1992).

Lateralization effects may be more substantial when the spatial position is attended to over an extended time, as would be the case in paying sustained attention to a given sound source in a complex environment (Darwin & Carlyon, 1995). Listeners can attend across time to one of two spoken sentences distinguished by small differences in ITD, but they do not use such continuity of ITD to determine which individual frequency components should form part of a sentence. These results suggest that ITD is computed on the peripheral representation of the frequency components in parallel to a grouping of components on the basis of harmonicity and synchrony. Subsequently, direction is computed on the grouped components, and the listener attends to the direction of the grouped object (Darwin & Hukin, 1999).

General Considerations Concerning Concurrent Grouping

Note that there are several possible cues for grouping and segregation, which raises the possibility that what the various cues signal in terms of source structures in the environment can diverge. For example, many kinds of sound sources are not harmonic, but the acoustic components of the events produced by them would still start and stop at the same time and probably have a relatively fixed spatial position that could be attended to. In many cases, however, redundancy of segregation and integration cues works against ambiguities in inferences concerning grouping on the basis of sensory information. Furthermore, the cues to scene analysis are not all-or-none. The stronger they are, the more they affect grouping, and the final perceptual result is the best compromise on the basis of both the strength of the evidence available and the perceptual task in which the listener is engaged (Bregman, 1993). As many of the results cited earlier demonstrate, the grouping and segregation of information in the auditory sensory representation precedes and thus determines the perceptual properties of a complex sound source, such as its spatial position, its pitch, or its timbre. However, the perceived properties can in turn become cues that facilitate sustained attending to, or tracking of, sound sources over time.

New Event Detection versus Perception of a Changing Event

The auditory system appears to be equipped with a mechanism that triggers event-related computation when a sudden change in the acoustic array is detected. The computation performed can be a resampling of some property of the environment, such as the spatial position of the source, or a grouping process that results in the decomposition of an acoustic mixture (Bregman, 1991). This raises the questions of what constitutes a sudden change indicating the arrival of a new event and how it can be distinguished from a more gradual change that results from an evolution of an already present event.

An example of this process is binaural adaptation and the recovery from such adaptation when an acoustic discontinuity is detected. Hafter, Buell, & Richards (1988) presented a rapid (40/s) series of clicks binaurally with an interaural time difference that gave a specific lateralization of the click train toward the leading ear (Figure 10.3a). As one increases the number of clicks in the train, accuracy in discriminating the spatial position between two successive click trains increases, but the improvement is progressively less (according to a compressive power function) as the click train is extended in duration. The binaural system thus appears to become

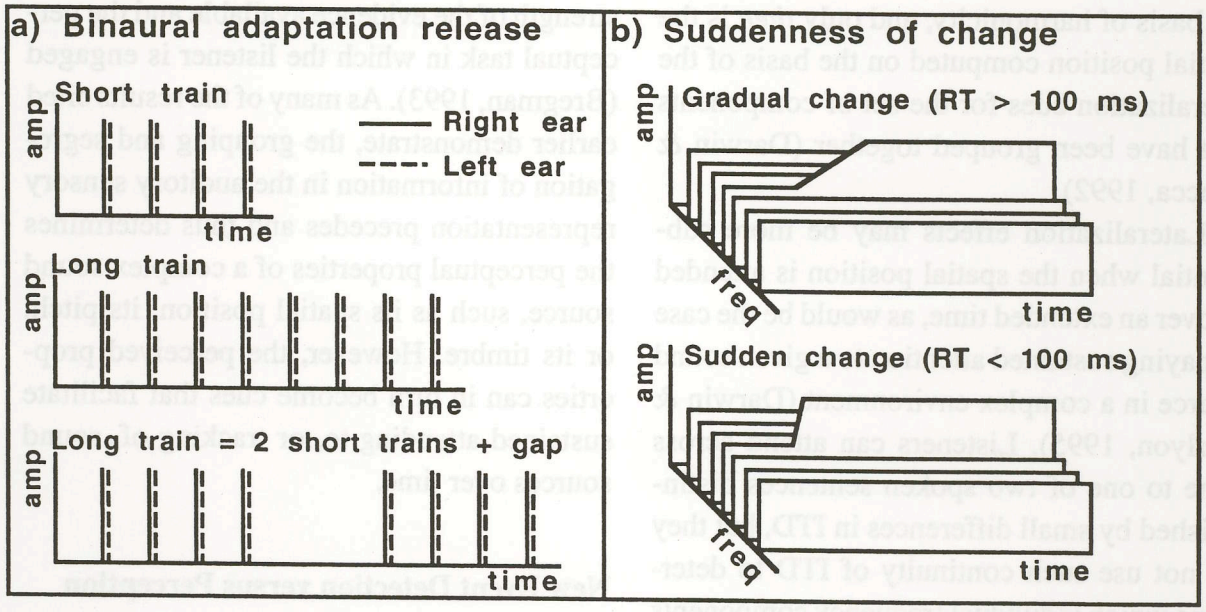


Figure 10.3 Stimuli used to test the resetting of auditory sampling of the environment upon new event detection.

NOTE: a) Binaural adapatation release. A train of clicks (interclick separation = 2.5 ms) is sent to the two ears with a small interaural time difference (ITD) that displaces the perceived lateralization of the sound toward the leading ear (the right ear in this example). The just noticeable ITD decreases as a function of the number of clicks in the train, but the relative contribution of later clicks is lesser than is that of the earlier clicks, indicating binaural adaptation. Release from adaptation is triggered by the detection of a new event, such as a discontinuity in the click train (e.g., a silent gap of 7.5 ms). b) Suddenness of change. The amplitude envelopes on harmonic components are shown. All harmonics are constant in level except one, which increases in level in the middle. A slow change in level (>100 ms) is heard as a change in the timbre of the event, whereas a sudden change (<100 ms) is heard as a new (pure-tone) event.

progressively quiet beyond stimulus onset for constant stimulation. However, if some kind of discontinuity is introduced in the click train (a longer or shorter gap between clicks, or a brief sound with a sudden onset in a remote spectral region, even of fairly low intensity), the spatial environment is suddenly resampled at the moment of the discontinuity. A complete recovery from the process of binaural adaptation appears to occur in the face of such discontinuities and indicates that the auditory system is sensitive to perturbations of regularity. Hafter and Buell (1985) proposed that at a fairly low level in the auditory system, multiple bands are monitored for changes in level that might accompany the start of a new signal or a variation in the old one. Sudden changes cause the system to resample the binaural inputs and to update its spatial map at the time of the restart, suggesting that knowledge about the direction of a source may rely more on memory than on the continual processing of ongoing information.

Similarly, an acoustic discontinuity can provoke the emergence of a new pitch in an otherwise continuous complex tone. A sudden interaural phase disparity or frequency disparity in one component of a complex tone can create successive-difference cues that make the component emerge (Kubovy, 1981; Kubovy, Cutting, & McGuire, 1974). In this case, the successive disparity triggers a recomputation of which pitches are present. Thus, various sudden changes trigger resampling. But how fast a change is "sudden"? If listeners must identify the direction of change

in pitch for successive pure-tone events added in phase to a continuous harmonic complex (Figure 10.3b), performance is a monotone decreasing function of rise time; that is, the more sudden the change, the more the change is perceived as a new event with its own pitch, and the better is the performance. From these results Bregman, Ahad, Kim, and Melnerich (1994) proposed that "sudden" can be defined as basically less than 100 ms for onsets.

Auditory Stream Formation (Sequential Grouping)

The processes of sequential organization result in the perceptual integration of successive events into a single auditory stream or their perceptual segregation into two or more streams. Under everyday listening conditions, an auditory stream corresponds to a sequence of events emitted by a single sound source.

General Considerations Concerning Sequential Grouping

Several basic principles of auditory stream formation emerge from research on sequential grouping. These principles reflect regularities in the physical world that shaped the evolution of the auditory mechanisms that detect them.

1. *Source properties change slowly.* Sound sources generally emit sequences of events that are transformed in a progressive manner over time. Sudden changes in event properties are likely to signal the presence of several sources (Bregman, 1993).
2. *Events are allocated exclusively to streams.* A given event is assigned to one or another stream and cannot be perceived as belonging to both simultaneously (Bregman & Campbell, 1971), although there appear to be exceptions to this principal in interactions between sequential and concurrent grouping processes and in duplex perception (discussed later).
3. *Streaming is cumulative.* The auditory system appears by default to assume that a sequence of events arises from a single source until enough evidence to the contrary can be accumulated, at which point segregation occurs (Bregman, 1978b). Also, if a cyclical sequence is presented over a long period of time (several tens of seconds), segregation tends to increase (Anstis & Saida, 1985).
4. *Sequential grouping precedes stream attribute computation.* The perceptual properties of sequences depend on what events are grouped into streams, as was shown for concurrent grouping and event attributes. A corollary of this point is the fact that the perception of the order of events depends on their being assigned to the same stream: It is easier to judge temporal order on within-stream patterns than on across-stream patterns that are perceptually fragmented (Bregman & Campbell, 1971; van Noorden, 1975).

The cues that determine sequential auditory organization are closely related to the Gestalt principles of proximity and similarity (see Chap. 5, this volume). The notion of proximity in audition is limited here to the temporal distance between events, and similarity encompasses the acoustic similarity of successive events. Given the intrinsically temporal nature of acoustic events, grouping is considered in terms of continuity and rate of change in acoustic properties between successive events. In considering the acoustic factors that affect grouping in the following, keep in mind that not all acoustic differences are equally important in determining segregation (Hartmann & Johnson, 1991).

Frequency Separation and Temporal Proximity

A stimulus sequence composed of two alternating frequencies in the temporal pattern

ABA—ABA— (where "—" indicates a silence) is heard as a galloping rhythm if the tones are integrated into a single stream and as two isochronous sequences (A—A—A—A— and B———B———) if they are segregated. At slower tempos and smaller frequency separations, integration tends to occur, whereas at faster tempos and larger frequency separations, segregation tends to occur. Van Noorden (1975) measured the frequency separation at which the percept changes from integration to segregation or vice versa for various event rates. If listeners are instructed to try to hear the gallop rhythm or conversely to focus on one of the isochronous sequences, temporal coherence and fission boundaries are obtained, respectively (see Figure 10.4). These functions do not have the same form. The fission boundary is limited by the frequency resolution of the peripheral auditory system and is relatively unaffected by the event rate. The temporal coherence boundary reflects the limits of inevitable segregation and strongly depends on tempo. Between the two is an ambiguous region where the listener's perceptual intent plays a strong role.

Streaming is not an all-or-none phenomenon with clear boundaries between integration and segregation along a given sensory continuum, however. In experiments in which the probability of a response related to the degree of segregation was measured (Brochard, Drake, Botte, & McAdams, 1999), the probability varied continuously as a function of frequency separation. This does not imply that the percept is ambiguous. It is either one stream or two streams, but the probability of hearing one or the other varies for a given listener and across listeners.

It is not the absolute frequency difference that determines which tones are bound together in the same stream, but rather the relative differences among the frequencies. Bregman (1978a), for example, used a sequential tone pattern ABXY. If A and B are within a critical band (i.e., they stimulate overlapping sets of auditory nerve fibers) in a high frequency region, and if X and Y are within a critical band in a low frequency region, then A and B form one stream, and X and Y form another stream (see Figure 10.5). If X and Y are now moved to the same frequency region as A and B such that A and X are close and B and Y are close, without changing the frequency ratios between A and B nor between X and Y, then the relative frequency differences predominate and streams of A-X and B-Y are obtained.

The abruptness of transition from one frequency to the next also has an effect on stream segregation. In the studies just cited, one tone stops on one frequency, and the next tone begins at a different frequency. In many sound sources that produce sequences of events and vary the fundamental frequency, such as the voice, such changes may be more gradual. Bregman & Dannenbring (1973) showed that the inclusion of frequency ramps (going toward the next tone at the end and coming from the previous tone at the beginning) or even complete frequency glides between tones yielded greater integration of the sequence into a single stream.

The Cumulative Bias toward Greater Segregation

Anstis and Saida (1985) showed that there is a tendency for reports of a segregated percept to increase over time when listening to alternating-tone sequences. This stream biasing decays exponentially when the stimulus sequence is stopped and has a time constant of around 4 s on average (Beauvois & Meddis, 1997). Anstis and Saida proposed a mechanism involving the fatigue of frequency jump detectors to explain this phenomenon, but Rogers and Bregman (1993a) showed that an inductor sequence with a single tone could induce a bias toward streaming in the absence of jumps. The biasing mechanism requires

