DOI 10.1007/s11055-024-01746-z
Neuroscience and Behavioral Physiology, Vol. 54, No. 9, November, 2024

Auditory System

Perceived Trajectories of the Cyclic Movement of Sound Images

L. B. Shestopalova, E. A. Petropavlovskaia, D. A. Salikova, and P. I. Letyagin

UDC 612.821

Translated from Sensornye Sistemy, Vol. 38, No. 3, pp. 51–62, July–September, 2024. Original article submitted April 12, 2024. Accepted June 2, 2024.

Binaural beats are a phenomenon occurring as a result of binaural integration during dichotic stimulation. This phenomenon is apparent as a cyclic movement of a sound image in subjective space when the beat frequency range is below 3 Hz. Subjects were presented with noise stimuli to create a sensation of motion due to a linear or stepwise pattern of changes in the interaural delay (ITD). The ranges of changes in ITD determined the position of the trajectories of motion in the central or lateral sectors of space. The results confirmed that both patterns of ITD created the effect of binaural beats. The effect of spatial position on perceived trajectory length is interpreted in terms of the nonlinear properties of lateralization. The effect of the ITD pattern on perceived trajectory length is presumptively mediated by the mechanisms of temporal integration operating in binaural hearing.

Keywords: binaural beats, spatial hearing, binaural integration, interaural time differences.

Introduction. The phenomenon of binaural beats has been known for over 100 years. It occurs in conditions of dichotic presentation of sound signals and consists of periodic changes in loudness or cyclic movement of the sound image from one ear to the other. If tonal signals with a slight difference in frequency are presented to both ears, the listener experiences the illusion of a tone of intermediate frequency and pulsating volume, with the pulsation frequency equal to the difference in frequencies of the presented fundamental tones.

In general, binaural beats occur in the low-frequency region of the fundamental tone (about 1000 Hz or lower) with a frequency difference between the two tones of no more than 35 Hz [Licklider et al., 1950]. When the interaural frequency difference decreases to 3 Hz and below, a new sensation occurs – a fused sound image moves from one ear to the other and back, creating the illusion of cyclic movement in azimuth. This is termed the rotating tones phenomenon. It is important there are no periodic changes in the stimuli in the signals presented to each ear. The perceived beats arise exclusively due to binaural integration, and their frequency range (below 35 Hz) lies mainly beyond the sensitivity of human hearing but coincides with the range of the main oscillations of neuronal activity of the brain (the δ, θ, α, β, and γ rhythms).

Classical works on this topic have created beat effects using dynamic changes in the binaural characteristics of sound signals, specified by interaural differences in phase IPD [Perrott and Nelson, 1969; Perrot and Musicant, 1977], time ITD [Blauert, 1972; Grantham and Wightman, 1978], or level ILD [Blauert, 1972; Grantham, 1984] or by interaural correlation of signals [Grantham, 1982]. Binaural beats are perceived as cyclic movements of the sound image only when the differences between the frequencies of two tones are small, about 1–3 Hz [Perrott and Musicant, 1977].

Most studies of binaural beats have been performed using tonal stimuli. However, the real acoustic environment mostly contains complex signals with wide frequency spectra. Binaural beats have been described in a number of psychophysical studies (e.g., [Grantham and Wightman, 1978; McFadden and Pasanen, 1975; Saberi, 1995; Bernstein and Trahiotis, 1996; Akeroyd, 2010]).

In particular, studies reported by Akeroyd [2010] created cyclic movement of a broadband signal by frequency shifting each component of the Fourier spectrum of the original noise. A more distinct perception of noise signal movement was found as compared with use of tonal signals. It should be noted that in terms of methodology, these

---

Pavlov Institute of Physiology, Russian Academy of Sciences, St. Petersburg, Russia; e-mail: shestopalovalb@infran.ru, shestolido@mail.ru.

studies were restricted to discrimination tasks and did not address the issues of the magnitude of the angular displacement of the sound image, the length of the perceived trajectories, or the speed of the cyclic movement of the stimulus. The present study is aimed at filling this gap.

In the context of studying the inertial properties of binaural hearing, there is a need to distinguish between the concepts of beat frequency and the speed of cyclic movement of the sound image. Beat frequency is the number of cycles per second, i.e., how many times the sound image returns to the same position per second. Within a single cycle, the sound image can move faster or slower, depending on the pattern of changes in interaural differences. The pattern can theoretically be specified by a linear, a nonlinear (including the classical sinusoidal), or a stepwise function of time. The present study proposes the use of smooth motion created by linear changes in ITD and instantaneous movement of the sound image created by stepwise changes in ITD.

