Reconsidering evidence for the suppression model of the octave illusion

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The octave illusion is elicited by a sequence of tones presented to each ear that continuously alternate in frequency by one octave, but with high and low frequencies always in different ears. The percept for most listeners is a high pitch in one ear, alternating with a low pitch in the other ear. The influential *suppression model* of the illusion proposed by Deutsch and Roll (1976) carries three postulates: first, that listeners perceive only the pitch of the tones presented to their dominant ear; second, that this pitch is heard in whichever ear received the higher frequency tone; and third, that this apparent dissociation between *what* and *where* mechanisms arises from sequential interactions between the tones. In the present article, we reappraise evidence for the suppression model and demonstrate (1) the incompatibility of the theory with the existing literature on pitch perception, sound localization, and ear dominance and (2) methodological limitations in studies that have claimed to provide support for the suppression model. We conclude by proposing an alternative theory of the octave illusion that is based on established principles of fusion, rather than suppression, between ears.

The octave illusion is a compelling perceptual phenomenon that arises when each ear is presented with an alternating sequence of tones separated by one octave, but with the high- and the low-frequency tones in different ears (Figure 1). The majority of listeners are unable to accurately describe these stimuli and, instead, report a high pitch in one ear alternating with a low pitch in the opposite ear. Deutsch (1974) noted that, when presented with these stimuli via headphones, most listeners heard the higher pitch toward the right and the lower pitch toward the left. This trend was particularly salient for right-handed listeners, but not for left-handed listeners. Deutsch (1974) suggested that this handedness effect indexed the lateralization of the higher pitch “toward the side producing the most effective input to the dominant hemisphere” (p. 308).

The unique and influential *suppression model* of this phenomenon was later proposed by Deutsch and Roll (1976). From an analysis of subjective reports, the authors suggested that the octave illusion arises from a

high-frequency dominance for sound localization, combined with ear dominance for pitch in which the dominant ear “exercises a steady suppression on the other [ear], so that only the frequencies arriving at one ear are heard” (p. 24). According to this theory, the interplay of ear dominance for pitch and high-frequency dominance for localization results in conflict when the high-frequency tone is presented to the nondominant ear. Under this condition, Deutsch and Roll suggested that listeners perceive the pitch presented to their dominant ear but localize this percept in the opposite ear. The authors thus concluded that the octave illusion reveals separate neural mechanisms governing the *what* and *where* of auditory perception, which may be placed in conflict under appropriate conditions. Deutsch (1978, 1980a, 1988) later included a third tenet to the suppression model, suggesting that this unique division of object- and location-based auditory mechanisms was facilitated by sequential interactions between the tones—specifically, the repeated alternation of the same frequencies between the ears.

A recent study by Chambers, Mattingley, and Moss (2002) has challenged the validity of the suppression model. From a psychophysical investigation, their results suggest instead that (1) the pitch variation during the octave illusion may arise from established mechanisms of harmonic fusion, (2) the high-frequency dominance for localization proposed by the suppression model regularly fails to emerge, and (3) both the pitch differences between alternate dichotic octaves¹ and the apparent lateralization of single dichotic octaves can occur indepen-

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Figure 1. The octave illusion arises from an alternating sequence of dichotic octaves presented via headphones (A). Most listeners perceive these stimuli as a single tone shifting between a high pitch in one ear and a low pitch in the other ear (B). The suppression model (C) suggests that listeners perceive the pitch presented to their dominant ear (italicized) but localize this pitch in the ear receiving the higher frequency tone (white border). The predicted percept according to suppression (D) thus comprises an octave pitch alternation between 400 and 800 Hz.

dently of sequential interactions. This interpretation contrasts with the theoretical explanation of the illusion that has dominated opinion for the past quarter century. In the present article, we consider this conflict from a theoretical standpoint and review evidence for the three tenets of the suppression model. The purpose of this analysis is to point out several inconsistencies between the suppression model and previous research, in addition to identifying methodological limitations in past studies that have been used to support a suppression hypothesis.

Section 1 of the present article considers the discrepancy between the suppression model and evidence demonstrating fusion, rather than suppression, in the perception

of pitch. Section 2 shows that the suppression model is inconsistent with explanations of similar binaural phenomena that involve illusions of auditory localization. Section 3 demonstrates that the suppression model is inconsistent with a related body of literature on ear dominance. Section 4 reviews three landmark investigations that appear to provide evidence for suppression and sequential interactions but that relied on subjective report data and may, therefore, have been compromised by response bias. In section 5, we consider the contribution to this debate by two recent electrophysiological studies. Finally, in section 6, we propose an alternative theory of the octave illusion that reconciles the phenomenon with evidence for pitch perception based on harmonic fusion.

1. The Suppression Model Is Inconsistent With Theories of Pitch Perception

The suppression model proposed by Deutsch and Roll (1976) suggests that during the octave illusion, listeners perceive only the frequencies presented to their dominant ear. Therefore, if the illusion is elicited with alternating sequences of 400- and 800-Hz tones, the perceived pitch is predicted to alternate between 400 and 800 Hz. This tenet contrasts with theories of pitch perception, which predict that a dichotic complex of 400 and 800 Hz should either be perceptually segregated into two distinct pitches or be fused into a single percept with a pitch corresponding to the overall repetition rate of the complex (known as the *fundamental frequency*, F_0). In the present section, this discrepancy will be explored through a brief review of pitch theories—specifically, those theories that deal with the pitch perception of complex tones.

One of the oldest and most robust observations in psychoacoustics is that the pitch of harmonic complex tones approximates F_0 , even when spectral energy at F_0 is absent or masked, and even when harmonics are presented to different ears (Arehart & Burns, 1999; Demany & Semal, 1988; Hermann, 1890; Houtstma & Fleuren, 1991; Houtstma & Goldstein, 1972; Licklider, 1954; Patterson, 1969; Seebeck, 1841; Small, 1955; Small & Campbell, 1961; Thurlow & Small, 1955). This phenomenon is often referred to as *virtual pitch*, because the auditory system synthesizes a pitch sensation that is not physically present in the stimulus. The perception of virtual pitch is thought to arise either from analysis of periodicity (e.g., Schouten, 1938, 1940a, 1940b, 1940c) or through a pattern-matching mechanism that assigns pitch to the most likely F_0 (e.g., Terhardt, 1974).

A distinction may also be drawn between virtual pitch and *spectral pitch*. Spectral pitch arises when listeners perceptually segregate a complex tone into distinct pitches, each relating closely to the frequency of the resolved sinusoid (Terhardt, 1974). Thus, for a dichotic octave of 400 and 800 Hz, listeners should perceive either a single virtual pitch at F_0 (400 Hz) or separate spectral pitches at 400 and 800 Hz. Terhardt's (1974) influential pattern-matching the-

ory of pitch perception suggests that spectral and virtual pitches compete during pitch extraction, with the final percept determined by the listener's ability to segregate components of the stimulus. For a highly *analytic* listener, the theory predicts that the spectral pitches of 400 and 800 Hz in a dichotic octave would be segregated and would dominate over virtual pitch. For a highly *synthetic* listener, however, the individual spectral pitches would be strongly fused, and the 400-Hz virtual pitch would dominate the percept. Clearly, the balance between these pitch extraction mechanisms would be likely to influence the eventual timbre, or *color*, of the percept.

This body of psychoacoustic theory and evidence contrasts with the predictions of the suppression model proposed by Deutsch and Roll (1976). These authors suggested that listeners perceive a single pitch during the octave illusion but that this pitch is equivalent to the frequency in the dominant ear, rather than approximating the virtual pitch predicted through harmonic fusion. Because this theory predicts neither a split percept consisting of two spectral pitches nor a single percept equivalent to the virtual pitch, the suppression model is, therefore, inconsistent with repeated observations concerning the pitch of harmonic complex tones (Houstma, 1979; Houstma & Goldstein, 1972).

One difficulty with current pitch theories, however, is that they provide no immediate explanation for the pitch alternation of the octave illusion. Instead, previous observations concerning the pitch of two-tone harmonic complexes suggest that the illusion should be heard as a single unchanging pitch at F_0 . Since this perception does not occur in the majority of listeners, one might be tempted to conclude that, ipso facto, the alternation of pitch during the octave illusion provides evidence for a suppression mechanism that supercedes normal harmonic fusion. Chambers et al. (2002), however, suggested an alternative explanation involving a combination of harmonic fusion and an interaural asymmetry in which the same stimulus is perceived as a different pitch in one ear than in the other (known as *binaural diplacusis*, or *interaural pitch difference*; see Stevens & Egan, 1941; van den Brink, 1965, 1970a, 1970b, 1975a, 1975b, 1979; Ward, 1963). They observed that, for most listeners tested, the pitch difference during the octave illusion was less than the octave alternation predicted by the suppression of frequencies in the nondominant ear (see Figure 1). Further analysis indicated that the phenomenon of binaural diplacusis could evoke a pitch difference between alternate dichotic octaves, independently of sequential interactions. The authors noted that the higher pitch dichotic octave usually contained components that were perceived as higher in pitch than the same components in the opposite ear. For example, a listener who heard a 400-Hz tone as higher in the left ear than in the right ear, but an 800-Hz tone as higher in the right ear than in the left ear, perceived a dichotic octave of 400-Hz-left–800-Hz-right (400L800R) as higher in pitch than a dichotic octave of 800L400R.

The performance of listeners in a discrimination task has provided further evidence of harmonic fusion during the octave illusion (Chambers et al., 2002). Chambers et al. noted that when listeners were required to detect deviants of 400 or 800 Hz embedded in an illusion sequence, the 400-Hz deviant was always more difficult to discriminate, irrespective of whether this deviant replaced the high- or the low-pitch percept (see Figure 2). The authors interpreted this result as evidence that both the high and the low pitches of the octave illusion more closely approximate 400 than 800 Hz and, thus, that harmonic fusion mechanisms, in combination with binaural diplacusis, can evoke small differences in the virtual pitch of alternate dichotic octaves.

