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The Octave Illusion Revisited Again

Diana Deutsch
University of California, San Diego

The octave illusion (D. Deutsch, 1974) occurs when 2 tones separated by an octave are alternated repeatedly, such that when the right ear receives the high tone, the left ear receives the low tone, and vice versa. Most subjects in the original study reported hearing a single tone that alternated from ear to ear, whose pitch also alternated from octave to octave, and D. Deutsch (1975a) proposed an explanation in terms of separate *what* and *where* auditory pathways. C. D. Chambers, J. B. Mattingley, and S. A. Moss (2002) argued that the perceived pitch difference generally corresponds more to a semitone and proposed an alternative explanation in terms of diplacusis. This article argues that Chambers et al. used problematic procedures and reports a new experiment on the octave illusion. The findings confirm that an octave difference is generally perceived, and they agree with the model of Deutsch (1975a) but are at variance with the diplacusis hypothesis.

The octave illusion, which was originally described by Deutsch (1974), is a paradoxical auditory phenomenon that is characterized by large individual differences in perception. The pattern that was first used to create this illusion consisted of two tones that were spaced an octave apart and that were repeatedly presented in alternation. The identical sequence was presented via headphones to both ears simultaneously; however, when the right ear received the high tone, the left ear received the low tone, and vice versa. This pattern gave rise to a number of different illusory percepts, the most common one (termed *octave*) being of a single tone that alternated from ear to ear, whose pitch also alternated from one octave to the other in synchrony with the localization shift.

Deutsch (1975a) proposed a model to account for the *octave* percept, based on a hypothesized separation between *what* and *where* decision mechanisms in the auditory system. The model, hereafter referred to as the *two-channel model*, assumes that (a) to produce the perceived pitches, the frequencies arriving at one ear are perceived, while those arriving at the other ear are suppressed from conscious perception and that (b) each perceived tone is localized at the ear receiving the higher frequency signal, regardless of whether a pitch corresponding to the higher or lower frequency is in fact perceived. The model therefore assumes that the octave illusion results from illusory conjunctions of pitch and location values.

Chambers, Mattingley, and Moss (2002) argued from a series of experiments that the phenomenology of the octave illusion differs from that originally described by Deutsch (1974). More specifically, they asserted that, on listening to the octave illusion, the perceived difference between the alternating tones generally corresponds more to a semitone than to an octave. On this basis, the authors hypothesized that the tones at the two ears fuse harmonically to produce a pitch that corresponds to the low tone,[1] and that the slight pitch difference between the alternating tones that is perceived is the result of diplacusis.[2] They also reported that some of their subjects lateralized each tone to the ear receiving the higher frequency and that some lateralized each tone to the ear receiving the lower frequency, though they did not offer an explanation for the lateralization patterns they obtained.

In this article, I first review early findings concerning the phenomenology of the octave illusion and describe the two-channel model that was proposed to explain the *octave* percept. There follows a critique of the study by Chambers et al. (2002), which questions the validity of their observations. Because their hypothesis could hold only if these observations were valid, this hypothesis is also challenged. Finally, a new experiment is reported in which the phenomenology of the octave illusion is documented more explicitly than in previous studies. The findings from this new experiment confirm that an octave difference between the alternating tones is generally perceived, and they are in accordance with the two-channel model but cannot be explained on the diplacusis hypothesis.

Previous Findings Concerning the Phenomenology of the Octave Illusion and the Two-Channel Model

In the original experiment of Deutsch (1974), subjects were presented with dichotic sequences consisting of 250-ms tones. As shown in Figure 1, the tones alternated between 400 Hz and 800 Hz, such that when the right ear received 400 Hz, the left ear

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Correspondence concerning this article should be addressed to Diana Deutsch, Department of Psychology, University of California, San Diego, La Jolla, CA 92093. E-mail: ddeutsch@ucsd.edu

[1] When two sine-wave tones that stand in octave relation are presented simultaneously, they fuse perceptually so that a single tone is heard, whose pitch corresponds to the low tone (the fundamental frequency). This effect of harmonic fusion has also been found to occur when the tones are presented dichotically (Houtsma & Goldstein, 1972).

[2] The term *diplacusis* refers to a slight difference in perceived pitch (of a small fraction of a semitone) that can occur when the same tone is presented to the left and right ears (van den Brink, 1975a, 1975b). This effect is usually attributed to the structural characteristics of the ear.

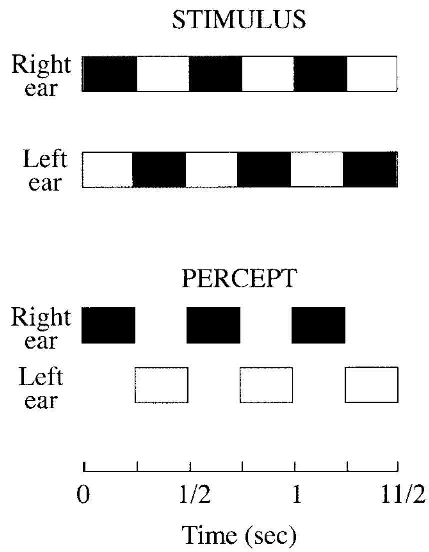

Figure 1. The stimulus pattern used in the original experiment of Deutsch (1974) describing the octave illusion, together with the percept most commonly obtained. Black boxes indicate tones at 800 Hz, and white boxes indicate tones at 400 Hz. From "An Auditory Illusion," by D. Deutsch, 1974 (September 27), *Nature, 251,* p. 307. Copyright 1974 by Macmillan Publishers Ltd. Adapted with permission.

received 800 Hz, and vice versa. The tones were sine waves, at equal amplitude, with no gaps between tones. To minimize transients, there were no amplitude drops at the frequency transitions, and phase continuity was preserved at the transitions.