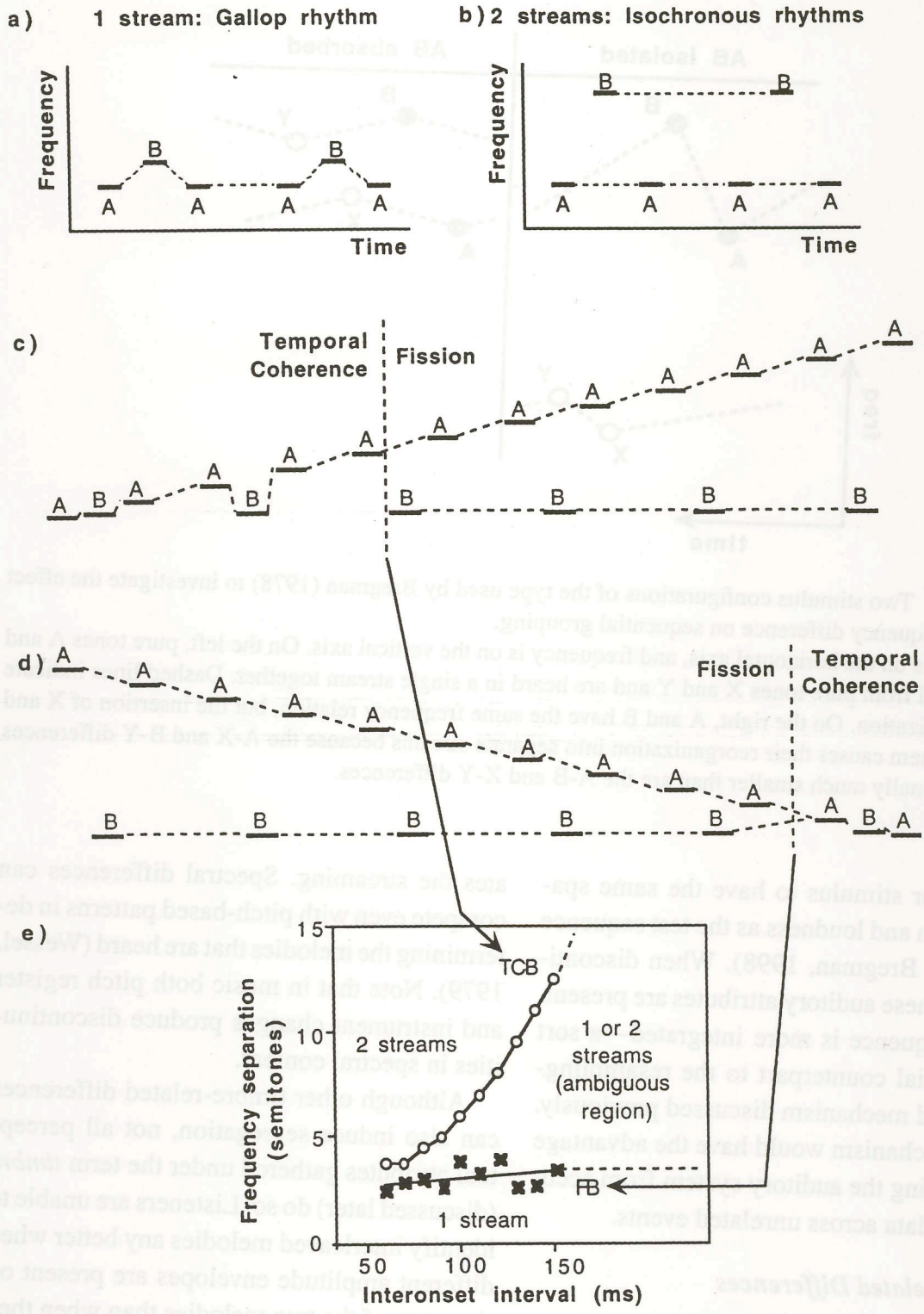


Figure 10.4 Van Noorden's temporal coherence and fission boundaries.
NOTE: A repeating "ABA—" pattern can give a percept of either a) a gallop rhythm or b) two isochronous sequences, depending on the presentation rate and AB frequency difference. c) To measure the temporal coherence boundary (TCB), the initial frequency difference is small and increases while the listener attempts to hold the gallop percept. d) To measure the fission boundary (FB), the initial difference is large and is decreased while the listener tries to focus on a single isochronous stream. In both cases, the frequency separation at which the percept changes is recorded. The whole procedure is repeated at different interonset intervals, giving the curves shown in (e).
SOURCE: Adapted from van Noorden (1975, Figure 2.7). Copyright © 1975 by Leon van Noorden. Adapted with permission.

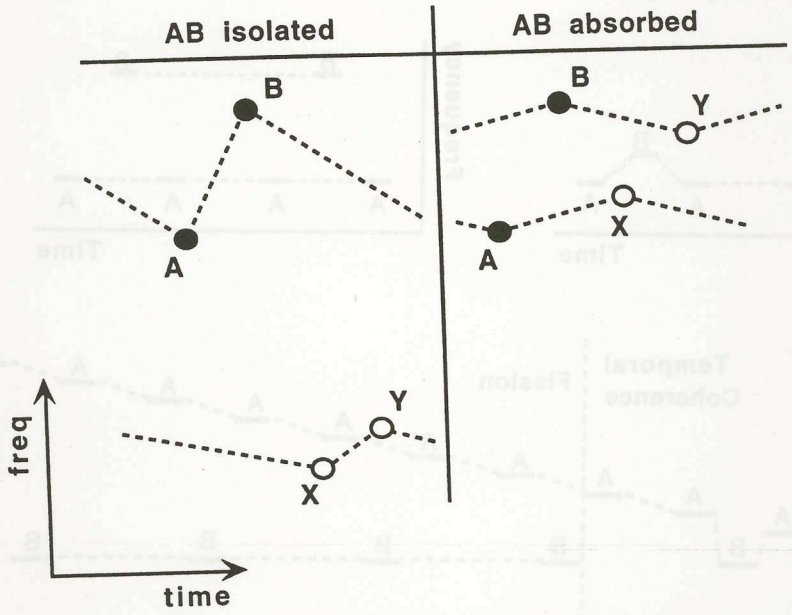


Figure 10.5 Two stimulus configurations of the type used by Bregman (1978) to investigate the effect of relative frequency difference on sequential grouping.
NOTE: Time is on the horizontal axis, and frequency is on the vertical axis. On the left, pure tones A and B are isolated from pure tones X and Y and are heard in a single stream together. Dashed lines indicate stream organization. On the right, A and B have the same frequency relation, but the insertion of X and Y between them causes their reorganization into separate streams because the A-X and B-Y differences are proportionally much smaller than are the A-B and X-Y differences.

the inductor stimulus to have the same spatial location and loudness as the test sequence (Rogers & Bregman, 1998). When discontinuities in these auditory attributes are present, the test sequence is more integrated—a sort of sequential counterpart to the resampling-on-demand mechanism discussed previously. Such a mechanism would have the advantage of preventing the auditory system from accumulating data across unrelated events.

Timbre-Related Differences

Sequences with alternating tones that have the same fundamental frequency (i.e., same virtual pitch) but that are composed of differently ranked harmonics derived from that fundamental (i.e., different timbres) tend to segregate (Figure 10.6a; van Noorden, 1975). Differences in spectral content can thus cause stream segregation (Hartmann & Johnson, 1991; Iverson, 1995; McAdams & Bregman, 1979). It is therefore not pitch per se that creates the streaming. Spectral differences can compete even with pitch-based patterns in determining the melodies that are heard (Wessel, 1979). Note that in music both pitch register and instrument changes produce discontinuities in spectral content.

Although other timbre-related differences can also induce segregation, not all perceptual attributes gathered under the term *timbre* (discussed later) do so. Listeners are unable to identify interleaved melodies any better when different amplitude envelopes are present on the tones of the two melodies than when they are absent, and differences in auditory roughness are only weakly useful for melody segregation, and only for some listeners (Hartmann & Johnson, 1991). However, dynamic (temporal) cues can contribute to stream segregation. Iverson (1995) played sequences that alternated between different musical instruments at the same pitch and asked listeners for ratings of the degree of segregation.

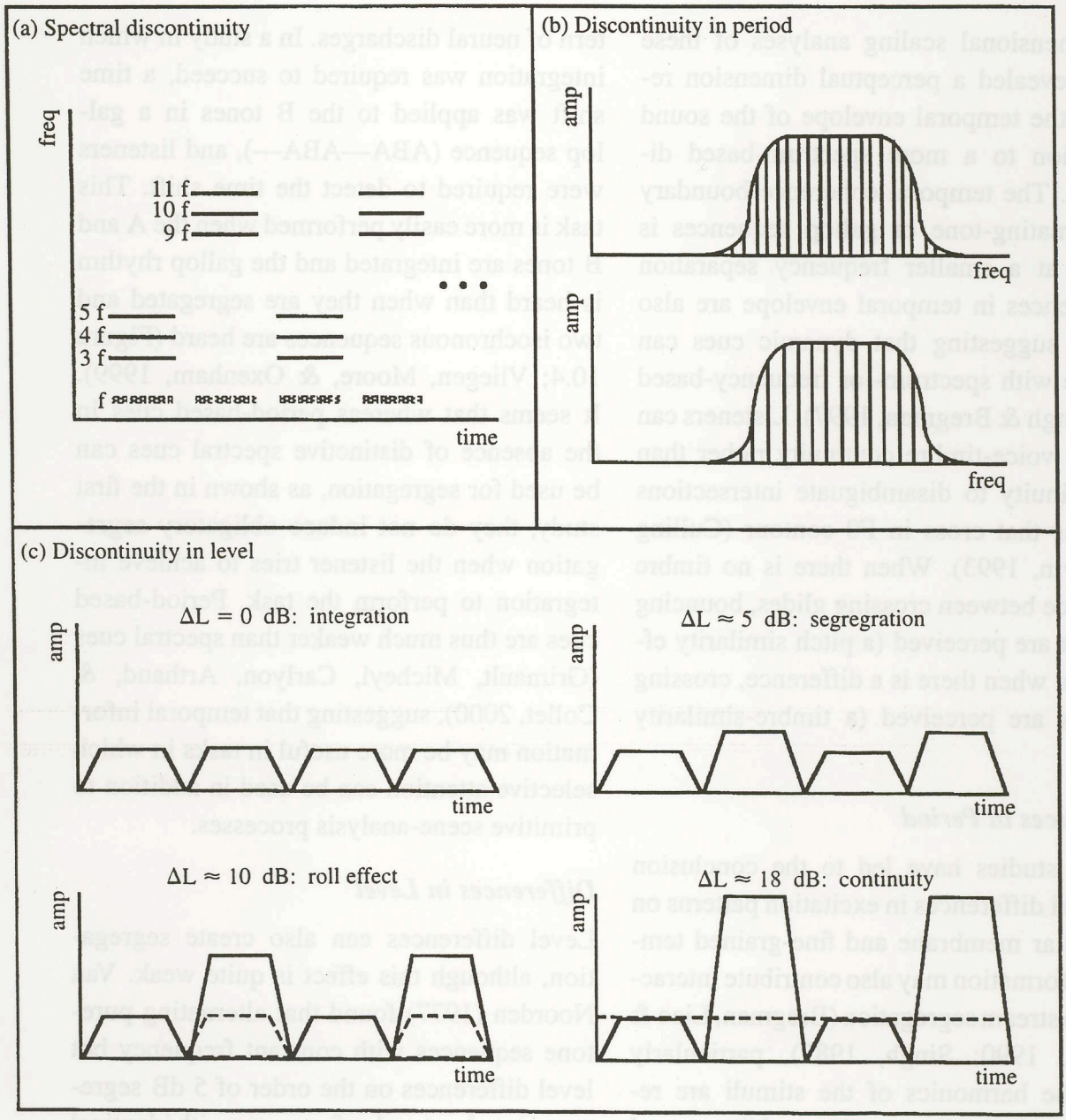


Figure 10.6 Stimuli used to test sequential grouping cues.
NOTE: a) Spectral discontinuity. An alternating sequence of tones with identical fundamental frequencies gives rise to a perception of constant pitch but differing timbres when the spectral content of the tones are different. This discontinuity in spectral content also creates a perceptual segregation into two streams. b) Discontinuity in period. A harmonic complex that is filtered in the high-frequency region gives rise to a uniform pattern of excitation on the basilar membrane, even if the period of the waveform (the fundamental frequency) is changed. The upper diagram has a lower F0 than has the lower diagram. There can be no cue of spectral discontinuity in a sequence of tones that alternates between these two sounds, yet segregation occurs on the basis of the difference in period, presumably carried by the temporal pattern of neural discharges in the auditory nerve. c) Discontinuity in level. A sequence of pure tones of constant frequency but alternating in level gives rise to several percepts depending on the relative levels. A single stream is heard if the levels are close. Two streams at half the tempo are heard if the levels differ by about 5 dB. A roll effect in which a louder half-tempo stream is accompanied by a softer full-tempo stream is obtained at certain rapid tempi when the levels differ by about 10 dB. Finally, at higher tempi and large differences in level, a louder pulsing stream is accompanied by a softer continuous tone.

Multidimensional scaling analyses of these ratings revealed a perceptual dimension related to the temporal envelope of the sound in addition to a more spectrum-based dimension. The temporal coherence boundary for alternating-tone or gallop sequences is situated at a smaller frequency separation if differences in temporal envelope are also present, suggesting that dynamic cues can combine with spectrum- or frequency-based cues (Singh & Bregman, 1997). Listeners can also use voice-timbre continuity rather than F0 continuity to disambiguate intersections in voices that cross in F0 contour (Culling & Darwin, 1993). When there is no timbre difference between crossing glides, bouncing contours are perceived (a pitch similarity effect), but when there is a difference, crossing contours are perceived (a timbre-similarity effect).

Differences in Period

Several studies have led to the conclusion that local differences in excitation patterns on the basilar membrane and fine-grained temporal information may also contribute interactively to stream segregation (Bregman, Liao & Levitan, 1990; Singh, 1987), particularly when the harmonics of the stimuli are resolved on the basilar membrane. Vliegen and Oxenham (1999) used an interleaved melody recognition task in which the tones of a target melody were interleaved with those of a distractor sequence. If segregation does not occur at least partially, recognition of the target is nearly impossible. In one condition, they applied a band-pass filter that let unresolved harmonics through (Figure 10.6b). Because the harmonics would not be resolved in the peripheral auditory system, there would be no cue based on the tonotopic representation that could be used to segregate the tones. However, segregation did occur, most likely on the basis of cues related to the periods of the waveforms carried in the temporal pattern of neural discharges. In a study in which integration was required to succeed, a time shift was applied to the B tones in a gallop sequence (ABA—ABA—), and listeners were required to detect the time shift. This task is more easily performed when the A and B tones are integrated and the gallop rhythm is heard than when they are segregated and two isochronous sequences are heard (Figure 10.4; Vliegen, Moore, & Oxenham, 1999). It seems that whereas period-based cues in the absence of distinctive spectral cues can be used for segregation, as shown in the first study, they do not induce obligatory segregation when the listener tries to achieve integration to perform the task. Period-based cues are thus much weaker than spectral cues (Grimault, Micheyl, Carlyon, Arthaud, & Collet, 2000), suggesting that temporal information may be more useful in tasks in which selective attention can be used in addition to primitive scene-analysis processes.