Given the persistence of binaural integration (binaural sluggishness), the processing of moving sound stimuli in the auditory system can be addressed within the framework of the leaky integrator concept [Carlile and Leung, 2016]. This concept describes the smoothing function of the binaural system and suggests that its response to an auditory event is based on the temporal integration of information received from both ears [Kollmeier and Gilkey, 1990; Culling and Summerfield, 1998; Bernstein et al., 2001]. The smoothing effect of the leaky integrator has the result that at short sound signal durations (up to 200 msec), psychophysical discrimination between smooth and instantaneous displacement becomes possible only at large ITD values (600–800 μsec) [Shestopalova et al., 2012], corresponding to stimulus displacement over large angular distances, such that the evoked potentials for instantaneous displacement and rapid stimulus movement are very similar structurally and topographically [Getzmann and Lewald, 2012; Shestopalova et al., 2021].

Thus, instantaneous displacement adequately models very high-velocity motion, and these two patterns of changes in ITD can be regarded as qualitatively similar for binaural hearing. Using different patterns of ITD in the present experiments will allow them to address interrelated effects – the speed of displacement between extreme points and the duration of stays at them – simulating smooth and instantaneous cyclic displacement of a sound image at the same beat frequency.

The objectives of this study were 1) to demonstrate the possibility of obtaining the effect of beat in noise signals in the form of cyclic motion, with trajectories located in different areas of acoustic space; 2) to investigate the relationship between beat amplitude and the position in space and the pattern of cyclic motion. We suggested that the perceived trajectory length (beat amplitude) of smooth motion might be shorter than that in the case of instantaneous displacement, because of averaging of dynamic binaural information in a continuous signal.

Methods. ***Ethical standards.*** All studies were conducted in accordance with the principles of biomedical ethics formulated in the 1964 Helsinki Declaration and its subsequent updates and were approved by the Ethics Committee of the Pavlov Institute of Physiology, Russian Academy of Sciences (Protocol No. 22–05). Each study participant provided voluntary written informed consent, signed after explanation of the potential risks and benefits and the nature of the study.

Experimental conditions and subjects. A total of 22 right-handed subjects aged 18–45 years with normal hearing (pure tone audiometry) and no history of neurological diseases (subjects' reports) took part in the study. The group included 12 men and 10 women, mean age 27 ± 7 years; 17 listeners were naïve and five had experience of taking part in experiments on hearing.

During experiments, the subjects sat in a chair in a shielded soundproof chamber and were presented with sound signals using a dichotic method. Experiments was conducted over 3–4 visits. Subjects were given breaks for rest during the experiment, at request.

Stimulation. Certain demands are placed on the sound signals when creating the effect of cyclic movement of broadband stimuli. As binaural beats occur only when using low-frequency signals [Mills, 1960; Altman, 2011], spatial effects in our experiments were created using a cyclic change in ITD with a frequency of 1 Hz. It should be noted that although the signal returns to the starting point once per second, each movement cycle actually contains two auditory events, corresponding to turns at the two extreme points of the trajectory, i.e., the starting point and the point furthest away from it.

The stimuli contained initial and final stationary segments and a segment of cyclic movement between them (Fig. 1, top). ITD at the initial and final sections took one of the constant values ± 800 μsec, ± 400 μsec, or 0 μsec in different stimuli. The movement of each stimulus began at the location of the initial stationary segment and reached the maximum distance from it, i.e., the turning point, at which ITD differed from initial by 800 μsec. The stimulus then returned to the beginning, the cycle was repeated several times, and stimulation ended with a stationary segment at the place at which it started. The influence of the position of the stationary section on perceived trajectory length was assessed by creating three pairs of trajectories (Table 1): left-sided LC and CL, central LR and RL, and right-sided RC and CR. The trajectories within each pair differed only in terms of the positions of the initial/final point and the turning point.

The initial signal was a segment of white noise synthesized with a sampling frequency of 96 kHz and filtered in the band 100–1300 Hz. The following types of dichotic stimuli were created on the basis of this signal:

1) stimuli simulating smooth cyclic movement along the azimuth (see Fig. 1, above). These stimuli consisted of

TABLE 1. Designations and Calculated Positions of Movement Trajectories of Dichotic Sound Stimuli

Stimulus code	ΔT at beginning and end, μsec	ΔT at turn point, μsec	Reference movement trajectory
LC	–800	0	Left to center and back
CL	0	–800	Center to left and back
LR	–400	+400	Left to right and back
RL	+400	–400	Right to left and back
CR	0	+800	Center to right and back
POC	+800	0	Right to center and back