Eighty-six subjects (53 right-handers and 33 left-handers), all naive concerning the octave illusion, were presented with a 20-s segment of the illusion and asked to report what they heard. The positions of the earphones were then reversed, and the procedure was repeated. A number of different illusory percepts were obtained, and these were divided into three categories. The first, termed *octave,* consisted of a single tone that alternated from ear to ear, whose pitch also alternated from one octave to the other in synchrony with the localization shift. For most subjects who obtained this percept, when the positions of the earphones were reversed, the apparent locations of the high and low tones did not reverse with them.[3] The *octave* category of percept was described in 58% of right-handers and 52% of left-handers. Furthermore, those right-handers who obtained this percept showed a strong tendency to hear the high tone on the right and the low tone on the left; however, the left-handers as a group did not preferentially localize the high and low tones either way.

The second category of percept, termed *single pitch,* consisted of a single tone that alternated from ear to ear, whose pitch either did not change or changed only slightly with the shift in the tone's perceived location. This percept was described in 25% of right-handers and 9% of left-handers. The third category, termed *complex,* comprised a number of different complex percepts, often involving at least three different pitches. This category of percept was obtained in 17% of right-handers and 39% of left-handers. The two handedness groups differed significantly, both in terms of type of percept obtained (with a higher proportion of left-handers reporting *complex* percepts) and also in terms of patterns of lateralization for the *octave* percept (with a higher proportion of right-handers reporting the high tone on the right).[4]

Deutsch (1983b) further studied handedness correlates with perception of the octave illusion in 250 subjects. The tendency to perceive the high tone on the right was found to be higher among right-handers than mixed-handers, and it was higher among mixed-handers than left-handers.[5] Furthermore, for all three handedness groups, the tendency to hear the high tone on the right was lower among those with left- or mixed-handed parents or siblings than among those with only right-handed parents and siblings. This pattern of results is in accordance with the neuropsychological literature relating patterns of cerebral dominance to handedness and familial handedness background (Herron, 1980) and leads to the conjecture that perception of the octave illusion might serve as a reflection of the direction and degree of cerebral dominance in most individuals.

Other work on the octave illusion was directed toward understanding the basis of the type of percept termed *octave.* Deutsch (1975a) hypothesized that this percept results from a dissociation between the *what* and *where* pathways in the auditory system. The proposed two-channel model is shown in Figure 2. To produce the perceived pitches, the listener follows the frequencies that are presented to the dominant ear and suppresses from conscious perception those that are presented to the nondominant ear. However, the listener lateralizes each perceived tone to the ear receiving the higher frequency signal, regardless of whether he or she perceives a tone corresponding to the higher frequency or the lower one. Because the pitch and lateralization decision mechanisms here use different rules, illusory conjunctions of pitch and location result.

Take, as an example, a listener whose pitch perceptions correspond to the frequencies presented to his or her right ear. When the high tone is presented to the right ear and the low tone is presented to the left ear, this listener perceives the high tone, because this tone is presented to the right ear. This listener also lateralizes the tone to his or her right ear, because this ear is receiving the higher frequency signal. However, when the low tone is presented to the right ear and the high tone to the left ear, the listener hears the low tone, because this is presented to the right ear, but the listener lateralizes the tone to his or her left ear instead, because this ear is receiving the higher frequency signal. So the listener hears the entire sequence as a high tone to the right alternating with a low tone to the left. However, now take a listener whose pitch perceptions correspond to the frequencies presented to the left ear, and hold the lateralization rule constant. This listener hears the same

[3] The earphone positions were reversed, rather than reversing the signals delivered to the earphones, in order to control for possible differences in earphone characteristics.

[4] In the experiment described by Deutsch (1974), the pitch differences perceived on listening to the octave illusion were documented by verbal reports, which were backed up either by musical notation or by marking the perceived pitch difference on a scale from zero to over an octave. Because of space limitations, these methods were not described in this article.

[5] Handedness and familial handedness background were evaluated using the questionnaire and procedure of Varney and Benton (1975).

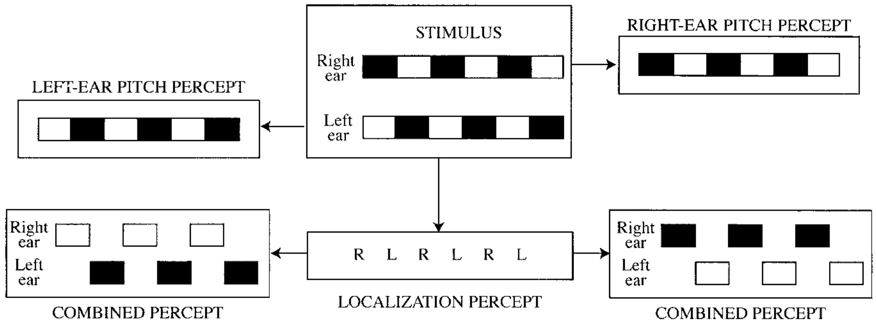

Figure 2. Illustration showing how the outputs of two decision mechanisms, one determining perceived pitch and the other determining perceived location, can combine to produce the octave illusion. Black boxes indicate tones at 800 Hz, and white boxes indicate tones at 400 Hz. R = right; L = left. From "Auditory Illusions, Handedness, and the Spatial Environment," by D. Deutsch, 1983, *Journal of the Audio Engineering Society, 31*, p. 608. Copyright 1983 by the Audio Engineering Society. Adapted with permission.

stimulus pattern as a high tone to the left alternating with a low tone to the right.[6]

To test this hypothesis, Deutsch and Roll (1976) presented 44 right-handers with repeating sequences consisting of 400–800-Hz dichotic tone pairs. One ear received a repeating pattern consisting of three high (800-Hz) tones alternating with two low (400-Hz) tones, while simultaneously the other ear received a repeating pattern consisting of three low (400-Hz) tones alternating with two high (800-Hz) tones. The tones were 250 ms in duration and were separated by 250-ms pauses. The subjects made two judgments: (a) how many high tones they heard in sequence and how many low tones they heard in sequence—so indicating which ear they followed for pitch—and (b) how many tones they heard in sequence in the right ear and how many in the left ear—so indicating to which ear each tone was lateralized. The results were as predicted from the two-channel model. Concerning the pitch component, most subjects reported hearing the patterns of high and low tones that were presented to their right ear rather than their left. However, each tone was lateralized to the ear that received the higher frequency signal, regardless of whether a pitch corresponding to the higher or lower frequency was perceived.

