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Published in:
The Journal of the Acoustical Society of America

DOI:
10.1121/1.3571425

2011

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Running title: Octave illusion using narrowband noises

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Abstract

The octave or Deutsch illusion occurs when two tones, separated by about one octave, are presented simultaneously but alternating between ears, such that when the low tone is presented to the left ear the high tone is presented to the right ear and vice versa. Most subjects hear a single tone that alternates both between ears and in pitch; i.e., they hear a low pitched tone in one ear alternating with a high pitched tone in the other ear. The present study examined whether the illusion can be elicited by aperiodic signals consisting of low-frequency band-pass filtered noises with overlapping spectra. The amount of spectral overlap was held constant, but the high- and low-frequency content of the signals was systematically varied. The majority of subjects perceived an auditory illusion in terms of a dominant ear for pitch and lateralization by frequency, as proposed by Deutsch [(1975a) Sci. Am. 233, 92–104]. Furthermore, the salience of the illusion increased as the high frequency of the content in the signal increased. Since no harmonics were present in the stimuli, it is highly unlikely that this illusion is perceived on the basis of binaural diplacusis or harmonic binaural fusion.

PACS number(s): 43.66.Rq, 43.66.Hg

I. INTRODUCTION

This paper reports experiments on the octave illusion using low-frequency narrowband noises with overlapping spectra. The octave illusion is an auditory phenomenon which occurs when two tones, separated by an octave, are presented simultaneously but in an alternating pattern between the ears, such that when the low tone is presented to the left ear the high tone is presented to the right ear and vice versa (see the upper portion of Fig. 1). This phenomenon was first described by Deutsch (1974) and appears to be restricted not only to tones that are separated by an octave but can also to that occur with larger and smaller intervals (Zwicker, 1984; Brancucci et al., 2009). As shown in the lower portion of Fig. 1, most subjects hear a single tone that alternates both between the ears and also in pitch; i.e., they hear a low pitched tone in one ear and a high pitched tone in the other ear, but not both simultaneously (Deutsch, 1983a). However, this relation only holds when the tones are presented in sequence (Deutsch, 1980; Zwicker, 1984) and are of roughly equal amplitude, although some subjects still perceive the illusion when the tones within a pair differ in amplitude (Deutsch, 1978, 1980, 1988). The pattern can also give rise to different auditory percepts (Deutsch, 1974; Craig, 1979; Deutsch, 1983a; Zwicker, 1984). Durations of about 200–500 ms, without gaps between tones within a pair, appear to produce the most salient percept of the illusion (Deutsch, 1983a; Zwicker, 1984; Brancucci et al., 2009), and longer interstimulus intervals appear to reduce its saliency (Deutsch, 1983a; Zwicker, 1984; Deutsch and Roll, 1976).

Based on experimental findings, Deutsch proposed the two-channel model of auditory perception (Deutsch, 1975a, 1981, 1983a). This model is based on the assumption that, to perceive an octave illusion, the auditory system invokes a decision mechanism that separates what from where caused by interactions between the alternating tones in the sequence. The model assumes that the listener perceives the frequencies arriving at one ear (lower portion of Fig. 1) and suppresses the frequencies arriving at the other ear. However at the same time, the listener localizes the perceived tones depending on which ear receives the higher frequency signal (Deutsch, 1975a, 1981, 1983a 2004a; Deutsch and Roll, 1976). This means that when the high-frequency tone is presented to the nondominant ear the listener perceives the pitch of the tone presented to the dominant ear, but lateralizes it to the nondominant ear.

The two-channel model proposed by Deutsch (1975a, 1981, 1983a) has been criticised by Chambers et al. (2002) and Chambers and Mattingley (2004). They found that the perceived pitch difference between the alternating tones rather corresponded to a semitone than to an octave, when using stimuli consisting of tones separated by an octave (Chambers et al., 2002). Based on a sequence of experiments, they suggested that when the two tones in a dichotic chord are presented simultaneously they generate a harmonic binaural fusion, and the pitch percept of this fusion corresponds to the pitch of the lower frequency tone (Houtsma and Goldstein, 1972; Chambers et al., 2002). Hence, they argued that the octave illusion is the result of peripheral asymmetries manifested as binaural diplacusis (Brink, 1970; Burns, 1982). This would account for the perception of small pitch differences between the ears but not of the lateralization effect in the octave illusion. For the latter effect they have no straightforward explanation; they found that the subjects lateralized the tones sometimes to the ear receiving the high-frequency tone and sometimes to the ear receiving the low-frequency tone (Chambers et al., 2002). Based on these findings they suggested that lateralization patterns originate from processing in low-level areas for binaural integration, with possible interaction with higher-level processes (Chambers et al., 2002; Chambers and Mattingley, 2004) (but see Deutsch, 2004b for a rebuttal).