In summary, it can be seen that the suppression model conflicts with literature on the perception of harmonic complex tones. Deutsch (1978, 1980a, 1980b, 1988) has suggested that this unique suppression relationship depends on sequential interactions between alternate dichotic octaves—a proposition that will be considered in section 4. Recent results by Chambers et al. (2002), however, have suggested an alternative explanation for the pitch variation during the octave illusion that is both consistent with established mechanisms of harmonic fusion and independent of sequential interactions. Further predictions of this alternative fusion theory will be considered in section 6.

2. The Suppression Model Is Inconsistent With Literature on Auditory Localization

In section 1 of this article, we considered the discrepancy between the suppression model and literature on the pitch perception of complex tones. In the present section, we discuss the relationship between the localization postulate of the suppression model and literature on auditory localization. Recall that, according to the suppression model, listeners perceive a change in location during the octave illusion as the result of a localization mechanism that skews the apparent position of the percept toward the higher frequency tone in each dichotic octave. The present discussion focuses on the unique nature of the high-frequency localization dominance proposed by the suppression model, which is neither predicted by established principles of sound localization nor clearly evident in similar illusions of auditory localization. Furthermore, recent data have shown that many listeners localize the illusion percept toward the *lower* frequency component in the illusion sequence, which indicates that a high-frequency localization dominance mechanism is inadequate to explain the shifts of apparent location (Chambers et al., 2002).

These issues are considered in two subsections. In subsection 2.1 we review established theories concerning sound localization in the horizontal plane. Unlike the suppression model, these theories do not suggest that the apparent position of a sound source in azimuth is determined by its frequency. In subsection 2.2, we consider three potentially related phenomena: *binaural interfer-*

Figure 2. The capacity to discriminate 400- and 800-Hz deviants from an octave illusion sequence, as obtained by Chambers, Mattingley, and Moss (2002). The detection cost in milliseconds, relative to ceiling performance, is plotted as a function of the expected pitch percept of the octave illusion. Results are collapsed across 7 listeners. Note that the 400-Hz tone was always more difficult to discriminate, irrespective of whether it replaced the high or the low pitch. This result implies that both high and low pitches in the illusion more closely approximate 400 Hz than 800 Hz. Error bars are ± 1 standard error of the means. (Figure replotted from Chambers et al., 2002.)

ence, the *precedence effect*, and the *Franssen effect*. Current evidence suggests that where localization is influenced by frequency, it is *low-frequency*, rather than high-frequency, stimuli that are likely to be dominant; thus, these illusions contrast with the high-frequency dominance proposed by the suppression model.

2.1 Auditory Localization in the Horizontal Plane Is Not Based on Frequency

Since the early work of Lord Rayleigh (1876, 1907), interactions between inputs from the two ears have been regarded as critical to the localization of sound in the horizontal plane.² Sounds that are emitted from lateral positions provide two principal cues. First, the ear closer to the source receives information first, resulting in an interaural time difference (ITD). Second, scattering of the wave by the shoulders, head, and pinnae attenuates the pressure level of the sound (SPL) received by the ear further from the source, resulting in an interaural pressure level difference (ILD; Kuhn, 1987). For the localization of pure tones, these cues are most effective in different frequency ranges: ITDs generally dominate perceived location at low frequencies (<1500 Hz), whereas ILDs are the dominant cue at higher frequencies (see Cohen & Knudsen, 1999, and A. W. Mills, 1972, for reviews).

The situation for complex sounds, however, is quite different. A significant body of evidence suggests that

as the frequency of complex sounds is increased, the envelope of the waveform, rather than the waveform fine structure, becomes more important in determining location (Bernstein & Trahiotis, 2002; Colburn & Esquissand, 1976; Hafter & DeMaio, 1975; Hafter & Ricard, 1973; Harris, 1960; Henning, 1974a, 1974b, 1980; McFadden & Pasanen, 1976; Nuetzel & Hafter, 1976; Young & Carhart, 1974). This effect emerges because the peripheral auditory system acts as a low-pass filter, preserving the low-frequency information in the waveform envelope more effectively than the high-frequency information in the fine structure (Bernstein & Trahiotis, 1996, 2002; Colburn & Esquissand, 1976). Nevertheless, lateralization discrimination is degraded for high-frequency complex sounds that are *high-pass* filtered (Yost, Wightman, & Green, 1971). Thus, information from both the fine structure and the temporal envelope of complex sounds appears to be necessary for the auditory system to derive the maximum benefit from timing cues.

From this brief consideration of horizontal sound localization, it is clear that the apparent location of both simple and complex stimuli is not determined by frequency. Therefore, the principles of sound localization do not provide a theoretical basis for the high-frequency localization dominance proposed by the suppression model. To determine potential alternative explanations for high-frequency dominance, it is necessary to con-

sider links between the suppression model and related illusions of auditory localization.

2.2 The Suppression Model Is Inconsistent With Theories of Related Illusions

Psychoacoustic investigations have revealed several localization phenomena that share certain characteristics with the lateral shifts observed during the octave illusion but are inconsistent with the suppression model. In the subsections that follow, three of these phenomena will be considered: *binaural interference*, the *precedence effect*, and the *Franssen effect*. In each case, potential links between these phenomena and the octave illusion will be explored.

2.2.1 Binaural interference. Binaural interference refers to the disruptive influence on the discrimination of interaural delays in one stimulus by a simultaneous, or near simultaneous, diotic distractor stimulus (see Stellmack & Dye, 1993, for a review). McFadden and Pasanen (1976) were perhaps the first to report this phenomenon. These authors compared ITD discrimination for narrow-band noises across five conditions, including (1) a delayed 500-Hz noise in isolation, (2) a delayed 500-Hz noise with a simultaneous 4000-Hz diotic noise distractor, (3) a delayed 4000-Hz noise in isolation, (4) a delayed 4000-Hz noise with a simultaneous 500-Hz diotic distractor, and (5) both 500- and 4000-Hz noises delayed by the same amount in the same direction. The most striking finding was that a 500-Hz diotic distractor impaired ITD discrimination of a 4000-Hz target, relative to the 4000-Hz target presented in isolation. However, this effect was shown to be asymmetrical, with no apparent interference of a 4000-Hz distractor on a 500-Hz target.

McFadden and Pasanen (1976) attributed this asymmetry to a floor effect, suggesting that ITD discrimination was optimal for the 500-Hz target and, thus, unable to be influenced by the distractor, but that above-floor performance for the 4000-Hz target left room for distraction by a low-frequency stimulus. Zurek (1985) has since suggested that binaural interference may originate from binaural fusion, with low frequencies more heavily weighted than high frequencies in determining the apparent location of the fused image. Consistent with this general notion, Bernstein and Trahiotis (2001) have suggested that the asymmetrical effects of binaural interference reflect differences in the peripheral processing of low- versus high-frequency complex sounds (see section 2.1). They suggested that the improved sensitivity to changes in ITD at low frequencies (1) results in an increased weight ascribed to low-frequency information relative to high-frequency information in localization based on ITD and (2) thus confers asymmetry of binaural interference, with low-frequency distractors more effective at interfering with high-frequency ITD discriminations than vice versa. The general suggestion that low-frequency stimuli have a greater *localization strength* than do high-frequency stimuli has also been advanced by Divenyi (1992) and will be revisited in section 2.2.2.

The apparent dominance of low-frequency stimuli in binaural interference, however, is perhaps not as clear as the studies by McFadden and Pasanen (1976) and Bernstein and Trahiotis (2001) suggest. Dye (1990), for instance, generated three-tone complexes centered on 750 Hz in which one or more components were delayed, with the remaining component(s) presented diotically. When the components in each complex were separated by 250 Hz or less, discrimination of the delayed target(s) was most impaired when only the mid-frequency component was delayed. However at a spacing of 450 Hz, ITD thresholds were highest when only the *low-frequency* component was delayed. These findings are inconsistent with the suggestion that binaural interference should be maximal for *high-frequency* discriminations combined with *low-frequency* distractors.

At least qualitatively, a parallel might be drawn between the mechanisms that give rise to binaural interference and those that result in the lateralization of dichotic octaves during the octave illusion. In each case, a lateralized percept may be evoked that is a *weighted average* of the spatial cues provided by the different spectral components. Could the spectral dominance observed by McFadden and Pasanen (1976), Zurek (1985), and Dye (1990) be analogous to mechanisms that skew the lateralization of dichotic octaves toward the higher or lower frequency components during the octave illusion? The variable nature of spectral dominance in binaural interference highlighted by Dye suggests that if this claim is correct, there may be substantial variability across listeners in the direction of spectral dominance for the lateralization of dichotic octaves, and that the direction of spectral dominance could differ depending on the frequency difference between ears. Although the suppression model maintains that listeners who perceive the octave illusion exhibit high-frequency dominance, evidence has emerged recently for such variability. Chambers et al. (2002) reported that of 15 listeners, 9 localized the illusion percept toward the lower frequency component (400 Hz), and 6 localized the percept toward the higher frequency component (800 Hz).

The observations by Chambers et al. (2002) contrast with the direction of spectral dominance observed by Deutsch (1974; see also Deutsch & Roll, 1976). The reasons for this discrepancy are not currently clear. Note, however, that listeners in most experiments on the octave illusion have been either preselected on the basis of exhibiting high-frequency localization dominance (e.g., Deutsch, 1978, 1988) or classified as perceiving the illusion without the direction of spectral dominance being measured (e.g., Akerboom, ten Hoopen, & van der Knoop, 1985; McClurkin & Hall, 1981; Ross, Tervaniemi, & Näätänen, 1996). Thus, variability in the direction of spectral dominance during the octave illusion may have gone unnoticed in previous studies.

2.2.2 The precedence effect. The successive presentation of two binaural sounds often results in the perception of a single fused image, particularly if the stimulus dura-

tion and interstimulus interval (ISI) are brief. The *precedence effect* refers to the observation that localization cues in the leading signal of the stimulus pair dominate the apparent position of the fused image, relative to those contributed by the lagging signal (Haas, 1951; Wallach, Newman, & Rosenzweig, 1949). This phenomenon is generally interpreted as evidence for a mechanism that suppresses the perception of echoes, thus reducing confusion regarding the location of sound sources in reverberant environments (e.g., Lindemann, 1986; for reviews, see Blauert, 1997, Litovsky, Colburn, Yost, & Guzman, 1999, and Zurek, 1987).

