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A Psychophysiological Study of Auditory Illusions of Approach and Withdrawal in the Context of the Perceptual Environment

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Auditory perception of the depth of space is based mainly on spectral and amplitude changes of sound waves originating from the sound source and reaching the listener. The perceptive illusion of movement of an auditory image caused by changes in amplitude and/or frequency of the signal tone emanating from an immobile loudspeaker was studied. Analysis of data obtained from the participants revealed the diapason of combinations of amplitude and frequency changes for which the movement direction was perceived similarly by all participants, despite significantly different movement assessment criteria. Additional auditory and visual information of the conditions of radial movement (near or far fields) determined listeners' interpretation of changes in the signal parameters. The data obtained about the perception of approach and withdrawal models are evidence of the fact that the principal cues of the perception of the distance of immobile sound sources manifests similarly to that of an auditory image moving along a radial axis.
Keywords: auditory perception, illusion of movement, virtual reality

La percepción auditiva de la profundidad del espacio se basa principalmente en los cambios de espectro y amplitud de las ondas de sonido que originan desde la fuente del sonido y alcanzan al escuchador. Se estudió la ilusión perceptiva del movimiento de una imagen auditiva causada por los cambios en la amplitud y/o la frecuencia del tono de señal que emana desde un altavoz inmóvil. Análisis de los datos obtenidos de los participantes reveló el diapasón de combinaciones de las modulaciones de amplitud y frecuencia para las cuales el vector de movimiento se percibió de la misma forma por todos los participantes, a pesar de criterios de evaluación del movimiento significativamente diferentes. Información adicional auditiva y visual de las condiciones de movimiento radial (campos cercanos o lejanos) determinó la interpretación de los cambios en los parámetros de la señal por parte de los escuchadores. Los datos obtenidos acerca de la percepción de los modelos de acercamiento y retirada son evidencia del hecho de que los rasgos principales de la percepción de la distancia de fuentes de sonido inmóviles se manifiesta de forma similar a la de una imagen auditiva que se mueve a lo largo de un eje radia.
Palabras clave: percepción auditiva, ilusión de movimiento, realidad virtual

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The orientation of an individual in space and the adequate perception of the surrounding environment take place with the participation of the auditory sensory system. Auditory perception of the depth of space is mainly based on spectral and amplitude changes in sound waves originating from sound sources and reaching the listener (Coleman, 1963). However, how these cues form auditory space and whether or not the auditory image is perceived equally by different individuals remains almost unknown. There is basis for the supposition that the perception of egocentric space (from the listener to the sound source) is unique for each individual and is largely dependent on additional information, such as visual information (Ashmead, Davis, & Northington, 1995). Depending on the distance diapason (near or far fields), spectral changes from distant sound sources possess varying vectors. Changes in the spectrum of the signal are important for the assessment of the distance of the sound sources in near field with distances of less than 3 m (the precise distance limit depends on the spectral diapason of the signal and the dimensions of the source), and more than 15 m (Blauert, 1983). With short distances, the changes are caused by distortion of the sound wave edge by the head and ear concha and are significant for frequencies exceeding 1500 Hz (Haustein, 1969). In distances exceeding 15 m, the high frequency portion of the spectrum weakens with increasing distance from the sound source increasingly in direct relation to frequency. This is due to the fact the coefficient of sound absorption depends on its frequency and increases from 10^{-2} dB/100 m to 10 dB/100 m as frequency increases from 100 to 10000 Hz (Piercy, Embleton, & Sutherland, 1977).

However, even the most universal and unambiguous perceptive cue, such as the level signal intensity, is insufficient for adequate distance assessment. In free field, the magnitude of change in signal intensity, which causes the perception of doubling the distance, varied between 9 and 30 dB and significantly differed from calculated values (Begault, 1991; Gardner, 1969; Mershon, & King, 1975; Warren, 1977; Petersen, 1990; Stevens & Guirao, 1962).

Our interest was captured by the question of the possibility, despite the noted ambiguity of listeners' assessment of the distance of the sound source, of forming an unambiguous perception equal for all individual listeners as a receding (or approaching) auditory image. For this purpose, sensory scaling of the signals with varying cues of approach or withdrawal of the sound source was carried out. Furthermore, the perception of signals in varying perceptual environments of near and far acoustic fields, with and without additional visual information, was studied.

Models of Auditory Image Approach and Withdrawal

Auditory illusions causing a sensation of movement have been noted as far back as the beginning of the last century (Burtt, 1917). Illusions arise with the continuous perception of consecutive sounds emitted from spatially separate sources with minimal temporal intervals (fractions of seconds) between sounds. For the creation of an illusion of movement, it is sufficient to fulfill two conditions: (a) the presence of a pair of spatially remote sound sources and (b) the interval between stimuli should be maintained within a specific temporal range. The possibility to create, using two immobile sound sources, the illusion of auditory image motion has been demonstrated along all coordinates of auditory space—azimuth, vertical, and horizontal (Altman & Andreeva, 2004; Middlebrooks & Green, 1991; Strybel & Neale, 1994). The imitation of extensive trajectories of the auditory image was carried out with a range of loudspeakers (Strybel, Manligas, & Perrott, 1992). However, as is well known, the illusion of radial motion can be created by changing the amplitude of the signal emitted from an immobile sound source (Vartanian & Chernigovskaia, 1980).

Experiment 1.
The Perception of the Motion of an Auditory Image included Amplitude and Spectral Cues

Method

Participants

Thirty-two healthy individuals with normal hearing (15 males and 17 females within the ages of 18 and 36 years) participated in this study.