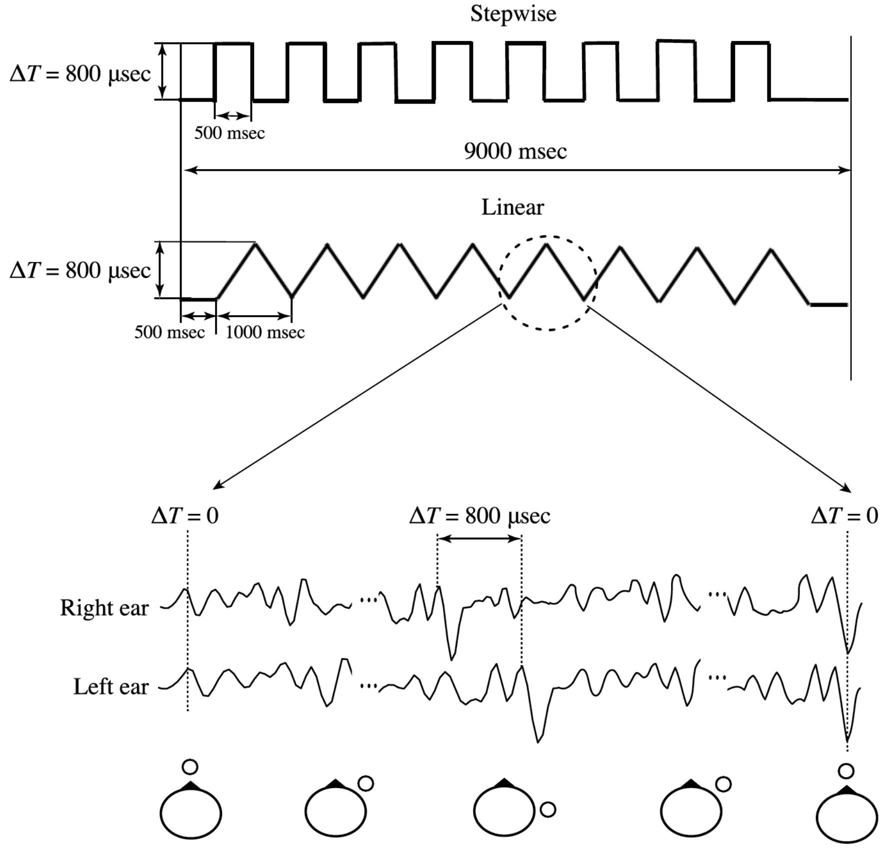

Fig. 1. Changes in interaural delay in binaural sound stimuli simulating smooth and stepwise cyclic motion. Top: temporal structure of stimuli within a single trial. The horizontal axis shows time (msec); the vertical axis shows interaural delay (ITD, μsec). Different initial ITD values determine different positions of cyclic motion trajectories in the subjective auditory space. Bottom: dichotic stimulation in one cycle of the linear pattern (from 0 μsec to 800 μsec and back to 0 μsec). The head diagrams show the sequential change in the position of the sound image as determined by changes in ITD.

three segments following each other without pauses: two stationary segments, one at the beginning and one at the end of the signal, and a moving segment between them. The durations of the initial and final segments, with constant ITD, were 500 msec. Signal intensity in the initial segment gradually increased, while that in the final segment gradually decreased, following the cosine law, during the entire 500 msec, with the aim of reducing the influence of responses to initiation and termination of the signal. Intensity in the mid part of the stimulus was constant, while ITD changed linearly by 800 μsec (relative to ITD in the initial segment) for 500 msec and then returned to the original value over the next 500 msec (Fig. 1, bottom). This cycle of changes in ITD with a period of 1000 msec was repeated eight times. The total duration of the stimulus was 9000 msec. This simulated a cyclic smooth movement along an arc of azimuth between two fixed positions. The direction of movement was inverted every 500 msec. This signal is referred to below as “linear;”

2) stimuli simulating a cyclic instantaneous displacement of the sound image (Fig. 1, top). In this case, ITD in the middle part of the signal changed instantaneously by 800 μsec (relative to ITD of the initial segment), then remained constant for 500 msec, and then instantaneously

returned to the original value, again remaining constant for 500 msec. ITD of the initial and final segments took the same constant values of ±800, ±400, or 0 μsec, as in the case of smooth movement. The full cycle also lasted 1000 msec and was repeated eight times. This signal produced a sound image whose position changed abruptly between two extreme points every 500 msec. The initial and final stationary segments corresponded completely to the conditions described for the first type of signal. The total duration of the stimulus was 9000 msec. This type of signal is referred to below as "stepped;"

3) each subject was presented with reference points consisting of stimuli modeling stationary sound images located at different points in the left and right hemispheres of the subjective acoustic space. The interaural delays in these stimuli were ±800, ±600, ±400, ±200, and 0 μsec. Stimuli with ITD = ±600 and ±200 μsec, which did not correspond to the extreme ITD values of stimuli with cyclic motion, were introduced into the series to ensure that the listener would not have the feeling of a limited set of possible positions that could be remembered and then reproduced during subsequent assessment of the positions of moving stimuli. Responses to additional stationary stimuli were not included in the analysis. The duration of a single stationary stimulus was 2000 msec, including 500-msec rise and fall fronts, smoothed by a cosine function. Each presentation of the reference stimulus was repeated three times with intervals of 1000 msec. This was followed by recording of the subject's response on the position of the sound image. The total duration of the stimulation period from the beginning of the first stimulus to the end of the last was 8000 msec.