If the precedence effect arises from an echo suppression mechanism, one might assume that the phenomenon would be stronger when the leading and the lagging signals are spectrally alike, as they would be in nature. Divenyi (1992) examined this question in an experiment that included the presentation of two successive binaural noises via headphones. In this study, the lag frequency was fixed at 2000 Hz, while the lead frequency was varied between 500 and 3000 Hz. Contrary to the echo suppression hypothesis, the precedence effect was strongest when the lead frequency was *lower* than the lag frequency, suggesting that some other factor was involved. Divenyi pointed out that the easier lateralizability of lower, rather than higher, frequency narrow-band noise may facilitate a *localization masking effect* (see also Blauert & Divenyi, 1988). Under this interpretation, the precedence effect arises from the relative salience of the lateralization cues in the leading stimulus, as compared with those of the lagging stimulus, rather than from their spectral relationship. Thus, leading stimuli that are more easily localized are more effective at *masking* the localization cues, but not the spectral information, provided by the lagging stimuli.

Qualitatively, the dominance of low-frequency stimuli in the precedence effect is similar to the low-frequency dominance that has been observed in binaural interference (Heller & Trahiotis, 1995; McFadden & Pasanen, 1976; Yang & Grantham, 1997; Zurek, 1985). In each case, spectral dominance may arise from the greater localization strength of lower frequency signals. With these observations in mind, how might the precedence effect relate to lateral shifts during the octave illusion? Although both phenomena involve a localization percept that appears to be influenced by frequency, the direction of spectral dominance in the precedence effect is the opposite of that assumed by the suppression model. Note, however, that studies in which the precedence effect has been examined have used stimuli that differ in several ways from the stimuli that elicit the octave illusion (Divenyi, 1992; Shin-Cunningham, Zurek, Durlach, & Clifton, 1995). For instance, the signals used by these workers were narrow-band noises, rather than pure tones, and were delivered asynchronously. The extent to which these differences could influence the direction of spectral dominance remains unclear. Nevertheless, the general pattern

of spectral dominance observed in the precedence effect is inconsistent with the high-frequency localization dominance proposed by the suppression model of the octave illusion.

2.2.3 The Franssen effect. Divenyi (1990a, 1990b) has suggested a potential link between the octave illusion and a mislocalization phenomenon known as the Franssen effect. This illusion is elicited by the simultaneous presentation of two spectrally identical sounds (A and B) from different spatial locations. Sound A is presented with a sudden onset and decays over the next 50 msec to zero. At the same time, Sound B is presented with a 50-msec rise time, so that it peaks at the moment that Sound A disappears. Sound B then remains at the peak amplitude for several seconds. Under certain conditions, listeners perceive a single percept from the speaker that emitted Sound A, even after Sound A disappears and Sound B is the only incident stimulus. This illusion is so compelling that the speaker that previously emitted Sound A can be physically removed from the room and listeners will continue to localize the percept toward its previous source (Yost, Mapes-Riordan, & Guzman, 1997). Franssen (1962; cited in Hartmann & Rakerd, 1989) suggested that this mislocalization phenomenon arises from the dominance of onset cues, as compared with steady-state cues, in sound localization mechanisms. The localization cues associated with the sudden onset of Sound A thus override the continuous and conflicting cues provided by Sound B, even when Sound A no longer exists.

Divenyi (1990a, 1990b) has suggested that lateralization shifts during the octave illusion may arise from an interaction between cross-correlation localization mechanisms and a Franssen-type effect. He pointed out that the cochlear traveling wave induced by an 800-Hz tone in one ear should peak earlier and with greater intensity than the wave induced by a simultaneous 400-Hz tone in the other ear should. Invoking a Franssen-type effect, Divenyi's model predicts that the 800-Hz tone should provide a positional onset cue that precedes and dominates both the 400-Hz onset cue and the weaker steady-state cues contained in both signals. The result is that the apparent position of the dichotic percept should always be skewed toward the higher frequency (800-Hz) component within each dichotic octave.

Although Divenyi's (1990a, 1990b) theory is parsimonious, there are reasons to question the model in its current form. First, the Franssen effect declines as the angular separation between signals is increased and disappears completely when the stimuli are presented over headphones (see Hartmann & Rakerd, 1989). By contrast, the octave illusion appears to be elicited most clearly via headphones (Deutsch, 1974, 1975). Second, the lateralization bias that Divenyi (1990a, 1990b) proposed is insensitive to the frequencies in each ear; thus, a two-tone dichotic complex should always be lateralized toward the signal with the higher frequency. In contrast, dichotic chords of 1500 and 1900 Hz are generally localized cen-

trally, as are single dichotic octaves by some listeners (Efron & Yund, 1974; Lamminmäki & Hari, 2000). Note also that Chambers et al. (2002) observed lateralizations toward the lower frequency component (400 Hz) within dichotic octaves.

2.2.4 Summary. In section 2.2 we considered the relationship between the octave illusion and several similar phenomena, including binaural interference, the precedence effect, and the Franssen effect. This discussion highlights the unusual nature of spectral dominance proposed by the suppression model: an invariable high-frequency localization dominance that contrasts with either low-frequency dominance (precedence effect) or mixed dominance (binaural interference) in other illusions. Recent evidence suggests that the direction of spectral dominance in the octave illusion is more variable than is assumed by the suppression model (Chambers et al., 2002), which opens a potential avenue for reconciling the localization shifts of the octave illusion with other binaural phenomena. A possible amalgamation of these mechanisms will be considered in section 6.

3. The Suppression Model Is Inconsistent With Literature on Ear Dominance

In sections 1 and 2 of this review, we considered discrepancies between the suppression model and theories of pitch perception and sound localization. In the present section, we consider the relationship between the suppression model and an extensive literature on ear dominance effects. The pitch predictions of the suppression model are closely related to literature on ear dominance, which suggests that the pitch of an inharmonic dichotic complex is often skewed toward the frequency in one ear.³ However, despite this apparent theoretical derivation, there are notable differences between the two conceptual frameworks. In the following discussion, key elements of this inconsistency will be considered, with a focus on ear dominance paradigms that share the greatest similarity with the conditions that elicit the octave illusion. Note also that for the purposes of the present discussion, the terms *suppression* and *dominance* refer to opposite manifestations of the same theoretical mechanism.

Efron and Yund (1974) reported perhaps the first evidence for ear dominance involving pure tones. They presented listeners with two inharmonic dichotic chords, each of 50-msec duration. The first chord consisted of a 1500-Hz tone in one ear presented simultaneously with a 1900-Hz tone in the other ear. The second chord comprised the same stimuli, but with the frequencies reversed between ears. Following the presentation of both chords, listeners decided whether a high pitch followed a low pitch or vice versa. This task was undertaken with the relative intensities of the left and the right ears equivalent or with the signals in one ear attenuated by 10–50 dB. Ear dominance in this task was inferred by correlating the reported pitch sequence with the sequence of frequencies

presented in each ear. The authors assumed that the sequence of correlated frequencies was equivalent to the perceived pitch and, thus, that the ear receiving these frequencies was *dominant* for determining the pitch of each dichotic complex (although, as will be seen, this interpretation later changed). Variations in the consistency of subjective reports, as a function of changes in the relative intensity of the stimuli between the ears, were plotted as a psychometric function, as is shown in Figure 3. This method will subsequently be referred to as the *two-trial subjective report* (TTSR) technique.⁴

The central finding from Efron and Yund's (1974) study was that pitch reports tended to correlate with the sequence of frequencies in one ear even when the signals in this ear were significantly attenuated relative to those in the opposite ear. However, when forced to decide whether a particular trial pair moved from left to right or from right to left, listeners' reports followed the amplitude relationships closely. This result suggested that one ear (usually the left) was dominant for pitch but was not dominant for lateralization. According to the explanation proposed by the authors, this divergence of mechanisms resulted in an auditory illusion in which the *dominant* ear determined the pitch, but in which the amplitude relationship *between* ears determined the apparent position of this pitch.

Yund and Efron (1975) followed up their initial investigation in a larger sample of 70 listeners, using the same TTSR method and stimulus parameters, but with stimuli that were presented for longer (320 msec) than previously (50 msec; see also Efron & Yund, 1975). One observation to emerge from this study was the phenomenological complexity of the perception. Although listeners were forced to decide whether a single high pitch followed a single low pitch (or vice versa), listeners often perceived more complex sounds that did not fit either choice. For example, some listeners perceived both stimuli in each chord and, thus, perceived both left and right sequences independently. It is not clear how listeners might have responded under these circumstances, because the pitch sequence would be simultaneously both of a *low-high* and a *high-low* type. Yund and Efron suggested that when able to hear more than one stimulus on each trial, listeners based their pitch reports "on the tonal sequence which was 'louder,' 'more obvious,' or 'more salient'" (p. 140). Several factors, including response bias and selective attention, could influence the internal state that determines this decision. For instance, exposure to repeated *split* sequences could encourage listeners to attend to one ear or the other (to resolve confusion) and, thus, to report the pitch sequence in this ear only. Such an attentional bias could enhance the perceptual salience of the tones in one ear and would, therefore, be indistinguishable from an ear dominance effect.