Differences in Level

Level differences can also create segregation, although this effect is quite weak. Van Noorden (1977) found that alternating pure-tone sequences with constant frequency but level differences on the order of 5 dB segregated into loud and soft streams with identical tempi (Figure 10.6c). Hartmann and Johnson (1991) also found a weak effect of level differences on interleaved melody recognition performance. When van Noorden increased the level difference and the sequence rate was relatively fast (greater than 13 tones/s), other perceptual effects began to emerge. For differences of around 10 dB, a percept of a louder stream at one tempo accompanied by a softer stream at twice that tempo was obtained. For even greater differences (>18 dB), a louder intermittent stream was accompanied by a continuous softer stream. In both cases, the more intense event would seem to be interpreted as being composed of two events of identical

spectral content. These percepts are examples of what Bregman (1990, chap. 3) has termed the *old-plus-new heuristic* (discussed later).

Differences in Spatial Location

Dichotically presented alternating-tone sequences do not tend to integrate into a trill percept even for very small frequency separations (van Noorden, 1975). Similarly, listeners can easily identify interleaved melodies presented to separate ears (Hartmann & Johnson, 1991). Ear of presentation is not, however, a sufficient cue for segregation. Deutsch (1975) presented simultaneously ascending and descending musical scales such that the notes alternated between ears; that is, the frequencies sent to a given ear hopped around (Figure 10.7). Listeners reported hearing an up-down pattern in one ear and a down-up pattern in the other, demonstrating an organization based on frequency proximity despite the alternating ear of presentation. An interaural time difference is slightly less effective in creating segregation than is dichotic presentation (Hartmann & Johnson, 1991).

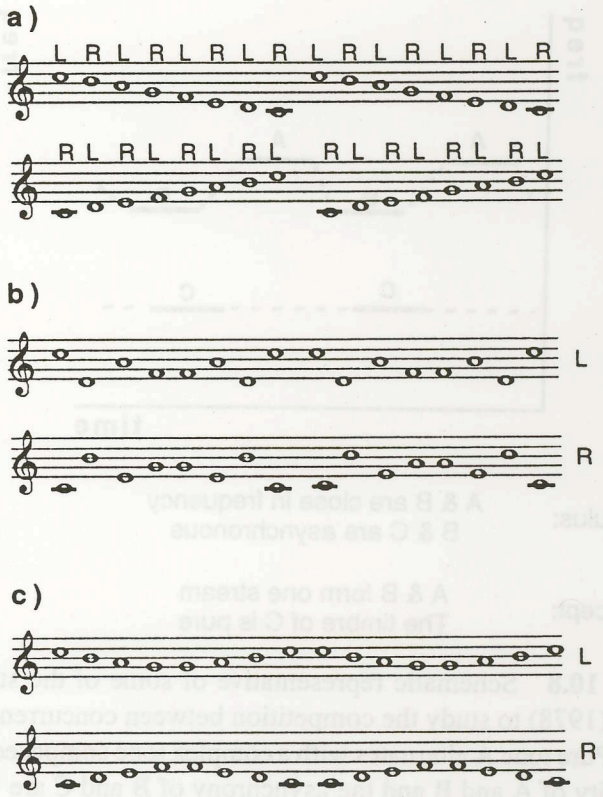


Figure 10.7 Melodic patterns of the kind used by Deutsch (1975).
NOTE: a) Crossing scales are played simultaneously over headphones. In each scale, the tones alternate between left (L) and right (R) earpieces. b) The patterns that would be heard if the listener focused on a given ear. c) The patterns reported by listeners.

Interactions between Concurrent and Sequential Grouping Processes

Concurrent and sequential organization processes are not independent. They can interact and even enter into competition, the final perceptual result depending on the relative organizational strength of each one. In the physical environment, there is a fairly good consensus among the different concurrent and sequential grouping cues. However, under laboratory conditions or as a result of compositional artifice in music, they can be made to conflict with one another. Bregman and Pinker (1978) developed a basic stimulus (Figure 10.8) for testing the situation in which a concurrent organization (fusion or segregation of B and C) and a sequential organization (integration or segregation of A and B) were in competition for the same component (B). When the sequential organization is reinforced by the frequency proximity of A and B and the concurrent organization is weakened by the asynchrony of B and C, A and B form a single stream, and C is perceived with a pure timbre. If the concurrent organization is reinforced by synchrony while the sequential organization is weakened by separating A and B in frequency, A forms a stream by itself, and B fuses with C to form a second stream with a richer timbre.

The Transparency of Auditory Events

In line with the belongingness principle of the Gestalt psychologists, Bregman (1990,

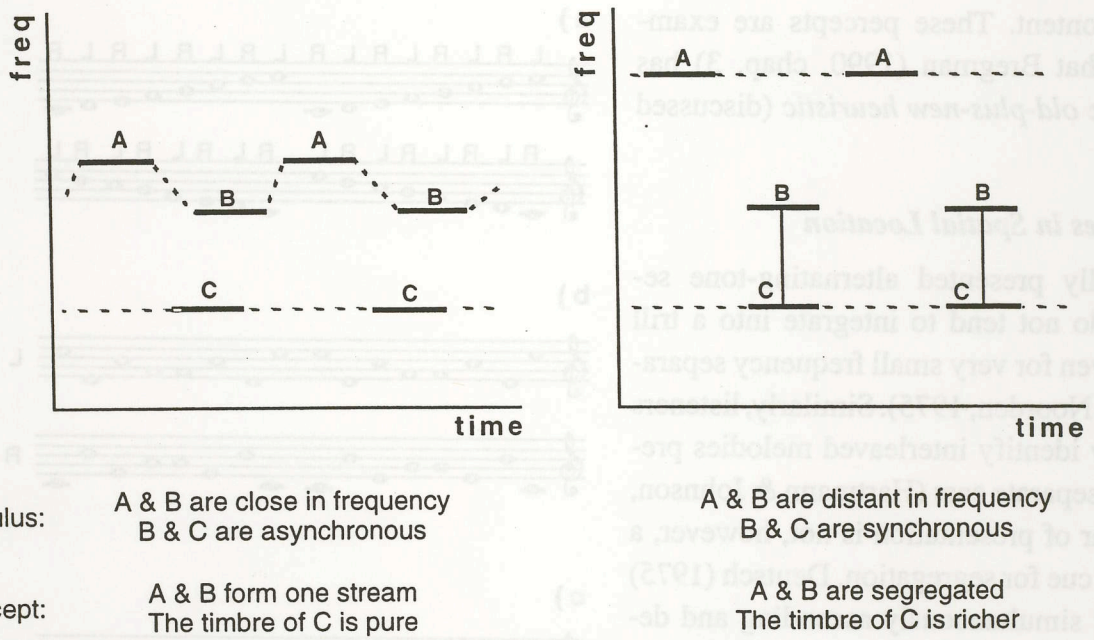


Figure 10.8 Schematic representative of some of the stimulus configurations used by Bregman and Pinker (1978) to study the competition between concurrent and sequential grouping processes.
NOTE: Pure tone A alternates with a complex tone composed of pure tones B and C. The relative frequency proximity of A and B and the asynchrony of B and C are varied. When A and B are close in frequency and B and C are sufficiently asynchronous (left diagram), an AB stream is formed, and C is perceived as having a pure timbre. When A and B are distant in frequency and B and C are synchronous (right diagram), A forms a stream by itself, and B and C fuse into a single event with a richer timbre.

chap. 7) has proposed the principle of exclusion allocation: A given bit of sensory information cannot belong to two separate perceptual entities simultaneously. In general, this principle seems to hold: Parts of a spectrum that do not start at the same time are exhaustively segregated into temporally overlapping events, and tones presented sequentially are exhaustively segregated into streams. There are, however, several examples of both speech and nonspeech sounds that appear to violate this principle.

Duplex Perception of Speech

If the formant transition specifying a stop consonant such as /b/ (see Chap. 12, this volume) is excised from a consonant-vowel syllable and is presented by itself, a brief chirp sound is heard. The remaining base part of the original sound without the formant transition gives a /da/ sound. If the base and transition are remixed in the same ear, a /ba/ sound results. However, when the formant transition and base sounds are presented to opposite ears, listeners hear both a /ba/ sound in the ear with the base (integration of information from the two ears to form the syllable) and a simultaneous chirp in the other ear (Cutting, 1976; Rand, 1974). The formant transition thus contributes both to the chirp and to the /ba/—hence the term *duplex*. It is not likely that this phenomenon can be explained by presuming that speech processing is unconstrained by primitive scene analysis mechanisms (Darwin, 1991).

To account for this apparent paradox, Bregman (1990, chap. 7) proposes a two-component theory that distinguishes sensory evidence from perceptual descriptions. One component involves primitive scene analysis processes that assign links of variable strength among parts of the sensory evidence. The link

strength depends both on the sensory evidence (e.g., the amount of asynchrony or mistuning for concurrent grouping, or the degree of temporal proximity and spectral dissimilarity for sequential grouping) and on competition among the cues. The links are evidence for belongingness but do not necessarily create disjunct sets of sensory information; that is, they do not provide an all-or-none partitioning. A second component then builds descriptions from the sensory evidence that *are* exhaustive partitionings for a given perceptual situation. Learned schemas can intervene in this process, making certain descriptions more likely than others, perhaps as a function of their frequency of occurrence in the environment. It is at this latter level that evidence can be interpreted as belonging to more than one event in the global description. But why should one allow for this possibility in auditory processing? The reason is that acoustic events do not occlude other events in the way that most (but not all) objects occlude the light reflected from other objects that are farther from the viewer. The acoustic signal arriving at the ears is the weighted sum of the waveforms radiating from different vibrating objects, where the weighting is a function of distance and of various transformations of the original waveform due to the properties of the environment (reflections, absorption, etc.). It is thus possible that the frequency content of one event coincides partially with that of another event. To analyze the properties of the events correctly, the auditory system must be able to take into account this property of sound, which, by analogy with vision, Bregman has termed *transparency.*

This theory presumes (a) that primitive scene analysis is performed on the sensory input prior to the operation of more complex pattern-recognition processes, (b) that the complex processes that build perceptual descriptions are packaged in schemas embodying various regularities in the sensory evidence, (c) that higher-level schemas can build from regularities detected in the descriptions built by lower-level schemas, (d) that the descriptions are constrained by criteria of consistency and noncontradiction, and (e) that when schemas (including speech schemas) make use of the information that they need from a mixture, they do not remove it from the array of information that other description-building processes can use (which may give rise to duplex-type phenomena). Although many aspects of this theory have yet to be tested empirically, some evidence is consistent with it, such as the fact that duplex perception of speech can be influenced by primitive scene-analysis processes. For example, sequential organization of the chirp component can remove it from concurrent grouping with the base stimulus, suggesting that duplex perception occurs in the presence of conflicting cues for the segregation and the integration of the isolated transition with the base (Ciocca & Bregman, 1989).

Auditory Continuity

A related problem concerns the partitioning on the basis of the surrounding context of sensory information present within overlapping sets of auditory channels. The *auditory continuity phenomenon,* also called auditory induction, is involved in perceptual restoration of missing or masked sounds in speech and music interrupted by a brief louder sound or by an intermittent sequence of brief, loud sound bursts (for reviews, see Bregman, 1990, chap. 3; Warren, 1999, chap. 6). If the waveform of a speech stream is edited such that chunks of it are removed and other chunks are left, the speech is extremely difficult to understand (Figure 10.9a). If the silent periods are replaced with noise that is loud enough to have masked the missing speech, were it present, and whose spectrum includes that of the original speech, listeners claim to hear continuous speech (Warren, Obusek, &

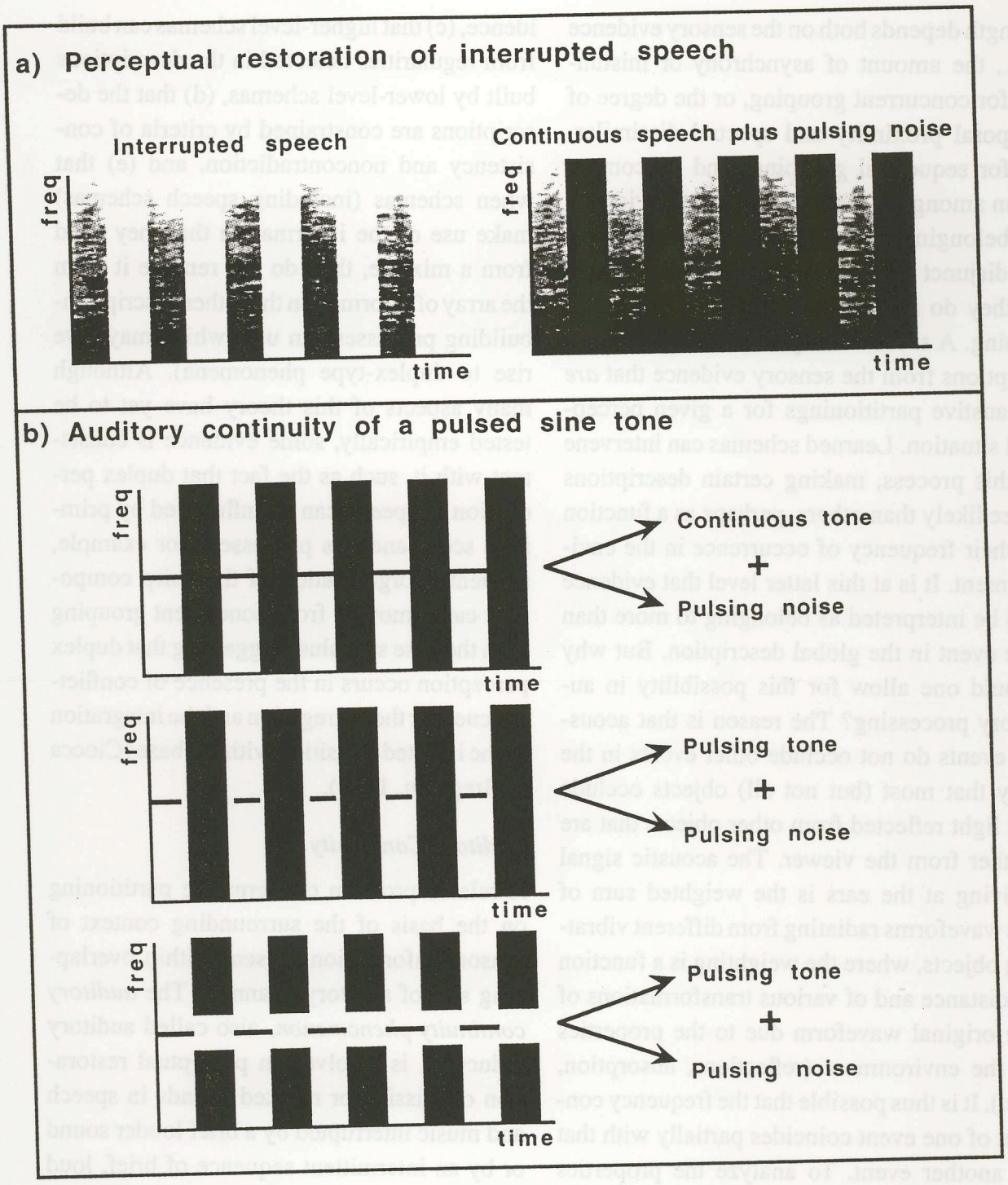


Figure 10.9 Stimuli used to test the auditory continuity phenomenon.
NOTE: a) Speech that is interrupted by silences is heard as such and is difficult to understand. If the silences are filled with a noise of bandwidth and level sufficient to have masked the absent speech signal, a pulsing noise is heard accompanied by an apparently continuous speech stream. b) Auditory continuity can be demonstrated also with a pulsed sine tone. When the silent gaps are filled with noise, a continuous tone is heard along with the pulsing noise. However, if small silent gaps of several milliseconds separate the tone and noise bursts, indicating to the auditory system that the tone actually ceased, then no continuity is obtained. Furthermore, the continuity effect does not occur if the noise does not have any energy in the frequency region of the tone.

