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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

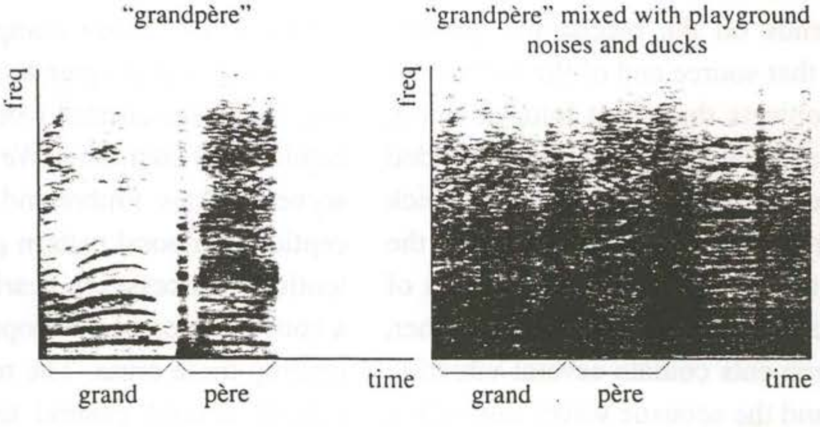


Figure 10.1 Spectrogram of (a) a target sound—the word *grandpère* ("grandfather" in French)—and (b) the target sound embedded in a noisy environment (a children's playground with voices and ducks).
NOTE: A spectrogram represents time on the horizontal axis and frequency on the vertical axis. The level 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.