Procedure and Apparatus

The illusion of sound source motion was created by altering amplitude and/or frequency of consecutive tonal impulses emitted from a stationary sound source (Vartanian, Andreeva, Mazing, & Markovich, 1999). The condition of continuous sounding was maintained: The temporal interval between tone impulses comprised 12.5 ms. The tonal impulses were consecutively linearly changed in amplitude form maximal to minimal values (imitation of withdrawal) or in the opposite order (imitation of approach). The spectrum of consecutiveness of tonal impulses was made up of narrowband noise with a maximum equal to the frequency of the tone and band width dependent on the duration of the impulses. With impulse duration 10 ms with ascending and descending parts of 2.5ms, the spectrum comprised 240 Hz. Figure 1a displays the sonogram of consecutive tonal impulses with increasing amplitude at every impulse. In an alternate model, the frequency of the tone (carrier frequency) changes with each impulse in a monotonous linear pattern with changes in the spectral maximum of noise (Figure 1b). A third variant motion model is made up of simultaneous changes of frequency and amplitude in the consecutiveness of tonal

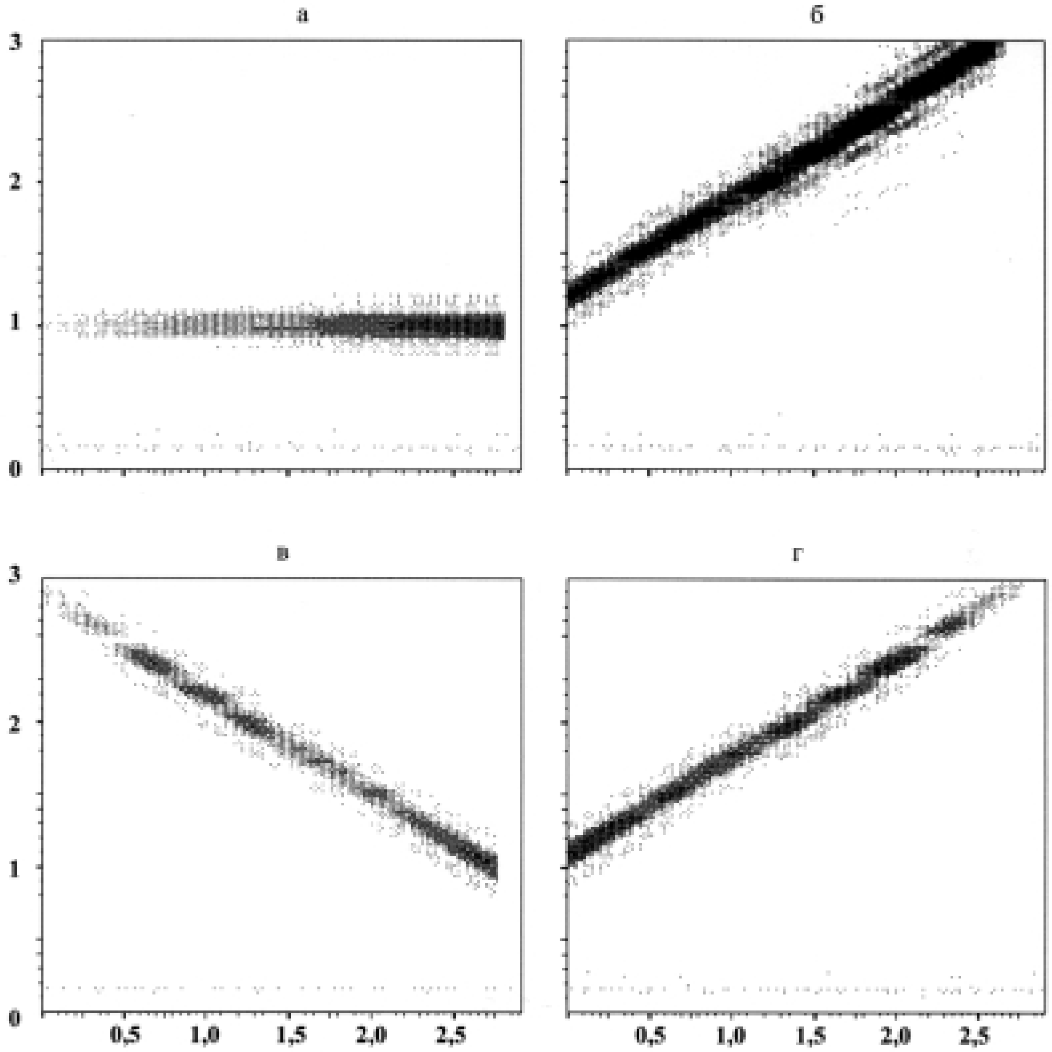

Figure 1. Sonogram of signals changed in amplitude (a), frequency (b) and imitating sound source approach (c) and withdrawal (d). X-axis = time in seconds; Y-axis = frequency in KHz. The color intensity indicates the spectral power of the signal.

impulses with varying combinations of increase and decrease of the named parameters (Figures 1 c–d). A total of six series were used in which the signals were altered in amplitude (Series 1), in frequency (Series 2), and in both parameters simultaneously (Series 3-6). Each series consisted of 20 signals with various parameter values per signal emitted from a stationary SONY XSF1720 loudspeaker (two-band coaxial loudspeaker, frequency range 24–23000 Hz). The loudspeaker was placed in a frontal plane (0º azimuth and 0º elevation) at a distance of 3 m from the listener. Measurement of the intensity of the sound signal at the location of the listener's head, calibration of the sound source, and measurement of the spectral forms of the signals was carried out using a 41–45 microphone, 26–29 preamplifier and 26–06 amplifier (Bruel & Kjaer Co.). Spectral analysis was carried out using interface CED-1401plus and Waterfall software. The synthesis of the signals was maintained by original software implemented on the basis of a standard SB 16 sound board.