Recognizing the potentially confounding role of attentional bias, Gregory, Efron, Divenyi, and Yund (1983) conducted an investigation of ear dominance in which perceptual segregation was prevented by reducing the fre-

Figure 3. A typical *ear dominance* function obtained using the two-trial subjective report technique. The percentage of pitch reports (triangles) and lateralization reports (circles) that correlate with the sequences in the left and right ears are shown. The magnitude of ear dominance is calculated as the SPL difference necessary to remove the correlation between subjective reports and the sequence in each ear (22 dB). (Figure replotted from Efron & Yund, 1974.)

quency difference within each dichotic complex to sub-threshold levels. Dichotic chords were presented with a center (or average) frequency of 200, 400, 600, 800, or 1700 Hz and with the frequency difference between ears maintained in such a way that the ratio of the frequency difference to the center frequency was 0.03. Thus, for the 200-Hz center frequency, the chord consisted of 197 and 203 Hz, for the 400-Hz center frequency, 394 and 406 Hz, and so on. The dichotic frequency differences were selected on the basis of a study by Odenthal (1963), which reported that if the ratio of the difference to the center frequency was equal to or less than 0.03, listeners always reported a unitary percept whose pitch was roughly equivalent to the average frequency of the complex. Above a ratio of 0.03, listeners in Odenthal's experiments reported a more complex stimulus with distinct pitch components. Note that for all previous investigations of ear dominance, this ratio was always set higher than 0.03 (0.058 – 0.235).

Listeners in Gregory et al.'s (1983) first experiment matched the frequency of a diotic pure tone to the pitch of the various dichotic chords, each of which was presented for 320 msec, and at an equivalent intensity in each ear. The results of this experiment are presented in Figure 4. For 3 listeners, the pitch of the intertone was biased up to 60% in the direction of the frequency in one ear. Thus, even with dichotic segregation prevented, ear dominance remained. Note, however, that the pitch of the intertone was never *equivalent* to the frequency in one ear or the other. This result contrasts with the assumption

of the suppression model that “only the frequencies arriving at one ear are heard” (Deutsch & Roll, 1976, p. 24) and, thus, that the pitch variation in the octave illusion arises from complete ear dominance.

In a second experiment, Gregory et al. (1983) had listeners perform the same task, but with amplitude differences of up to 80 dB introduced between the signals in each ear. The pitch matches for 3 listeners were skewed 20% toward the frequency in one ear, even when the SPL of the signal in this ear was attenuated by 50 dB, relative to the tone in the opposite ear. At smaller interaural level differences, the dominance of one ear was greater, peaking at around 60%. From these results, Gregory et al. concluded that neither ear dominance, nor the intensity independence of ear dominance can be explained solely by attentional bias. However, as the authors admit, the effects of attention cannot be excluded when *two* pitch components are heard for each dichotic chord, as may often have been the case in previous investigations.

From this review of ear dominance for pure tones, several concluding points may be made. First, ear dominance is unlikely to be driven solely by unilateral attentional bias, but involuntary mechanisms may be augmented by selective attention when listeners are able to segregate the tones in each ear. Second, when listeners perceive a single pitch, this pitch is unlikely to be *equivalent* to the frequency in the dominant ear but, rather, appears to be the result of a fusion *weighted* toward this frequency (Gregory et al., 1983). In this way, both the mechanisms of harmonic fusion dis-

Figure 4. Pitch-matching results obtained by Gregory, Efron, Divenyi, and Yund (1983) for 4 listeners. The ordinate plots the normalized pitch match of the diotic pure tone to the dichotic chord, on a scale ranging from the frequency in the left ear (+1.0) to the frequency in the right ear (−1.0). Note that the perceived pitch is never equivalent to the frequency in one ear. (Figure replotted from Gregory et al., 1983.)

cussed in section 1, and the ear dominance effects reviewed in the present section may be encompassed under a single fusion mechanism that operates differently on harmonic and inharmonic complexes. In contrast, ear dominance according to the suppression model requires complete suppression of frequency information, because the pitch is determined solely by the frequency in one ear. Therefore, this theory is inconsistent with observations of ear dominance. Furthermore, by suggesting that the pitch of a two-tone *harmonic* complex tone may be dominated by the frequency of the upper partial, the suppression model is inconsistent with literature on pitch perception reviewed in section 1. The suppression model is, therefore, incompatible with the notion of dichotic fusion.⁵

4. Evidence for Suppression and Sequential Interactions Is Confounded by Potential Response Bias

Thus far, this review has focused on inconsistencies between the suppression model and the literature on pitch perception, sound localization, and ear dominance. To account for these discrepancies, Deutsch (1978, 1980a, 1980b, 1988) has suggested that the octave illusion depends critically on sequential interactions between the tones. Specifically, she has suggested that sequential interactions increase the magnitude of ear dominance for pitch and facilitate high-frequency localization dominance. As the cornerstone of the suppression model, the

role of sequential interactions warrants close examination. In the present section, we consider three landmark articles that have claimed to provide evidence for a link between suppression and sequential interactions. We suggest that, in each case, methodological limitations cast doubt on the conclusion that the octave illusion is influenced by sequential interactions. Furthermore, recent studies by Lamminmäki and Hari (2000) and Chambers et al. (2002) have suggested that the perception of the octave illusion may be explained entirely by simultaneous interactions *within* dichotic octaves.

4.1 Lateralization and Sequential Interactions

The link between the suppression model and sequential interactions was first outlined by Deutsch (1978). In this investigation, listeners were presented with alternating sequences of dichotic octaves and decided whether each sequence began with a left percept and ended with a right percept or vice versa. Throughout this task, the relative amplitudes of the lower and higher frequency components were parametrically varied to assess the level of *frequency dominance* for lateralization. This procedure is, therefore, analogous to the TTSR method adopted by Efron, Yund, and colleagues. Over three experiments, 4 listeners undertook the TTSR task for sequences containing 20 alternating dichotic octaves and for sequences containing only 2 dichotic octaves (two-trial condition). Deutsch proposed that if sequential interactions influence the lateralization tendency during

the octave illusion, listeners should lateralize toward the *dominant* frequency more consistently when more tones are presented. The author also introduced a condition in which listeners decided, for an alternating sequence of 20 tones, whether a diotic 400-Hz complex seemed louder than a diotic 800-Hz complex. This treatment was included to determine whether any lateralization effects could be attributed to subjective loudness differences between the two frequencies.

The average results from Deutsch's (1978) experiment are presented in Figure 5A; individual results for each of the 4 listeners are shown in Figures 5B–5E. The abscissa of each figure is the SPL difference between the 400- and the 800-Hz signals, with a positive value indicating that the 400-Hz tone was more intense. Note that when the 400- and 800-Hz signals were of equal amplitude, listeners were approximately 20% more consistent in making lateralization judgments for longer sequences than in the two-trial condition. As the amplitude of the 400-Hz tone was increased in each dichotic octave, lateralization reports in the two-trial condition and loudness judgments in the diotic condition tended to follow the amplitude relationships closely (compare the open circles and open triangles). However, lateralization reports for the longer sequence condition (closed circles) remained correlated with the ear receiving the 800-Hz tone until the 400-Hz tone was ~12 dB louder. On this basis, Deutsch (1978) concluded that sequential interactions reinforce lateralization by frequency and that these lateralization effects cannot be attributed to subjective loudness differences between the frequencies in each dichotic octave.

Although influential, Deutsch's (1978) interpretation contains several potential problems. Most of these arise from the assumption that the consistency of subjective reports can be directly related to the perception of the illusion—a premise that ignores the influence of response bias and decision noise. For instance, by varying the number of tones in each sequence, Deutsch (1978) varied the amount of information delivered to her listeners. Consider the results when the 400- and the 800-Hz tones were of equivalent amplitude (Figure 5A). In this condition, the presentation of 20 stimuli (as compared with 2) increased the consistency of lateralization reports by about 20%, which the author interpreted as evidence for stronger lateralization by frequency. However, this result could just as easily reflect an increase in the *certainty* of a lateralization decision without altering lateralization at all, by providing listeners with more information on which to base their response. In terms of signal detection theory, an increase in response consistency for the longer illusion sequence could be explained by a reduction in decision noise as the number of observations is increased (Macmillan & Creelman, 1991).

The perceptual correlation between the pitch shift and the lateralization shift is equally problematic. Note that the listeners in Deutsch's (1978) study were preselected on the

basis of perceiving a high pitch in the right ear, alternating with a low pitch in the left. The perceived pitch could, therefore, be used to maintain a more consistent pattern of responses when the lateralization was in doubt. For example, if the sequence was of a high–low–high–low type, the listener might be more inclined to identify the sequence as a right–left–right–left type, particularly for longer sequences in which the correlation between these two perceptual characteristics is reinforced.

In a later study of sequential interactions and lateralization, Deutsch (1988) examined whether the consistency of subjective reports depended on whether the frequency presented to one ear was the same as the frequency presented to the opposite ear on the previous trial. Using a similar TTSR method, she presented listeners with three types of sequence, each containing 20 tones, with the same parametric variations of interaural intensity and the same response measure as previously (Deutsch, 1978). These conditions included (1) the standard octave illusion sequence, consisting of an alternating series of 400/800-Hz dichotic octaves; (2) the same sequence, but with frequencies of 600/1200 Hz; and (3) a sequence in which the 400/800-Hz octave alternated continuously with a 600/1200-Hz octave. The results of this experiment are shown in Figure 6.

The pivotal result from Deutsch's (1988) experiment was that the percentage of lateralization reports that correlated with the ear receiving the higher frequency tone was significantly greater in the standard octave illusion condition than when dichotic octaves were alternated in absolute register (Condition 3). On this basis, Deutsch concluded that “the strong tendency to lateralize toward the higher frequency signal in the octave illusion depends, in part, on the two ears receiving the same frequencies in succession” (p. 367). Once again, however, this interpretation is questionable. Because the perceived pitch and the lateral position are always correlated during the octave illusion, the pitch alternation may have encouraged response bias toward a lateralization report that was *consistent* with the pitch percept, despite there being no actual change in lateralization. With the dichotic octaves alternated in absolute register, this pitch *anchor* would be removed, thus explaining the less consistent subjective reports in Condition 3 than in Condition 1. As with Deutsch's (1978) earlier study, this limitation arises from the fundamental inseparability of subjective report consistency from response bias.