Further experiments (Deutsch, 1978, 1980, 1981, 1988) used the two-alternative forced-choice (2AFC) method to investigate perception of the octave illusion under parametric manipulation. Here, subjects were selected who showed strong and stable *octave* percepts. To explore the ear dominance component, I presented subjects with segments of the illusion and asked them to report on each trial whether they heard a pattern that began with the high tone and ended with the low tone (i.e., a *high–low–high–low* pattern) or a pattern that began with the low tone and ended with the high tone (i.e., a *low–high–low–high* pattern). In this way, the subjects indicated which ear they were following for pitch. The relative amplitudes of the tones at the two ears were varied, and the percentages of judgments that corresponded to the frequencies presented to the nondominant ear were plotted as a function of these amplitude relationships. The strength of the ear dominance effect was then measured by the size of amplitude difference between the tones at the two ears required to counteract it. The effect was found to be strong for sequences in which the two ears received the same frequencies in succession (i.e., when both the 400-Hz and the 800-Hz tones were presented in immediate succession to the left and right ears, as in the original octave illusion pattern), but it was weaker or absent for sequences in which this pattern of relationship did not hold (Deutsch, 1980). The effect was also found to be weaker when the interonset interval between successive tones was lengthened to 3,000 ms, regardless of whether this was achieved by inserting silent gaps between the tones or by increasing the durations of the tones themselves (Deutsch, 1981).

To explore the lateralization component, I again presented subjects with segments of the illusion but now asked them to report on each trial whether they heard a pattern that began at the left ear and ended at the right ear (i.e., a *left–right–left–right* pattern) or a pattern that began at the right ear and ended at the left ear (i.e., a *right–left–right–left* pattern). In this way, the subjects indicated whether the tones were lateralized to the ear receiving the higher frequency or the lower one. The relative amplitudes of the higher and lower tones were varied, and the percentages of judgments that corresponded to the ear receiving the lower frequency were plotted as a function of these amplitude relationships. It was found that the subjects lateralized the tones to the ear receiving the higher frequency until the amplitude of the lower tones exceeded those of the higher ones by a critical level. This effect occurred with tones presented in rapid repetitive sequence (as in the original octave illusion pattern) but was significantly weaker when only two dichotic tone pairs were presented (Deutsch, 1978) or when more complex pitch configurations were used (Deutsch, 1988).

Zwicker (1984) explored the phenomenology of the octave illusion in several experiments. Concerning the issue of perceived pitch differences between the alternating tones, the author re-

[6] Deutsch (1981) elaborated on this model to provide a more concrete explanation of the octave illusion in terms of its neurophysiological underpinnings. The elaborated model also accommodates findings from later parametric studies of the illusion, including those showing a dependence on the durations between onsets of successive tones. Because of space limitations, this model is not described here.

ported, from the judgments of 15 subjects, that "*mostly octaves, but also often smaller intervals were perceived* [italics added]" (p. 129). He also confirmed that, for 400-Hz and 800-Hz signals, there was a strong tendency to lateralize the tones to the ear receiving the higher frequency. In a further experiment, he presented 8 subjects with octave illusion patterns at tone durations (and, so, interonset intervals) ranging from 0.01 s to 2.00 s. He wrote,

> The observers' certainty in perceiving Deutsch's illusion . . . showed a clear maximum with tone durations around 200 ms; with decreasing tone durations other acoustic illusions appear, while with durations greater than about 1 s, the presentation can be perceived correctly. (p. 128)

Figure 3 plots the percentages of different perceptions of the illusion pattern at the different tone durations (and, so, interonset intervals) in Zwicker's study, and it can be seen that, at interonset intervals of 2,000 ms, over 80% of reports were of no illusion.

Study of Chambers et al. (2002)

Chambers et al. (2002) challenged the report of Deutsch (1974) concerning the octave illusion. From their experiments, they concluded that the perceived pitch difference between the alternating tones generally corresponds more to a semitone than to an octave. They further concluded that listeners do not uniformly lateralize each tone toward the ear receiving the higher frequency. On the basis of these claims, the authors proposed an alternative explanation of the octave illusion. This explanation assumes that

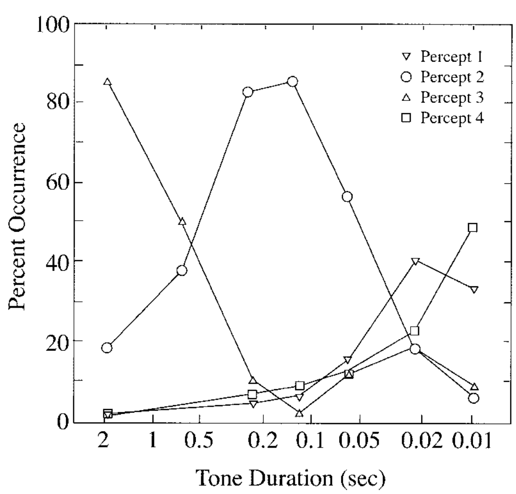

Figure 3. Percentage occurrence of different percepts of the octave illusion, as a function of tone duration and thus of interonset interval. The data were averaged across 8 subjects. Percept 1: Two tones of identical pitch alternating from ear to ear. Percept 2: A higher tone in one ear alternating with a lower tone in the other ear (i.e., the *octave* percept). Percept 3: A higher tone alternating from ear to ear, together with a lower tone alternating from ear to ear (i.e., no illusion). Percept 4: None of the above. From "Experimente zur dichotischen Oktav-Tauschung," by T. Zwicker, 1984, *Acustica, 55,* p. 135. Copyright 1984 by S. Hirzel Verlag, Stuttgart, Germany. Adapted with permission.

1. listeners perceptually fuse the dichotically presented high and low tones, so as to perceive a pitch that corresponds roughly to the fundamental frequency;

2. the slight pitch difference that is heard between the alternating tones is the result of diplacusis; and

3. the perceived tones are sometimes lateralized to the ear receiving the higher frequency and sometimes to the ear receiving the lower frequency.

The present section presents a critique of the study by Chambers et al. (2002) and questions the validity of their observations. Given that their model could hold only if these observations were valid, their theoretical proposal is also challenged. The study consisted of four experiments, and these are examined below.