Signals were converted into analog form using a Gina24 multichannel sound card (Echo Audio, USA) and presented dichotically using Etymotic ER-2 sound transducers (Etymotic Research Inc., USA). The transducer sound guides were fixed in the ear canals using ear plugs, which provided external noise suppression by 30 dB. Nonuniformity of the amplitude-frequency characteristics of the sound transducers in the range of 0.1–10 kHz was ±3 dB.

Experimental procedure. At the preliminary stage of each experiment, monaural hearing thresholds were measured in all subjects using noise pulses with bandwidth 100–1300 Hz and duration 700 msec. The difference in the thresholds of the left and right ears was no greater than 10 dB. The intensity level was then set at 50 dB above the threshold on both channels, identical noise signals were diotically presented, and the sound image was centered.

The centering procedure consisted of the subject reporting, by pressing keys on the keyboard, whether, using sounds of equal intensity in the right and left channels, they felt that the sound position was "central" (sound image located along the midline of the head) or to the right or left of the center. Depending on the subject's reports, intensity was adjusted by 1–3 dB such that the stimulus occupied the central position. Signal intensity was then set at 50 dB above the subject's corrected hearing threshold.

During the experiment, the sound stimuli were grouped into series. Series type was determined by the stimulus pattern (linear, stepped, reference). The subject was instructed to listen to each stimulus from beginning to end and then to indicate, using a Genius G-pen 450 graphic tablet, the positions of the extreme points between which the sound image moved or the positions of the stationary reference in the control series. For this purpose, an arc was drawn on the working surface of the tablet and was used by the subject to indicate the perceived positions of the sound signals.

The interstimulus interval was not fixed and was selected individually as a period comfortable for the listener between giving a response and presentation of the next stimulus. Within a single series, stimuli of each type were repeated eight times in pseudorandom order, and each series in the full study program was presented three times. Thus, each type of stimulus (moving and stationary) was presented to the subject 24 times. Series alternation was randomized individually and for the entire group of subjects. The duration of a series was 12–15 minutes, depending on the subject's work pace.

Data analysis. The perceived angular positions of the ends of the trajectories of moving stimuli were recorded in degrees relative to the midline of the head; perceived trajectory lengths were then calculated. The distances between the perceived positions of the stationary reference stimuli with ITD = ± 800 μsec and 0 μsec, as well as those between the positions of stimuli with ITD = –400 and +400 μsec were calculated in the same way. Then, for each stimulus type, the values obtained were averaged using the data from each subject separately, as well as for the entire group as a whole.

After eliminating random errors, each individual value corresponded to the mean of 20–24 measurements. Measured values were subjected to two-factor analysis of variance (repeated measures ANOVA, rmANOVA) with the factors Pattern (reference, linear, step) and Position (CL, CR, RC, LC, RL, LR). For paired comparisons, the Šidák correction was used for the Position factor and the Bonferroni correction was used for the Pattern factor. All comparisons were performed with a significance level of $p < 0.05$.

Results. All listeners confidently identified the positions of the ends of the trajectories of both fast and slow movements. The perceived positions of the reference and movement trajectories are shown in Fig. 2.

Statistical comparisons using rmANOVA (Pattern (reference, linear, step) × Position (CL, CR, RC, LC, RL, LR)) confirmed high levels of significance of both factors (Pattern: F(1,69, 35.45) = 69.18, $p < 0.001$, $\eta^2 = 0.77$; Position: (F(1,73, 36.42) = 102.34, $p < 0.001$, $\eta^2 = 0.83$) and their interaction (F(4,69, 98.47) = 11.73, $p < 0.001$, $\eta^2 = 0.36$).