In addition to the logical arguments against Deutsch's (1978, 1988) conclusions, there is empirical evidence that sequential interactions are not necessary to induce lateralization of dichotic octaves. For instance, in a study by Lamminmäki and Hari (2000), several listeners lateralized a single dichotic octave of 400- and 800-Hz tones toward the right or the left, depending on the frequency configuration. In addition, Demany and Semal (1988) reported an instance in which the upper partial of a single dichotic octave “disappeared” for 1 listener. Furthermore,

Figure 5. The pattern of subjective lateralization reports obtained by Deutsch (1978), averaged across the sample (A) and for each of 4 listeners (B–E). In each panel, the percentage of reports that correlated with the ear receiving the low-frequency (400-Hz) tones is plotted as a function of the relative amplitudes of the two frequencies. Lateralization reports for sequences containing 2 dichotic octaves (open circles) and 20 dichotic octaves (closed circles) are shown. Open triangles denote the percentage of reports that the 400-Hz tone was subjectively louder than the 800-Hz tone. Error bars are ± 1 standard error of the means. (Figure replotted from Deutsch, 1978, and Deutsch, 1981; error bars added.)

Chambers et al. (2002) noted that 12 of 15 listeners lateralized single dichotic octaves in the same direction, whether the dichotic octave was presented alone or in an alternating sequence. Finally, Deutsch's (1988) results in-

dicate that when dichotic octaves were alternated by absolute register, lateralization reports remained 25% more consistent than would be expected if no lateralization was occurring. Therefore, even ignoring the potential limita-

Figure 6. The pattern of subjective reports obtained by Deutsch (1988), collapsed across 8 listeners. The ordinate is the percentage of lateralization reports that correlated with the ear receiving the lower frequency in each dichotic octave. The percentage of reports is plotted as a function of the SPL difference between the low and the high frequencies, for each of the three sequencing conditions. Error bars are ± 1 standard error of the means. (Figure replotted from Deutsch, 1988; error bars added.)

tions in methodology, this result could be interpreted as lateralization during the octave illusion without continuous alternation of the same stimuli between ears.

4.2 Ear Dominance and Sequential Interactions

As mentioned previously, the concept of ear dominance under the suppression model is more extreme than that suggested by Efron and colleagues. To account for this divergence, the suppression model proposes that ear dominance for pitch, like lateralization by frequency, is strengthened by sequential interactions. In an influential study, Deutsch (1980a) conducted several experiments that addressed the relationship between ear dominance and sequential interactions. The basic paradigm in this investigation was similar to the TTSR method employed in Deutsch's (1978, 1988) lateralization experiments, with the exception that instead of judging the starting and finishing *positions* of sequences, listeners reported the starting and finishing *itches*. Thus, a sequence might be reported as a high–low type or a low–high type. Throughout the experiments, the amplitude relationship between ears was parametrically varied to gauge the *strength* of ear dominance.

In Deutsch's (1980a) first experiment, sequences were presented under two conditions. Condition 1 was the standard octave illusion sequence, consisting of 20 alternating dichotic octaves of 400 and 800 Hz, each 250 msec in duration and without silent intervals. Condition 2 was a hybrid sequence in which a dichotic octave (400/800 Hz)

alternated with a dichotic minor third (504/599 Hz) and in which the higher and the lower frequencies in each complex were presented to opposite ears on successive trials. Under both conditions, listeners undertook the TTSR pitch task for each sequence, with the amplitude difference between the left and the right ears varied parametrically. Deutsch (1980a) hypothesized that if ear dominance depends on sequential interactions of the same dichotic stimulus, listeners should follow the sequence of frequencies in the dominant ear for Condition 1, but not for Condition 2. The results of this experiment for each of the 4 listeners are presented in Figure 7. As Deutsch (1980a) predicted, pitch judgments for Condition 1 (open circles) corresponded to the sequence in one ear, even when the tone in the opposite ear was 6–9 dB louder. In Condition 2, the listeners appeared highly inconsistent in their judgments and did not follow the amplitude relationships of the tones. Deutsch (1980a) showed that, in Condition 2 (closed circles), the listeners were following the melodic contour of the sequence by tracking either the higher or the lower frequencies within each dichotic complex.

In a second experiment, Deutsch (1980a) examined whether the harmonic change from an octave to a minor-third could have influenced the pitch reports in Experiment 1. In this experiment, listeners were presented with two dichotic octaves on each trial and judged the pitch order as low–high or high–low. In Condition 1, the sequence was one alternation of the standard octave illu-

Figure 7. Subjective reports obtained in Experiment 1 of Deutsch (1980a) for 4 listeners (initials marked in each panel). In each panel, the percentage of subjective pitch reports that correlated with the sequence in the listener's *nondominant* ear is plotted as a function of the SPL difference between ears. Open circles are the results in Condition 1 (standard octave illusion sequence). Closed circles are the results in Condition 2 (hybrid sequence of alternating dichotic octave and minor-third intervals). The sequence of frequencies presented to each ear is indicated in the legend. (Figure replotted from Deutsch, 1980a.)

sion (400L800R followed by 800L400R, and vice versa). In Condition 2, the sequence consisted of two dichotic octaves that shifted in absolute register. One subcondition consisted of 259L518R followed by 732L366R (including the reverse order and the reverse ear frequency assignment within each complex). The other subcondition was identical, except that the dichotic octaves consisted of 435 and 870 Hz and 308 and 616 Hz. As with Experiment 1, the amplitude was varied parametrically between the ears. The results of this experiment are presented for each of the 4 listeners in Figure 8. The data exhibited a very similar pattern to those in Experiment 1, with the pitch reports correlating with the sequence to one ear in Condition 1, but not in Condition 2. Deutsch again showed that listeners were following melodic contour in Condition 2, as might be expected if they were judging the pitch relationships by shifts in F_0 . She concluded, once again, that to establish ear dominance, each ear must receive the same frequencies in succession and that the phenomenon does not arise simply by alternation of the same harmonic interval.

In a final experiment, Deutsch (1980a) considered whether the absence of ear dominance in Condition 2 of Experiment 1 might have arisen not from the insertion of

a 504-/599-Hz dichotic complex into the octave illusion sequence, but from the resulting time interval between alternating dichotic octaves. Listeners undertook the same task as that in Experiment 2 under two different conditions. Condition 1 consisted of one alternation of a 400-/800-Hz dichotic octave with a 750-msec silent interval between the complexes. Condition 2 was identical to Condition 1, except that an irrelevant diotic 599-Hz tone was inserted between the two dichotic octaves (with listeners instructed to ignore this stimulus). The results of this experiment for each of the 4 participants are presented in Figure 9. Listeners appeared to follow the sequence in the dominant ear less consistently with the distractor inserted than with a silent interval. On this basis, Deutsch (1980a) concluded that ear dominance was reduced by the interpolated tone, but not by the silent interval. From the results of all three experiments, she suggested that ear dominance depends "critically on the frequency relationships between the tones as they occur in sequence at the two ears" (p. 227). She therefore concluded that ear dominance does not occur for alternating dichotic sequences in which the harmonic interval between ears is repeatedly switched (Experiment 1), the average frequency of the dichotic octave is changed (Exper-

Figure 8. Subjective reports obtained in Experiment 2 of Deutsch (1980a) for 4 listeners (including the author, D.D.). In each panel, the percentage of pitch reports that correlated with the sequence in the listener's *nondominant* ear is plotted as a function of the SPL difference between ears. Open circles are the results in Condition 1 (standard octave illusion sequence). Closed circles are the results in Condition 2 (alternation of dichotic octaves in different absolute register). The sequence of frequencies presented to each ear is indicated in the legend; note that the stimulus sequence shown for Condition 2 is limited to one of the subconditions. (Figure replotted from Deutsch, 1980a.)

iment 2), or an intervening distractor is inserted between dichotic octaves (Experiment 3).

Deutsch's (1980a) conclusions immediately appear inconsistent with the results of Efron and colleagues, who demonstrated ear dominance in single dichotic complexes without any sequential interactions (e.g., Efron & Yund, 1976; Gregory et al., 1983; see Yund, 1982, for a discussion). In addition, the potential influence of response bias casts doubt on Deutsch's (1980a) interpretation. Note, for instance, that the results for Condition 1 across all the experiments were almost always more consistent than the results in Condition 2, regardless of which ear was "followed" in Condition 1 (see Figures 7, 8, and 9). A response bias could explain these findings in several ways. Listeners may have maintained a consistent pattern of responses based on the distinctiveness of the trials in which large amplitude differences occurred between ears. Alternatively, listeners may have used the lateral position of the percept to anchor their responses to one mode of pitch response (analogous to the pitch anchoring suggested to be involved in Deutsch's [1978, 1988] lateralization studies). These factors weaken Deutsch's (1980a) interpretation that sequential interac-

tions are necessary for listeners to perceive a difference in pitch between alternate dichotic octaves.

4.3 Recent Findings Suggest No Effect of Sequential Interactions on the Octave Illusion

Chambers et al. (2002) conducted the first investigation of sequential interactions during the octave illusion in which an objective psychophysical measure was used. Listeners were presented with a dichotic complex tone and, in different blocks, decided which ear received the higher or lower frequency. This task was undertaken across three sequencing conditions: (1) a single dichotic complex presented alone, (2) a single dichotic complex presented at the end of a repeating sequence of the same dichotic complex, and (3) a single dichotic complex presented at the end of an alternating sequence in which the same complex was repeatedly reversed between the ears. The authors predicted that if sequential interactions influence the octave illusion, segregation performance for dichotic octaves would be poorer in the alternating sequence (3) than in the nonsequenced (1). This hypothesis followed from the prediction of the suppression model that sequential interactions enhance ear dominance for

Figure 9. Subjective reports obtained in Experiment 3 of Deutsch (1980a) for 4 listeners (including the author, D.D.). In each panel, the percentage of pitch reports that correlated with the sequence in the listener's *nondominant* ear is plotted as a function of the SPL difference between ears. Open circles are the results in Condition 1 (two alternating dichotic octaves separated by 750-msec interval). Closed circles are the results in Condition 2 (dichotic distractor inserted between two alternating dichotic octaves). The sequence of frequencies presented to each ear is indicated in the legend. (Figure replotted from Deutsch, 1980a.)

pitch, thus reducing the perceptual salience of the frequency in the nondominant ear and making the comparison between the inputs at the two ears more difficult. This result, however, was not obtained. Performance in the alternating sequence condition did not differ from performance in the nonsequenced condition, although both were significantly above chance. This study therefore provided no evidence that sequential interactions influence the simultaneous perceptual grouping of dichotic octaves.