The participants listened to the moving auditory images in a soundproof non-echo chamber with a special floor, walls, and ceiling covering, eliminating reverberation within the chamber. Audiograms of all the participants were carried out using a standard MA-31audiometer in the same chamber. Perception testing of the participants was carried out using a sensory scaling method. Participants listened to and assessed consecutively all 6 series of signals containing cues of auditory image motion. The assessment scale was made up of 9 response choices to the question: "To what extent does the perceived sound relate to approach and withdrawal of the sound source?" Possible responses were: 1 (*distinct withdrawal*), 2 (*relatively clear withdrawal*), 3 (*fair withdrawal*), 4 (*slight signs of withdrawal*), 5 (*no movement*), 6 (*slight signs of approach*), 7 (*fair approach*), 8 (*relatively clear approach*), and 9 (*distinct approach*). Thus, the participants' response variants corresponded to an ordinal scale for the assessment of sound image motion. Participants' responses were recorded in a protocol.

Results

In the entire studied amplitude change range (11–65 dB), approach was perceived unambiguously. There were no assessment responses of these signals as receding. Less than 2% of the assessment responses of the signal were of "no movement." Statistical analysis of the total of signals with varying amplitude changes was carried out. The total data obtained in the participants' task of multiple choice assessments of the signals of consecutive tonal impulses with varying alteration in amplitude is shown on the top left section of Figure 2. Signals with decreasing amplitude of impulse series were perceived by the majority of participants as having "slight signs of withdrawal" of the sound source independent of the magnitude of amplitude change (Figure 3, top right). Participants rated 70–80% of the signals as receding auditory images.

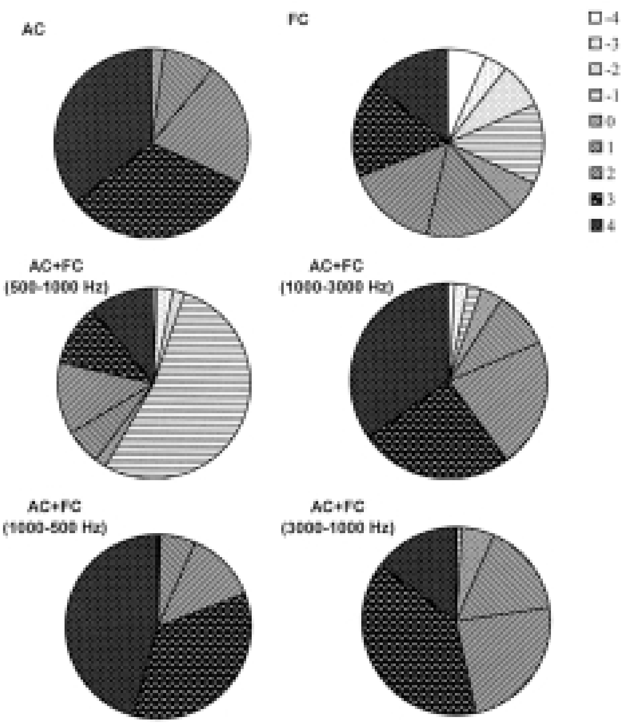

Figure 2. Signal assessment by participants with the modeling of sound source approach using the combination of signal amplitude change (AC) and/or frequency change (FC). $N = 120$.
On the left above the pie chart are indicated the signal parameter being changed, numbers indicate the range and direction of change of signal frequency in hertz. On the right, response choices are indicated: –4 = distinct withdrawal; –3 = moderately clear withdrawal; –2 = fair withdrawal; –1 = slight signs of withdrawal; 0 = no motion; 1 = slight signs of approach; 2 = fair approach; 3 = moderately clear approach; 4 = distinct approach.

Discussion

Thus, the modeling of approach and withdrawal of a sound source by altering amplitude indicated the following: (a) Alterations of this parameter of the signal in a wide range has no effect on the perception of radial motion; (b) the approach of the source modeled by amplitude change is perceived by participants more distinctly than its withdrawal.

The perception of a sound source in motion when modeled by spectral changes in the frequency range of 500–3000 Hz was studied with the frequency always either starting or ending at 1000 Hz. With the alteration of frequency by 100 Hz and 200Hz in both directions, 34% of the responses were "no movement" and 44% only reflected only "slight signs of withdrawal." Large changes in frequency of over 1000 Hz resulted in contradicting responses in the participants and none of the proposed choices exceeded 20%. With frequencies of less than 1000 Hz and with alterations in frequency of 300–500 Hz, the listeners perceived motion more distinctly. The participants' responses were summarized for this range of frequency change and are shown in Figure 2, top right. With the increase of frequency, there was perception of withdrawal of the source (77% of the responses) and with frequency decrease, approach of the source, as shown by 72% of the responses. One can conclude that linear changes in the frequency of impulse consecutiveness with fixed amplitude does not lead to distinct perception either of approach or withdrawal.

In reality of motion of a radial sound source, both parameters of the signal—amplitude and spectrum—may change in relation to the vantage point when approaching or withdrawing. Therefore, participants listened to a series of signals in which the image of a moving source was created by simultaneous linear changes in amplitude and frequency. With increasing amplitude of the consecutive tonal impulses (11–65 dB) and decreasing frequency (from 3000 to 1000 or 1000 to 500 Hz), the participants perceived the source as approaching more often. The results of the assessment of all signals by all participants with varying amplitude is shown in Figure 2, bottom. The results were similar to those observed with signals when only changing amplitude, and were significantly more accurate than with signals when only changing frequency. With frequency change from 3000 to 1000 Hz, there was 1% of contradictory responses (withdrawal instead of approach), and in 6% of cases, the signals were assessed as immobile auditory images (see Figure 2, right). The combination of increasing amplitude and increasing frequency led to contradictory assessments (see Figure 2, middle). The percentage of these assessments was particularly large (up to 65%) with increasing frequency from 500 to 1000 Hz (see Figure 2, left).