The aim of the present study was to examine whether the octave illusion, explained in terms of a dominant ear for pitch and lateralization by frequency, can be elicited by aperiodic signals. A pitch sensation can be elicited using noises with steep spectral slopes (Fastl and Zwicker, 2007). For narrowband noises where the spectral edges are close together, the pitch often corresponds to the center frequency of the noise band (Fastl and Zwicker, 2007). We used low-frequency narrowband noises with overlapping spectra. The overlap was held constant, but the high- and low-frequency content of the signals was systematically varied. This means that although we sometimes refer to the phenomenon as octave illusion, our stimuli mainly comprised frequency differences of less than an octave. The rationale for using narrowband noises with overlapping spectra is that this type of signal is highly unlikely to result in binaural diplacusis since it does not contain any harmonics and, hence, any lateralization pattern must emerge from the frequency content of the signals. If so, Deutsch's two-channel model, since it relies on spatial cues, would be corroborated. On the other hand, if not, the model must be rejected and alternative explanations such as binaural fusion must be further considered.

II. METHOD

A. Subjects

Sixteen subjects participated in the study (eight men and eight women; mean age 41.1 yr, range from 22 to 58 yr). None of the subjects reported previous experience with the octave illusion. All subjects had hearing thresholds for pure tones that were better than 25 dB hearing level (HL) for octave frequencies 125–1000 Hz (ISO, 1998, 2003), exhibited normal external ear canals and tympanic membranes verified by otoscopy and reported no tinnitus. All subjects were right-handed, ranging between 80 and 100 (maximum 100, minimum –100) on the Edinburgh inventory (Oldfield, 1971). All investigations were performed in accordance to the Helsinki declaration. The Institutional Review Board at the Section of Logopedics, Phoniatrics, and Audiology, Lund University, approved this project.

B. Stimuli, equipment, and procedures

Eighteen narrowband noises were generated by applying digital Butterworth band-pass filters to white noise. This was achieved using commercially available computer software (COOL EDIT PRO 2.0). A 44.1 kHz sample rate was used. Filter slopes were set to ≥60 dB/octave. The noise duration was 500 ms, including 10 ms rise and fall times (linear ramps). The frequency content of the narrowband noises and how the noises were combined into dichotic chords are presented in Table I and Fig. 2. As can be seen, the spectral overlap was held constant for all stimulus patterns (100 Hz wide; between 400 and 500 Hz) and hence some of the spectral content was always present binaurally. Each dichotic chord was used to form sequences in which the narrowband noises comprising the chord were alternated between channels, forming sequences that were 16-s in duration. When the high-frequency narrowband noise was presented to one ear the low-frequency narrowband noise was simultaneously presented to the other ear, and vice versa. There were no silent gaps between consecutive chords. The presentation level of the sequences was 60 dB sound pressure level (SPL) average rms (root-mean-square). White noise was added to the sequences at a level of –20 dB rms to mask any unwanted spectral content due to the filtering.

The equipment used was an external Technics SLPS740A CD player (Panasonic, Germany) connected to a GSI 16 audiometer (Grason-Stadler, Madison, MI). A pair of Telephonics TDH-39P with MX41/AR cushions (Telephonics, Interacoustics, Assens, Denmark) completed the set-up and was used for the presentation of all stimuli. All tests were performed in a double-walled soundproof booth complying with the maximum permissible ambient sound pressure levels as specified in ISO 8253-1 (1998), and each subject participated in one session. The complete equipment set-up was calibrated in accordance with IEC 60318-3 and ISO 389-1 using a Brüel and Kjaer 2231 sound level meter (B&K, Naerum, Denmark) with a 4144 microphone in a 4152 artificial ear (IEC, 1998; ISO, 2003). The sequences of narrowband noises were calibrated using a continuous 1000 Hz tone with the same average rms as the sequences.

In each test condition a sequence was presented twice to the subject. First, a 1000 Hz tone of 4-s duration was presented binaurally to indicate that the test had begun. The 1000 Hz tone was followed by 3-s silence before the first presentation of the sequence. This presentation was followed by 3-s silence and then by a second presentation of the identical sequence. The next condition was then presented in similar manner. This entire procedure was used with both normal earphone placement and also reverse earphone placement. It was repeated twice for each test condition, one for a lateralization response and one for a pitch response. (The term “normal earphone placement” indicates that the narrowband noise with high-frequency content was first presented to the right ear and then to the left ear. The term “reverse earphone placement” indicates that the narrowband noise with high-frequency content was first presented to the left ear and then to the right ear.) The orderings of test condition and earphone placement were counterbalanced across subjects using a reversed Latin squares design. Responses were made by the subject concerning pitch and lateralization separately, using standardized response sheets. For each condition the subjects were instructed to note whether they heard (a) a sequence that began in the right ear and ended in the left ear, (b) a sequence that began in the left ear and ended in the right ear, or (c) neither of the above. The subjects were also instructed to note whether they heard (a) a sequence that began with a high tone and ended with a low tone, (b) a sequence that began with a low tone and ended with a high tone, or (c) neither of the above. The response order of (a), (b), and (c) was counterbalanced on the response sheets within and across subjects.

C. Statistical analysis

A one sample Chi-square test was used to determine whether the number of subjects who reported an octave illusion was larger than those who did not; alpha-values <0.05 were considered statistically significant. Spearman's rank correlation coefficient (rho) was calculated between the frequency distribution in each test condition (mainly high- or low-frequency content, or equal distribution of high and low frequencies) and which part of the frequency spectrum the subjects had used for their lateralization; a probability value of $p < 0.05$ was considered to be statistically significant.