Experiment 1

Experiment 1, titled "Subjective Report," was intended to be preliminary; as Chambers et al. (2002) wrote, "*Subjective reports were purely qualitative and were not statistically analyzed* [italics added]" (p. 1292). Fifteen subjects participated; 3 of these were the authors, and no information was given concerning whether or not the remaining subjects were naive concerning the octave illusion. The subjects first listened extensively to single dichotic tone pairs at 400 Hz and 800 Hz, at several tone durations, which ranged from 200 to 800 ms. The dichotic 400–800-Hz tones were then presented in alternating sequence. The tone durations again ranged from 200 to 800 ms. Furthermore, on half the trials, the tones were separated by pauses that were equal in duration to the tones themselves, so the interonset intervals between successive tones varied from 200 ms to 1,600 ms.

The issue of tone duration. Chambers et al. (2002) stated that the subjects' judgments exhibited no dependence on tone duration nor on the presence of regular silent intervals, and they claimed that this was in accordance with findings obtained by others. However, the authors also stated that the subjects' reports were not statistically analyzed, and they presented no data from patterns at specific tone durations; neither did they present any other evidence to support their assertion that judgments were indeed independent of tone duration. Further, the authors were incorrect in asserting that their observations were in accordance with previous ones. As outlined above, Deutsch (1981) compared interonset intervals of 250 ms with those of 3,000 ms and obtained a highly significant effect of interonset interval (see also Deutsch, 1983a). This study used subjects who had been selected for obtaining a strong *octave* percept in the first place, which leads to the surmise that unselected subjects might show an even stronger effect of interonset interval. Such a result was obtained in the study by Zwicker (1984) referenced above. As shown in Figure 3, from Zwicker's data, one would expect that at interonset intervals of 800 ms, no illusion would be perceived roughly 30% of the time, and one would expect that at interonset intervals of 1,600 ms, no illusion would be perceived roughly 80% of the time. Yet, these values of interonset interval were among those used by Chambers et al. (2002).

The issue of lateralization. In Experiment 1, Chambers et al. (2002) used the following method to evaluate how each tone was lateralized. The subjects were presented with alternating 400–800-Hz sequences at the various interonset intervals described above and were instructed to indicate their judgments by tapping (e.g., "Tap in time with the higher pitch" or "Tap in time with the left tone"). The experimenter then evaluated, by visual observation of the subjects' tappings, to which ear the higher and the lower tones were lateralized. The authors reported, on the basis of these observations, that 9 subjects lateralized the tones toward the ear receiving the lower frequency, whereas 6 subjects lateralized the tones toward the ear receiving the higher frequency.

However, the authors presented no actual data to support this assertion. They did not state that the experimenter monitored the signals that were presented to the subjects, and it is unclear how, without such monitoring, he could determine how the subjects' tappings corresponded to their perceptions. Even assuming that the experimenter had monitored the sound signals, no evidence was provided that he could reliably synchronize his visual perceptions of the subjects' tappings with these signals, nor that the subjects were able to synchronize their tappings with these signals. This problem of validity is particularly severe for the fast rates of presentation needed to produce the octave illusion; yet, at slow rates of presentation, the illusion becomes degraded and may even disappear (Figure 3). It is important to note that these informal observations concerning lateralization in Experiment 1 were not confirmed elsewhere in the article by Chambers et al. (2002). In contrast, a number of other experiments, which were reviewed above, have indicated that, on listening to the octave illusion, there is a strong tendency for subjects to lateralize each perceived tone toward the ear receiving the higher frequency signal (Deutsch, 1978, 1988; Deutsch & Roll, 1976; Zwicker, 1984).

The issue of the size of the perceived pitch difference. To evaluate the size of the perceived pitch difference between the alternating tones, Chambers et al. (2002) presented the subjects, for comparison, with sequences in which tones alternated between 400 Hz and 800 Hz (an octave) and between 400 Hz and 424 Hz (a semitone). The authors reported that 2 of the subjects perceived a pitch difference of an octave, 8 (2 of whom were authors) perceived a pitch difference of a semitone, 4 (1 of whom was an author) perceived a pitch difference of between an octave and a semitone (this difference not being further specified), and 2 subjects perceived no pitch difference. However, several points should here be made.

1. The subjects' judgments were based on sequences in which the interonset intervals varied substantially, including some in the range where Zwicker (1984) had reported that sometimes no illusion was obtained. Comparison cannot, therefore, be made directly between these results and those of Deutsch (1974).

2. The subjects had earlier been given extensive experience with dichotic 400–800-Hz chords and patterns at these different tone durations, and this prior experience may have influenced their judgments.

3. At least 3 of the subjects (i.e., the authors) had prior knowledge of the illusion, and this could have influenced their judgments.

4. Twenty-five percent of right-handers in the original large-scale experiment of Deutsch (1974) reported little or no pitch difference between the alternating tones (i.e., their percepts fell into the *single pitch* category). In Experiment 1 of Chambers et al. (2002), the authors reported on the responses of only 12 subjects (excluding themselves), so that sampling bias could have contributed to their results.

However, as the authors pointed out, Deutsch (1974) did not publish the means by which the subjects' reports of the octave illusion were obtained (see Footnote 4). This is rectified in a new experiment, which is described later in this article.

Experiment 2

In Experiment 2, Chambers et al. (2002) did not investigate the octave illusion itself, but rather a different effect, and they related their results to the informal observations reported in Experiment 1. The experiment used 8 subjects who had all participated in Experiment 1, including 2 authors (the 2 subjects who had reported hearing an octave difference between the tones in Experiment 1 were not tested). The subjects were presented with tones at 400 Hz or at 800 Hz to one ear, and they were asked to match the tone that they heard to a tone of variable pitch that was presented to the other ear, thereby obtaining a measure of diplacusis. The subjects' matches varied between no pitch difference to a difference of less than half a semitone, with the majority of matches being in the lower part of this range. None of the matches involved a pitch difference that approached a semitone.