Decreasing amplitude of the model signal and increasing its frequency led to participants' perception of a withdrawing auditory image. With increasing frequency from 500 to 1000 Hz, withdrawal was perceived by 94% of the participants; increasing frequency from 1000 to 3000 Hz led to the perception of withdrawal in 86% of cases (see Figure 2, middle). The quantity of contradictory responses was 5 and 8%, respectively. This figure was significantly better than with changes only of amplitude (81%) and only of frequency (77%). With simultaneous decrease of amplitude and frequency of the consecutive tonal impulses, participants gave contradictory responses (Figure 3, bottom). This proportion was particularly high with decreasing amplitude and decreasing frequency from 1000 to 500 Hz and comprised 41%. Thus, depending on the direction of changes in frequency and amplitude of consecutive tonal impulses, perception of the modeled motion either improved in comparison to perception of modeling with changes in only one of the parameters, or sharply worsened. In the latter case, the proportion of contradictory responses increased.

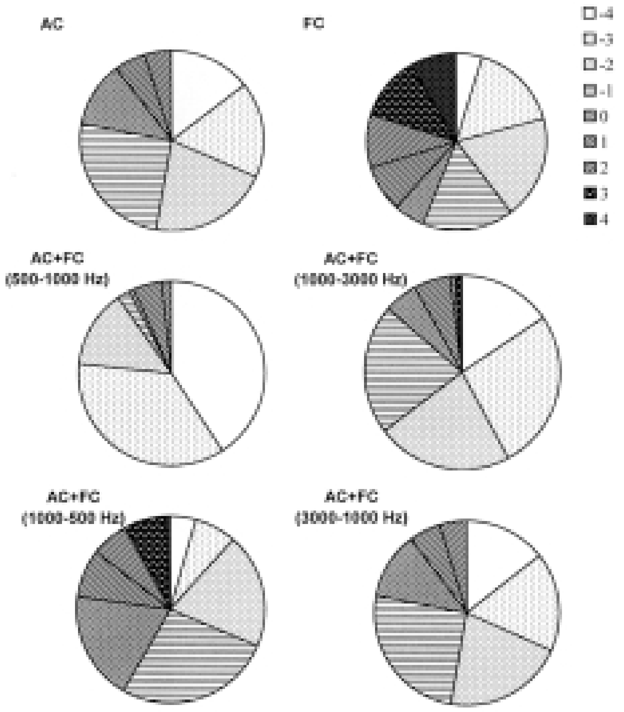

Figure 3. Signal assessment by participants with the modeling of sound source withdrawal using the combination of signal amplitude change (AC) and/or frequency change (FC). Initial and final values of signal tonal impulse frequency in hertz indicated in brackets. $N = 120$.
On the left above the pie chart are indicated the signal parameter being changed, numbers indicate the range and direction of change of signal frequency in hertz. On the right, response choices are indicated: –4 = distinct withdrawal; –3 = moderately clear withdrawal; –2 = fair withdrawal; –1 = slight signs of withdrawal; 0 = no motion; 1 = slight signs of approach; 2 = fair approach; 3 = moderately clear approach; 4 = distinct approach.

According to a review of literature, changes in signal intensity from 9 to 30 dB cause the sensation of distance from source to double (Begault, 1991; Gardner, 1969; Mershon & King, 1975; Petersen, 1990; Stevens & Guirao, 1962; Warren, 1977). Thus in the present study, the change in amplitude from 11 to 65 dB was proposed for the creation of the perception of motion between two remote points in space. Increasing the amplitude of the consecutive tonal impulses evoked approaching image in the participants, practically independent of the magnitude of change. The dynamic change in the location of the auditory image of approach was assessed unambiguously by all participants.

Withdrawal of the auditory image was perceived by listeners as motion less distinctly and unambiguously than the perception of approach. For this direction of dynamic change in the location of the sound source increasingly greater changes in the amplitude of the model signal are needed: the percentage of responses such as "immobile" and the opposite directions dropped to 15-20%.

One could hypothesize that the listener compared the initial point of the trajectory for the modeled motion and the actual position of the loudspeaker. If our assumption is right, the listener would have perceived the approach of the sound image as taking place at a distance of less than 3 m. Withdrawal would have been perceived with a trajectory with points at a distance of more than 3 m. In conic loudspeakers, the direction diagram is practically spherical and for this type of small loudspeakers, the acoustic field is practically the same as for a pulsating sphere (Blauert, 1983). At a distance from the listener less than 1 m, head-related transfer function significantly depends on distance (Brungart & Rabinowitz, 1999). A review of literature on spatial hearing shows that such distances are referred to as the "near field." In distances of about 3 m from the listener, the so-called near field effect, changes in distances of interaural dimension lead to changes in the perceived signal of approximately 1 dB, that is, approximately the differentiation threshold (Blauert). Therefore, the region of 1 to approximately 4 m should be referred to as "transitional," as the effects noted for small distances are poorly defined and are close to the human hearing threshold magnitude. For greater distances, the radius of the spherical wave increases to such an extent that, in comparison to head size, it becomes plane, and is known as the "far field."

In the present experiment with the supposed fixation by the listener of the initial motion trajectory points of the auditory image for the approach of the image, the trajectory was located in the transition area and near field. The trajectory of withdrawal was correspondingly located in the transitional area and far field, in which the resolution of distance was significantly worse (Brungart & Rabinowitz, 1999; Loomis, Klatzky, Philbeck, & Golledge, 1998). Changes in distance from the sound source modeled by withdrawal of the auditory image, with mean part of the studied range of amplitude change, corresponded to the distance range for which spectral changes are insignificant for the assessment of distance (3–15 m, according to the data of Coleman, 1968. Greater or lesser trajectory length modeled by amplitude change greater or lower than the above-mentioned interval of values should have been accompanied by spectral changes which were absent in the real signal.