4.4 Summary

Although influential, the claim that the octave illusion arises from the enhancement of suppression mechanisms by sequential interactions is open to several criticisms. First, evidence for sequential interactions is based on a paradigm that relies entirely on subjective reports and measures the success or failure of predictions from the *consistency* of these reports (Deutsch 1978, 1980a, 1988). Without the use of objective methods, there is no way of distinguishing subjective report consistencies from response bias. Second, a recent study by Chambers et al. (2002) has provided psychophysical evidence that the perception of dichotic octaves is unaffected by sequential alternating presentation. Finally, because the suppression model relies on the influence of sequential interactions to

explain inconsistencies with past literature on pitch perception, sound localization, and ear dominance, these concerns question the general validity of the suppression model.

5. Recent Electrophysiological Studies Do Not Support the Suppression Model

Having raised theoretical and empirical concerns about the validity of the suppression model, we now consider the contribution to this debate by recent electrophysiological studies. To our knowledge, only two investigations have combined an examination of the octave illusion with electrophysiological recordings. As will be seen, the results of both studies have implications for the suppression model.

Ross et al. (1996) conducted the first electrophysiological study of the octave illusion. Nine listeners were presented with an octave illusion sequence while event related potentials (ERPs) were recorded from various scalp locations. The ERP waveform of interest was the mismatch negativity (MMN), a negative potential recorded over primary auditory cortex (AI) that is elicited by any occasional and discriminable change in auditory stimulation, even when attention is focused elsewhere (Schröger,

1996). The authors monitored AI for the MMN while subjects listened passively to octave illusion sequences in which an occasional monaural deviant tone could occur. The deviant could be either *illusion consistent*, in which case the frequency and ear of reception were equivalent to the predicted percept according to the suppression model, or *illusion inconsistent*, in which case both the frequency and the ear of reception were the opposite of that predicted by the suppression model. For example, an illusion-consistent deviant that replaced the higher pitch heard on the right was a monaural 800-Hz tone in the right ear. The analogous illusion-inconsistent replacement, however, was an 800-Hz tone presented to the left ear.

Ross et al. (1996) reasoned that if the octave illusion arises below AI, presentation of the illusion-consistent deviant should not elicit the MMN, because the representation of the percept would be identical to that of the deviant at the site of ERP measurement. If, however, the octave illusion arises at or above AI, Ross et al. predicted that both illusion-consistent and illusion-inconsistent deviants would elicit the MMN, because the octave illusion sequence would still be represented with respect to its physical, rather than perceptual, characteristics and would, therefore, be encoded differently to both deviants.

Ross et al. (1996) obtained the MMN for all deviants and, on this basis, concluded that the octave illusion arises at or above AI. Their interpretation, however, presumes the validity of the suppression model: that the illusion-consistent deviant was *perceptually indistinguishable* from the octave illusion percept. If listeners were able to discriminate the illusion-consistent deviant from the octave illusion sequence, it is not surprising that the MMN was yielded in all conditions. Unfortunately, Ross et al. presented no data to suggest that the illusion-consistent deviant was, in fact, consistent with listeners' perception of the illusion. The presence of the MMN in their illusion-consistent condition might, therefore, represent a failure of the suppression model in assuming that the illusion pattern is *equivalent* to the frequencies presented to the *dominant* ear or the location of the *dominant* frequency.

Although the discriminability of deviants from the octave illusion percept has been examined in few studies, there is increasing evidence that Ross et al.'s (1996) assumption is unjustified. Sonnadara and Trainor (2002), for instance, inserted monaural deviants in the octave illusion sequence that were consistent with the predicted percept according to the suppression model. Critically, they noted that these deviants were perceived differently from the octave illusion percept on 99% of the trials. This recent finding is consistent with earlier informal observations by Efron, Koss, and Yund (1983). In addition, listeners in Experiment 4 of Chambers et al. (2002) discriminated 400- and 800-Hz deviant tones from the octave illusion at ceiling level. Thus, Ross et al.'s conclusion that the octave illusion arises at or above AI may be incorrect. Instead, their results could be interpreted

as adding electrophysiological evidence to the claim that the suppression model does not accurately reflect the phenomenology of the octave illusion.

In a more recent study, Lamminmäki and Hari (2000) used whole-scalp magneto-encephalography (MEG) to study neural correlates of the octave illusion. Listeners were presented with sequences that contained four types of stimuli: (1) a diotic 400-Hz tone, (2) a diotic 800-Hz tone, (3) a 400L800R dichotic octave, and (4) an 800L400R dichotic octave. These stimuli were presented for 500 msec each, separated by 1,330-msec silent intervals, matched for subjective loudness (rather than SPL) and combined in random order within sequences. The authors examined two MEG waveforms recorded from the auditory cortex: the N100m, a negative peak potential that occurs approximately 100 msec after stimulation, and the sustained field (SF), a negative plateau potential that begins after the N100m and continues for approximately 100 msec following stimulus offset.

Lamminmäki and Hari (2000) noted that the magnitude of the N100m was significantly higher for dichotic octaves in which the 800-Hz tone was presented to the ear contralateral to the recorded hemisphere. The magnitude of the SF, however, tended to be higher for dichotic octaves in which the 400-Hz tone was contralateral to the recorded hemisphere (although this trend was not significant). The authors also calculated the net difference between the SF and the N100m magnitudes for each dichotic octave and each hemisphere. Consistent with the N100m result, this analysis revealed that the SF – N100m difference was significantly greater for dichotic octaves in which the 800-Hz tone was presented to the ear contralateral to the recorded hemisphere. Following MEG testing, listeners were presented with a sequence of alternating dichotic octaves (without electrophysiological measurements) and reported the percept. Nine of the 11 subjects reliably reported a high pitch in one ear, alternating with a low pitch in the other ear.

From the N100m results, Lamminmäki and Hari (2000) suggested that, during the octave illusion, "the interhemispheric balance of the transient responses determines the perceived location of the sound" and that "the perceived pitch co-varies with the relative SF strength" (p. 1472). Two aspects of this interpretation, however, are questionable. First, although it has been established that monaural sounds elicit stronger N100m responses in the hemisphere contralateral to the side of stimulation (Hari, 1990), it has not been shown that their apparent position is caused by this difference in activation. Thus, to conclude that the lateralization percept during the octave illusion arises from asymmetrical cortical activation assumes a causal relationship between variables that have only been shown to correlate. Interhemispheric differences in cortical activation could just as easily reflect the output of a localization mechanism that operates at a lower level, consistent, for instance, with cellular networks in the brainstem that are involved in this function

(Irvine, 1986). Second, Lamminmäki and Hari's conclusion that the relative SF strength indexes the perceived pitch may be incorrect, because the SF – N100m difference also was correlated with the ear receiving the higher frequency and, thus, presumably was correlated with the apparent position. Lamminmäki and Hari's most robust finding appears to be that neural activity is increased in the hemisphere contralateral to the apparent location of a dichotic octave percept. Moreover, because the authors generated stimulus runs that did not include alternating dichotic octaves, their results add further evidence to the contention that sequential interactions are not necessary to induce differences in apparent location between alternate dichotic octaves.

6. Toward a Fusion Theory of the Octave Illusion

Five sections of this review have considered the suppression model in relation to theories of pitch perception for harmonic complex tones, auditory localization, ear dominance, evidence for sequential interactions, recent psychophysical evidence reported by Chambers et al. (2002), and electrophysiological studies of auditory cortex activation. Overall, this review demonstrates the inconsistency of the suppression model with a broad auditory literature. Furthermore, upon direct psychophysical examination, each of the three tenets of the suppression model described in the introduction has been brought into question (Chambers et al., 2002).

Although there is, at present, insufficient data to propose a definitive alternative to the suppression model, a considerable weight of evidence favors a fusion mechanism. A comprehensive fusion theory of the octave illusion must be able to explain three key aspects of the phenomenon: (1) the difference in pitch between alternate dichotic octaves, (2) the difference in apparent location between alternate dichotic octaves, and (3) the variability in the direction of spectral dominance for apparent location revealed by Chambers et al. (2002). As was noted previously, the effects of binaural diplacusis combined with harmonic fusion provide a possible explanation for small pitch differences between alternate dichotic octaves. In the following sections, the implications of this alternative hypothesis will be considered more formally within the framework of Terhardt's (1974, 1979) pattern-matching theory of pitch perception.

6.1 Modeling the Pitch Variation of the Octave Illusion

We modeled the pitch variation of the octave illusion according to Terhardt's (1974, 1979) pattern-matching theory of pitch perception (see also Terhardt, Stoll, & Seewann, 1982a, 1982b).⁶ Our principal objective was to determine whether the perception of the octave illusion could be predicted by established theory. Specifically, we sought to (1) calculate the relative perceptual salience of *spectral* pitches and *virtual* pitches in di-

chotic octaves, (2) correct the pitch outputs for binaural diplacusis between alternate dichotic octaves, and (3) examine the consistency of these pitch outcomes with both fusion and suppression accounts of the octave illusion.

Terhardt et al. (1982a, 1982b) formalized the extraction of spectral and virtual pitch into an algorithm that encompasses five principal stages. Initially, a sound is received by the auditory system, and the frequency spectrum is decomposed through a process that approximates Fourier analysis (Stage 1). Tonal components are then extracted from the sound (Stage 2), followed by an evaluation of masking effects, the listener's absolute threshold of hearing, and pitch shifts (Stage 3). The contribution of these tonal components to spectral pitch is then weighted according to their perceptual salience (Stage 4). Finally, the most salient virtual pitches are extracted through the fusion of the weighted spectral pitches (Stage 5). The outcome of this analysis is a pattern of spectral and virtual pitches and their accompanying weights.