On the basis of these findings, Chambers et al. (2002) claimed that pitch differences obtained on hearing the octave illusion are a reflection of diplacusis. However, the very slight pitch differences they found in Experiment 2 were inconsistent with this interpretation, given their reports in Experiment 1 of an octave difference by 2 subjects and of differences that were greater than a semitone but smaller than an octave by 4 additional subjects. So, even setting aside the problems of interpretation outlined above, and the previous reports of an octave difference between the alternating tones by other researchers (Deutsch, 1974; Zwicker, 1984), diplacusis could only account for some of the reports of the octave illusion obtained by Chambers et al. in their own Experiment 1.

Experiment 3

In Experiment 3, subjects were presented with dichotic sequences of various types and were asked on each trial to report which ear was receiving the higher pitch. *The subjects were not asked to report their actual percepts but, rather, to infer what signal configurations were being presented.* Eight subjects were tested. These had all participated in Experiment 1 and so had received extensive experience with octave illusion patterns of differing durations, some of which may well have been perceived veridically (Zwicker, 1984). Chambers et al. (2002) wrote, "The most surprising result from this experiment was the capacity listeners demonstrated to correctly segregate the octave illusion sequence by ear, despite reporting a standard single-image percept" (p. 1297). However, this result is unsurprising given the subjects' prior experience with variants of the illusion in Experiment 1, some of which would have enabled them to infer what signals were being presented to each ear.

Experiment 4

Seven subjects participated in Experiment 4. These had all participated in Experiment 1, though their percepts of the octave illusion in this experiment were not given. The subjects were presented with dichotic 400–800-Hz sequences, in which tones at 400 Hz, 800 Hz, or 2,000 Hz were embedded as deviants. The deviant tones were presented diotically (i.e., simultaneously to both ears) but offset in time so that they were perceptually displaced to the side of the midline. Averaged across subjects, reaction times were shorter for detecting 800-Hz than 400-Hz deviants. Chambers et al. (2002) interpreted this finding as indicating that, on hearing the standard octave illusion, listeners would perceive both of the alternating tones as closer to 400 Hz than to 800 Hz. However, the finding by Deutsch (1980) that perception of the octave illusion is sensitive to sequential context leads to the possibility that the diotically presented tones may have affected perception of the illusion here also. Furthermore, the data were averaged across all 7 subjects, so that the inclusion of even 1 or 2 subjects whose percepts fell into the *single pitch* category would have skewed it in the direction reported by Chambers et al.

In sum, taking together the four experiments by Chambers et al. (2002), the following can be noted:

1. Chambers et al.'s (2002) conclusions relied heavily on the informal observations from Experiment 1, which the authors themselves stated were "*purely qualitative and were not statistically analyzed* [italics added]" (p. 1292). These findings were based on perceptions of sequences of tones with widely differing interonset intervals, including some in the range where Zwicker (1984) had reported that sometimes no illusion was obtained. Other aspects of the procedures used in this study (such as the tapping procedure for establishing lateralization patterns) were problematic, and many of the observations were at variance with those of Deutsch (1974, 1978, 1980, 1981, 1988), Deutsch and Roll (1976), and Zwicker (1984).

2. Chambers et al.'s (2002) interpretation of the pitch differences heard in the octave illusion in terms of diplacusis cannot explain the pitch differences of an octave that were reported by others (Deutsch, 1974; Zwicker, 1984)—or even a sizable proportion of the pitch differences that were reported by the authors themselves in their Experiment 1.

However, Chambers et al. (2002) have challenged the claim made by Deutsch (1974) that the majority of subjects, on listening to the octave illusion, perceive a pitch difference of an octave between the alternating tones. Instead, they have argued that the most common percept of this illusion involves a very small pitch difference (i.e., of a semitone or less). Their argument was based on the informal observations of a small number of subjects, some of whom were the authors themselves, and all of whom had experienced intensive prior training with dichotic chords at different durations before listening to the illusion. However, given that the authors have raised this issue, an experiment was carried out to examine the size of the perceived pitch difference between the alternating tones on listening to the octave illusion, using the stimulus parameters that had originally been used by Deutsch (1974). This new experiment used a procedure that enabled more explicit conclusions to be drawn than those from earlier experiments.

Experiment

In this experiment, musically trained subjects were asked to listen to the octave illusion pattern and to write down in musical notation what they heard. The subjects were furnished with the note name of the low tone in the pattern (G4) and were told that this was one of the tones they would hear. They then used relative pitch to notate the other tones that they perceived. If the octave illusion simply reflected diplacusis, one should expect that, on hearing this pattern, the subjects would notate only a small pitch difference between the alternating tones. To control for the possibility that the subjects might mistakenly attribute an octave difference between tones of the same pitch that were presented to the left and right ears, two further patterns were presented. The first consisted of the high tone of the octave illusion pattern alone (G5) alternating from ear to ear, and the second consisted of the low tone of the octave illusion pattern alone (G4) alternating from ear to ear.

Method

Subjects. Twelve individuals with normal hearing (5 male and 7 female, ages 18–32 years) participated in the experiment. They had all received at least 4 years of formal musical training and could read and write in simple musical notation. On the basis of the handedness questionnaire of Varney and Benton (1975), they comprised 8 right-handers (3 with left- or mixed-handed relatives), 3 mixed-handers, and 1 left-hander. All subjects were naive concerning the octave illusion.

Apparatus and stimuli. Three sequences of sine-wave tones were created. The first, the *octave illusion pattern,* was as in the experiment of Deutsch (1974). This constituted a sequence of tones that alternated between 400 Hz and 800 Hz (corresponding to approximately G4 and G5 in the musical scale). The tones were of equal amplitude and were 250 ms in duration. To minimize transients, there were no amplitude drops between tones, and the frequency transitions occurred at zero crossing.[7] The identical sequence was presented to both ears simultaneously; however, when the right ear received the high tone, the left ear received the low tone, and vice versa. The second, the *alternating high tone pattern,* consisted of tones at 800 Hz (corresponding approximately to G5) that were presented in alternation at the two ears. All tones were at equal amplitude and were 250 ms in duration. The third, the *alternating low tone pattern,* was identical to the second, except that the tones were at 400 Hz (corresponding approximately to G4).