Changes in carrier frequency with stationary amplitude of the consecutive tonal impulses permit research into the influence of frequency band of the sound source on the perception of radial motion. Within the range of studied carrier frequencies of 500 to 3000 Hz, the most successful approach models was with carrier frequencies of 500-600 Hz, and the imitation of withdrawal with carrier frequencies of 800–1000 Hz. Furthermore, the modeling of approach was more successful than the modeling of withdrawal. Considering the data obtained with respect to the above-mentioned hypothesis that the approach of the auditory image occurs according to the participants' assessment in near field, low frequency signals should increase the listeners' sensation of proximity of the auditory image, as reported in a study of stationary sound sources (Haustein, 1969). In conditions where the withdrawal of the auditory image occurs on a trajectory of over 3 m (location of the loudspeaker) and a certain position corresponding to the far field, signals of greater frequency additionally amplify the sensation of withdrawal, as noted in studies of perception of stationary sound sources (Bekesy, 1960).

In fact, signals undergo both amplitude and spectrum changes. Only in very specific conditions are the changes in signal spectrum in radial motion negligibly minute (Coleman, 1968). Therefore, the present study included research into the perception of auditory image motion with its modeling by the combination of cues—amplitude and frequency change of varying magnitude and direction. The combination of these changes in the consecutiveness of tonal impulses dependent on their direction either improved the quality of the modeled motion in comparison to modeling using only one of the parameters for the imitation of motion, or else led to an increase in the amount of contradictory responses. Optimal was the combination of parameters creating approaching auditory image—amplitude change by 47–59 dB in combination with frequency change from 1000 to 500 Hz—and of withdrawal—amplitude change of 25–65 dB with frequency change of 500 to 1000 Hz.

With simultaneous increase of amplitude and decrease of carrier frequency of the consecutiveness of tonal impulses, the effect of approach of the sound source intensified in comparison to the use of only one type of change in the signal, especially with frequencies of less than 1000 Hz. Such combinations correspond with the above-mentioned effects occurring with sound source motion at short distances (less than 3 m) between source and listener. With increasing amplitude and decreasing frequency (modeling of distances of over 15 m between source and listener), participants' responses were contradictory. Such ambiguity may be explained by the influence of additional information on the dimensions of the experimental chamber (62.5 m_) and the distance to the actual sound source, which could somehow determine the participant's choice of response about the direction of the aurally perceived motion. The importance of additional information in the assessment of sound-source distance has been noted by several works (Coleman, 1962, 1963, 1968).

With the simultaneous decrease in amplitude and increase in frequency of the consecutiveness of tonal impulses, the withdrawal of the sound source was perceived distinctly and with high probability. Indices of perception improved not only in comparison to the use of spectral changes, but also in comparison to the use of isolated signal amplitude change. These results are evidence of the fact that assessment of the direction of motion is maximally accurate when the listener analyses both amplitude and spectral changes of the sound signal.

For the explanation of the results above described, additional information was made available to the participants during listening. The visual assessment of the distance from the loudspeaker emitting the model signals was an important component of the additional information.

Experiment 2.
Perception of Auditory Image Motion in Near and Far Fields

Method

Participants and Procedure

The influence of the listener's distance from the sound source was studied. For this purpose, the 3-6 series were listened to by participants with normal hearing (6 males and 6 females – aged 18–34 years), with three varying distances of the listener to the loudspeaker: 0.8, 3.0 and 5.0 m. The loudspeakers were arranged frontally (0º azimuth and 0º elevation). With a distance of the participant to the loudspeaker comprising 0.8 m, conditions of near field were maintained; at 5.0 m, far field; and at 3.0 m, transitional area. The participants' tasks were the same as the previous ones.

Results

The influence of the listener's distance to loudspeaker emitted model signals was minimal. As a rule, the ratio of response variants remained unchanged with changing distance (see Figures 4 and 5). Approach was perceived distinctly in 75–79% of responses with the combination of increasing amplitude and decreasing frequency from 1000 to 500 Hz, and with frequency change of 3000–1000 Hz, in 51–56% of responses. Thus, to a greater extent, the responses were determined not by the distance between listener and loudspeaker, but by signal type.

It should be noted that in far field, the opposite assessment of motion occurred, comprising 6% of the total responses of the specified series (see Figure 4, bottom). This was indicative of the fact that the signal was perceived by the participant as withdrawing, not approaching, with changes in frequency from 1000 to 500 Hz in combination with amplitude increase. Withdrawal was distinctly perceived with the combination of decreasing amplitude and increasing frequency from 500 to 1000 Hz in 75–83% of responses (see Figure 5). In near field (0.8 m from listener to loudspeaker) increasing frequency from 1000 to 3000 Hz and decreasing amplitude resulted in contradictory responses in 11% of cases. However, the listeners unambiguously assessed the signal modeling sound source withdrawal at a distance of 3.0 to 5.0 m from the loudspeaker. In far field with frequency increase from 500 to 1000 Hz, also resulted in contradictory responses (2%). To summarize, according to the data obtained, the conclusion would be that, in near field the modeling of motion with frequency change is more effective within a range not exceeding 1000 Hz, and, in far field with frequency change in the range exceeding 1000 Hz. Within the distance of 3.0 m (transitional area) from the loudspeaker, both frequency diapasons form steady perceptions of approach and withdrawal without contradictory responses.