The results of pairwise comparisons are shown in Fig. 3. Comparisons in terms of the Pattern factor showed that for all positions, the trajectories of smooth movements were significantly shorter than those of stepwise movements and the distance between fixed references ($p < 0.001$), and there were no other differences ($p > 0.05$). The lengths of lateral trajectories

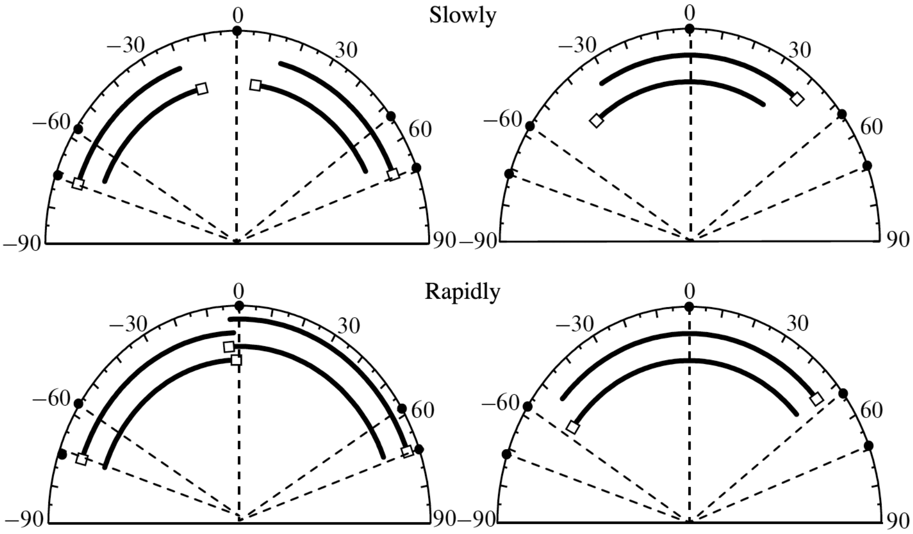

Fig. 2. Perceived angular positions of the trajectories of moving stimuli and stationary reference stimuli. Arcs correspond to the trajectories of moving stimuli. Black dots and dashed lines correspond to the positions of reference stimuli. Squares on arcs indicate the positions of the stationary section in the stimulus. Diagrams at left show two pairs of lateral trajectories: left-sided (LC and CL) and right-sided (RC and CR), while diagrams at right show a pair of central trajectories (RL and LR).

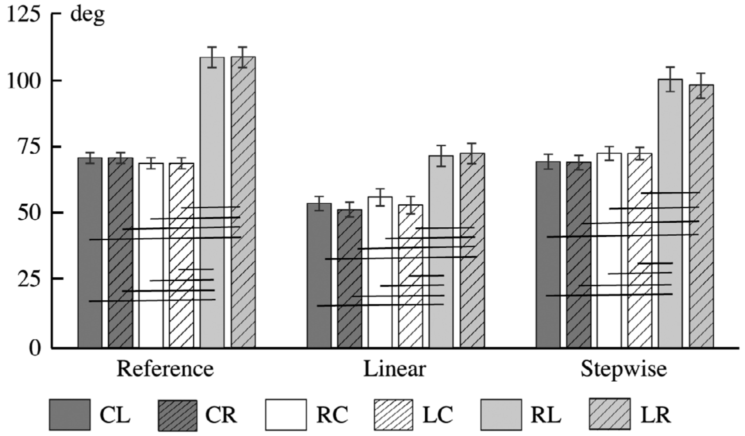

Fig. 3. Angular distance between stationary reference points and lengths of cyclic movement trajectories. Horizontal lines indicate significant differences in pairwise comparisons ($p < 0.001$). Vertical lines show the standard error of the mean. The vertical axis shows angular distances in degrees and the horizontal axis shows stimulus type.

averaged 54 ± 3° for smooth motion and 71 ± 3° for stepwise motion; the distance between references was 70 ± 2°. The lengths of central trajectories were 72 ± 4° for smooth motion and 99 ± 5° for stepwise motion, with the distance between references being 109 ± 4°. In addition, in the case of the RL position, the stepwise motion trajectory was also shorter than the distance between references ($p < 0.05$).

Comparisons in terms of the Position factor showed that for all signal types, the RL and LR trajectories did not differ from each other ($p > 0.05$) but were longer than the others ($p < 0.001$), and there were no other differences ($p > 0.05$). Thus, the analysis revealed no differences within the pairs of trajectories CL and LC, CR and RC, and RL and LR ($p > 0.05$). This is equivalent to the position of the stationary segment having no effect on the lengths of the left-sided, right-sided, and central trajectories.

Discussion. This is the first investigation of the effects of the movement pattern and spatial position of trajectories on trajectory lengths in conditions of cyclic movement of internalized noise signals. The data obtained indicate that both smooth and stepped movements created clear binaural beat effects in all listeners. Different patterns of changes in ITD provided the first acquisition and measurement of beat trajectories located in different parts of the subjective acoustic space.