Ackroff, 1972). Speech intelligibility can even improve if contextual information that facilitates identification of key words is present (Warren, Hainsworth, Brubaker, Bashford, & Healy, 1997).

Similar effects of continuity can be demonstrated with nonspeech stimuli, such as a sine tone interrupted by noise (Figure 10.9b) or by a higher-level sine-tone of similar frequency. An intermittent sequence superimposed on a continuous sound is heard, as if the more intense event were being partitioned into two entities, one that was the continuation of the lower-level sound preceding and following the higher-level event and another that was a sound burst. This effect works with pure tones, which indicates that it can be a completely within-channel operation. However, if any evidence exists that the lower-level sound stopped (such as short, silent gaps between the sounds), two series of intermittent sounds are heard. Furthermore, the spectrum of the interrupting sound must cover that of the interrupted sound for the phenomenon to occur; that is, the auditory system must have evidence that the interrupting sound could have masked the softer sound (Figure 10.9).

The partitioning mechanism has been conceived by Bregman (1990) in terms of an "old-plus-new" heuristic. The auditory system performs a subtraction operation on the high-level sound. A portion of the energy equivalent to that in the lower-level sound is assigned to the continuous stream, and the rest is left to form the intermittent stream. Indeed, the perceived levels of the continuous sound and intermittent sequence depend on the relative level change and are consistent with a mechanism that partitions the energy (Warren, Bashford, Healy, & Brubaker, 1994). However, the perceived levels are not consistent with a subtraction performed either in units of loudness (sones) or in terms of physical pressure or power (McAdams, Botte, & Drake, 1998). Furthermore, changes occur in the timbre of the high-level sounds in the presence of the low-level sounds compared to when these are absent (Warren et al., 1994). The relative durations of high- and low-level sounds are crucial to the phenomenon. The continuity effect is much stronger when the interrupting event is short compared to the uninterrupted portion. The perceived loudness is also a function of the relative levels of high and low portions, their relative durations, and the perceptual stream to which attention is being directed (Drake & McAdams, 1999). Once again, this continuity phenomenon demonstrates the existence of a heuristic for partitioning acoustic mixtures (if there is sufficient sensory evidence that a mixture indeed exists). It provides the listener with the ability to deal efficiently and veridically with the stimulus complexity resulting from the transparency of auditory events.

Schema-Based Organization

Much mention has been made of the possibility that auditory stream formation is affected by conscious, controlled processes, such as searching for a given source or event in the auditory scene. Bregman (1990) proposed a component that he termed *schema-based scene analysis* in which specific information is selected on the basis of attentional focus and previously acquired knowledge, resulting in the popout of previously activated events or the extraction of sought-after events. Along these lines, van Noorden's (1975) ambiguous region is an example in which what is heard depends in part on what one tries to hear. Further, in his interleaved melody recognition experiments, Dowling (1973a) observed that a verbal priming of an interleaved melody increased identification performance.

Other top-down effects in scene analysis include the role of pattern context (good continuation in Gestalt terms) and the use of previous knowledge to select target information

from the scene. For example, a competition between good continuation and frequency proximity demonstrates that melodic pattern can affect the degree of streaming (Heise & Miller, 1951). Frequency proximity alone cannot explain these results.

Bey (1999; Bey & McAdams, in press) used an interleaved melody recognition paradigm to study the role of schema-based organization. In one interval an interleaved mixture of target melody and distractor sequence was presented, and in another interval an isolated comparison melody was presented. Previous presentation of the isolated melody gave consistently better performance than when the mixture sequence was presented before the comparison melody. Furthermore, if the comparison melody was transposed by 12, 13, or 14 semitones—requiring the listener to use a pitch-interval-based representation instead of an absolute-pitch representation to perform the task—performance was similar to when the isolated comparison melody was presented after the mixture. These results suggest that in this task an absolute-pitch representation constitutes the "knowledge" used to extract the melody. However, performance varied as a function of the frequency separation of the target melody and distractor sequence, so performance depended on both sensory-based organizational constraints and schema-based information selection.

TIMBRE PERCEPTION

Early work on timbre perception paved the way to the exploration of sound source perception. The word *timbre* gathers together a number of auditory attributes that until recently have been defined only by what they are not: Timbre is what distinguishes two sounds coming from the same position in space and having the same pitch, loudness, and subjective duration. Thus, an oboe and a trumpet playing the same note, for example, would be distinguished by their timbres. This definition indeed leaves everything to be defined. The perceptual qualities grouped under this term are multiple and depend on several acoustic properties (for reviews, see Hajda, Kendall, Carterette, & Harshberger, 1997; McAdams, 1993; Risset & Wessel, 1999). In this section, we examine spectral profile analysis, the perception of auditory roughness, and the multidimensional approach to timbre perception.

Spectral Profile Analysis

The sounds that a listener encounters in the environment have quite diverse spectral properties. Those produced by resonating structures of vibrating objects have more energy near the natural frequencies of vibration of the object (string, plate, air cavity, etc.) than at more distant frequencies. In a frequency spectrum in which amplitude is plotted as a function of frequency, one would see peaks in some frequency regions and dips in others. The global form of this spectrum is called the spectral envelope. The extraction of the spectral envelope by the auditory system would thus be the basis for the evaluation of constant resonance structure despite varying fundamental frequency (Plomp & Steeneken, 1971; Slawson, 1968) and may possibly contribute to source recognition. This extraction is surely strongly involved in vowel perception, the quality of which is related to the position in the spectrum of resonance regions called *formants* (see Chap. 12, this volume). Spiegel and Green (1982) presented listeners with complex sounds in which the amplitudes were equal on all components except one. The level of this component was increased to create a bump in the spectral envelope. They showed that a listener is able to discriminate these spectral envelopes despite random variations

in overall intensity, suggesting that it is truly the profiles that are being compared and not just an absolute change in intensity in a given auditory channel. This analysis is all the easier if the number of components in the spectrum is large and the range of the spectrum is wide (Green, Mason, & Kidd, 1984). Further, it is unaffected by the phase relations among the frequency components composing the sounds (Green & Mason, 1985). The mechanism that detects a change in spectral envelope most likely proceeds by estimating the level in each auditory channel and then by combining this information in an optimal way across channels (for a review, see Green, 1988).

Auditory Roughness

Auditory roughness is the sensory component of musical dissonance (see Chap. 11, this volume), but is present also in many environmental sounds (unhappy newborn babies are pretty good at progressively increasing the roughness component in their vocalizations, the more the desired attention is delayed). In the laboratory roughness can be produced with two pure tones separated in frequency by less than a critical band (the range of frequencies that influences the output of a single auditory nerve fiber tuned to a particular characteristic frequency). They interact within an auditory channel producing fluctuations in the amplitude envelope at a rate equal to the difference between their frequencies. When the fluctuation rate is less than about 20 Hz to 30 Hz, auditory beats are heard (cf. Plomp, 1976, chap. 3). As the rate increases, the perception becomes one of auditory roughness, peaking at around 70 Hz (depending on the center frequency) and then decreasing thereafter, becoming smooth again when the components are completely resolved into separate auditory channels (cf. Plomp, 1976, chap. 4). The temporal coding of such a range of modulations has been demonstrated in primary auditory cortex in awake monkeys (Fishman, Reser, Arezzo, & Steinschneider, 2000). For two simultaneous complex harmonic sounds, deviations from simple ratios between fundamental frequencies create sensations of beats and roughness that correlate very strongly with judgments of musical dissonance (Kameoka & Kuriyagawa, 1969; Plomp & Levelt, 1965). Musical harmony thus has a clear sensory basis (Helmholtz, 1885; Plomp, 1976), although contextual factors such as auditory grouping (Pressnitzer, McAdams, Winsberg, & Fineberg, 2000) and acculturation (Carterette & Kendall, 1999) may intervene.

One sensory cue contributing to roughness perception is the depth of modulation in the signal envelope after auditory filtering (Aures, 1985; Daniel & Weber, 1997; Terhardt, 1974), which can vary greatly for sounds having the same power spectrum but differing phase relations among the components. The importance of such phase relations has been demonstrated in signals in which only one component out of three was changed in phase in order to leave the waveform envelope unmodified (Pressnitzer & McAdams, 1999b). Marked differences in roughness perception were found. The modulation envelope shape, after auditory filtering, thus contributes also to roughness, but as a factor secondary to modulation depth. In addition, the coherence of amplitude envelopes across auditory filters affects roughness: In-phase envelopes create greater roughness than do out-of-phase envelopes (Daniel & Weber, 1997; Pressnitzer & McAdams, 1999a).

The Multidimensional Approach to Timbre

One important goal in timbre research has been to determine the relevant perceptual dimensions of timbre (Plomp, 1970; Wessel,

1979). A systematic approach was made possible by the development of multidimensional scaling (MDS) analyses, which are used as exploratory data analysis techniques (McAdams, Winsberg, Donnadieu, De Soete & Krimphoff, 1995). These consist in presenting pairs from a set of sounds to listeners and asking them to rate the degree of similarity or dissimilarity between them. The (dis)similarity ratings are translated into distances by a computer algorithm that, according to a mathematical distance model, projects the set of sound objects into a multidimensional space. Similar objects are close to one another, and dissimilar ones are far apart in the space.

A structure in three dimensions representing the sounds of 16 musical instruments of the string and wind families was interpreted qualitatively by Grey (1977). The first dimension (called brightness; see Figure 10.10a) appeared to be related to the spectral envelope. The sounds having the most energy in harmonics of high rank are at one end of the dimension (oboe, O1), and those having their energy essentially confined to low-ranking harmonics are at the other end (French horn, FH). The second dimension (called spectral flux) was related to the degree of synchrony in the attacks of the harmonics as well as their degree of incoherent fluctuation in amplitude over the duration of the sound event. The flute (FL) had a great deal of spectral flux in Grey's set, whereas the clarinet's (C1) spectrum varied little over time. The position on the third dimension (called attack quality) varied with the quantity of inharmonic energy present at the beginning of the sound, which are often called the attack transients. Bowed strings (S1) can have a biting attack due to these transients, which is less the case for the brass instruments (e.g., trumpet, TP). To test the psychological reality of the brightness dimension, Grey and Gordon (1978) resynthesized pairs of sounds, exchanging their spectral envelopes (the patterns of bumps and dips in the frequency spectrum). This modification created a change in position along the brightness dimension, with a few shifts along other axes that can be fairly well predicted

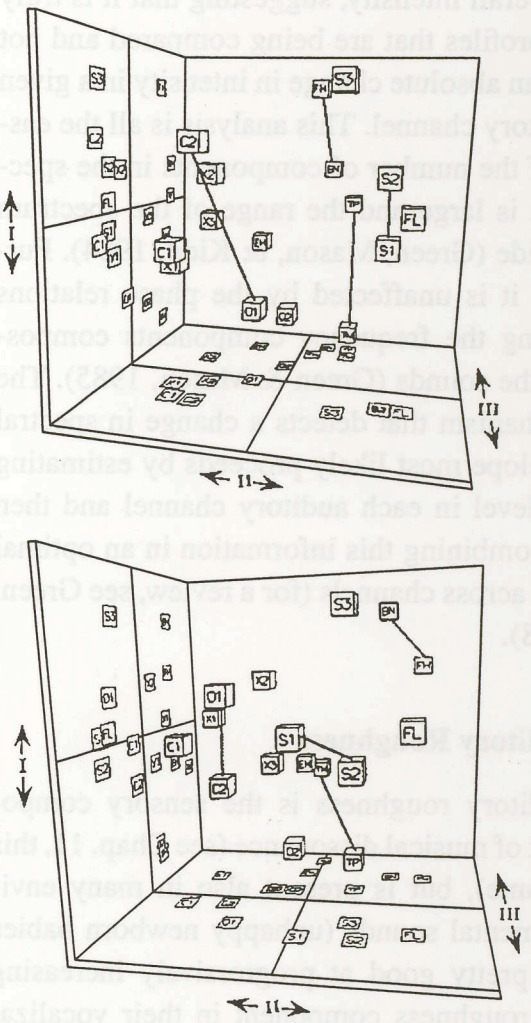


Figure 10.10 Three-dimensional timbre spaces found by a) Grey (1977) and b) Grey & Gordon (1978) from multidimensional scaling analyses of similarity judgments.
NOTE: Pairs of musical instrument sounds from the original Grey (1977) study were modified by exchanging their spectral envelopes in Grey & Gordon (1978) to test the hypothesis that dimension I was related to spectral envelope distribution. Note that the pairs switch orders along dimension I, with small modifications along other dimensions in some cases.
SOURCE: Adapted from Grey & Gordon (1978, Figures 2 and 3) with permission. Copyright © 1978 by the Acoustical Society of America.

by the side-effects of the spectral envelope change on other acoustic parameters (Figure 10.10b).