A brief summary of the modeling procedure is described in section 6.1.1, and the results are reported in section 6.1.2. To anticipate, the modeling data support an explanation of the octave illusion in terms of dichotic fusion, rather than suppression. Specifically, Terhardt et al.'s (1982a, 1982b) model provides possible explanations for several aspects of the illusion percept, including spontaneous reversals and octave pitch variation.

6.1.1 Pitch-modeling procedure. In modeling the octave illusion, we began with Stage 3 because the quantity, frequency spectrum, and SPL of the tonal components in a dichotic octave are known and need not be derived.⁷ We considered the first eight subharmonics of 400 and 800 Hz as candidates for virtual pitch, with the tonal components presented at 70 dB SPL.⁸ The effect of binaural diplacusis was examined by inputting frequency values to the model that were adjusted against a veridical baseline of 400 or 800 Hz. Thus, a diplacusis bias in which the pitch of a 400-Hz tone was, for instance, 1% higher in the left ear than in the right ear was modeled as a 404-Hz input to the left ear. Similarly, the opposite diplacusis effect for 800 Hz (i.e., 1% higher in the right ear than in the left ear) would be modeled as an 808-Hz input to the right ear.

6.1.2 Pitch-modeling results without diplacusis.

The obtained spectral and virtual pitch weights for dichotic octaves without binaural diplacusis are presented in Figure 10. Panels A and B of Figure 10 show the results for a dichotic octave composed of 400- and 800-Hz tones, whereas panels C and D show the results for a dichotic octave composed of 800- and 1600-Hz tones. We consider first the obtained pitch weights for the 400-/800-Hz complex. The spectral pitch weights for both components are close to the maximum value of 1, with the 400-Hz component ($WS_u = 0.94$) weighted slightly higher than the 800-Hz component ($WS_u = 0.91$; Figure 10A). Although virtual pitch weights were obtained for all eight subharmonics of 400 Hz, the strongest virtual

Figure 10. Pitch-modeling results for a listener without binaural diplacusis. The upper panels describe the spectral (A) and virtual (B) pitch weights for a 400-/800-Hz dichotic octave. The lower panels describe the same results for an 800-/1600-Hz dichotic octave.

pitch corresponded to the first subharmonic (400 Hz, $W_{im} = 0.62$; Figure 10B). Thus, for a 400-/800-Hz dichotic octave that is perceived as a unitary percept, the predicted virtual pitch is always 400 Hz—the fundamental frequency. Note that, according to this model, the virtual pitch of a 400-/800-Hz dichotic octave can *never* be 800 Hz. This outcome is consistent with psychoacoustic evidence for harmonic fusion discussed in section 1 and with pitch measurements of dichotic octaves obtained by Chambers et al. (2002).

The equivalent results for the 800-/1600-Hz complex are shown in panels C and D of Figure 10. The spectral pitch weights are similar to those for 400/800 Hz, with the exception that the difference between the 800-Hz ($WS_\mu = 0.99$) and the 1600-Hz ($WS_\mu = 0.86$) weights is slightly larger. Again, virtual pitch weights were obtained for all eight subharmonics, but due to the higher frequencies of the components, the virtual pitch weights were substantially reduced, relative to the 400-/800-Hz stimulus. Note

also that the pitch weights for the first and second subharmonics (800 Hz, $W_{im} = 0.33$; 400 Hz, $W_{im} = 0.31$; Figure 10D) are quite similar, indicating the likelihood of perceptual uncertainty in virtual pitch. This result raises the intriguing possibility that octave-level pitch shifts during the octave illusion, such as those reported by Deutsch (1974), might arise because of octave ambiguity between virtual pitches, rather than from the suppression of frequency information. In this way, the probability of an octave pitch shift would be expected to *increase* as the difference in virtual pitch weights between the two most prominent virtual pitches is *decreased*.

Figure 11 presents two measures of this difference in virtual pitch weights: the net linear difference (solid line) and the proportional difference (dotted line). For the net difference function, the relative dominance of the higher virtual pitch decreases for dichotic octaves in which the lower frequency component is less than or greater than 350 Hz; thus, one would expect octave pitch shifts to

arise more readily when the octave illusion is elicited by either very low or very high frequencies. However, it is also conceivable that octave pitch shifts may depend on the proportional difference in pitch salience (dotted line). In this instance, the probability of octave pitch shifts would increase only for higher frequencies. Terhardt et al.'s (1982a, 1982b) model of pitch perception thus provides two key hypotheses concerning the role of virtual pitch ambiguity in the octave illusion: (1) that octave pitch shifts should exhibit a dependence on the frequencies used to elicit the illusion and (2) that octave pitch shifts should occur between the first and the second subharmonics of the *low*-frequency component, rather than between the spectral pitches of the low- and high-frequency components.

6.1.3 Pitch modeling results with diplacusis. The modeling results obtained under various conditions of binaural diplacusis are shown in Figure 12. Each row of panels in Figure 12 reports the pitch weights of the higher pitch dichotic octave for a different diplacusis condition (note that the ear frequency assignments in the legends are arbitrary and that the diplacusis magnitudes are calculated with respect to an alternate 400-/800-Hz dichotic octave). The left and right columns of Figure 12 indicate spectral and virtual pitch weights, respectively. Figures 12A and 12B show the modeling results for a diplacusis condition in which the pitch of the 400-Hz tone is 1% higher in the *left* ear than in the right ear and the pitch of the 800-Hz tone is 1% higher in the *right* ear than in the left ear. In this case, the equivalent magnitude of diplacusis between frequencies and the opposite direction

of diplacusis between ears evoke dominant spectral and virtual pitches at 404 Hz—the fundamental frequency. These virtual and spectral pitch predictions are consistent with the diplacusis patterns obtained by Chambers et al. (2002) and van den Brink (1975a, 1975b). Furthermore, the small predicted shift in virtual pitch is consistent with the suggestion that binaural diplacusis, in combination with harmonic fusion, can induce pitch variation between alternate dichotic octaves.

Figures 12C and 12D present a condition in which the direction of diplacusis is consistent with that in Figures 12A and 12B, but in which the *magnitude* of diplacusis differs between frequencies. These diplacusis magnitudes (0.3% for 400 Hz, 2.3% for 800 Hz) were taken from empirical measurements of Chambers et al. (2002, Experiment 2, Subject J.M.). Note that although the spectral pitch weights are consistent with earlier results, there are now *two* dominant virtual pitches: 401.2 Hz (the first subharmonic of the lower pitch tonal component, 401.2 Hz) and 409.2 Hz (the second subharmonic of the higher pitch tonal component, 818.4 Hz). This finding implies that, if perceived synthetically, the pitch difference between the higher and the lower pitch dichotic octave might oscillate for this listener between 0.3% (1.2 Hz/400 Hz) and 2.3% (9.2 Hz/400 Hz). Since most listeners do not exhibit identical magnitudes of diplacusis between ears (Chambers et al., 2002), the implication of this prediction is that the octave illusion pitch variation may be unstable for many individuals.

Figures 12E and 12F present a condition in which the magnitude of diplacusis is identical between frequen-

Figure 11. Two measures of the difference in pitch weights between the dominant and the second-most dominant virtual pitches, plotted as a function of the lower frequency in a dichotic octave (zero diplacusis assumed). The solid line is the net linear difference (ΔW_{im}) between the two pitch weights. The dotted line is the proportional difference between pitch weights, calculated relative to the weight of the dominant virtual pitch ($\Delta W_{im}/W_{im}$).

Figure 12. Pitch-modeling results for 400-/800-Hz dichotic octaves under three conditions of binaural diplacusis. Each row of panels corresponds to a different diplacusis condition. The left column of panels reports the obtained spectral pitches and their accompanying weights. The right column of panels displays the obtained virtual pitches and their accompanying weights. Panels A and B show the predicted results for a listener with a 1% diplacusis in which the direction between ears is opposite for 400- and 800-Hz tones. Panels C and D show the predicted results for a listener with the same pattern of diplacusis, but with uneven magnitudes between frequencies. Panels E and F show the predicted results for a listener with an equivalent magnitude of diplacusis between frequencies, but for whom both frequencies have a higher pitch in one ear than in the opposite ear.

cies, but in which the *direction* of diplacusis is biased toward one ear for both frequencies. The pivotal outcome in this instance is the presence of two dominant virtual pitches on either side of a 400-Hz fundamental frequency: 404 Hz (the first subharmonic of the lower pitch tonal component) and 396 Hz (the second subharmonic of the higher pitch tonal component). Note that this outcome implies a virtual pitch ambiguity in which the dichotic octave may oscillate between being higher (404 Hz) or lower (396 Hz) in pitch than an alternate dichotic octave (400 Hz; see Figure 10B). This result may explain occasional reports by listeners that the higher pitch during the octave illusion “reverses” to become lower in pitch, either spontaneously or through conscious intent (Chambers et al., 2002; Deutsch, 1975). If this explanation is correct, spontaneous reversals should be perceived more readily by listeners for whom both the low- and the high-frequency components of a dichotic octave have a higher pitch in one ear than in the opposite ear.

6.1.4 Do spectral and virtual pitch compete during the octave illusion? An important qualitative feature of Terhardt et al.’s (1982a) pattern-matching theory is the proposal that spectral and virtual pitch are placed in competition. As the authors noted, the eventual pitch of a complex tone is dependent on whether the individual is listening analytically or synthetically and, thus, the extent to which the tonal components can be perceptually segregated. Chambers et al. (2002) observed that listeners were able to segregate dichotic octaves during the octave illusion at a performance level of approximately 10% above chance, indicating that spectral pitch is likely to be influential. Furthermore, Chambers et al.’s observation that binaural diplacusis correlates with virtual pitch is strong evidence that virtual pitch is largely determined by spectral pitch and, therefore, that both spectral and virtual pitch are important in the octave illusion.