Effect of spatial position on trajectory length. Central trajectories were longer than lateral trajectories for both movement patterns. It is important to note that the distance between the fixed reference points with ITD = –400 and +400 μsec was also greater than the distance between the stimuli with ITD = ±800 and 0 μsec, though the difference between the extremes of ITD was the same, at 800 μsec. As a result, the reason for the differences in the lengths of the central and lateral trajectories is not related to movement. The differences in lengths are probably due to the nonlinearity of the relationship between ITD and perceived stimulus position, which was particularly characteristic of the lateral areas.

S-shaped lateralization curves for stimuli with ITD were presented in the classic work of Blauert [1979] and in a more modern study by Dingle et al. [2013]. The relationships of the perceived trajectory endpoint positions when short stimuli move from the center to the periphery are described in the work of Petropavlovskaia et al. [2011]. Data reported by these authors indicated that at ITD = = ±400 μsec, the stationary sound image was displaced by almost 60° of azimuth, while further increases in ITD with a step of 100 μsec produced a shift amounting to 70° at ITD = ±800 μsec and the positions of stationary sound images were not significantly different at ITD = ±600, ±700, and ±800 μsec.

The trajectories of moving stimuli with ITD = ±400 μsec appeared in the present experiment to overlap the linear region of the lateralization curves, where equal increments in ITD corresponded to equal increments in azimuth, while left- and right-sided trajectories went beyond the linear region. Maximum lateralization at the periphery was no more than 70°, as in the work of Petropavlovskaia et al. [2011], so lateral trajectories were perceived as shorter than central trajectories.

The nonlinear relationship between the perceived position and ITD appeared to be a determining property of localization, equally affecting stationary stimuli and cyclic motion trajectories. Taking this into account, with a limited range of possible ITD, trajectories in the central sector of the acoustic space, intersecting the midline of the head, should be selected when creating maximum-amplitude beats.

Effect of the position of the stationary segment on trajectory length. The stimuli of each pair (LR and RL, LC and CL, RC and CR) differed from each other only in terms of the position of the stationary segment. The effect of the stationary segment on the perception of the subsequent movement should be considered from the point of view of selective spatial adaptation [Getzman and Lewald, 2011].

Prolonged exposure to an adapting stimulus is known to lead to a decrease in the sensitivity of neurons specific to its features [Barlow and Hill, 1963; Movshon and Lennie, 1979; Maffei et al., 1973; Barlow, 1990]. Thus, selective adaptation (i.e., adaptation to particular features of the stimulus) leads to a shift in the patterns of the subsequent responses of the neuronal population away from the activation patterns initially evoked by the adapter [Clifford et al., 2000; Gutschalk et al., 2008].

The duration of the adapting stimulus can vary widely, from several seconds to hundreds of milliseconds [Getzmann and Lewald, 2011; Andreeva, 2015; Shestopalova et al., 2023]. As for spatial hearing, selective adaptation at the perceptual level is most often apparent as a shift in the perceived position of the target stimulus away from the adapter [Salminen et al., 2012 (review); Carlile et al., 2001; Dingle et al., 2012, 2013; Shestopalova et al., 2023]. In the delayed movement paradigm, the initial stationary segment of the stimulus can be regarded as a stationary adapter and the response to movement onset can be seen as the result of release from selective adaptation and the involvement of new groups of neurons in the response [Getzmann and Lewald, 2011].

The central and lateral stationary segments could presumptively have different effects on perceived trajectory length. Expansion of the perceived trajectory away from the central adapter (as compared with the hypothetical trajectory without adaptation) is limited by the maximum degree of lateralization in the ear. The possible expansion from the lateral adapter, when moving from the periphery to the center, could cross the midline and extend up to the limit of maximum lateralization on the opposite side, so the LC and RC trajectories could be longer than the CL and CR trajectories. However, no differences were found between them. Thus, the effects of the central and lateral stationary segments on the beat amplitude were identical.

Effect of movement pattern on trajectory length. The literature (reviews by [Garcia-Argibay et al., 2018; Basu and Banerjee, 2022]) indicates that studies of the effects of binaural beats on memory, attention, and psychophysiological states in humans usually characterize beats exclusively in terms of their frequency range, by analogy with the frequencies of brain rhythms. The θ, α, β, and γ bands are the most widely used. At frequencies from the θ band and above, binaural beats are perceived as pulsations rather than cyclic movement. In general, the literature contains no data on the effects of cyclic movement speed on perception of the spatial features of sound.

From the point of view of spatial hearing, it is fundamentally important that cyclic movement speed is not necessarily related to beat frequency, that is, the number of cycles per second. In our work, different speeds are realized at the same beat frequency (1 Hz) solely as a result of the pattern of interaural differences. Our experiments showed that trajectory length, which determined the amplitude of beats in subjective space, was strongly dependent on the pattern of changes in the interaural delay ITD corresponding to different speeds of perceived movement.