This seminal work has been extended to (a) synthesized sounds representing orchestral instruments or hybrids among them, including more percussive sounds produced by plucking or striking strings or bars (Krumhansl, 1989; McAdams et al., 1995); (b) recorded sounds, including percussion instruments such as drums and gongs in addition to the standard sustained vibration instruments such as winds and bowed strings (Iverson & Krumhansl, 1993; Lakatos, 2000); and (c) car sounds (Susini, McAdams, & Winsberg, 1999). In some cases, new acoustical properties corresponding to the perceptual dimensions still need to be developed to explain these new timbre spaces. For example, attack quality is strongly correlated with the rise time in the amplitude envelope when impact-type sounds are included (Krimphoff, McAdams, & Winsberg, 1994). More advanced MDS procedures allow for individual items to be modeled not only in terms of dimensions shared with all the other items but also as possessing perceptual features that are unique and specific to them (Winsberg & Carroll, 1988). They also provide for the estimation of latent classes of listeners that accord differing weights to the perceptual dimensions (Winsberg & De Soete, 1993) and for the establishment of functional relations between the perceptual dimensions and the relevant acoustic parameters using MDS analyses constrained by stimulus properties (Winsberg & De Soete, 1997). All these advances in data analysis have been applied to musical timbre perception (Krumhansl, 1989; McAdams & Winsberg, 2000; McAdams et al., 1995).

Timbre Interval Perception

On the basis of such a multidimensional model of timbre perception, Ehresman and Wessel (1978) proposed a definition of a timbre interval, by analogy with a pitch interval in musical scales. According to their conception, a timbre interval is an oriented vector in the perceptual space. The equivalent to a transposition of a pitch interval (changing the absolute pitches while maintaining the pitch interval) would thus be a translation of the vector to a different part of the space, maintaining its length and orientation. Both musician and nonmusician listeners are sensitive to such abstract relations among timbres. However, when intervals are formed from complex musical instrument sounds, the specific features possessed by certain timbres often distort them (McAdams & Cunibile, 1992).

SOUND SOURCE PERCEPTION

Human listeners have a remarkable ability to understand quickly and efficiently the current state of the world around them based on the behavior of sound-producing objects, even when these sources are not within their field of vision (McAdams, 1993). We perceive the relative size and form of objects, properties of the materials that compose them, as well as the nature of the actions that had set them into vibration. On the basis of such perception and recognition processes, listening can contribute significantly to the appropriate behaviors that we need to adopt with respect to the environment. To begin to understand these processes more fully, researchers have studied the perception of object properties such as their geometry and material composition as well as the acoustic cues that allow recognition of sound sources. Although pitch can communicate information concerning certain source properties, timbre seems in many cases to be the primary vehicle for sound source and event recognition.

Perception of Source Shape

Listeners are able to distinguish sources on the basis of the geometry of air cavities and of solid objects. Changes in the positions of the two hands when clapping generate differences in the geometry of the air cavity between them that is excited by their impact and can be discriminated as such (Repp, 1987). Rectangular bars of a given material and constant length, but varying in width and thickness, have mechanical properties that give modes of vibration with frequencies that depend on these geometrical properties. When asked to match the order of two sounds produced by bars of different geometries to a visual representation of the cross-sectional geometry, listeners succeed as a function of the difference in ratio between width and thickness, for both metal and wood bars (Lakatos, McAdams, & Caussé, 1997). There are two potential sources of acoustic information in these bars: the ratio of the frequencies of transverse bending modes related to width and thickness and the frequencies of torsional modes that depend on the width-thickness ratio. Both kinds of information are more reliably present in isotropic metal bars than in anisotropic wood bars, and indeed listeners' judgments are more coherent and reliable in the former case.

The length of dowels and dimensions of plates can also be judged in relative fashion by listeners. Carello, Anderson, and Kunkler-Peck (1998) demonstrated that listeners can reproduce proportionally (but not absolutely) the length of (unseen) dowels that are dropped on a floor. They relate this ability to the inertial properties of the dowel, which may give rise to both timbral and rhythmic information (the "color" of the sound and the rapidity of its clattering), although the link between perception and acoustic cues was not established. Kunkler-Peck and Turvey (2000) presented the sounds of (unseen) rectangular and square plates to listeners and asked them to reproduce the vertical and horizontal dimensions for objects formed of metal, wood, and Plexiglas. Again listeners reproduced the proportional, but not absolute, dimensions. They further showed that listeners could identify the shape of plates across materials when asked to choose from among rectangles, triangles, and circles.

Perception of Source Material

There are several mechanical properties of materials that give rise to acoustic cues: density, elasticity, damping properties, and so on. With the advent of physical modeling techniques in which the vibratory processes extended in space and time are simulated with computers (Chaigne & Doutaut, 1997; Lambourg, Chaigne, & Matignon, 2001), fine-grained control of complex vibratory systems becomes available for perceptual experimentation, and a true psychomechanics becomes possible. Roussarie, McAdams, and Chaigne (1998) used a model for bars with constant cross-sectional geometry but variable material density and internal damping factors. MDS analyses on dissimilarity ratings revealed that listeners are sensitive to both mechanical properties, which are carried by pitch information and by a combination of amplitude envelope decay and spectral centroid, respectively, in the acoustic signal. Roussarie (1999) has further shown that listeners are sensitive to elasticity, viscoelastic damping, and thermoelastic damping in thin plates that are struck at constant force. He used a series of simulated plates that were hybrids between an aluminum plate and a glass plate. MDS analyses of dissimilarity ratings revealed monotonic relations between the perceptual and mechanical parameters. However, when listeners were required to identify the plate as either aluminum or glass, they used only the acoustic information related to damping factors, indicating an ability to select the most

appropriate from among several sources of acoustic information, according to the perceptual task that must be performed.

Recognition and Identification of Sources and Actions

Studies of the identification of musical instruments have revealed the properties of the acoustic structure of a complex sound event to which listeners are sensitive (for a review, see McAdams, 1993). For example, if the attack transients at the beginning of a sound are removed, a listener's ability to identify instruments that have characteristic transients is reduced (Saldanha & Corso, 1964). Other studies have demonstrated the importance of spectral envelope and temporal patterns of change for identification of modified instrument tones (Strong & Clark, 1967a, 1967b).

A large class of sounds that has been relatively little studied until recently—ostensibly because of difficulties in analyzing and controlling them precisely under experimental conditions—consists of the complex acoustic events of our everyday environment. The breaking of glass, porcelain, or clay objects; the bouncing of wooden, plastic, or metal objects; the crushing of ice or snow underfoot; the scraping of objects against one another—all carry acoustic information both about the nature of the objects involved, about the way they are interacting, and even about changes in their geometric structure (a broken plate, becomes several smaller objects that vibrate independently).

Warren and Verbrugge (1984) asked listeners to classify a sound event as a breaking or bouncing glass object. The events were created by letting jars fall from different heights or from various acoustic manipulations of the recordings. Bouncing events were specified by simple sets of resonances with the same accelerating rhythmic pattern as the object came to rest. Breaking events were specified by a broad-spectrum burst followed by a multiplicity of different resonating objects with uncorrelated rhythmic patterns. Thus, both the resonance cues (derived from a large unitary object or multiple smaller objects) and the rhythmic cues (unitary or multiple accelerating patterns) were possible sources of identification. To test these cues, the authors used synthetically reconstructed events in which the rhythmic patterns and spectral content (the various resonances present) were controlled. Most of the variance in identification performance was accounted for by the rhythmic behavior.

Cabe and Pittenger (2000) studied the listeners' sensitivities to the acoustic information in a given action situation: accurately filling a vessel. When water is poured into a cylindrical vessel and the rate of (silent) outflow and turbulent (splashy) inflow are controlled, listeners can identify whether the vessel is filling, draining, or remaining at a constant level. Their perception ostensibly depends on the fundamental resonance frequency of the unfilled portion of the vessel. Participants were asked to fill a vessel themselves while seeing, holding, and hearing the water pouring, or while only hearing the water pouring. They were fairly accurate at judging the moment at which the brim level was attained, although they tended to underestimate the brim level under auditory-only conditions. Consideration of the time course of available acoustic information suggests that prospective behavior (anticipating when the full-to-the-brim level will be reached) can be based on acoustic information related to changes in fundamental resonance frequency.

Work in the realm of auditory kinetics concerns the listeners' abilities to estimate the kinetic properties of mechanical events (mass, dropping height, energy). Guski (2000) studied the acoustic cues that specify such kinetic properties in events in which collisions between objects occur. He found that listeners'

estimates of the striking force of a ball falling on a drumhead are linearly related to physical work (the energy exchange between the drum and the head at impact). They were less successful in judging the mass of the ball and could not reliably judge the dropping height. The acoustic cues that seem to contribute to these judgments include the peak level (a loudness-base cue) and the rhythm of the bouncing pattern of the ball on the drumhead. The former cue strongly affects judgments of force, which become unreliable if sound events are equalized in peak level. The rhythm cue depends on the energy of the ball and is thus affected by the height and the mass (hence, perhaps, the lower reliability of direct judgments of these parameters). The time interval between the first two bounces explains much of the variance in judgments of force and is strongly correlated with the amount of physical work. Considerations of the timbre-related spectral and temporal characteristics of individual bounces were not examined.

This nascent area of research provides evidence for human listeners' remarkable sensitivity to the forms and material compositions of the objects of their environment purely on the basis of the sounds they produce when set into vibration. The few results already available pave the way for theoretical developments concerning the nature of auditory source and event recognition, and may indeed reveal aspects of this process that are specific to the auditory modality.

TEMPORAL PATTERN PROCESSING IN HEARING

As described in the auditory scene analysis section, the acoustic mixture is perceptually organized into sound objects and streams. In this way, sound events that originate from a single source are perceptually grouped together and are not confused with events coming from other sources. Once auditory events and streams have been perceptually created, it is necessary to establish the relationship between successive events within a stream. We enter the realm of sequence perception, in which each event takes its existence from its relation with these surrounding events rather than from its own specific characteristics. An essential function of the perceptual system is thus to situate each event in time in relation to other events occurring within a particular time span. How do listeners follow the temporal unfolding of events in time? How do they select important information? How are they able to predict "what" and "when" something will occur in the future? The way in which the auditory system identifies the characteristics of each event (the "what") has been described in the section on sound source perception. We now discover the type of temporal information coding involved (the "when").

The Limits of Sequence Perception

Temporal processes occur over a wide range of rates (see Figure 10.11). In this section we focus on those that are relevant to sequence perception and temporal organization. Sound events are perceived as isolated if they are separated from surrounding events by about 1.5 s. This constitutes the upper limit of sequence perception and probably corresponds to the limits of echoic (sensory) memory (Fraisse, 1963). At the other extreme, if the onsets of successive tones are very close in time (less than about 100 ms), a single event is perceived, and the lower limit of sequence perception is surpassed. The zone of sequence perception falls between these two extremes (100–1500 ms interonset interval, or IOI). This range can be subdivided into three separate zones depending on sequence rate or tempo (ten Hoopen et al., 1994). It has been suggested that different

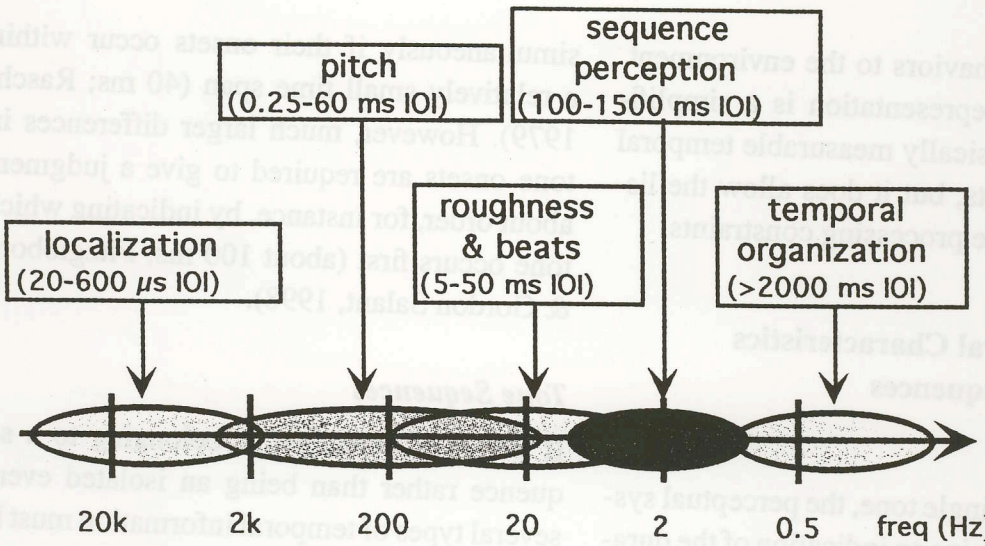


Figure 10.11 The temporal continuum.
NOTE: Event rate greatly influences the perceived nature of event sequences. At extremely fast rates, event attributes such as spatial position, pitch, and timbre are perceived, and at intermediate rates sequence attributes are perceived. Higher-level cognitive processes allow listeners to organize event structures over longer time spans. Event rate can be described in terms of the number of events per second (Hz) or the duration between the onset of successive events (interonset interval, or IOI).

processes are involved at different sequence rates: an intermediate zone (300–800 ms IOI) for which sequence processing is optimum and within which Weber's law applies; a fast zone (100–300 ms IOI) with a fixed time constant (Weber's law does not apply); and a slow zone (800–1500 ms IOI), also with a fixed time constant.