III. RESULTS

The overall results for illusory percepts are presented in Fig. 3 as a function of test condition; i.e., the frequency distribution of the narrowband noises. The illusory percept indicates that the subject reported a clear lateralization pattern and a clear pitch pattern. The figure shows that the number of subjects with an illusory percept was significantly higher than the number of those without an illusory percept in 10 out of 18 tested conditions ($p < 0.05$) and significantly lower in two conditions ($p < 0.05$). In the two latter cases, the signals presented to the ears had an identical frequency distribution and were thus completely overlapping (i.e., the bandpassed narrowband noises presented to both ears contained only spectral content between 400 and 500 Hz). This finding was evidently as expected, since the signals presented via the two channels were identical. Taken together, these findings indicate that the majority of combinations of narrowband noises elicited illusory percepts.

The results were further classified into two groups according to the subjects' responses regarding pitch and lateralization. In the first group, the pooled results indicated lateralization toward a signal with high- or low-frequency content, together with pitch perception determined by a dominant ear. Note that these results are in a broader definition of the illusion than that described by Deutsch (see also Deutsch, 2004a,b). Sixty-six percent of the responses fell within this group with normal earphone placement and 65 % with reverse earphone placement. In the other group, the pooled results indicated that the subjects perceived the pitches presented to a dominant ear, but with no lateralization (13% with normal earphone placement and 11% with reverse earphone placement); lateralization but no dominant ear (12 % with normal earphone placement and 12 % with reverse earphone placement); or neither lateralization nor a dominant ear for pitch (9 % with normal earphone placement and 12 % with reverse earphone placement). It should be noted that the latter group included responses that were made when the frequency distribution consisted only of completely overlapping signals.

The first group (i.e., those whose responses indicated both lateralization by frequency and pitch perception in accordance with a dominant ear) was further divided into two subgroups. The reports of one subgroup, termed Deutsch's illusion, indicated a dominant ear for pitch and a lateralization toward the ear receiving the high-frequency content; i.e., their results were according to Deutsch's definition (Deutsch, 2004a). The reports of the other subgroup, termed other illusory percept, indicated a dominant ear for pitch but a lateralization toward the ear receiving the low-frequency content. This division was made separately for each test condition and earphone placement. The condition where only completely overlapping spectra were presented was excluded from this analysis and further analyses, since these stimuli by definition cannot elicit an illusion.

In Fig. 4, the results from the two subgroups, Deutsch's illusion and other illusory percept, are presented as a function of test condition; i.e., the frequency distribution of the narrowband noises. Overall, the frequency content of the signals affected the type of illusory percept that the subjects obtained. It can be seen in Fig. 4 that the number of subjects reporting Deutsch's illusion was low when they were listening to sequences containing predominantly low-frequency content; however this number increased with reduced low-frequency content and increased high-frequency content. On the other hand, the number of subjects reporting other illusory percept was high when the subjects were listening to sequences containing predominantly low-frequency content; however this number decreased with reduced low-frequency content and increased with high-frequency content.

In the correlation analysis examining associations between the frequency distribution in each test condition, and which part of the frequency spectrum the subjects had used for their lateralization responses, the results showed a significant positive association between the number of reported Deutsch's illusions and signals with predominantly high-frequency content (DF = 2, rho = 0.927, $p < 0.001$). The number of other illusory percepts showed a significant negative association with signals with predominantly high-frequency content (DF = 2, rho = –0.728, $p = 0.001$). Furthermore, as shown in Fig. 4, other illusory percepts were less salient when the protruding low-frequency part of the narrowband noise was only 50 Hz wide and the other frequency content overlapped completely, than when the protruding part was 100 Hz wide. For the corresponding conditions in Deutsch's illusion (i.e., when the protruding high-frequency part of the narrowband noise was only 50 Hz wide and the other frequency content overlapped completely), this effect was much less pronounced.

However, this analysis has so far only considered the number of percepts obtained under the different test conditions; it has not considered the consistency of the percepts when the earphone placements were reversed in individual subjects. Figure 5 shows the number of subjects who were consistent in their percepts; i.e., who did not change their dominant ear or lateralization pattern when earphone placement was reversed. Also seen in this figure is the number of subjects who were consistent in their responses regarding both their dominant ear for pitch (left or right) and lateralization to the ear presented with the narrowband noise with higher frequency content, irrespective of earphone placement; i.e., whose responses were completely in accordance to the two-channel model. The number of subjects who did not change their lateralization pattern varied across the test conditions. The lowest number was seen when the signal content protruded by 100 or 50 Hz on both sides of the overlapping spectra; in contrast when the protruding frequency content increased in one channel, either toward the lower or higher frequencies, this number increased markedly. The same tendency was seen for the dominant ear for pitch; however the effect of signal content was not as clear as for lateralization. The number of subjects whose responses were completely in accordance with the two-channel model regardless of the amount of protrusion of high or low frequency content in the signal; i.e., who showed a consistent dominant ear for pitch together with lateralization toward the ear receiving more high-frequency content, was generally low, but showed a significant positive association with increasing high-frequency content in one channel (DF = 3, rho = 0.784, p = 0.01).