Tones were generated on a NeXTStation Turbo (NeXT Computers, Inc., Redwood City, CA) using the cmusic sound synthesis system (F. R. M. Moore, 1982). The signals were transferred to a Macintosh G4 computer, passed through a mixer (Mackie CR1604; LOUD Technologies, Inc., Woodinville, WA) and then through an amplifier (NAD 304; NAD Elec-

[7] The tones were generated in phase at the two channels.

tronics, Sharon, MA), and were presented to subjects via headphones (Grason-Stadler TDH-49, calibrated and matched; Grason-Stadler, Inc., Madison, WI) at an amplitude of 70-dB SPL. The subject was seated in front of a Keystation 61 synthesizer keyboard (M-Audio, Irwindale, CA) that was interfaced with the computer, so that the subject was able to play on the keyboard and hear the output through earphones while at the same time listening to the test patterns.

Procedure. All subjects were tested individually, and they listened to the patterns through earphones. They were told that on each trial, they would hear a repeating sequence of tones and that they should notate both the sequence of pitches they heard and the perceived ear of input for each tone. They were given no initial practice sequences.

The subjects first listened to the octave illusion pattern for as long as they wished. They were informed that one of the tones approximated G4 but were given no further information. They were enabled to confirm their perceptions by matching the tones in the pattern with tones they played on the synthesizer keyboard. When they were certain of their judgments, they notated the sequence of pitches they perceived, together with the perceived locations of the tones. Following this, the subjects were asked to place their earphones in reverse position (see Footnote 3), to repeat the procedure, and to notate again the sequence of pitches they perceived, together with the perceived locations of the tones. Next, the alternating high tone pattern was presented, and the same procedure was followed. Then, the alternating low tone pattern was presented, and the same procedure was followed. Finally, the octave illusion pattern was again presented, and the subjects were asked to report the pitch differences that they heard.

Results

Figure 4 presents, as examples, the notations of 3 of the subjects. Subjects SY and RR notated the octave illusion pattern as a tone corresponding to G5 on the right, alternating with a tone corresponding to G4 on the left, with earphones placed both ways. In contrast, Subject JP notated the same pattern as a tone corresponding to G5 on the left, alternating with a tone corresponding to G4 on the right, with earphones placed both ways. When presented with patterns consisting of single tones (i.e., G5 alternating from ear to ear, and G4 alternating from ear to ear), all these subjects notated the tones correctly.

The data from all 12 subjects are summarized in Table 1. On listening to the octave illusion pattern, 7 of the 12 subjects notated

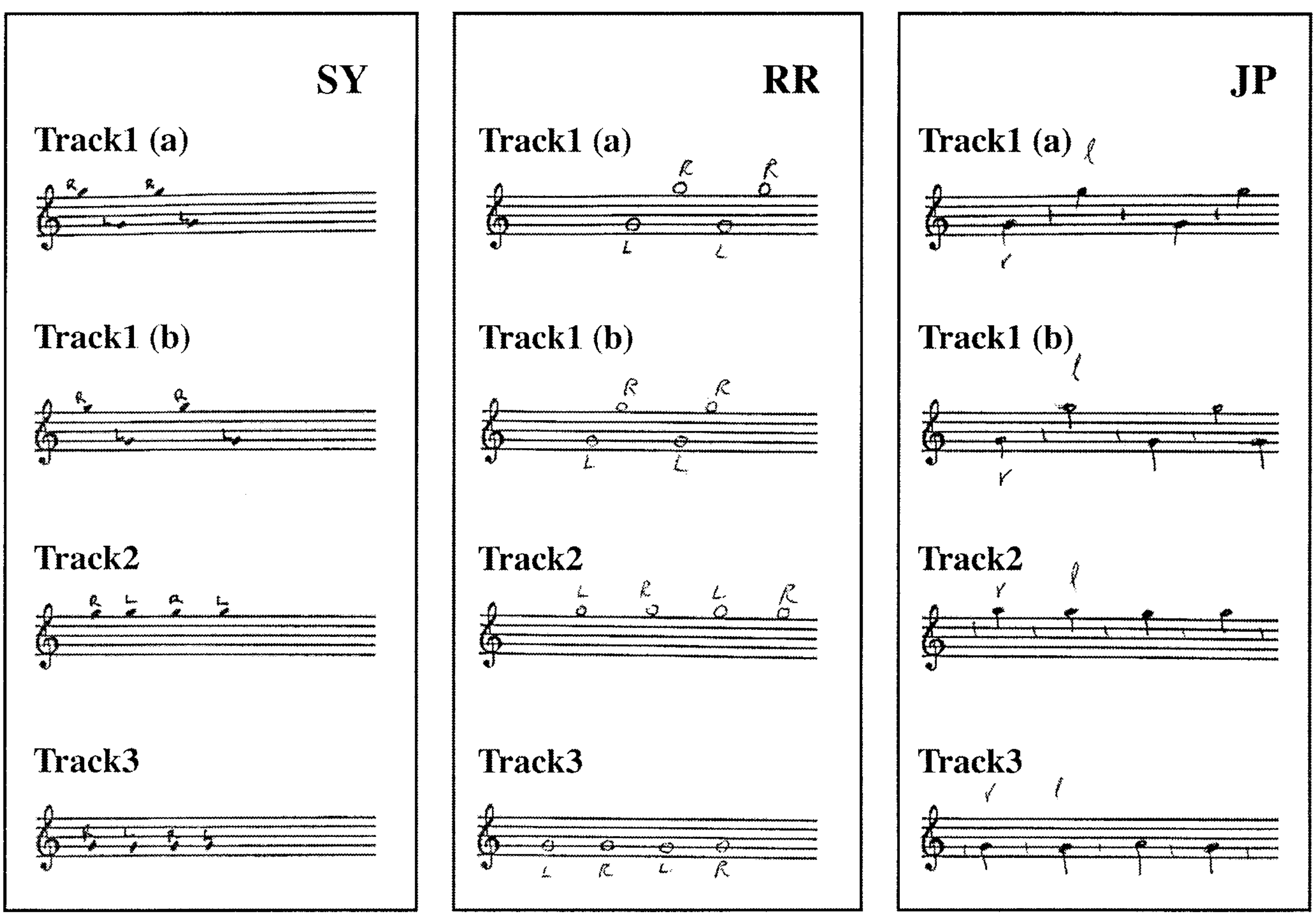

Figure 4. Percepts of the different patterns in the experiment, notated by 3 of the subjects (SY, RR, and JP). The notations for Track 1 (a) are of the octave illusion pattern and for Track 1 (b) are of the octave illusion pattern with earphone positions reversed. The notations for Track 2 are of a single tone at G5 (high tone), which alternated from ear to ear, and the notations for Track 3 are of a single tone at G4 (low tone), which alternated from ear to ear.