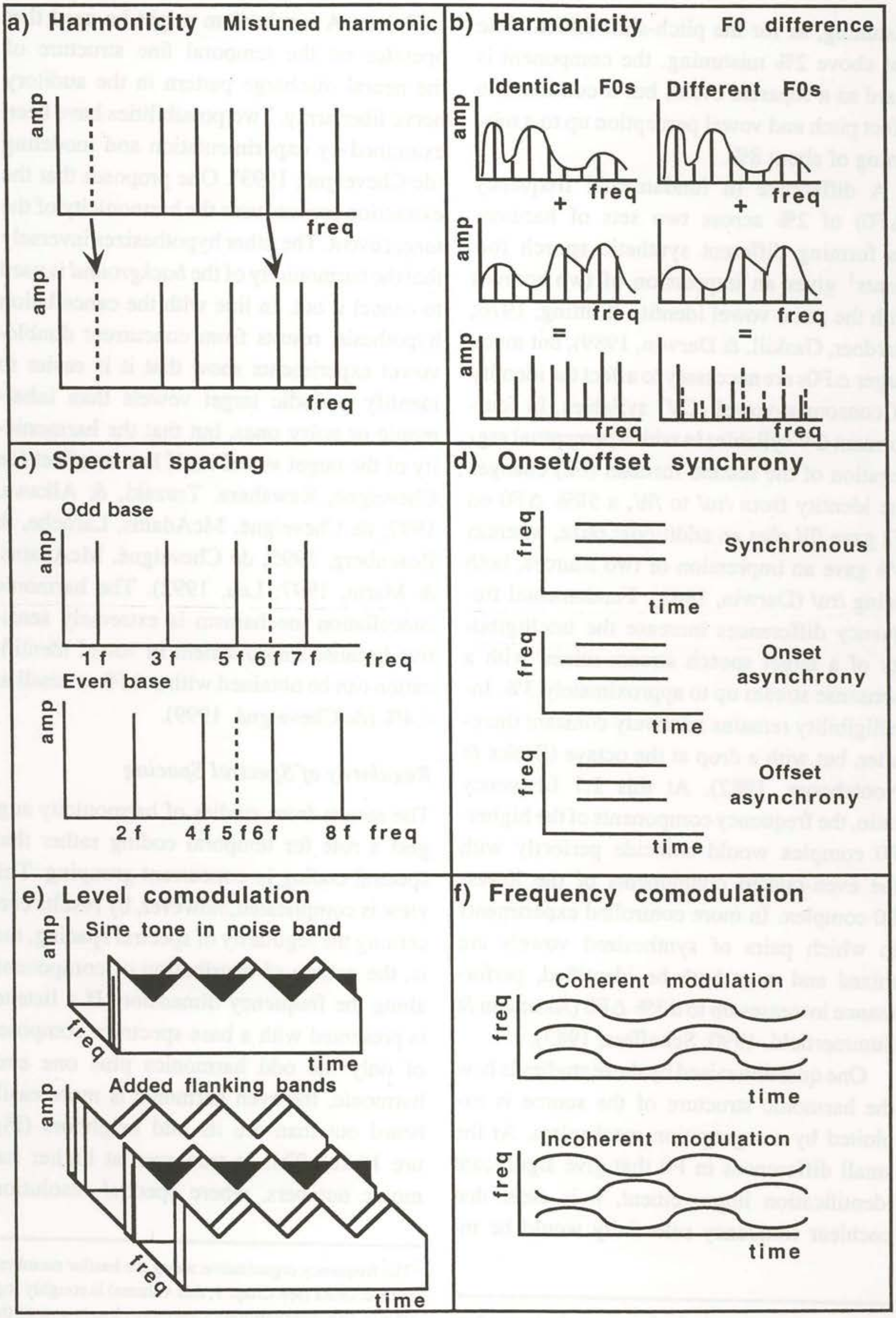
Harmonicity

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 of the harmonics makes it easier to hear out because of the time-varying inharmonicity that is created.


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
amp
Sine tone in noise band
freq
time
amp
Added flanking bands
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

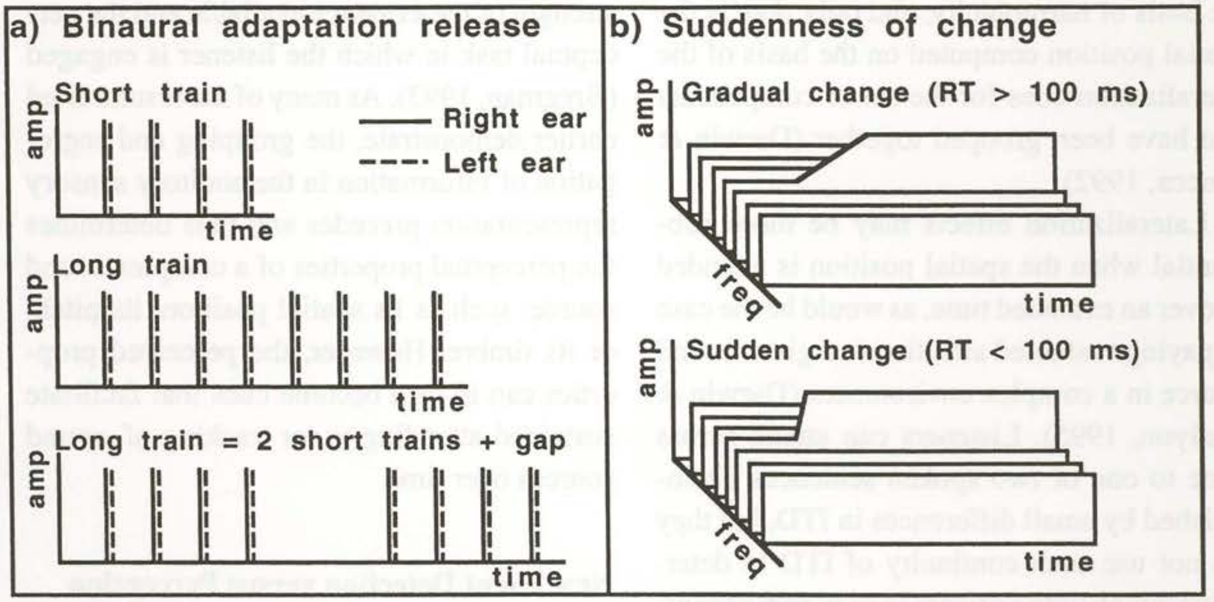


Figure 10.3 Stimuli used to test the resetting of auditory sampling of the environment upon new event detection.
NOTE: a) Binaural adapatation release. A train of clicks (interclick separation = 2.5 ms) is sent to the two ears with a small interaural time difference (ITD) that displaces the perceived 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