IV. DISCUSSION AND CONCLUSION

The present findings indicate that illusory percepts based on a dominant ear for pitch in combination with a frequency- dependent lateralization were perceived by most subjects (65%–66%) for the majority of combinations of narrowband noises with partly overlapping spectra. This prevalence was similar to results previously reported for naïve listeners who were presented with pure-tone stimuli (Deutsch, 1974). Thus, aperiodic stimuli appear to elicit illusory percepts similar to those obtained for pure-tone stimuli. However the present study only used aperiodic stimuli and did not formally explore this possible relationship with percepts from sine wave stimuli. Yet the number of subjects who reported percepts that were completely consistent with the two-channel model under all the stimulus conditions used here (cf. Fig. 5) was generally low (Deutsch, 1974, 1975b) and this number depended on how much high-frequency content was contained in the test signals.

This study has demonstrated an association between the frequency content of the signal and the subjects' responses using narrowband noises as stimuli. For subjects with illusory percepts, we found a significant association between the frequency content of the narrowband signals and the type of illusory percept they obtained. Deutsch's illusion (i.e., lateralization toward the signal with higher frequency content and a dominant ear for pitch) was perceived when there was a predominance of high-frequency content in the stimuli. Other illusory percept (i.e., lateralization toward the signal with low-frequency content and a dominant ear for pitch) was perceived when there was a predominance of low-frequency content in the stimuli. The lateralization pattern therefore varied with the frequency content of the signal.

However, this analysis was based on a summary of reported percepts for each test condition and did not take into account how consistent the responses were across conditions. In doing so, the number of subjects who reported the same dominant ear with both types of earphone placement, but a change in lateralization between earphone placements, was found to be generally small but highly associated with the amount of high-frequency content in the signal. Thus, predominant high-frequency content yielded more responses that were consistent for both earphone placements and in accordance to the two-channel model. Since no harmonics were present in the stimuli, it is highly unlikely that this illusion is perceived on the basis of binaural diplacusis or harmonic binaural fusion, as suggested by Chambers and colleagues (Chambers et al., 2002; Chambers and Mattingley, 2004). Thus, the interaction between pitch and lateralization appears to emanate from spatial components (Deutsch, 1981, 1983a) rather than afferent pathways from each ear (Chambers et al., 2002).

Furthermore, the mechanisms of binaural diplacusis and harmonic binaural fusion proposed by Chambers and colleagues can be questioned on the basis of previous research using pure-tone stimuli, which showed that Deutsch's illusion can be elicited by intervals smaller than an octave (Zwicker, 1984; Brancucci et al., 2009). Furthermore, Brancucci and colleagues showed that the salience of Deutsch's illusion decreased with reduced frequency separation between pure tones (Brancucci et al., 2009). This is problematic for an illusion elicited by binaural diplacusis and harmonic binaural fusion, since in Brancucci's study only a few subjects perceived the illusion for sequences of tones forming small frequency ratios (e.g., 400 and 480 Hz). Yet if the mechanisms underlying the illusion were the result of binaural fusion and binaural diplacusis, the illusion should also have been a salient percept for very small frequency ratios (Brink, 1970; Burns, 1982).

The comparison between the present aperiodic stimuli and results obtained using pure-tone stimuli requires further investigation: There might be differences that depend on the filter bandwidth for these two types of signal in the inner ear and in more central parts of the auditory system. Further studies are needed to examine this relationship between illusory percepts elicited by pure-tones and aperiodic stimuli, perhaps only studying subjects whose responses were consistent for the original illusion.

There are other differences between the present study and previous ones also: We used a three-interval forced-choice (3IFC) test paradigm previously used by (Zwicker 1984), while most research has mainly been conducted using a two-alternative forced-choice (2AFC) (Deutsch, 1978, 1980, 1988; Chambers et al., 2002; Sonnadara and Trainor, 2005; Brancucci et al., 2009), qualitative responses (Deutsch, 1975b; Deutsch and Roll, 1976; Chambers et al., 2002; Deutsch, 2004a), or four-interval forced-choice (4IFC) by the subjects on the presented stimuli (Deutsch, 1983b). However, since previous research has shown that some subjects obtain different types of percept (e.g., Deutsch, 1974, 1983a), we decided to use 3IFC in order to minimize the bias produced by including such subjects, as would have been the consequence if we had used 2AFC test paradigm. Also, all our subjects were strongly right-handed on the Edinburgh inventory (Oldfield, 1971). Due to this small variation within the group of subjects tested we chose not to examine associations between responses and handedness. On the other hand, this small handedness variation may well have contributed to the homogeneity of the results produced by the group studied here.

In summary, the present findings suggest that an auditory illusion in terms of a dominant ear for pitch, together with lateralization by frequency, can be elicited by aperiodic signals in most subjects in a majority of the test conditions we employed. Also, the number of subjects reporting illusory percepts that were completely in accordance with the two-channel model increased with increasing high-frequency content in the signal. The present findings therefore support the two-channel model proposed by Deutsch (1975a).

ACKNOWLEDGMENTS

The authors are indebted to a reviewer for valuable comments and suggestions to a previous version of this manuscript.

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LEGENDS

Table I. The frequency content of the narrowband noises in the study and their combinations into dichotic chords using normal earphone placement.

Figure 1. A schematic presentation of the stimuli (upper portion) used to elicit the most common percept of the octave illusion (lower portion). Adapted from Deutsch (1974).