The trajectories of slow (smooth) movements were significantly shorter than the trajectories of fast (stepped) movements and the distances between the corresponding stationary references. This pattern was true for both central and lateral trajectories. Stepwise movement trajectory length coincided with the distance between stationary stimuli. This means that averaging of binaural information by the leaky integrator does not lead to a reduction in the amplitude of beats created by the stepped ITD function as compared with the distance between stationary stimuli.

These results differ fundamentally from results reported from a recent study in which a segment of translational (non-cyclic) movement created by interaural differences in intensity, ILD, was enclosed between two stationary segments [Salikova et al., 2023]. This study indicated that stimulus speed did not affect the perceived positions of movement trajectories. It can be suggested that the speed of translational motion in the middle segment in the study cited was not a significant factor because the initial and final stationary segments were located on different sides of the trajectory and these are the segments determining the locations of the moving signals as a whole. In addition, speeds in this work were modeled as two different slopes of linear change in ILD, which gave a smaller difference between movement speeds than in our experiment with smooth and instantaneous displacement.

The fundamental feature of the present study is that it used cyclic motion. This made it possible to arrange the stationary segments at the beginning and end of the stimulus in such a way that they coincided in terms of spatial features; the perceived position of the other end of the trajectory was entirely determined by the pattern of changes in ITD at the turning point. If the change in ITD in the stimulus were to occur infinitely quickly, then ITD would be constant in the next time interval, corresponding to half the period of the binaural beat. If the width of the integration time window were smaller than this interval, averaging of binaural information by the leaky integrator would not reduce the beat amplitude. Conversely, if the change in ITD were to occupy the entire beat half-period, then a significantly shorter time interval would correspond to being at the turning point. In this case, the decrease in the length of the perceived trajectory can be explained in terms of averaging of binaural information preceding the moment of turning and immediately following it.

Thus, with a cyclic movement lasting 8 sec, the influence of the positions of the initial and final stationary segments on the perceived length of the trajectory of the moving stimulus is reduced to a minimum and the pattern of changes in ITD becomes a significant factor. The pattern effect is based on the mechanisms of temporal integration of binaural features. Temporal integration clearly gives different results with a linear change in ITD, simulating slow movement, and with a step change, i.e., with instantaneous switching between regions with constant ITD to simulate rapid motion. These aspects of auditory processing of cyclic motion require more detailed analysis based on data not only on trajectory lengths, but also on the perceived positions of start/end points and turning points.

Conclusions. 1) The use of noise stimuli with both linear and stepwise patterns of interaural differences showed that binaural beats had marked effects in the form of cyclic motion;

2) Cyclic motion trajectories can be located in different parts of the subjective space, depending on the range of interaural delays;

3) The beat amplitude depends on the range of changes in interaural delays. Beat amplitude in the central sector of the subjective auditory space is larger than that on the left or right sides for the same range of changes in ITD;

4) Amplitudes for a fixed beat frequency depend on the pattern of changes in interaural delays. When the pattern was linear, perceived trajectories were shorter than with a stepped pattern.

This study was supported by grant from the Russian Science Foundation, No. 24–25–00106.

Authors' contributions: L. B. Shestopalova – synthesis of sound stimuli, preliminary data processing, analysis of results, preparation of publication; E. A. Petropavlovskaia – organization of experiments, development of MatLab scripts for data recording and processing, analysis of results, preparation of publication; D. A. Salikova – conducting experiments, preliminary data processing, working with sources; P. I. Letyagin – conducting experiments, visualization of results.

The authors of this article confirm that they have no conflicts of interests to report.

REFERENCES

Akeroyd, M. A., "A binaural beat constructed from noise," *J. Acoust. Soc. Am.*, **128**, 3301–3304 (2010), https://doi.org/10.1121/1.3505122.

Altman, Ya. A., *Spatial Hearing*, Pavlov Institute of Physiology, Russian Academy of Sciences, St. Petersburg, (2011).

Andreeva, I. G., "Motion aftereffect as a universal phenomenon for sensory systems involved in spatial orientation. III. Auditory aftereffect," *Zh. Evol. Biokhim. Fiziol.*, **51**, No. 3, 145–153 (2015).

Barlow, H. B. and Hill, R. M., "Evidence for a physiological explanation of the waterfall phenomenon and figural after-effects," *Nature*, **28**, 1345–1347 (1963), https://doi.org/10.1038/2001345a0.

Barlow, H. B., *Vision: Coding and Efficiency. A Theory About the Functional Role and Synaptic Mechanism of Visual After-Effects,* Cambridge University Press, New York (1990), pp. 363–375.