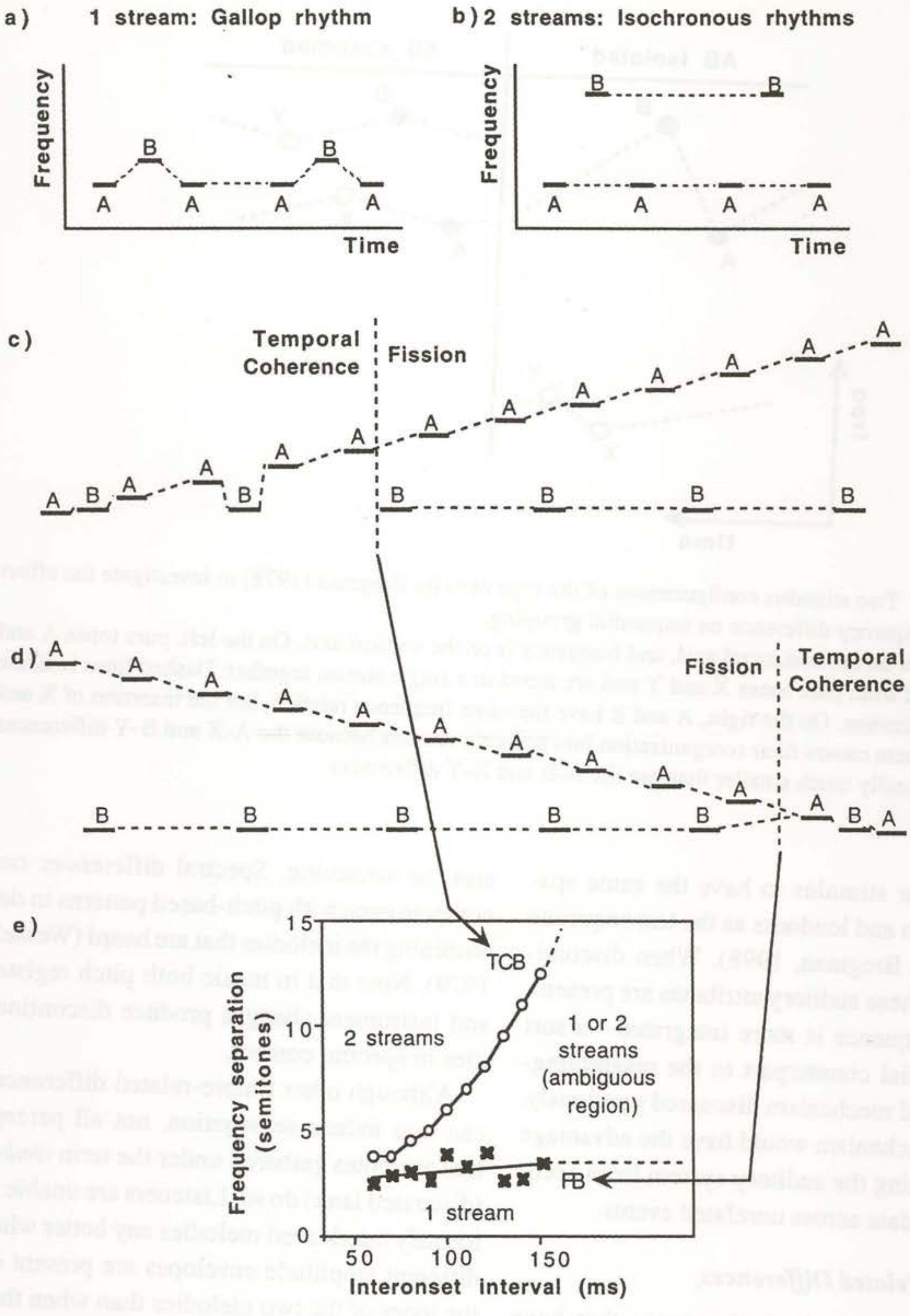


Figure 10.4 Van Noorden's temporal coherence and fission boundaries.

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.