The Problem of Temporal Coding

Psychologists investigating temporal processing have to confront a tricky problem: the absence of an observable sensory organ for coding time (unlike the ear for hearing and the eye for vision). A detailed discussion of the possible existence of an internal clock or a psychological time base is beyond the scope of this chapter (see Block, 1990; Church, 1984; Killeen & Weisse, 1987). For our present concerns, it suffices to say that there is no single, identifiable part of the brain devoted to time perception. Numerous models have been proposed to explain temporal behavior, either by the ticks of a clock (Creelman, 1962; Divenyi & Danner, 1977; Getty, 1975; Kristofferson, 1980; Luce, 1972; Sorkin, Boggs, & Brady, 1982; Treisman, 1963) or by concepts of information processing independent of a clock (Allan, 1992; Block, 1990; Michon, 1975; Ornstein, 1969). Not surprisingly, each model explains best the data for which it was developed. Thus, models without clocks best explain behavior that requires only temporal order processing, whereas models with clocks best explain behavior requiring relative or absolute duration coding.

For our present interests, it suffices to consider that our perceptual system provides an indication of the duration of events in relative terms (same, longer, or shorter) rather than absolute terms (the first tone lasts x beats, the second x beats; or the first tone occurred at 12:00:00, the second at 12:00:01). In the next sections we discover how information concerning these relative durations allows individuals to create elaborate and reliable temporal representations that are sufficient for

adapting their behaviors to the environment. Of course, this representation is a simplification of the physically measurable temporal structure of events, but it does allow the listener to overcome processing constraints.

Coding Temporal Characteristics of Tones and Sequences

Single Tones

In the case of a single tone, the perceptual system probably retains an indication of the duration of the sound (*a* in Figure 10.12). However, the onset is usually more precisely coded than is the offset, due to the usually more abrupt nature of tone onsets (Schulze, 1989; P. G. Vos, Mates, & van Kruysbergen, 1995). It is less likely that there remains an absolute coding of the precise moment in time at which the tone occurred (*b* in Figure 10.12). Rather, there is probably an indication of the time of occurrence of the tone relative to other events. Listeners are able to indicate quite precisely whether two tones are perceived as occurring simultaneously if their onsets occur within a relatively small time span (40 ms; Rasch, 1979). However, much larger differences in tone onsets are required to give a judgment about order, for instance, by indicating which tone occurs first (about 100 ms; Fitzgibbons & Gordon Salant, 1998).

Tone Sequences

If a tone is perceived as belonging to a sequence rather than being an isolated event, several types of temporal information must be coded. First, the temporal distance between successive events must be coded. A possible solution would be the coding of the duration of the interval between the offset of one tone and the onset of the following tone (*c* in Figure 10.12). However, numerous studies (Schulze, 1989; P. G. Vos et al., 1995) indicate that this parameter is not the most perceptually salient. Rather, the most dominant information concerns the duration between successive onsets (IOIs; *d* in Figure 10.12). For instance, the capacity to detect slight changes in tempo

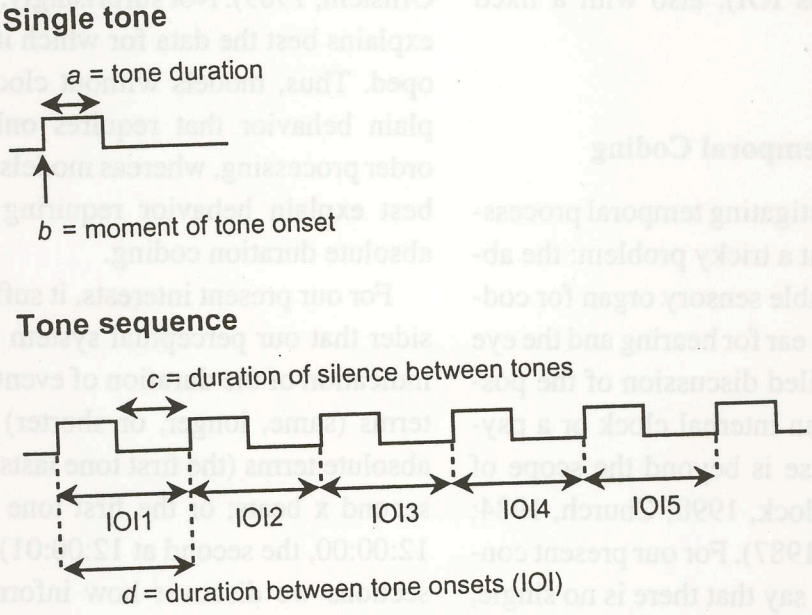


Figure 10.12 The physical parameters of isolated tones and tones within a sequence are not all of equal perceptual importance.
NOTE: The moment of tone onset (b) and the duration between successive tone onsets (d) appear to be the most perceptually salient.

between two sequences is unaffected by either tone duration (*a*) or off duration (*c*), but rather by the duration between the onsets of successive tones (*d*; J. Vos & Rasch, 1981; P. G. Vos et al., 1995; P. G. Vos, 1977). More precisely, it is not the physical onset of the tone, but rather the perceptual center (P-center) of the tone that determines the IOI, which in turn is influenced by tone duration, off duration, and the shape of the tone attack (P. G. Vos et al., 1995).

In the case of sequences of several events, it could be supposed that the temporal coding may involve the coding of the duration between the onset of each successive tone in the sequence. For instance, in the case of the sequence in Figure 10.12, this would involve the coding of IOI1, IOI2, IOI3, IOI4, and IOI5. This sort of coding is probably possible if the sequence does not contain more than five or six events, does not last longer than several seconds, and does not display a clearly-defined temporal structure (i.e., irregular sequences; Povel, 1981). However, this type of processing appears to be the exception rather than the rule.

Basic Temporal Organization Principles in Sequence Processing

Multiple-Look Model

Is the processing of a sequence of events the same as the sum of the processing of each individual event? The multiple-look model (Drake & Botte, 1993; Schulze, 1978; P. G. Vos, van Assen, & Franek, 1997) suggests that this is not the case. Listeners were presented with two isochronous sequences varying slightly in tempo (mean IOI). The sequences contained either a single interval (two tones) or a succession of intervals (2, 4, 6). Listeners were required to indicate which was the faster of the two sequences (tempo discrimination). The just noticeable difference (JND) in relative tempo decreased as the number of intervals in the sequence increased. These findings suggest that the more observations the system has concerning the duration of intervals within the sequence (remember that they are all identical), the more precise is the memory code for that interval, and thus the more precise is the temporal coding. Therefore, the temporal coding of intervals contained within a sequence is more precise than is that of isolated intervals.

A second parameter enters into the equation: the degree of regularity of the sequence. If the sequence is regular (isochronous with all IOIs equal), the multiple-look process can work perfectly (no variability). However, if a high degree of irregularity is introduced into the sequence by varying the IOIs (increased standard deviation between IOI), relative tempo JNDs are considerably higher, indicating less efficient processing. It is therefore suggested that the multiple-look process incorporates an indication of both the mean and the variability of intervals within a sequence: The multiple-look process works more efficiently as the number of intervals increases and as the degree of variability decreases.

However, most environmental sequences (footsteps, music, speech) are not entirely regular but contain a low level of temporal irregularity. Does this interfere with a precise temporal coding? It appears not. Relative temporal JNDs are as low for quasi-regular sequences (with a low standard deviation) as they are for truly regular sequences (standard deviation = 0). These findings suggest the existence of a tolerance window by which the system treats sequences that vary within this window as if they were purely regular sequences.

Temporal Window

A third parameter influencing the multiple-look process concerns sequence rate or

tempo: The faster the sequence, the greater the number of events over which an increase in sensitivity is observed. For relatively slow sequences (800–1500 ms IOI) JNDs decrease up to 2 or 3 intervals and then remain stable, whereas for fast sequences (200–400 ms IOI) adding additional intervals up to about 20 results in decreased JNDs. This finding suggests the existence of another factor involved in sequence processing: a temporal window.

The idea is that all events would be stored in a sensory memory buffer lasting several seconds (3 s according to Fraisse, 1982; 5 s according to Glucksberg & Cowen, 1970). It probably corresponds to echoic or working memory (see Crowder, 1993). During this time the exact physical characteristics remain in a raw state without undergoing any conscious cognitive processing (Michon, 1975, 1978). Higher-level processes have access to this information as long as it is available (until it decays), which allows the system to extract all relevant information (e.g., interval duration; Fraisse, 1956, 1963; Michon, 1975, 1978; Preusser, 1972). The existence of such an auditory buffer has been suggested by many psychologists under various names: psychological present (Fraisse, 1982), precategorical acoustic storage (Crowder & Morton, 1969), brief auditory store (Treisman & Rostran, 1972), nonverbal memory trace (Deutsch, 1975), and primary or immediate memory (Michon, 1975). One can imagine a temporal window gliding gradually through time, with new events arriving at one end and old events disappearing at the other due to decay. Thus only events occurring within a span of a few seconds would be accessible for processing at any one time, and only events occurring within this limited time window can be situated in relation to each other by the coding of relevant relational information.

Segmentation into Groups

One way to overcome processing limitations and to allow events to be processed together is to group the events into small perceptual units. These units result from a comparison process that compares incoming events with events that are already present in memory. If a new event is similar to those that are already present, it will be assimilated. If the new event differs too much (by its acoustical or temporal characteristics), the sequence will be segmented. This segmentation leads to the closure of one unit and the opening of the next. Elements grouped together will be processed together within a single perceptual unit, and thus can be situated in relation to each other.

An essential question concerns the factors that determine when one perceptual unit ends and the next one begins. A first indication was provided by Gestalt psychologists who described the physical characteristics of sounds that determine which events are perceived as belonging to a single unit (Koehler, 1929; Wertheimer, 1925). They considered that unit boundaries are determined by a relatively important perceptual change (pitch, loudness, articulation, timbre, duration) between successive events. For instance, two notes separated by a long temporal interval or by a large jump in pitch are perceived as belonging to separate groups. They described three principles: temporal proximity (events that occur relatively close in time), similarity (events that are relatively similar in timbre, pitch, loudness and duration), and continuity (events oriented in the same direction, i.e., progressive increase in pitch). Much research has confirmed the essential role of these principles in sequence segmentation (Bregman, 1990; Deutsch, 1999; Dowling & Harwood, 1986; Handel, 1989; Sloboda, 1985). They also appear to function with musical sequences (Clarke & Krumhansl, 1990; Deliège, 1987).

Temporal Regularity Extraction

Segmentation into basic perceptual units provides one means of overcoming memory limits and allows adjacent events to be processed together. However, this process poses the inconvenience of losing information concerning the continuity of the sequence over time between successive perceptual units. In order to maintain this continuity, a second basic process may occur in parallel: the extraction of temporal regularities in the sequence in the form of an underlying pulse. In this way the listener may extract certain temporal relationships between nonadjacent events. Thus, the process of segmentation breaks the sequence down into small processing units, whereas the process of regularity extraction pulls together temporally nonadjacent events.

Rather than coding the precise duration of each interval, our perceptual system compares each newly arriving interval with preceding ones. If the new interval is similar in duration to preceding intervals (within an acceptable temporal window, called the tolerance window), it will be categorized as "same"; if it is significantly longer or shorter than the preceding intervals (beyond the tolerance window), it will be categorized as "different." There may be an additional coding of "longer" or "shorter." Thus, two or three categories of durations (same/different, or same/longer/shorter) may be coded, but note that this is a relative, rather than an absolute, coding system.

One consequence of this type of processing is that if a sequence is irregular (each interval has a different duration) but all the interval durations remain within the tolerance window, then we will perceive this sequence as the succession of "same" intervals and therefore perceive a regular sequence. Such a tolerance in our perceptual system is quite understandable when we examine the temporal microstructure of performed music: Local lengthenings and shortenings of more than 10% are quite common and are not necessarily picked up by listeners as being irregularities per se (Drake, 1993a; Palmer, 1989; Repp, 1992).

Coding events in terms of temporal regularity is thus an economical processing principle that has other implications. If an incoming sequence can be coded in such a fashion, processing resources are reduced, thus making it easier to process such a sequence. Indeed, we can say that the perceptual system exploits this predisposition by actively seeking temporal regularities in all types of sequences. When listening to a piece of music, we are predisposed to finding a regular pulse, which is emphasized by our tapping our foot in time with the music (*tactus* in musical terms). Once this underlying pulse has been identified, it is used as an organizational framework with respect to which other events are situated.

The Hypothesis of a Personal Internal Tempo

The fact that we appear to be predisposed to processing temporal regularities and that temporal processing is optimum at an intermediate tempo has led Jones and colleagues (Jones, 1976; Jones & Boltz, 1989) to suggest that we select upcoming information in a cyclic fashion. Each individual would have a personal tempo, a rate at which incoming events would be sampled. For a given individual, events that occur at his or her personal tempo would be processed preferentially to events occurring at different rates.

Temporal Organization over Longer Time Spans

The temporal processes described so far occur within a relatively short time window of several seconds. When the sequence becomes more complicated (longer or having more events), the number of events that must

be processed quickly goes beyond the limits of the buffer. However, it is clear that we are able to organize events over longer time spans; otherwise the perception of music and speech would be impossible. Consequently, simple concatenation models (Estes, 1972), which propose that the characteristics of each event are maintained in memory, are not able to account for the perception of long sequences because of problems of processing and memory overload. Imagine the number of intervals that would need to be stored and accessed when listening to a Beethoven sonata! We now explore how several coding strategies have developed to overcome these limits and to allow the perception of longer and more complex sequences.

The organization of information into hierarchical structures has often been proposed as a means of overcoming processing and memory limits. This idea, originally formulated by Miller (1956), presupposes that the information processing system is limited by the quantity of information to be processed. By organizing the information into larger units, the limiting factor becomes the number of groups, not the number of events. Applying this principle to music perception, Deutsch and Feroe (1981) demonstrated that the units at each hierarchical level combine to create structural units at a higher hierarchical level. The presence of regularly occurring accents allows the listener to extract regularities at higher hierarchical levels, and thus attention can be guided in the future to points in time at which upcoming events are more likely to occur. This process facilitates learning and memorization (Deutsch, 1980; Dowling, 1973b; Essens & Povel, 1985; Halpern & Darwin, 1982). Sequences that are not structured in such a hierarchical fashion are harder to organize perceptually and require greater attentional resources. Events that occur at moments of heightened attention are better encoded and then remembered better than are events occurring at other moments in time (Dowling, 1973b). Learning and memorization are deteriorated, and listeners have difficulty in analyzing both temporal and nontemporal aspects of the sequence (Boltz, 1995). This type of hierarchical organization appears to function with music, of course, but with other types of natural sequences as well, such as speech, walking, and environmental sounds (Boltz, 1998; Boltz, Schulkind, & Kantra, 1991; Jones, 1976).