Figure 2. The frequency content of the narrowband noises and their combinations into dichotic chords using normal earphone placement. The gray areas indicate frequency content presented via the right and left channels, respectively. The black areas indicate spectral content presented via both channels at the same time.

Figure 3. The total number of subjects reporting an illusory percept as a function of test condition; i.e. the frequency distribution of the narrowband noises and earphone placement. An illusory percept indicates that the subject reported a clear lateralization pattern and a clear pitch pattern. Black bars indicate normal earphone placement and white bars indicate reverse earphone placement. In the cases where the bars surpass the reference line (located between 11 and 12 subjects), the difference between those obtaining and those not obtaining an illusory percept was significant ($p < 0.05$).

Figure 4. The total number of subjects reporting Deutsch's illusion and other illusory percept (see text for definition) as a function of test condition; i.e. frequency distribution of the narrowband noises and earphone placement. Filled circles indicate Deutsch's illusion and empty circles indicate other illusory percept.

Figure 5. The total number of subjects who reported consistent responses in accordance with the two-channel model when earphone placement was reversed. The results are reported as a function of test condition; i.e. frequency distribution of the narrowband noises. Empty squares indicate a consistent dominant ear. Empty diamonds indicate the same pattern of lateralization. Filled circles indicate responses completely consistent with the two-channel model.

Table I. The frequency content of the narrowband noises in the study and their combinations into dichotic chords using normal earphone placement.

Condition	Left channel Low cut-off (Hz)	High cut-off (Hz)	Right channel Low cut-off (Hz)	High cut-off (Hz)
1	300	500	400	500
2	350	500	400	500
3	300	500	400	550
4	300	500	400	600
5	350	500	400	550
6	400	500	400	500
7	350	500	400	600
8	400	500	400	550
9	400	500	400	600

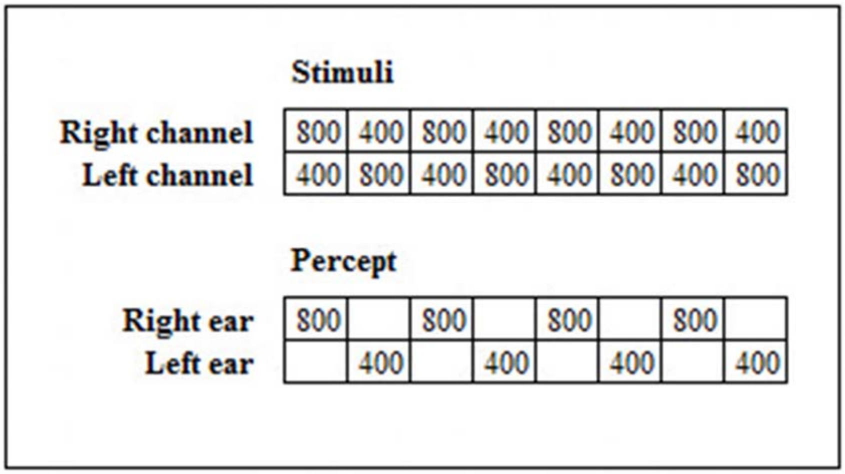
Stimuli
Right channel
800 400 800 400 800 400 800 400
Left channel
400 800 400 800 400 800 400 800
Percept
Right ear
800 800 800 800
Left ear
400 400 400 400

Figure 1.

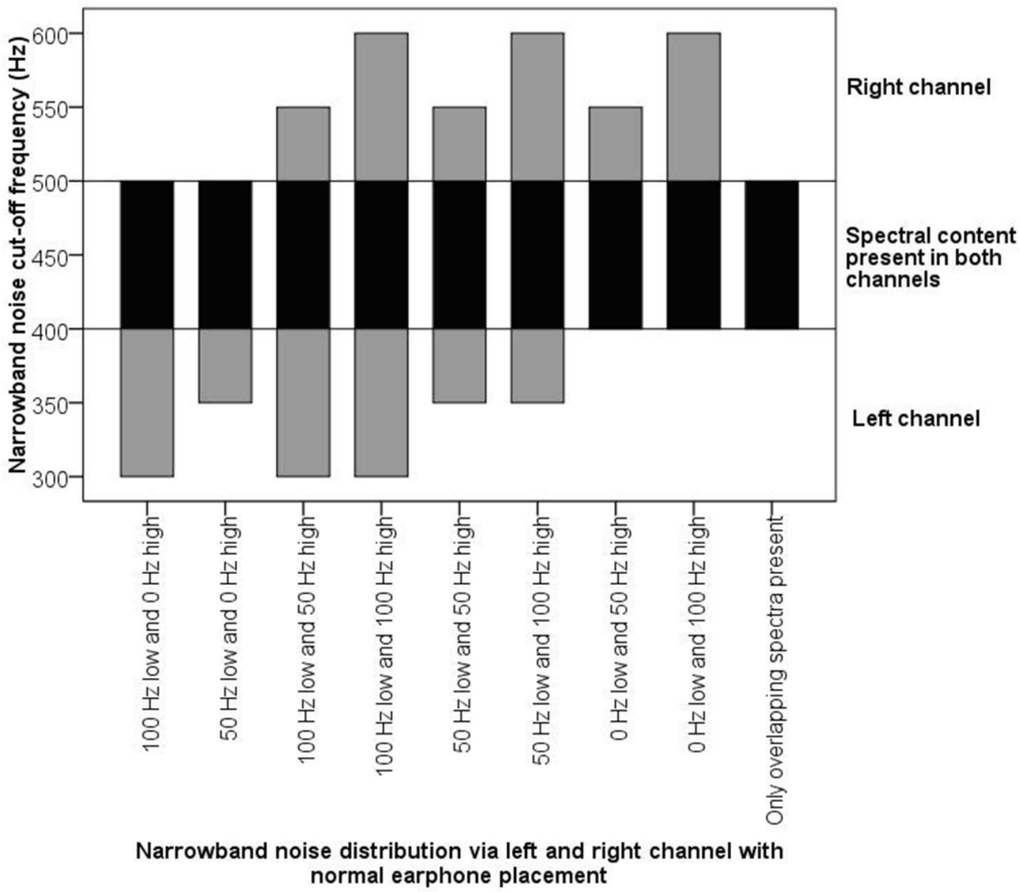
Narrowband noise cut-off frequency (Hz)
600
550
500
450
400
350
300
Right channel
Spectral content present in both channels
Left channel
100 Hz low and 0 Hz high
50 Hz low and 0 Hz high
100 Hz low and 50 Hz high
100 Hz low and 100 Hz high
50 Hz low and 50 Hz high
50 Hz low and 100 Hz high
0 Hz low and 50 Hz high
0 Hz low and 100 Hz high
Only overlapping spectra present
Narrowband noise distribution via left and right channel with normal earphone placement