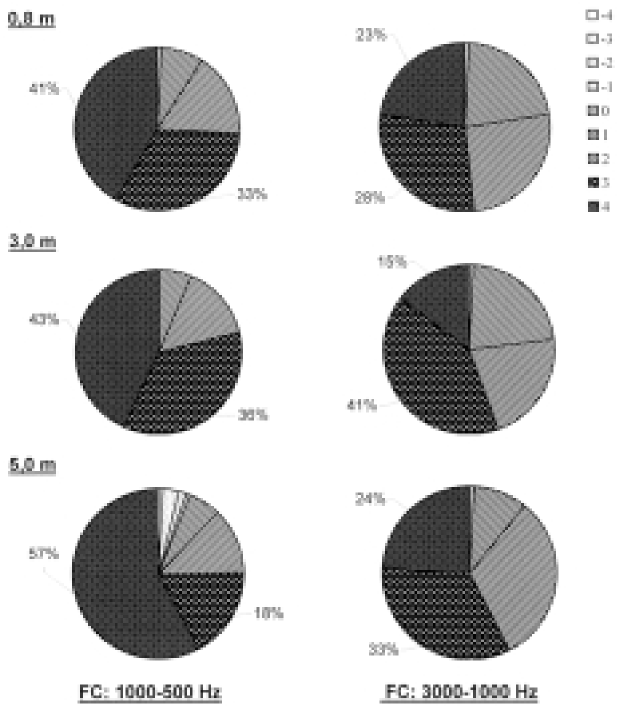

Figure 4. Signal assessment by participants with the modeling of sound source approach using the combination of signal amplitude change and frequency change with loud speakers at varying distances. $N = 120$.
On the left above the pie charts are indicated the distance from the loudspeaker in meters; at the bottom = frequency changes (FC): initial and final values of signal tonal impulse frequency in hertz. Right = response variants.
On the right, response choices are indicated: –4 = distinct withdrawal; –3 = moderately clear withdrawal; –2 = fair withdrawal; –1 = slight signs of withdrawal; 0 = no motion; 1 = slight signs of approach; 2 = fair approach; 3 = moderately clear approach; 4 = distinct approach.

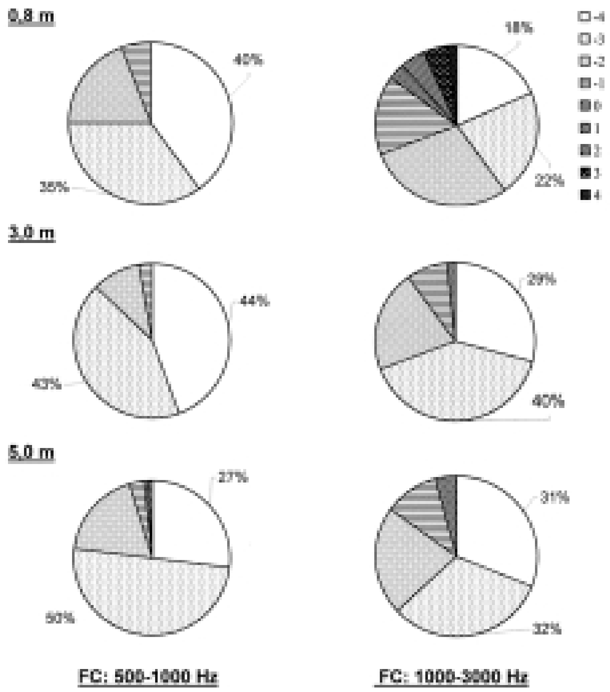

Figure 5. Signal assessment by participants with the modeling of sound source withdrawal using the combination of signal amplitude change and frequency change with loudspeakers at varying distances. $N = 120$.
Left above the pie charts = distance from loudspeaker in meters; bottom = frequency change (FC): initial and final values of signal tonal impulse frequency in hertz.
On the right, response choices are indicated: –4 = distinct withdrawal; –3 = moderately clear withdrawal; –2 = fair withdrawal; –1 = slight signs of withdrawal; 0 = no motion; 1 = slight signs of approach; 2 = fair approach; 3 = moderately clear approach; 4 = distinct approach.

Discussion

These results confirm the conception that additional information about the conditions of radial motion (near or far field) determines the listener's interpretation of perceived changes in signal parameters. In particular, the modeling of approach in far field using frequency change of 1000–500 Hz with increasing amplitude evoked 6% responses of motion as "receding." Evidently, the specific combination of conditions of presentation and signal structure evoked contradictory responses of motion, which may be related to the fact that, with large distances between the source and the listener, spectral distortion in the signal occurs, caused by the absorption of high frequencies. This effect has been studied previously with the perception of stationary sound sources, including the implementation of spectral distortion (Coleman, 1968; Hornbostel, 1923). Despite the fact that such signal spectrum distortion primarily occurs at high frequencies, its modeling in the frequency band below 1000 Hz may have influenced the perception of the direction of the sound image motion.

The second evidence of the importance of additional information about listening conditions is the data that listening in near field with frequency increase from 1000 to 3000 Hz and amplitude decrease led to the characterization of the auditory image as approaching in 11% of cases. In near field a significant role is played by the orientation of the ear concha (Brungart & Rabinowitz, 1999). Specifically, nearby sound sources as a result of the filtering properties of the concha significantly distort in spectrum with alteration of distance. Furthermore in approaching, their height can increase. This influence on the perception of low-frequency signals from more far located stationary sources, have been noted in studies of externalized sounds (Butler, Levy, & Neff, 1980; Levy & Butler, 1978). It is important to note that, in both conditions, the assessment of the direction of motion (6 and 11% of cases) contradicted the direction of amplitude change, considered to be the most universal and important cue of radial motion.

Experiment 3. Auditory Perception of Approach and Withdrawal outside Visible Space

Method

Participants

Twenty-eight individuals with normal hearing (12 males and 16 females, aged 18–38 years) participated in this study.