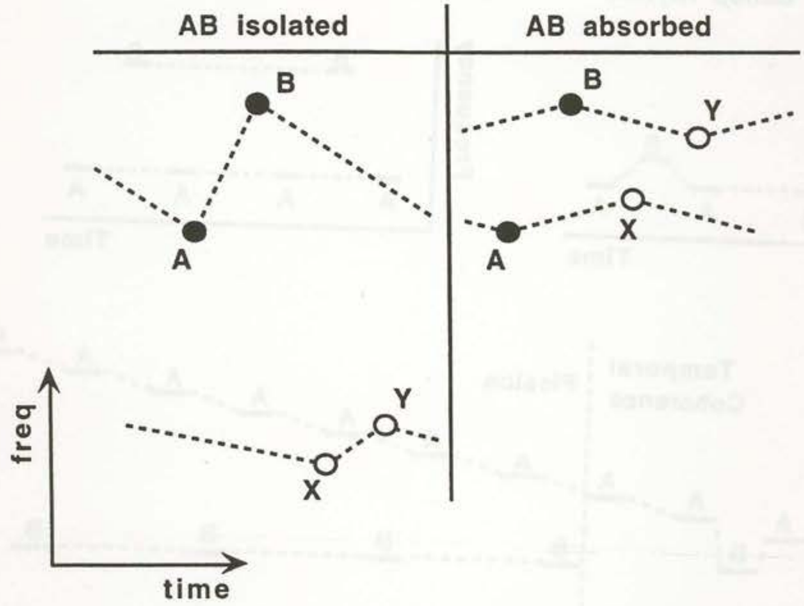


Figure 10.5 Two stimulus configurations of the type used by Bregman (1978) to investigate the effect of relative frequency difference on sequential grouping.
NOTE: Time is on the horizontal axis, and frequency is on the vertical axis. On the left, pure tones A and B are isolated from pure tones X and 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.