Figure 2.

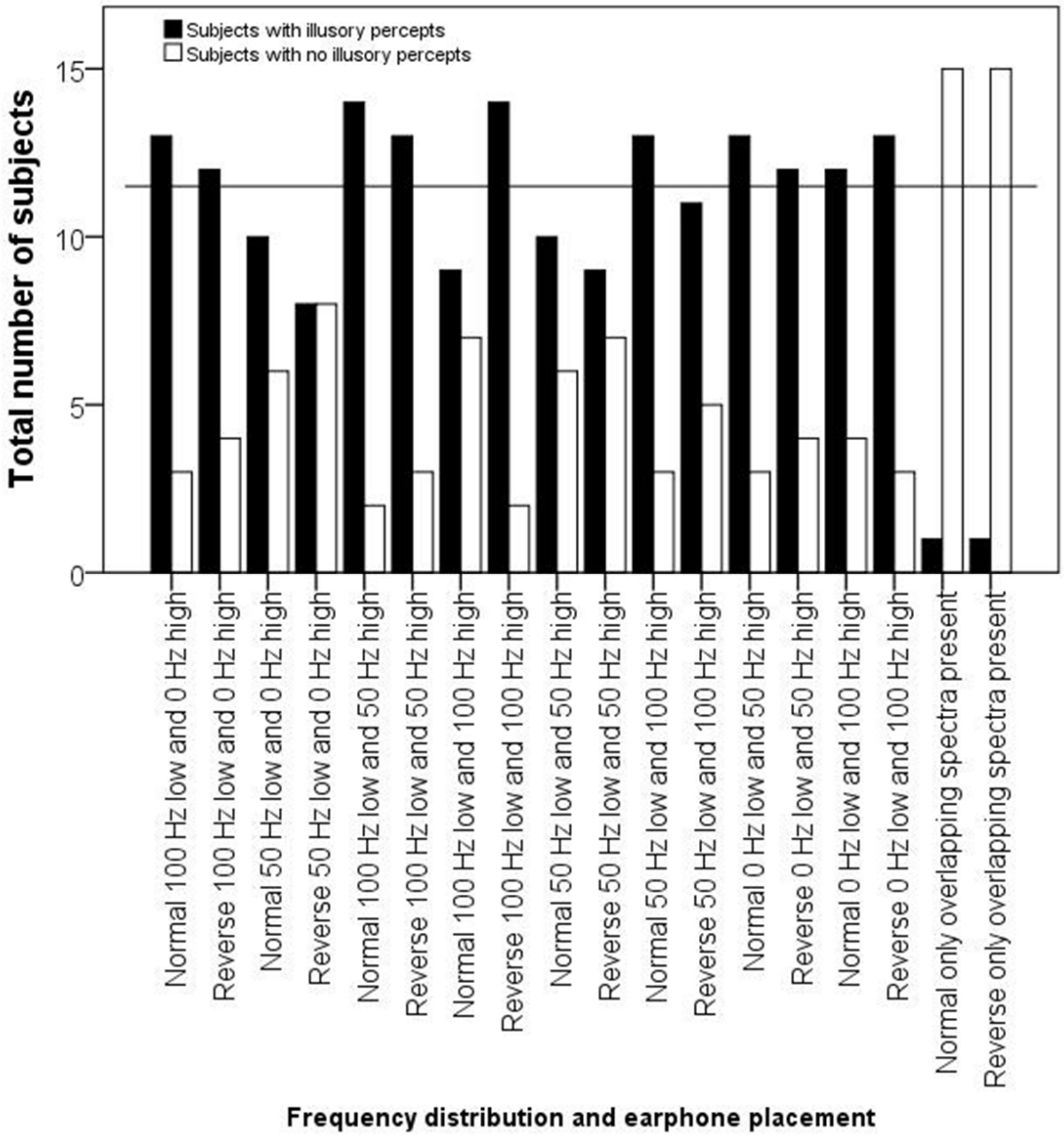
Subjects with illusory percepts
Subjects with no illusory percepts
Total number of subjects
15
10
5
0
Normal 100 Hz low and 0 Hz high
Reverse 100 Hz low and 0 Hz high
Normal 50 Hz low and 0 Hz high
Reverse 50 Hz low and 0 Hz high
Normal 100 Hz low and 50 Hz high
Reverse 100 Hz low and 50 Hz high
Normal 100 Hz low and 100 Hz high
Reverse 100 Hz low and 100 Hz high
Normal 50 Hz low and 50 Hz high
Reverse 50 Hz low and 50 Hz high
Normal 50 Hz low and 100 Hz high
Reverse 50 Hz low and 100 Hz high
Normal 0 Hz low and 50 Hz high
Reverse 0 Hz low and 50 Hz high
Normal 0 Hz low and 100 Hz high
Reverse 0 Hz low and 100 Hz high
Normal only overlapping spectra present
Reverse only overlapping spectra present
Frequency distribution and earphone placement