Do the present modeling results allow us to speculate about the degree of competition between spectral and virtual pitch during the octave illusion? Terhardt et al. (1982a) remarked that the spectral and virtual pitch weights are not directly comparable; thus, the considerably higher spectral pitch weights in the present results cannot be interpreted as a perceptual dominance of spectral pitch. To compare spectral and virtual pitch salience, Terhardt et al. (1982a) suggested reducing the spectral weights by approximately 50% (see also Terhardt et al., 1982b). In most conditions of the present modeling, this adjustment would roughly equate virtual and spectral pitch weights. However, given the extent to which this balance is likely to depend on attentional dynamics that vary both between and within listeners, we suggest that such comparisons should be made with caution.

6.1.5 Conclusions on pitch modeling. In summary, Terhardt et al.’s (1982a) pattern-matching theory of pitch perception is consistent with evidence that harmonic fusion, rather than suppression, causes the octave illusion (Chambers et al., 2002). In addition, the model provides three testable hypotheses that will enable the role of fu-

sion in the illusion to be expanded empirically. First, depending on the frequencies used to elicit the illusion, octave pitch shifts might occasionally arise between the first and the second subharmonics of the lower frequency component. Second, the degree of pitch variation during the illusion may fluctuate for listeners who exhibit a different magnitude of diplacusis between the low- and the high-frequency components. Third, perceptual reversals of the relative pitch of alternate dichotic octaves may be induced when the two dominant virtual pitches span the computed virtual pitch of the opposite dichotic octave. Specifically, the model predicted this nature of percept when the direction of diplacusis favored one ear for both the low- and the high-frequency stimuli that elicit the octave illusion.

6.2 Speculations on Dichotic Lateralization

Compared with a substantial literature on pitch perception, relatively few studies have addressed the perceptual lateralization of two-tone dichotic complexes. As noted in section 6.1, a theory of the octave illusion must be able to account not only for lateralization of dichotic octaves, but also for the variability in the direction of lateralization observed by Chambers et al. (2002). We suggest that, at present, there is insufficient objective evidence upon which to frame a comprehensive explanation. However, on the basis of the results of Lamminmäki and Hari (2000) and Chambers et al., it seems that (1) the direction of spectral dominance during the octave illusion is variable between listeners and (2) sequential interactions do not appear necessary for lateralization to occur. We must, therefore, look beyond Deutsch and Roll’s (1976) suppression model for an explanation.

One possible explanation for lateralization in the octave illusion is that dichotic presentation of harmonics stimulates competition between localization mechanisms dominated by opposite frequency differences. For instance, in a dichotic octave of 400 and 800 Hz, the 400-Hz component may have a greater initial *localization strength*, consistent with the dominance of low-frequency stimuli in the precedence effect. However, the simultaneous presentation of 800 Hz to the opposite ear may also evoke the Franssen-type effect suggested by Divenyi (1990a, 1990b), in which the earlier peripheral activation of 800 Hz, as compared with 400 Hz, evokes a localization bias toward the 800-Hz tone. Depending on the balance of these competing mechanisms, the percept might be skewed toward one ear or the other.

Divenyi’s (1990a, 1990b) lateralization proposal provides several testable predictions for future investigation. For instance, two-tone dichotic complexes with smaller frequency differences should be lateralized less readily toward the higher frequency component, because the difference in peripheral activation times is reduced. To our knowledge, this hypothesis has not been addressed experimentally. In addition, delaying the onset of the higher frequency tone by the difference in peripheral activation times should eliminate high-frequency lateralization dominance. Deutsch (1981) tested this hy-

pothesis by obtaining subjective lateralization reports of illusion sequences in which ITDs of up to 5 msec were applied between the 400- and the 800-Hz components. Regardless of the direction or magnitude of the ITD, listeners consistently lateralized the percept toward the 800-Hz tone. These results therefore appear inconsistent with a Franssen-type model and imply that lateralization toward the higher frequency tone is not determined by an interaural mechanism that is sensitive to information in the stimulus onsets.

Divenyi (2002, personal communication), however, has noted informally that the application of 50- to 100-msec amplitude ramps during the octave illusion reduces or eliminates lateralization. In contrast to Deutsch's (1981) results, this observation implies that the lateralization percept may be determined by information in stimulus onsets and offsets, rather than from ongoing binaural disparities. The inconsistent nature of these subjective reports, as well as the variable nature of spectral dominance observed by Chambers et al. (2002), suggests that a thorough investigation of these factors is required, using objective methods.

6.3 Conclusions and Future Directions

This article has addressed the influential suppression model of the octave illusion proposed by Deutsch and Roll (1976). Three central postulates of this model were considered: first, that listeners perceive a pitch variation during the octave illusion that is caused by suppression of frequency information in the nondominant ear; second, that the apparent position of this pitch is determined by a high-frequency dominance in sound localization; and third, that sequential interactions between alternating dichotic octaves are critical for dissociating these different perceptual mechanisms. Considered against a substantial literature on pitch perception, sound localization, and ear dominance, we conclude that previous observations provide little support for this suppression hypothesis. In addition, logical arguments may be raised against Deutsch's (1978, 1980a, 1988) conclusion that suppression and sequential interactions are instrumental in the illusion, because this interpretation is based on subjective report data that may be contaminated by response bias. Throughout this examination, key findings of Chambers et al. (2002) have been discussed. These recent results are inconsistent with the suppression model and suggest, instead, that established mechanisms of dichotic fusion can account for the phenomenon independently of sequential interactions.

The empirical findings of Chambers et al. (2002), in addition to Terhardt et al.'s (1982a, 1982b) theory of pitch perception, open several avenues for further investigating the causes of the octave illusion. With respect to dichotic lateralization, the variable nature of the spatial aspect of the illusion observed by Chambers et al. suggests the need for a more comprehensive investigation of the lateralization of two-tone dichotic complexes, examining the effects of such factors as harmonicity, ear frequency as-

signments, frequency proximity of tonal components, and the duration of amplitude ramps. Chambers et al.'s results also provide an alternative explanation for the pitch difference during the octave illusion, based on the effects of binaural diplacusis. Combined with the modeling data that we obtained using Terhardt et al.'s pitch extraction algorithm, these results give rise to several testable predictions, including (1) that the pitch variation perceived by many listeners may be unstable over time, (2) that spontaneous reversals may be caused by particular patterns of binaural diplacusis, (3) that octave-level pitch variations may be caused by ambiguity between virtual pitches, rather than from suppression of frequency information, and (4) that octave-level pitch variations should depend on the frequencies used to elicit the illusion.

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NOTES

1. The term *dichotic octave* refers to a stimulus in which the lower harmonic (e.g., 400 Hz) is presented to one ear, while the higher harmonic (e.g., 800 Hz) is presented simultaneously to the opposite ear.
2. Throughout this article, the terms *localization* and *lateralization* refer to the processes by which the direction of a sound source is determined. We use *localization* to describe the mechanism for stimuli that are presented in free field, as would be expected in a natural listening environment. The waveforms of free-field stimuli interact physically in space and are spectrally transformed by both pinnae before entering the middle ear. In the case of *lateralization*, the stimuli are presented via headphones, thus negating both external physical interactions and spectral transformation by the pinnae. The subjective experiences of localization and lateralization are quite different; lateralized events are generally confined to a source within the head, whereas localized events are perceived outside the head. A percept in far space can be elicited through headphone presentation if the wave structure of the input is modified according to the transfer function of the pinnae (see Blauert, 1997, and Wightman & Kistler, 1993, for reviews).
3. The term *inharmonic* refers to a complex tone in which the harmonics do not share a common *F0*. For instance, a complex tone consisting of 493 and 827 Hz is inharmonic. In practice, complexes that are related by an *F0* that is so distant as to be imperceptible may also be termed inharmonic; for example, a complex tone of 1500 and 1900 Hz is often regarded as inharmonic even though the tones are the 15th and 19th harmonics of a 100-Hz *F0*.
4. Although Efron and Yund (1974) adopted a forced-choice paradigm, their methodology remains *subjective* because there was no correct response. Note that the adoption of a forced-choice methodology is orthogonal to this issue. For a task to be classified as *objective*, responses must be assessed against the physical characteristics of the stimulus and classified as correct or incorrect (Fechner, 1860/1966). This point holds for the studies by Deutsch (1978, 1980a, 1988), in which the octave illusion was examined with a forced-choice, subjective report technique (see section 4 for a discussion).
5. Note that the term *fusion* has occasionally been adopted in articles that argue in favor of a suppression account (Deutsch, 1988; Efron & Yund, 1975). We note, however, that these studies employed the term merely to describe the process by which a single stimulus is perceived when two are presented; thus, the broad definition of *fusion* in these articles could apply equally to the suppression or the fusion account of the octave illusion. As was noted in Chambers et al. (2002), the use of *fusion* in these previous reports reflects an ambiguity of terminology, rather than addressing evidence for *harmonic fusion* (see section 1 for a discussion).
6. We are grateful to Pierre Divenyi for suggesting the use of Terhardt's (1974) pattern-matching theory and Terhardt et al.'s (1982a, 1982b) pitch extraction algorithm.
7. Note that Terhardt et al.'s (1982a) algorithm was originally designed to extract the pitch of monotic, rather than dichotic, complex sounds. In applying the algorithm to dichotic stimuli, the assumption is made that the listener has identical absolute thresholds between ears. In addition, the calculation of masking effects in the algorithm is based on excitation patterns derived from peripheral masking studies, whereas

dichotic presentation of tones is likely to result primarily in central masking (J. H. Mills, Dubno, & He, 1996; Zwislowski, 1972). Because central masking is less effective than peripheral masking, the magnitude of masking within a dichotic octave, as calculated using Terhardt et al.'s model, will be overestimated. Note, however, that a correction for dichotic presentation is not required in the present context because, even for monotic presentation, masking between octave-related stimuli is low enough to be ineffective in altering the calculated spectral pitch weights.

8. The mathematical details of the model may be found in Terhardt et al. (1982a, 1982b). A full description of our modeling procedure, including software and formulae, is available upon request from the corresponding author or via supplementary on-line information at http://www.psych.unimelb.edu.au/staff/cc/pbr_supp.html.

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