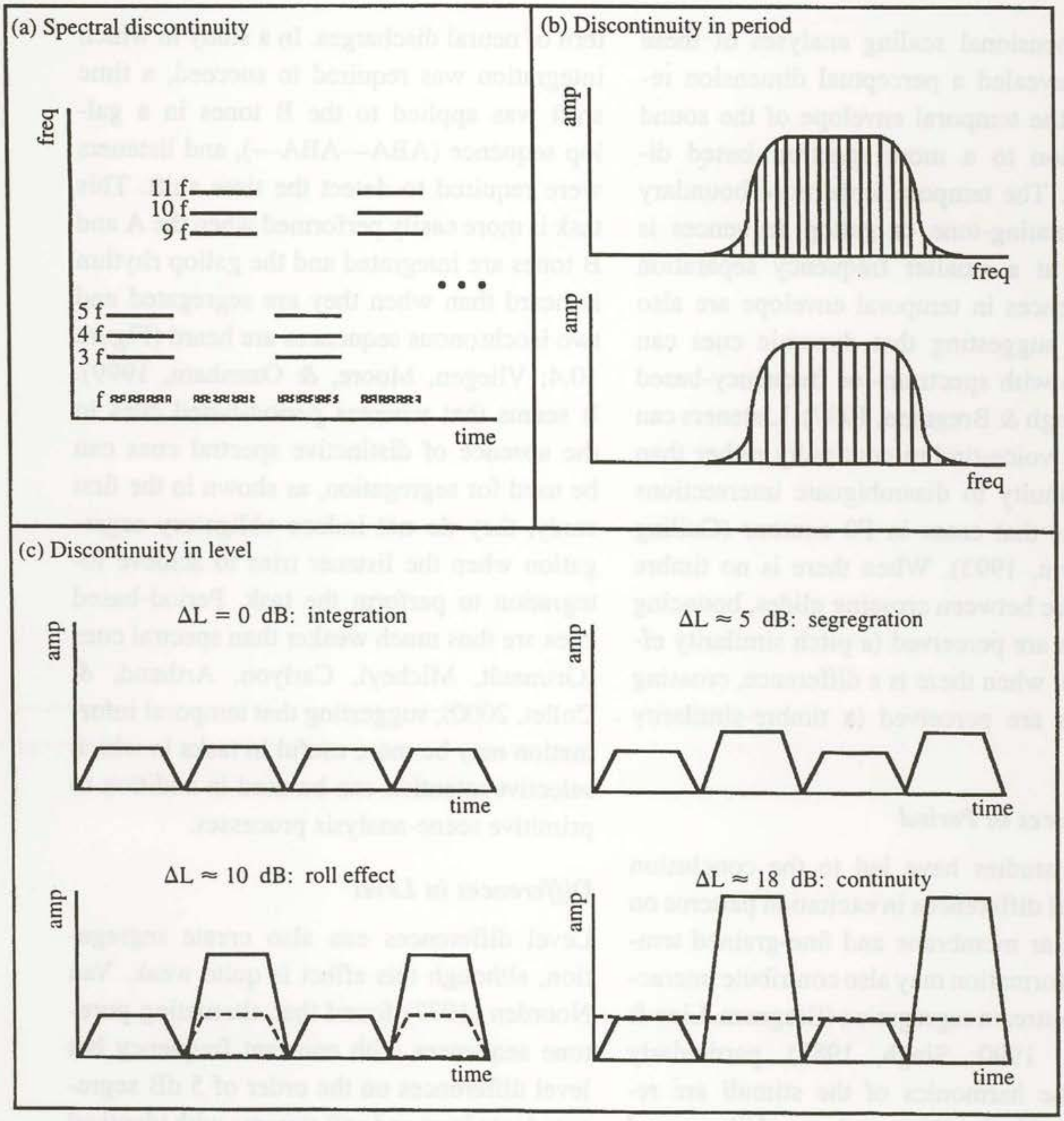


Figure 10.6 Stimuli used to test sequential grouping cues.

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,

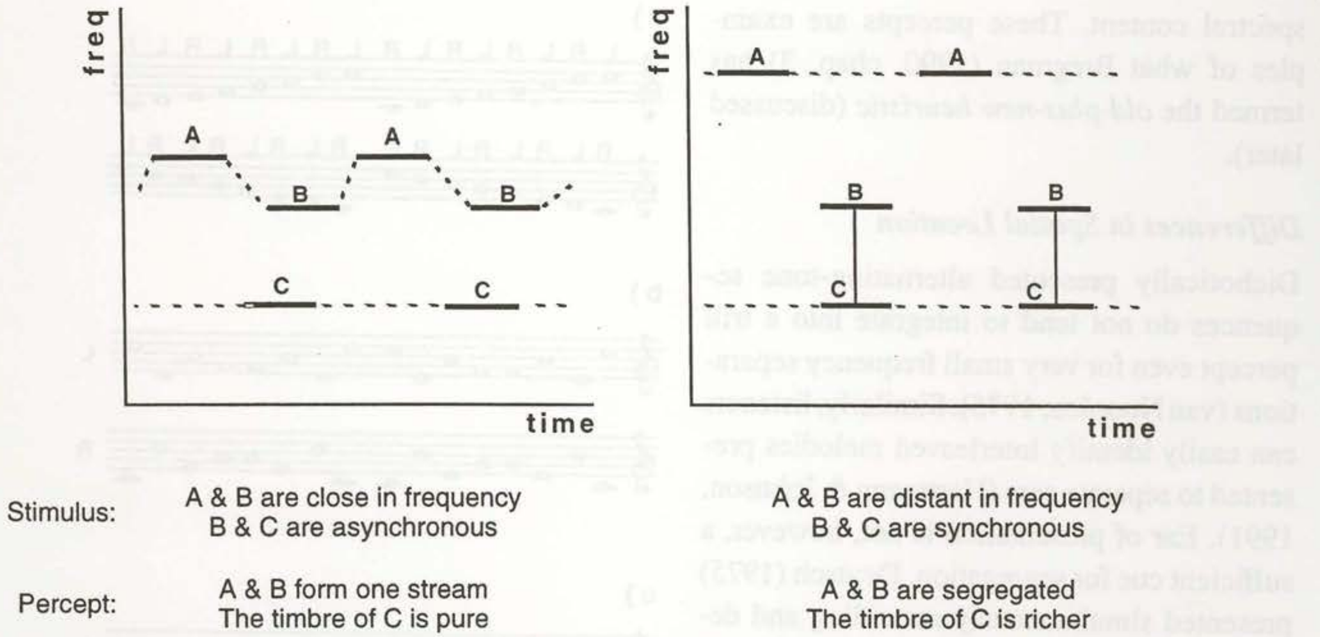


Figure 10.8 Schematic representative of some of the stimulus configurations used by Bregman and Pinker (1978) to study the competition between concurrent and sequential grouping processes.
NOTE: Pure tone A alternates with a complex tone composed of pure tones B and C. The relative frequency proximity 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, &