Figure 3.

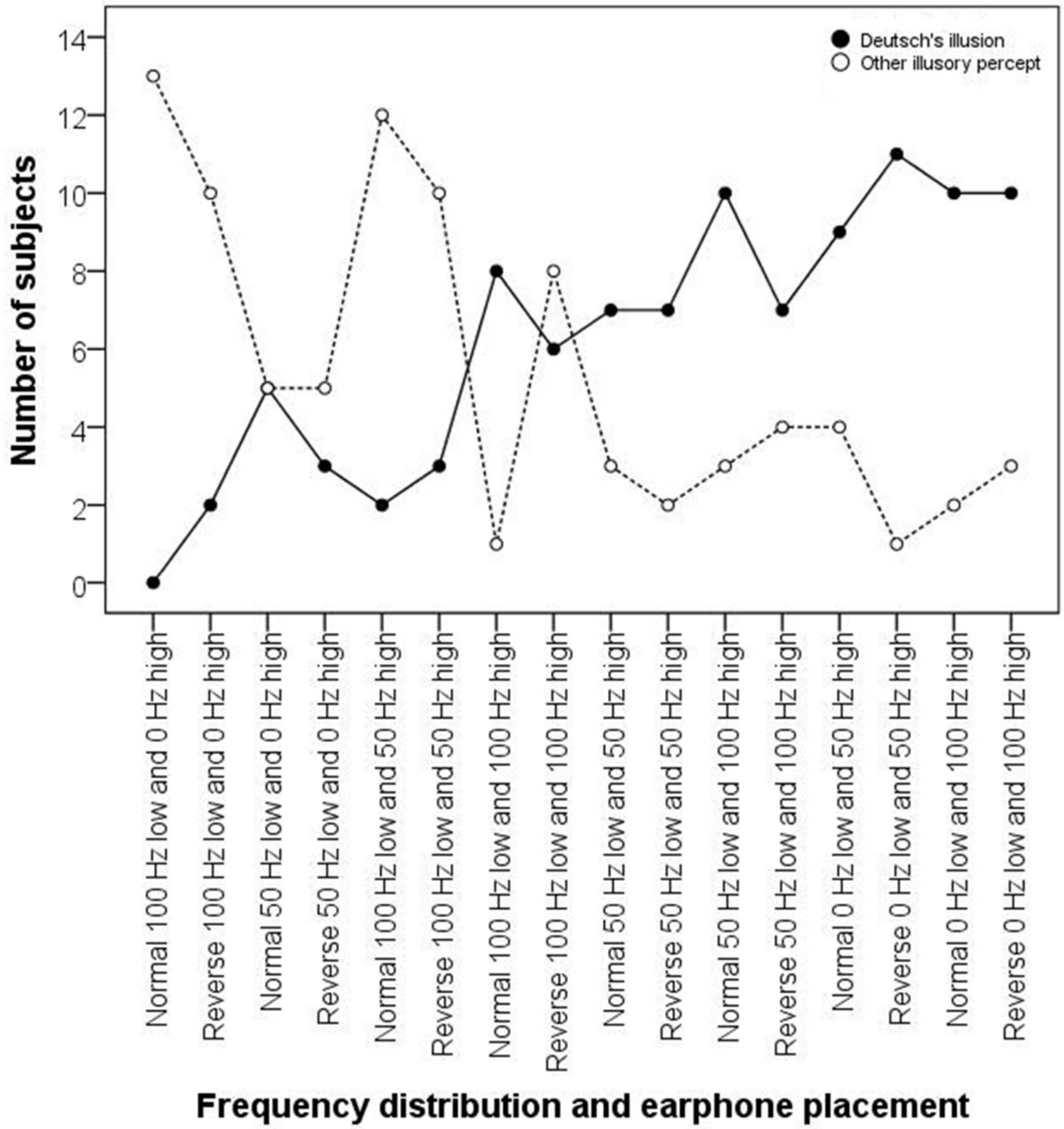
Deutsch's illusion
Other illusory percept
Number of subjects
14
12
10
8
6
4
2
0
Normal 100 Hz low and 0 Hz high
Reverse 100 Hz low and 0 Hz high
Normal 50 Hz low and 0 Hz high
Reverse 50 Hz low and 0 Hz high
Normal 100 Hz low and 50 Hz high
Reverse 100 Hz low and 50 Hz high
Normal 100 Hz low and 100 Hz high
Reverse 100 Hz low and 100 Hz high
Normal 50 Hz low and 50 Hz high
Reverse 50 Hz low and 50 Hz high
Normal 50 Hz low and 100 Hz high
Reverse 50 Hz low and 100 Hz high
Normal 0 Hz low and 50 Hz high
Reverse 0 Hz low and 50 Hz high
Normal 0 Hz low and 100 Hz high
Reverse 0 Hz low and 100 Hz high
Frequency distribution and earphone placement