Table 1
Subject Characteristics and Notated Categories of Percept

Subject	Age (yrs.)	Handedness	Percept of octave illusion	Percept of alternating high tone	Percept of alternating low tone
EA (F)	22	Mixed (Right)	Complex	High tone (G5) in both ears	Low tone (G4) in both ears
MT (M)	21	Right (Mixed)	Complex	High tone (G5) in both ears	Low tone (G4) in both ears
KD (F)	32	Right (Right)	Octave (LL)	High tone (G5) in both ears	Low tone (G4) in both ears
JC (F)	19	Right (Left)	Complex	High tone (G5) in both ears	Low tone (G4) in both ears
KF (F)	19	Left (Left)	Octave (RR)	High tone (G5) in both ears	Low tone (G4) in both ears
SY (M)	18	Mixed (Left)	Octave (RR)	High tone (G5) in both ears	Low tone (G4) in both ears
JP (M)	23	Mixed (Right)	Octave (LL)	High tone (G5) in both ears	Low tone (G4) in both ears
RR (M)	23	Right (Left)	Octave (RR)	High tone (G5) in both ears	Low tone (G4) in both ears
JW (F)	20	Right (Right)	Complex	High tone (G5) in both ears	Low tone (G4) in both ears
DM (M)	19	Right (Right)	Octave (RR)	High tone (G5) in both ears	Low tone (G3) in both ears
TH (F)	18	Right (Right)	Octave (Both)	G5 in left, G#5 in right	G3 in left, G#3 in right
KG (F)	27	Right (Right)	Single pitch (G4)	High tone (G5) in both ears	Low tone (G4) in both ears

Note. All subjects listened to the octave illusion pattern twice, with earphones placed first one way and then the other. Notations in parentheses under "Handedness" refer to subjects' familial handedness background: Right = only right-handed parents and siblings; Mixed = at least one mixed-handed parent or sibling; Left = at least one left-handed parent or sibling. For subjects who notated *octave* percepts, RR indicates notation of the high tone (G5) on the right and the low tone (G4) on the left, with earphones placed both ways; LL indicates notation of the high tone on the left and the low tone on the right, with earphones placed both ways; and Both indicates notation of the high tone on the right and the low tone on the left on one presentation and the opposite localization pattern on the other. yrs. = years; F = female; M = male.

the standard *octave* percept described by Deutsch (1974), that is, a single tone that alternated from ear to ear, that simultaneously alternated between G4 and G5, with earphones placed both ways. Of these, 4 subjects heard the high tone on the right and the low tone on the left, with earphones placed both ways; 2 heard the high tone on the left and the low tone on the right with earphones placed both ways; and 1 heard the high tone on the right and the low tone on the left on one presentation, with the opposite lateralization pattern on the other. On relistening to the octave illusion pattern at the end of the session, all these subjects again reported hearing tones an octave apart that alternated from ear to ear. Four additional subjects notated complex percepts that changed with continued listening, all of which involved G4 and G5, and so involved an octave difference between the tones. (One of these subjects notated G4 alternating from ear to ear, interspersed with other notations involving both G4 and G5.) The percepts of these 4 subjects therefore fell into the *complex* category described in Deutsch (1974). The final subject notated the same pitch (G4) alternating from ear to ear, with the tone in the right ear having a sharper timbre. The percept of this subject therefore fell into the *single pitch* category described by Deutsch (1974).

On listening to the alternating high tone pattern, 11 subjects correctly notated G5 alternating from ear to ear, whereas 1 subject notated a semitone difference between the tones at the two ears (i.e., G5 alternating with G#5). On listening to the alternating low tone pattern, 10 subjects correctly notated G4 alternating from ear to ear; 1 notated G3 alternating from ear to ear; and the subject who had notated G5 alternating with G#5 for the alternating high tone pattern notated G3 alternating with G#3 for the alternating low tone pattern. All subjects except 1 therefore notated these patterns correctly as consisting of the same pitch in both ears, and the one exception notated a semitone difference between the tones at the two ears.[8] The notations of an octave difference in listening to the octave illusion pattern could not, therefore, have been due to the subjects mistakenly attributing an octave difference between the tones at the two ears.

Discussion

This experiment provided more explicit documentation of percepts of the octave illusion than have so far been obtained. It should be noted that, because only 12 subjects were tested, the experiment did not provide a measure of the statistical distribution of the various percepts of the octave illusion, such as had been provided earlier in the large-scale study of Deutsch (1974). However, the subjects in the present experiment were selected at random with the only constraints being that they should be able to read and write in musical notation, to have normal hearing, and to be naive concerning the octave illusion. Eleven of the 12 subjects, including those who notated *complex* percepts, notated tones at G4 and G5, and so notated them as separated by an octave; and 7 of these notated the standard *octave* percept. One subject notated a single pitch alternating from ear to ear, so that her percept fell into the *single pitch* category described by Deutsch (1974).

In sum, 7 of the 12 subjects in this experiment notated the *octave* percept of the octave illusion, and the notations of 4 more subjects also included an octave difference between the tones, with only 1 subject notating a single pitch alternating from ear to ear. The results of this experiment were therefore at variance with the claim made by Chambers et al. (2002) that the *octave* percept of the octave illusion is rare and that the perceptions of most subjects involve pitch differences so small as to be amenable to an explanation in terms of diplacusis. Rather, they supported the finding by Deutsch (1974) that the majority of subjects perceived an octave difference between the alternating tones—a finding that was also in accordance with the report of Zwicker (1984).