Two Types of Temporal Hierarchical Organizations

Two types of temporal hierarchical organizations have been proposed (see Figure 10.13; Drake, 1998; Jones, 1987; Lerdahl & Jackendoff, 1983) to work in parallel, each based on a basic process. One hierarchical organization is based on the combination of perceptual units (hierarchical segmentation organization). A second is created from the combination of underlying pulses (hierarchical metric organization). In both cases basic units combine to create increasingly larger perceptual units, encompassing increasingly larger time spans. Thus, a particular musical sequence may evoke several hierarchical levels at once. In theory, listeners may focus on each of these levels, switching attention from one to the other as desired.

Hierarchical segmentation organization involves the integration of small, basic groups into increasingly larger units that, in the end, incorporate whole musical phrases and the entire piece (levels A2, A3, and A4 in Figure 10.13). Similar segmentation processes probably function at each hierarchical level, except, of course, that the segmentation cues are more salient (larger temporal separation or larger pitch jump) at higher hierarchical levels (Clarke & Krumhansl, 1990; Deliège, 1993; Penel & Drake, 1998).

Hierarchical metric organization involves the perception of temporal regularities at

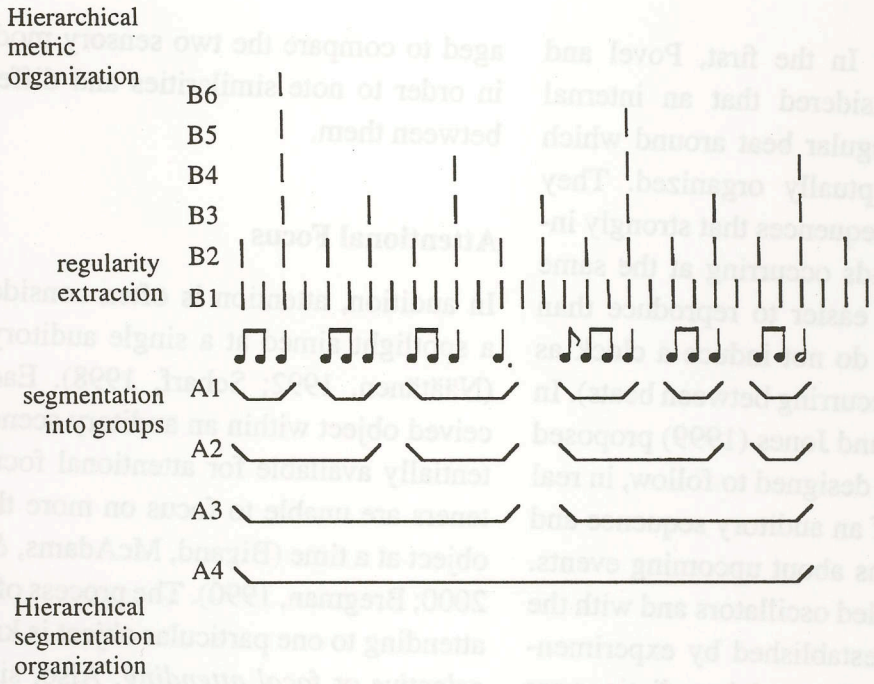


Figure 10.13 Grouping and metrical hierarchies in musical sequences.
NOTE: When listening to a tone sequence (here a musical rhythm), two basic processes function the same way in everyone: The sequence is perceptually segmented into small perceptual units (segmentation into groups, A), and a regular underlying pulse that retains a continuity between events is established (regularity extraction, B). Two types of hierarchical organization, each based on a basic process (hierarchical segmentation organization and hierarchical metric organization, respectively), allow the listener to organize events perceptually over longer time spans. The functioning of these organizational processes differs considerably across individuals.

multiple hierarchical levels. Regularly occurring events can be situated within a hierarchical structure by which multiples of the reference period (usually two, three, or four) are incorporated into larger units (level B3 in Figure 10.13), and these units can themselves be incorporated into increasingly larger units (levels B4, B5, and B6). Subdivisions (level B1) of the reference period are also possible. In Western tonal music, this type of organization corresponds to the metric structure involving the integration of regularly occurring beats, measures, and hyper-measures. Thus, events separated by time spans larger than the reference period can be processed together. Jones (1987) emphasized how these regularities allow the creation of expectations. The perception of regularly occurring accents (events that stand out perceptually from the sequence background) facilitates the identification and implementation of higher hierarchical levels.

Many models of meter have been proposed (Desain, 1992; Lee, 1991; Longuet-Higgins & Lee, 1982; Longuet-Higgins & Lee, 1984; for a review of these models, see Essens, 1995), and these are perhaps the most popular aspect of temporal processing. Most of the models try to demonstrate that a computer is able to identify correctly the metric structure of a piece of music, thus demonstrating which factors may intervene (e.g., the position of long or accented events). These models are certainly interesting for both computer science and musicology, but their usefulness for psychologists is currently limited because of the rarity of appropriate comparison with human behavior. There are, however, two

notable exceptions. In the first, Povel and Essens (1985) considered that an internal clock provides a regular beat around which rhythms are perceptually organized. They demonstrated that sequences that strongly induce a clock (sounds occurring at the same time as beats) are easier to reproduce than are sequences that do not induce a clock as strongly (sounds occurring between beats). In the second, Large and Jones (1999) proposed a neural net model designed to follow, in real time, the coding of an auditory sequence and to allow predictions about upcoming events. By the use of coupled oscillators and with the parameter values established by experimental data and theory, the model predictions are successfully confirmed by new experimental data.

ATTENTIONAL PROCESSES IN HEARING

Perceptual Organization Is an Active Process

We have described how listeners perceptually organize auditory scenes into objects, streams, and sources and how they follow changes over time. Listeners are active and through attentional processes are able to influence the resultant perceptual organization to a certain extent. What a listener tries to hear can affect the way a sound sequence is organized perceptually, indicating an interaction between top-down selection and perceptual integration or segregation (van Noorden, 1977). Indeed, the listener is "free" to focus attention on any individual auditory object or stream within an auditory stream, as was indicated in the section on auditory scene analysis (Alain, 2000; Giard, Fort, Mouchetant-Rostaing & Pernier, 2000). Luck and Vecera (Chap. 6, this volume) reviewed recent literature in visual attention. The reader is encouraged to compare the two sensory modalities in order to note similarities and differences between them.

Attentional Focus

In audition, attention is often considered as a spotlight aimed at a single auditory event (Näätänen, 1992; Scharf, 1998). Each perceived object within an auditory scene is potentially available for attentional focus. Listeners are unable to focus on more than one object at a time (Bigand, McAdams, & Forêt, 2000; Bregman, 1990). The process of focally attending to one particular object is known as *selective* or *focal attending*. Also, situations have been described in which listeners divide their attention between one or more objects, switching back and forth between them in a process know as *divided attention*. Selective or divided attention requires effort and becomes more difficult in more complex situations. For instance, focusing attention on a stream within a two-stream context is easier than focusing on the same stream within a three- or four-stream context (Brochard et al., 1999).

Attentional focus or selective attention results in enhanced processing of the selected object and limited processing of the remaining nonselected auditory scene. When attention is engaged, the representation of the object is more salient; semantic analysis is possible; cognitive decisions are faster; and the representation better resists decay. Conversely, when attention is directed elsewhere, stimuli are superficially processed; representations decay rapidly; and long-term storage is prevented. In short, selective attention enhances the representation of a target and inhibits the representation of distractors.

Such benefits have been demonstrated in the detection of pure tones (Scharf, 1998; Scharf, Quigley, Aoki, & Peachey, 1987). The detection of a pure tone in noise is facilitated

if attention is drawn to that frequency by preceding it with a cue at that frequency. Facilitation progressively declines as the frequency difference between the cue and the target is increased. Scharf (1998) suggests that attention acts as a filter enhancing the detection of the target and attenuating the detection of a distractor (whose properties differ from those of the target). Contrary to Broadbent (1958), Scharf considers that these attentional filters are fitted with frequency-selective auditory filters. If a signal has a frequency tuned to the central frequency of the attentional filter, the representation of this signal is amplified. If the pitch of the signal falls outside the bandwidth of the attentional filter, the signal is attenuated and neglected. Similar effects are obtained with more complex stimuli (simultaneous presentation of complex sequences composed of subsequences varying in tempo and frequency). When attention is focused on one subsequence (by preceding the complex sequence by a single sequence cue), it is easy to detect a temporal irregularity located within it. However, when the temporal irregularity is located in a nonfocused subsequence (no preceding cue), the intensity level has to be increased by 15 dB to allow the same level of detection performance (Botte, Drake, Brochard, & McAdams, 1997).

Determinants of Attentional Focus

What determines which object will receive this privileged attentional focus? Two sets of factors have been described: stimulus-driven attentional capture and directed attentional focus.

Stimulus-Driven Attentional Capture

Certain characteristics of an auditory event or of an individual increase the probability than a particular stream or object will receive capture attention. First, physical characteristics of events may make one particular object more perceptually salient than others: For instance, loud events tend to capture attention more than relatively quiet events do (Cowan, 1988; Sokolov, 1963); in the case of music, relatively high-pitched events tend to capture attention more than low-pitched events do (Huron & Fantini, 1989). Second, sudden changes in the sound environment (the appearance or disappearance of a new object or stream) will tend to attract attention away from previously focused objects: The sudden appearance of a motor engine or the stopping of a clock's ticking usually lead to a change in attentional focus (Cowan, 1988; Sokolov, 1963). Furthermore, events with particular personal significance (your own name, or your own baby's crying) have enhanced perceptual salience and lead to a change in attentional focus for that particular object (Moray, 1959; Wood & Cowan, 1995).

Personal characteristics, such as a person's spontaneous internal tempo (or referent period), may lead to a preferential focusing on events occurring at one particular rate (Boltz, 1994; Jones, 1976). People with faster referent periods will tend to focus spontaneously on streams containing faster-occurring events. Similarly, the more skilled an individual is at organizing events over longer time spans (such as musicians compared with nonmusicians), the more likely it is that the individual will focus at a higher hierarchical level within a complex sequence such as music (Drake, Penel, & Bigand, 2000).

Directed Attentional Focus

Thus, in any given sound environment, attention will tend to be focused spontaneously on one particular object according to the factors just described. Listeners can actively control attention, but this ability is limited by characteristics of both the stimulus and the listener. In the case of a complex sound sequence composed of multiple subsequences, not all subsequences are equally easy to direct attention

to. For instance, it is much easier to focus attention on subsequences with the highest or lowest pitch, rather than an intermediate pitch (Brochard et al., 1999). A corresponding finding has been observed in the perception of musical fugues in which it is easier to detect changes in the outer voices, in particular the voice with the highest pitch (Huron & Fantini, 1989). Similarly, it is easier to focus on one particular stream if it has been cued by tones resembling the target tones in some respect. The more physically similar a stream is to the object of spontaneous focus, the easier it is for a listener to direct attention to that particular object.

Individual characteristics also play an important role. The more a listener is familiar with a particular type of auditory structure, the easier it is for him or her to focus attention toward different dimensions of that structure. For instance, musicians can switch attention from one stream to another more easily than can nonmusicians, and musicians have access to more hierarchical levels than do nonmusicians (Drake et al., 2000; Jones & Yee, 1997).

Role of Attention in Auditory Organization

Much debate concerns whether stream formation is the result of attentional processes, precedes them, or is the result of some kind of interaction between the two.

More traditional approaches limit the role of attention to postorganizational levels (after object and stream formation). In the first cognitive model of attention proposed by Broadbent (1958), unattended information is prevented from reaching a central limited canal of conscious processing by a filter located after sensory storage and before the perceptual stage. Unattended information would therefore receive only extremely limited processing. Bregman (1990) holds stream formation to be a primarily primitive, preattentive process. Attention intervenes either as a partial selection of information organized within stream (a top-down influence on primitive organization) or as a focusing that brings into the foreground a particular stream from among several organized streams (the attended stream then benefits from further processing).

An alternative position (Jones, 1976; Jones & Boltz, 1989; Jones & Yee, 1993) considers that attention intervenes much earlier in processing, during the formation of streams themselves. The way in which an auditory scene is organized into streams depends on the listener's attentional focus: If an individual directs attention at some particular aspect of the auditory signal, this particular information will be a determinant in stream creation. Thus, Jones proposed that stream formation is the result of dynamic attentional processes with temporal attentional cycles. In this view, attention is viewed as a structuring and organizing process. It orchestrates information selection with a hierarchy of coupled oscillators. Therefore, fission is a breakdown of tracking caused by a noncorrelation between cyclic attentional processes and the periodicity of event occurrence. However, no effect of temporal predictability (Rogers & Bregman, 1993b) or of frequency predictability (van Noorden, 1977) on stream segregation has been found.

One way to disentangle this problem is to measure precisely when and where in the auditory pathway attention exerts its prime influence. Electrophysiological measures (Näätänen, 1992; Woods, Alho, & Algazi, 1994) consistently show that the earliest attentional modulation of the auditory signal appears 80 ms to 100 ms after stimulation, which is when the signal reaches the cortical level. Some authors have suggested that the efferent olivo-cochlear bundle that projects onto the outer hair cells (see Chap. 9, this volume)

could be a device that allows attention to operate at a peripheral level (e.g., Giard, Collet, Bouchet & Pernier, 1993; Meric & Collet, 1994).