Procedure

This part of the study excluded visual and sound information on the stationary loudspeaker by listening to the model signal through head-phones. In signal injection in the headphones, all combinations of amplitude and frequency change were studied, which were close to those used in free field. During the experiment, the participant was located in front of a monitor screen on which the following was represented: field of parameters divided into square buttons (stimuli with assigned parameters), several buttons with response variants and the question to which the participant was to respond. For approximately 20 minutes, at a rate convenient for them, participants were to listen to all the presented signals and assess their correspondence to the direction and extent of motion sensation (approach or withdrawal) of the auditory image. The studied parameter

Table 1
Modes of Participants' Assessment Distribution with the Imitation of Radial Motion Using Amplitude and Frequency Changes of Impulse Consecutiveness

Limits of frequency changes in Hz	Changes of signal amplitude in dB										
	–50	–40	–30	–20	–10	0	10	20	30	40	50
1000 → 500	0	w	0	0	0	A	DA	DA	DA	DA	DA
1000 → 875	W	w	w	w	0	A	A	A	DA	DA	DA
1000 → 1250	W	W	w	w	w	A	A	A	A	DA	A
1000 → 1625	W	W	W	W	W	0	a	a	A	a	0
1000 → 2000	W	W	W	W	W	W	0	a	A	a	a
2000 → 1000	w	w	0	0	0	A	A	A	A	A	A
1625 → 1000	w	w	0	0	0	A	A	A	DA	DA	A
1250 → 1000	w	w	w	w	w	A	A	A	A	A	A
875 → 1000	W	W	W	w	w	0	a	a	A	A	a
500 → 1000	W	W	W	W	w	0	0	a	A	a	a

Note. Participant response variants: DA = distinct approach; A = approach; a = possible approach; 0 = no motion; w = possible withdrawal; W = withdrawal. The modes obtained for 28 participants are presented.

of the motion model altered within the following limits: amplitude change from 50 to –50dB, in 10-dB steps; frequency change from 500 to 2000 Hz, with one of the obligatory limits of frequency at 1000 Hz. The parameter field consisted of 99 combinations of parameters.

Results

Listening to the signals containing arbitrary combinations of amplitude and frequency changes of the consecutiveness of tonal impulses revealed significant differences in individual perception of radial motion. Of the 28 participants, 14 assessed the modeled motion based on the cues of signal volume changes and ignored signal pitch. Eight participants used both cues of motion along a radial axis. Six persons decided the motion direction on the basis of the change in the frequency (pitch) of the signal. Typical responses of these three groups are presented in Figure 6. Alterations in the assessment of two-dimensional graphs occurred along one of the axes (Figures 6, 1, and 3) in accordance with the cue-determining motion assessment, or along a diagonal (Figures 6 and 2) in the case where both signal cues influenced the participant's assessment of motion. In repeated testing, the results of each individual participant did not change significantly—the principal cue used for assessment remained the same (Figure 7). Despite significant differences in motion assessment criteria, data analysis in the group permitted us to define the range of amplitude and frequency combination changes for which the perception of auditory image motion for all participants was unambiguous. The modes of response distribution were defined in the assessment of each of the 99 signals listened to. In the Table 1, the distribution of the assessment of motion with the gradation "distinct approach" (DA) is noted in eight varying combinations of amplitude and frequency changes, whereas "distinct withdrawal" is absent. Judgment of the signal as an approaching (A) or withdrawing (W) sound source observed for 21 combinations of amplitude and frequency change are indicated in the table.

The approach of the imitated sound source was noted in 41 combinations of these parameters (indicated accordingly as DA and A). The most stable sensation of approach for all participants occurred with increasing amplitude and decreasing signal frequency; the sensation of withdrawal occurred with the opposite direction of changes in parameters—decreasing amplitude and increasing frequency. With the aid of such signal types, it became possible to create clearer sensations of approach, whereas withdrawal, on the whole, was less defined. This data is in accord with the results obtained in free field.

The participants' three different attempts to assess motion direction did not influence the perception of the signals containing optimal parameter combinations. Signals with