Figure 4.

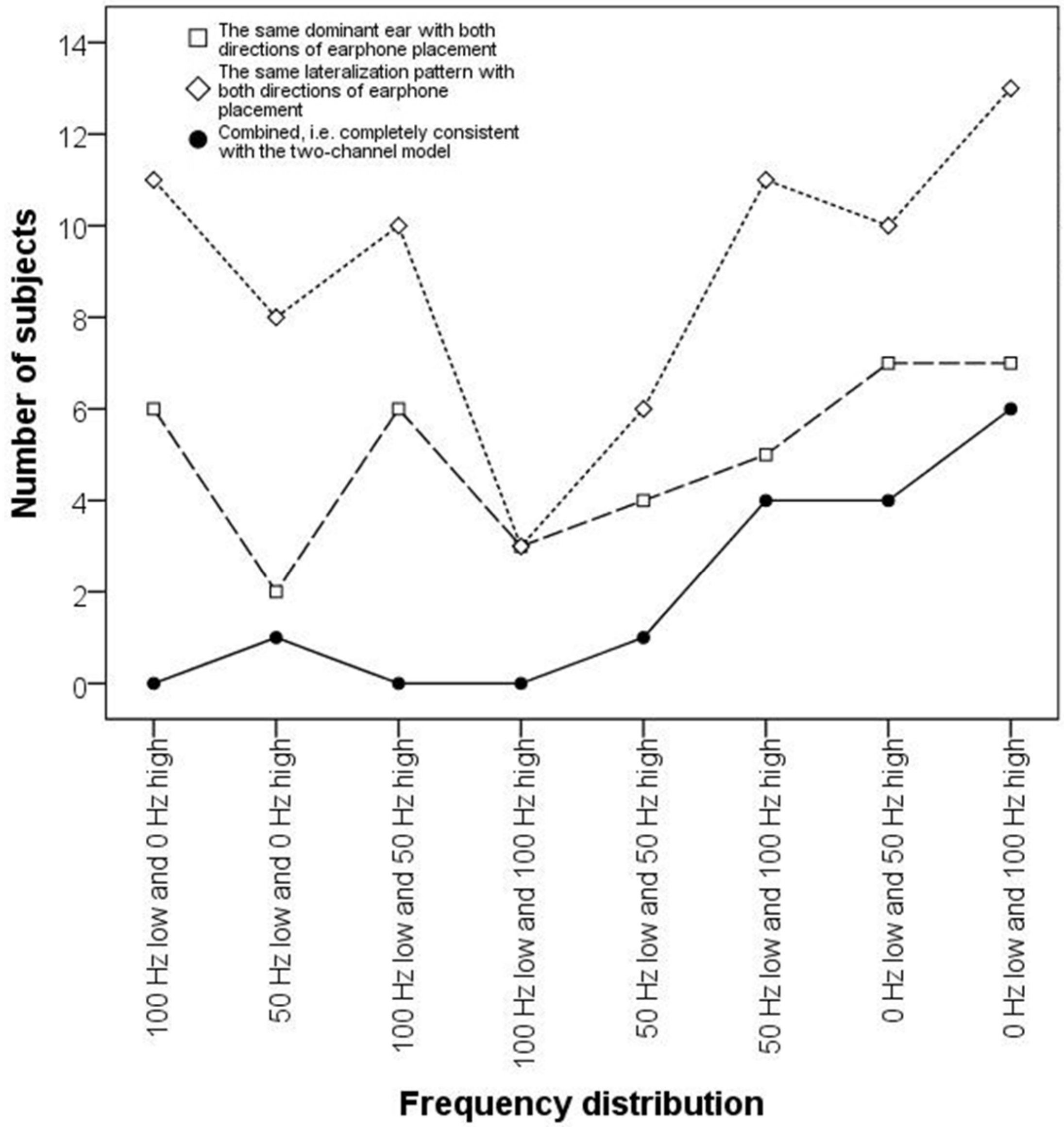
The same dominant ear with both directions of earphone placement
The same lateralization pattern with both directions of earphone placement
Combined, i.e. completely consistent with the two-channel model
Number of subjects
14
12
10
8
6
4
2
0
100 Hz low and 0 Hz high
50 Hz low and 0 Hz high
100 Hz low and 50 Hz high
100 Hz low and 100 Hz high
50 Hz low and 50 Hz high
50 Hz low and 100 Hz high
0 Hz low and 50 Hz high
0 Hz low and 100 Hz high
Frequency distribution

Figure 5.