The notated perceptions of the single tones of the same pitch alternating from ear to ear provided a control for the possibility

[8] The pitch difference perceived by this subject when the same tone was presented to the left and right ears may have reflected diplacusis. The direction of this pitch difference did not correspond to the subject's patterns of localization for the higher and lower tones in the octave illusion.

that the subjects, on listening to the octave illusion pattern, might have mistakenly attributed an octave difference between the tones at the two ears. The finding that the subjects notated the same pitch at the two ears, with the exception of 1 subject who notated a semitone difference between the alternating tones, is as expected from other findings on diplacusis, in which the size of this effect was generally found to be a small fraction of a semitone (see, e.g., van den Brink, 1975a, 1975b).

No correlate was here obtained between perception of the illusion and the subjects' handedness. This result was as expected from the small number of subjects tested, given that large groups of subjects are generally required for handedness correlates to emerge at the perceptual level (Herron, 1980). Zwicker (1984) also obtained no handedness correlates on comparing the perceptions of 3 right-handers with 3 congenital left-handers.

General Discussion

In this article, it has been argued that the study of Chambers et al. (2002) used problematic procedures, so that their conclusions concerning the lateralization of tones in the octave illusion were called into question, as were their conclusions concerning the most frequently perceived pitch differences between the alternating tones. In addition, an experiment was reported that used a new procedure that provided more explicit documentation concerning the phenomenology of the illusion than in previous studies. This experiment confirmed the observations in the original study of Deutsch (1974) on the octave illusion, and its findings were consistent with the two-channel model of the *octave* percept, which invokes a separation of the *what* and *where* pathways in the auditory system. The finding that the subjects notated an octave difference between the alternating tones cannot be explained on the proposal by Chambers et al. (2002) that the illusion results from diplacusis. In addition, the diplacusis hypothesis cannot explain the dependence of the illusion on tone duration or on sequential context; neither can it explain the handedness correlates with the type of percept obtained, which indicate that the illusion serves as a reflection of brain organization, rather than characteristics of the auditory periphery.

The two-channel model of the octave illusion has as its core the supposition that the decision mechanisms underlying pitch and lateralization are, at some point in the auditory system, distinct and separate. This supposition is in accordance with recent findings by auditory neurophysiologists. In particular, Rauschecker, Tian, and colleagues have obtained evidence that the lateral belt area of the auditory cortex of the rhesus monkey is subdivided into regions that are specialized for the processing of either *what* or *where* information: Neurons in the anterior belt are tuned specifically to type of monkey call, whereas neurons in the caudal belt are instead tuned to the spatial location of the signal (Rauschecker & Tian, 2000; Tian, Reser, Durham, Kustove, & Rauschecker, 2001). Furthermore, it appears that information from these two regions forms separate streams that project to spatial and nonspatial areas of the frontal lobe (Romanski et al., 1999).

The two-channel model is in accordance with other perceptual research indicating that different attributes of sound are processed along separate pathways that are at some stage independent and so can arrive at inconsistent conclusions (Carlyon, Demany, & Deeks, 2001; Darwin & Carlyon, 1995; Gardner, Gaskill, & Darwin, 1989; Hukin & Darwin, 1995; B. C. J. Moore, Glasberg, & Peters, 1986). Furthermore, Odenthal (1963); Efron and Yund (1974); Hall, Pastore, Acker, and Huang (2000); Thompson (1994); and Deutsch (1975b) have shown that illusory conjunctions of different attribute values can occur with other sound configurations also.

The question then arises as to why people should have evolved the two decision mechanisms that are hypothesized to produce the octave illusion. This question can be addressed for the ear dominance and lateralization components separately. Note that the ear dominance component has two characteristics: First, it becomes weaker as the duration between onsets of successive tones is increased; second, it occurs in configurations in which the two ears receive the same frequencies in succession and is weaker or absent when this condition does not hold. Given these characteristics, it was conjectured (Deutsch, 1981) that this effect reflects the operation of a mechanism that normally helps to counteract misleading effects of echoes and reverberation. In normal listening, when the same frequency emanates successively from two different regions of space, the second occurrence may be an echo. This interpretation becomes less probable as the delay between these two occurrences is lengthened, and it becomes less probable when other frequencies intervene between such two occurrences. On this line of reasoning, the octave illusion falls into the class of phenomena, of which the precedence effect is another example (Haas, 1951; Wallach, Newman, Rosenzweig, 1949), which reflect the activity of mechanisms that have evolved to counteract unwanted effects due to the acoustics of the environment.

Concerning lateralization to the higher frequency signal, it was conjectured (Deutsch, 1981) that this might reflect the action of a mechanism designed to handle head shadow effects. When a complex tone is presented in natural situations, the relative amplitudes of the partials arriving at the two ears may differ considerably, owing to the filtering action of the head. For example, when a complex tone is presented to the listener's right, then the higher frequency components at the left ear are attenuated relative to the lower frequency components. Assuming that the auditory system interprets the pattern that produces the octave illusion as the first and second harmonic of a complex tone, then it would make sense to interpret the signal as coming from the ear receiving the higher frequency—in this case, from the listener's right.[9]

Finally, it should be emphasized that, in order to evaluate the octave illusion, there is no substitute for listening to it as it was originally generated. Furthermore, given the large differences be-

[9] An anonymous reviewer raised the question of what would be expected on the two-channel model when the suppression component is weak or absent. In the case of short tones separated by pauses, it is expected that the normal process of harmonic fusion would take over and that the listener would perceive a pitch that corresponds to the fundamental. This could also explain the *single pitch* percepts obtained by some listeners. However, when the tones themselves are of long duration, the process of fusion also breaks down, and both the high and the low tones may be perceived and lateralized correctly. A partial breakdown of both suppression and fusion might also be responsible for the *complex* percepts obtained by some listeners. In addition, depending on sequential context, both tones may be perceived, but they may be incorrectly localized, as in the scale illusion reported by Deutsch (1975b).

tween listeners in the way the illusion is perceived, it is important to have others listen to it also. The illusion occurs as a sound demonstration in a number of publications, including Deutsch (1983a, 1995); Houtsma, Rossing, and Wagenaars (1987); Kubovy and Pomerantz (1981); and Pierce (1983).

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