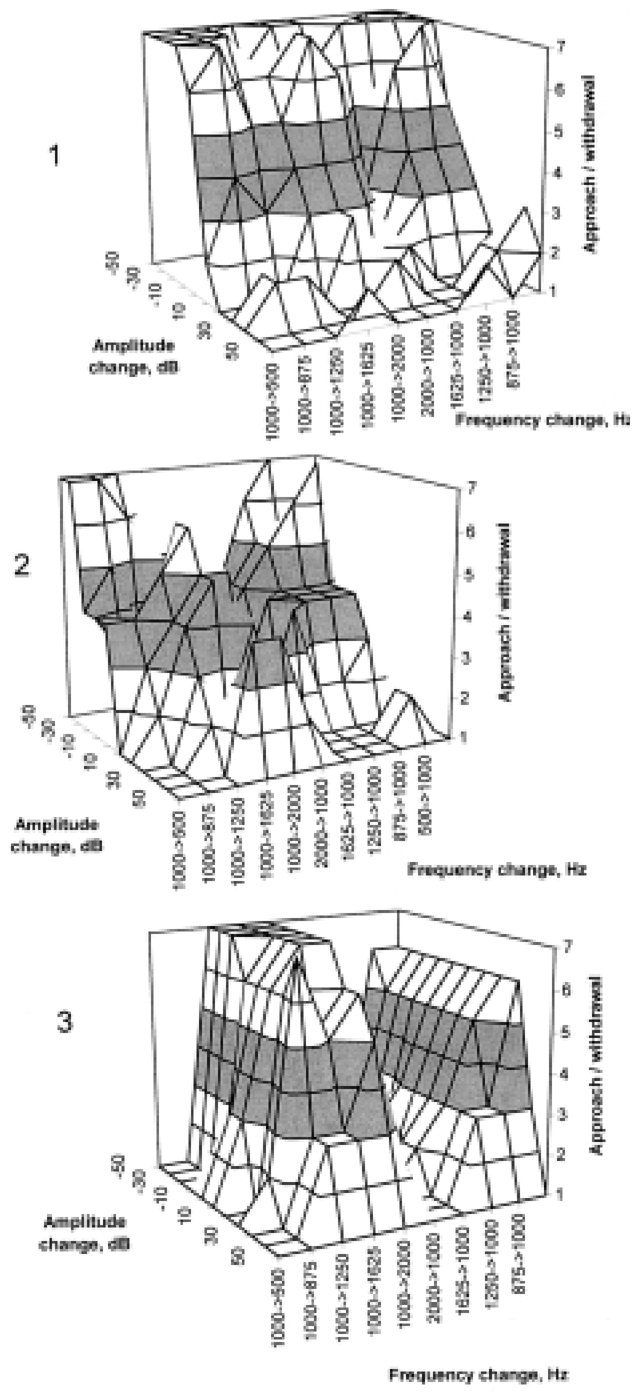

Figure 6. Individual differences in the perception of sound source motion. Results of experiments of 3 participants from different groups (1-3).

In grey are shown the combination of signal amplitude and frequency with distinct absence of the perception of motion. X-axis = frequency change (FC): initial and final values of signal tonal impulse frequency in hertz. Y-axis = amplitude change in dB. Along the vertical axis = participant responses: 1 = distinct approach; 2 = approach; 3 = possible approach; 4 = no motion; 5 = possible withdrawal; 6 = withdrawal; 7 = distinct withdrawal.

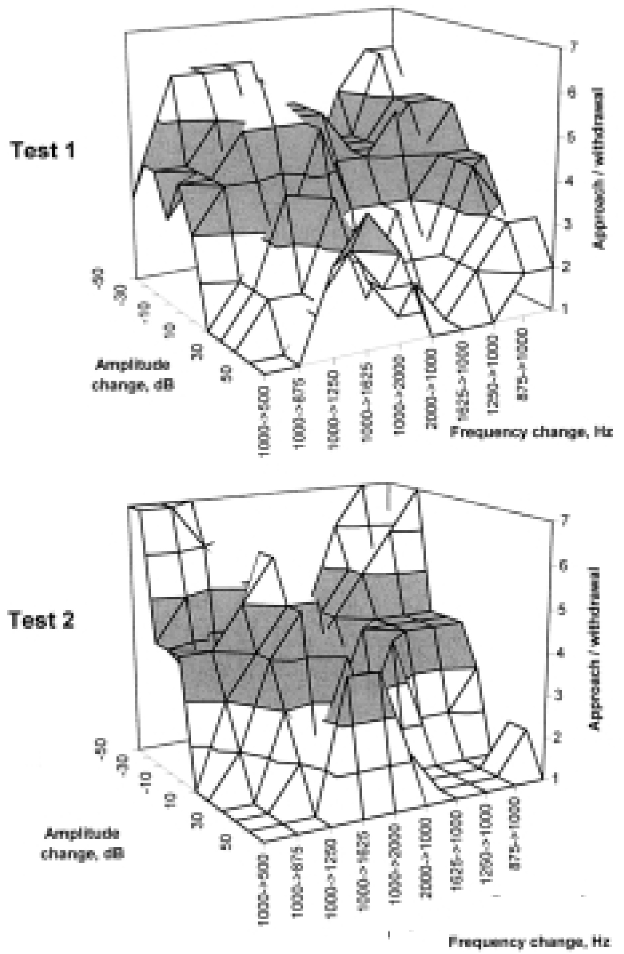

Figure 7. The constancy of individual perception of radially moving image. Results of two tests of participant 7 (Group 1).
In grey are shown the combination of signal amplitude and frequency with distinct absence of the perception of motion. X-axis = frequency change (FC): initial and final values of signal tonal impulse frequency in hertz. Y-axis = amplitude change in dB. Along the vertical axis = participant responses: 1 = distinct approach; 2 = approach; 3 = possible approach; 4 = no motion; 5 = possible withdrawal; 6 = withdrawal; 7 = distinct withdrawal.

optimal parameter combinations were taken to be those that the entire group of participants assessed equally in auditory image motion direction and distinctly as “moving” (responses of “slight signs of approach/withdrawal” were not included). With signal duration of 3 s and at 60 dB intensity, the following optimal combinations were above threshold:

1. For approaching image: amplitude increase by 10–50 dB, frequency decrease from 1000 to 500 Hz; or amplitude increase by 40 dB, frequency decrease from 1000 to 875 Hz;
2. For withdrawing image: amplitude decrease by –40—59 dB and frequency increase from 500 to 1000, from 875 to 1000, and from 1000 to 1625 Hz.

Conclusion

The data obtained in the present study on the perception of models of approach and withdrawal of auditory images provided evidence that the principal cues of perception of the distance of stationary sound sources are expressed in a similar way for the motion of a sound source along a radial axis. The ratio of signal amplitude and spectrum changes creates the perception of motion in accordance with additional information and the listener’s individual perception characteristics. It has been shown that the direction of amplitude change does not always determine the direction of the auditory image motion. The decision about the direction of motion can be made by the listener even despite easily defined directions of amplitude change. Listening and assessment of auditory image motion direction created by the combination of linear amplitude and frequency changes revealed individual characteristics of motion perception. Three types of radial motion perception were discovered, in which the determining cue was either only amplitude change, only frequency change, or both parameter change. Significant and repetitive individual variations were not of a quantitative, but of a qualitative nature. On the basis of this data, one can conclude that the assessment of the direction of radial motion under conditions of the absence of additional information about the sound source is determined by spectral changes, and furthermore, without additional information about the sound source, some participants are able to completely ignore amplitude changes.

The data obtained on the individual variations in the perception of cues of radial motion and the influence of additional information on the sound source, both visual and aural, extend the conception of auditory perception of spatial depth and are significant to the development of the theoretical basis of virtual acoustic environments.

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