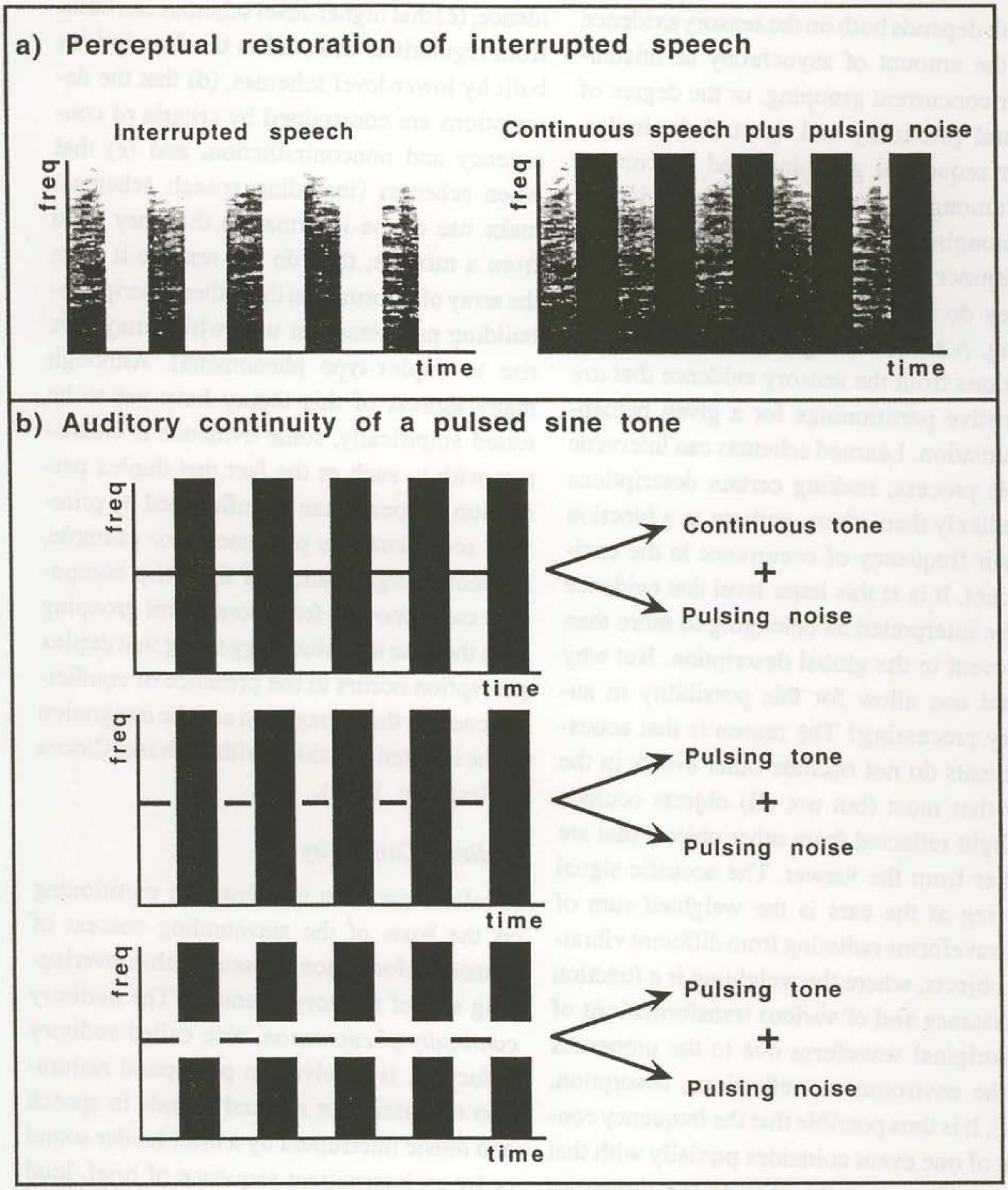


Figure 10.9 Stimuli used to test the auditory continuity phenomenon.

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 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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