Using electrophysiological measures, unattended sounds seem to be organized perceptually. Sussman, Ritter, and Vaughan (1999) found electrophysiological evidence for a preattentive component in auditory stream formation using the mismatch negativity (MMN; Näätänen, 1995), an electroencephalographic (EEG) component based on an automatic, preattentive deviant detection system. MMN responses were found on deviant subsequences only when presented at a fast tempo that usually yields two auditory streams under behavioral measures. Within-stream patterns whose memory traces give rise to the MMN response appeared to have emerged prior to or at the level of the MMN system. Sussman, Ritter, and Vaughan (1998) observed, however, that if tempo and frequency separation were selected so that the stimulus sequence was in the ambiguous zone (van Noorden, 1977; see also Figure 10.4), the MMN was observed for the deviant sequence only in the attentive condition (attend to the high stream)—not in the inattentive condition with a distracting (reading) task. This physiological result confirms the behavioral finding that streaming can be affected by attentional focus in the ambiguous region. In a similar vein, Alain et al. (1994) found an interaction between the automatic perceptual analysis processes and volitional attentional processes in EEG measures.

In a paradigm derived from work on concurrent grouping (mistuned harmonic segregation), Alain, Arnott, and Picton (in press) found two major ERP components related to segregation: one related to automatic segregation processes that are unaffected by attentional focus but that varied with stimulus conditions related to segregation, and another that varied depending on whether listeners were actively attending to the sounds. These results suggest a model containing a certain level up to which perceptual organization is automatic and impermeable to attentional processes and above which the information produced by this stage can be further processed if attended to. This view is consistent with data showing that listeners have difficulty detecting a temporal deviation in one of several simultaneous streams if they are not cued to the target stream. It is also consistent with an apparent inhibition of nonfocused events as a kind of perceptual attenuation that has been estimated to be as much as 15 dB (Botte et al., 1997).

DEVELOPMENTAL ISSUES

Up to this point, we have examined the functioning of the human perceptual system in its final state: that of the adult. However, much can be learned about these systems by comparing this "final" state with "initial" or "transitional" states observed earlier in life. Differences may be related to (a) the functional characteristics and maturity of the auditory system (e.g., speed of information transmission, neuronal connectivity, and properties of the cochlea), (b) acculturation through passive exposure to regularities in the sound environment, and (c) specific learning, such as music tuition, in which musicians learn explicit organizational rules. The relative importance of these factors can be demonstrated by comparing the behavior of (a) infants (as young as possible to minimize all influences of learning), (b) children and adults varying in age (opportunities for acculturation increase with age), and (c) listeners with and without musical training (explicit learning—together with many other factors—increases with training). Of considerable interest is the question of the relative roles of passive exposure (and maturation) compared with explicit training in the

development of these higher-level processes. Because it is impossible to find people without listening experience (except the recent emergence of profoundly deaf children fitted with hearing-aids and cochlear implants later in life), the usual experimental strategy has been to compare the performances of listeners who have received explicit training in a particular type of auditory environment (almost always music) with the performance of listeners who have not received such training. A newly emerging idea is to compare listeners from different cultures who have been exposed to different sound environments; commonalties in processing are considered to be fundamental, universal, or innate (Drake, in press; Krumhansl, Louhivuori, Toiviainen, Jaervinen, & Eerola, 1999; Krumhansl et al., 2000).

The dominant interactive hypothesis (Bregman, 1990; Deutsch, 1999; Dowling & Harwood, 1986; Drake et al., 2000; Handel, 1989; Jones, 1990; Sloboda, 1985) is that low-level perceptual processes (such as perceptual attribute discriminations, stream segregation, and grouping) are hardwired or innate, and thus more or less functional at birth. Slight improvements in functioning precision are predicted to occur during infancy, but no significant changes in functioning mode should be observed. However, higher-level cognitive processes (such as attentional flexibility and hierarchical organization) are less likely to be functional at birth. They will thus develop throughout life by way of passive exposure and explicit learning. These more "complex" processes do not appear from nowhere, but rather emerge from low-level processes as they extend in scope and combine into larger, more elaborate constructs.

Our knowledge about infants' and children's auditory perception and cognitive skills is currently extremely piecemeal (Baruch, 2001). Only a handful of auditory processes have been investigated. Moreover, of the studies that do exist, both the ages examined and the techniques used vary considerably. Researchers usually compare the performance of three sets of listeners: infants (aged 2 days to 10 months), children in midchildhood (aged 5–10 years), and adults (usually psychology students aged 18–25 years). Obviously, there is considerable room for change within each set of listeners (new-born infants and 1-year-olds do not have much in common!). There are also considerable periods in the developmental sequence that remain almost completely unexplored, probably because of experimental difficulties. For instance, we have very little idea of the perceptual abilities of toddlers and teenagers, but probably not for the same reasons. The tasks adopted are usually appropriate for each age group, but the degree of comparability between those used for different groups is debatable.

Despite these problems and limitations, general confirmation of the interactive developmental hypothesis is emerging, and it is possible to draw up a tentative picture of the auditory processes that are functional at birth, those that develop considerably during childhood through passive exposure, and those whose development is enhanced by specific training. We would like to emphasize, however, that this picture remains highly speculative.

Auditory Sensitivity and Precision

Most recent research indicates that infants' detection and discrimination thresholds are higher than those of adults, despite the presence of an anatomically mature peripheral auditory system at birth (e.g., Berg, 1993; Berg & Smith, 1983; Little, Thomas, & Letterman, 1999; Nozza & Wilson, 1984; Olsho, Koch, Carter, Halpin, & Spetner, 1988; Schneider, Trehub, & Bull, 1980; Sinnot, Pisoni, & Aslin, 1983; Teas, Klein, & Kramer, 1982;

Trehub, Schneider, & Endman, 1980; Werner, Folsom, & Mancl, 1993; Werner & Marean, 1991). Take, for example, the case of absolute thresholds. The magnitude of the observed difference between infants and adults has decreased significantly over recent years, mainly because of improvements in measurement techniques. However, even with the most sophisticated methods (observer-based psychoacoustic procedures), infants' thresholds remain 15 dB to 30 dB above those of adults. At six months the difference is 10 dB to 15 dB (Olsho et al., 1988). The difference continues to decrease with age (Schneider, Trehub, Morrongiello, & Thorpe, 1986), and by the age of 10 years, children's thresholds are comparable with those of adults (Trehub, Schneider, Morrongiello, & Thorpe, 1988).

It would be tempting to suggest that similar patterns of results have been found for the perception of various auditory attributes. In this field, however, the experimental data are so sparse and the developmental sequence so incomplete that such a conclusion would be premature. The best we can say is that most of the existing data are not incompatible with the proposed pattern (loudness: Jensen & Neff, 1993; Schneider & Trehub, 1985; Sinnot & Aslin, 1985; frequency selectivity: Olsho, 1985; Olsho et al., 1988; Sinnot & Aslin, 1985; Jensen & Neff, 1993; timbre: Trehub, Endman, & Thorpe, 1990; Clarkson, Martin, & Miciek, 1996; Allen & Wightman, 1995; and temporal acuity: Werner & Rubel, 1992).

Despite this poorer performance level in infants, the same functioning mode seems to underlie these low-level auditory processes. For instance, similar patterns of results in infants and adults indicate the existence in both groups of tuning curves and auditory filters (Abdala & Folsom, 1995), the double coding of pitch (pitch height and chroma; Demany & Armand, 1984, 1985), and the phenomenon of the missing fundamental and pitch extraction from inharmonic tones (Clarkson & Clifton, 1995).

Primary Auditory Organization Processes

In a similar fashion, certain primary auditory organization processes appear to function early in life in the same way as they do in adults, although not necessarily as efficiently and not in more complex conditions.

Stream Segregation

As stream segregation is such an important process in auditory perception, it is surprising to note how few studies have investigated its development. Stream segregation has been demonstrated at ages 2 months to 4 months for frequency-based streaming (Demany, 1982) as well as in new-born infants, but only in easy streaming conditions (slow tempi and large pitch jumps) for timbre and spectral position-based streaming (McAdams & Bertoncini, 1997). Surprisingly, even less is known about how stream segregation develops during childhood. One exception is the study by Andrews and Dowling (1991), who demonstrated that even 5-year-olds are able to identify a familiar tune within a complex mixture based on pitch and timbre differences between tones. These abilities develop with age, although the differences may be due to changes in performance level rather than to changes in functioning mode. Elderly people do not show a deficit in this process compared with young adults (Trainor & Trehub, 1989).

Segmentation into Groups

Segmentation into groups has been demonstrated in 6- to 8-month-old infants (Trainor & Adams, 2000; Krumhansl & Jusczyk, 1990; Thorpe & Trehub, 1989) and in 5- to 7-year-old children (Bamberger, 1980; Drake, 1993a, 1993b; Drake, Dowling & Palmer, 1991;

Thorpe & Trehub, 1989). Similar segmentation principles are used by adult musicians and nonmusicians, although musicians are more systematic in their responses (Fitzgibbons, Pollatsek, & Thomas, 1974; Peretz & Morais, 1989).

Temporal Regularity Extraction

Temporal regularity extraction is functional at an early age: The capacity to detect a small change in tempo of an isochronous sequence is present in 2-month-old infants (Baruch & Drake, 1997). Children are able to synchronize with musical sequences by the age of 5 years (Dowling, 1984; Dowling & Harwood, 1986; Drake, 1997; Fraisse, Pichot, & Clairouin, 1969), and their incorrect reproductions of musical rhythms almost always respect the underlying pulse (Drake & Gérard, 1989). Both musicians and nonmusicians use underlying temporal regularities to organize complex sequences (Povel, 1985).

Tempo Discrimination

Tempo discrimination follows the same pattern over age: The same zone of optimal tempo is observed at 2 months as in adults, although there is a significant slowing and widening of this range during childhood (Baruch & Drake, 1997; Drake et al., 2000).

Simple Rhythmic Forms and Ratios

Like children and adults, infants demonstrate a processing preference for simple rhythmic and melodic forms and ratios (e.g., isochrony and 2:1 ratios; Trainor, 1997). Two-month-old infants discriminate and categorize simple rhythms (Demany, McKenzie, & Vurpillot, 1977; Morrongiello & Trehub, 1987), and young children discriminate and reproduce better rhythmic sequences involving 2:1 time ratios compared with more complex ratios (Dowling & Harwood, 1986; Drake, 1993b; Drake & Gérard, 1989).

Higher-Level Auditory Organization

In contrast to a noted general absence of changes with age and experience in the preceding sections, considerable differences are expected both in the precision and mode of functioning of more complex auditory processes. Because higher-level processes are conceived as being harder, researchers have simply not looked for (or published) their functioning in infants and children: It is never clear whether the absence of effect is due to the lack of process or to methodological limits. Very few studies investigate these processes in infants or children. However, some studies do demonstrate significant differences between different groups of adults (musicians and nonmusicians, different cultures, etc.). Whereas few studies have investigated higher-level processing in infants for simple and musical sequences, more is known about such processes for speech signals (see Chap. 12, this volume).

Hierarchical Segmentation Organization

This type of organization has been investigated with a segmentation paradigm that has been applied to children and adults but not to infants. Participants are asked to listen to a piece of music and then to indicate where they perceive a break in the music. In both children (Bertrand, 1999) and adults (Clarke & Krumhansl, 1990; Deliège, 1990; Pollard-Gott, 1983), the smallest breaks correspond to low-level grouping processes, described earlier, that are based on changes in the physical characteristics of events and temporal proximity. Larger groupings over longer time spans were observed only in adults. These segmentations correspond to greater changes in the same parameters. Such a hierarchy in segmentation was observed in both musicians and nonmusicians, although the principles used were more systematic in adult musicians. This

type of organization has not been investigated in infants.

Hierarchical Metric Organization

The use of multiple regular levels has also not been investigated in infants. Whereas 4-year-old children do not demonstrate the use of this organizational principle, its use does increase with age. By the age of about 7 years, children use the reference period and one hierarchical level above or below this level (Drake, Jones & Baruch, 2000). However, the use of more hierarchical levels seems to be restricted to musicians (Bamberger, 1980; Drake, 1993b), and musicians tend to organize musical rhythms around higher hierarchical levels than do nonmusicians (Drake et al., 2000; Monahan, Kendall, & Carterette, 1987; Stoffer, 1985). The ability to use the metrical structure in music performance improves rapidly with musical tuition (Drake & Palmer, 2000; Palmer & Drake, 1997).

Melodic Contour

Infants aged 7 to 11 months can detect changes in melodic contours better than they can detect local changes in intervals, a pattern that is reflected in adult nonmusicians but not in adult musicians (Ferland & Mendelson, 1989; Trehub, Bull, & Thorpe, 1984; Trehub, Thorpe, & Morrongiello, 1987; for more details, see Chap. 11, this volume).

Focal Attending

Nothing is known about infants' ability to focus attention on particular events in the auditory environment. Four-year-old children spontaneously focus attention on the most physically salient event and have difficulty pulling attention away from this object and directing it toward others. Considerable improvements in this ability are observed up to the age of 10 years, and no additional improvement is observed for adult nonmusicans. However, adult musicians show a greatly enhanced ability to attend selectively to a particular aspect of an auditory scene, and this enhancement appears after only a couple of years of musical tuition (Drake et al., 2000).

Summary

The interactive developmental hypothesis presented here therefore provides a satisfactory starting point for future research. The existing data fit relatively well into this framework, but future work that more extensively investigates the principle findings concerning auditory perception and cognition in adults could conceivably invalidate such a position and lead to the creation of a completely different perspective.

CONCLUSIONS

One major theme running through this chapter has been that our auditory perceptual system does not function like a tape recorder, recording passively the sound information arriving in the ear. Rather, we actively strive to make sense out of the ever-changing array of sounds, putting together parts that belong together and separating out conflicting information. The result is the perception of auditory events and sequences. Furthermore, based on previous information and current desires, attentional processes help determine the exact contents of the perceived sound environment.

Such a dynamic approach to auditory perception and cognition has been developing gradually over the last 30 years, being greatly influenced by a handful of creative thinkers and experimentalists, to whom we hope we have done justice. In this chapter, the first in the *Stevens' Handbook* series devoted to auditory perception and cognition, we have tried to bring together evidence from a range of

complementary fields in the hopes that the resulting juxtaposition of ideas will facilitate and enable future research to fill in the gaps.

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