Basu, S. and Banerjee, B., "Potential of binaural beats intervention for improving memory and attention: insights from meta-analysis and systematic review," *Psychol. Res.*, **87**, No. 4, 951–963 (2022), https://doi.org/10.1007/s00426-022-01706-7.

Bernstein, L. R. and Trahiotis, C., "Binaural beats at high frequencies: listeners' use of envelope-based interaural temporal and intensity disparities," *J. Acoust. Soc. Am.*, **99**, 1670–1679 (1996), https://doi.org/10.1121/1.414689.

Bernstein, L. R., Trahiotis, C., Akeroyd, M. A., and Hartung, K., "Sensitivity to brief changes of interaural time and interaural intensity," *J. Acoust. Soc. Am.*, **109**, 1604–1615 (2001), https://doi.org/10.1121/1.1354203.

Blauert, I., *Spatial Hearing*, Energy (1979).

Blauert, J., "On the lag of lateralization caused by interaural time and intensity differences," *Audiology*, **11**, No. 5, 265–270 (1972), https://doi.org/10.3109/00206097209072591.

Carlile, S. and Leung, J., "The perception of auditory motion," *Trends Hear.*, **20**, 1–19 (2016), https://doi.org/10.1177/2331216516644254.

Carlile, S., Hyams, S., and Delaney, S., "Systematic distortions of auditory space perception following prolonged exposure to broadband noise," *J. Acoust. Soc. Am.*, **110**, 416–424 (2001), https://doi.org/10.1121/1.1375843.

Clifford, C. W., Wenderoth, P., and Spehar, B., "A functional angle on some after-effects in cortical vision," *Proc. Biol. Sci.*, **267**, 1705–1710 (2000), https://doi.org/10.1098/rspb.2000.1198.

Culling, J. F. and Summerfield, Q., "Measurements of the binaural temporal window using a detection task," *J. Acoust. Soc. Am.*, **103**, 3540–3553 (1998), https://doi.org/10.1121/1.423061.

Dingle, R. N., Hall, S. E., and Phillips, D. P., "The three-channel model of sound localization mechanisms: Interaural level differences," *J. Acoust. Soc. Am.*, **131**, No. 5, 40234029 (2012), https://doi.org/10.1121/1.3701877.

Dingle, R. N., Hall, S. E., and Phillips, D. P., "The three-channel model of sound localization mechanisms: Interaural time differences," *J. Acoust. Soc. Am.*, **133**, No. 1, 417424 (2013), https://doi.org/10.1121/1.4768799.

Garcia-Argibay, M., Santed, M. A., and Reales, J. M., "Efficacy of binaural auditory beats in cognition, anxiety, and pain perception: a meta-analysis," *Psychol. Res.*, **83**, No. 2, 357–372 (2019), https://doi.org/10.1007/s00426-018-1066-8.

Getzmann, S. and Lewald, J., "Cortical processing of change in sound location: smooth motion versus discontinuous displacement," *Brain Res.*, **1466**, 119–127 (2012), https://doi.org/10.1016/j.brainres.2012.05.033.

Getzmann, S. and Lewald, J., "The effect of spatial adaptation on auditory motion processing," *Hear. Res.*, **272**, No. (1–2), 21–29 (2011), https://doi.org/10.1016/j.heares.2010.11.005.

Grantham, D. W. and Wightman, F. L., "Detectability of varying interaural temporal differences," *J. Acoust. Soc. Am.*, **63**, No. 2, 511–523 (1978), https://doi.org/10.1121/1.381751.

Grantham, D. W., "Detectability of time-varying interaural correlation in narrow-band noise stimuli," *J. Acoust. Soc. Am.*, **72**, No. 4, 1178–1184 (1982), https://doi.org/10.1121/1.388326.

Grantham, D. W., "Discrimination of dynamic interaural intensity differences," *J. Acoust. Soc. Am.*, **76**, No. 1, 71–76 (1984), https://doi.org/10.1121/1.391009.

Gutschalk, A., Micheyl, C., and Oxenham, A. J., "The pulse-train auditory aftereffect and the perception of rapid amplitude modulations," *J. Acoust. Soc. Am.*, **123**, No. 2, 935945 (2008), https://doi.org/10.1121/1.2828057.

Kollmeier, B. and Gilkey, R. H., "Binaural forward and backward masking: evidence for sluggishness in binaural detection," *J. Acoust. Soc. Am.*, **87**, 1709–1719 (1990), https://doi.org/10.1121/1.399419.

Licklider, J. C. R., Webster, J. C., and Hedlun, J. M., "On the frequency limits of binaural beats," *J. Acoust. Soc. Am.*, **22**, 468–473 (1950), https://doi.org/10.1121/1.1906629.

Maffei, L., Fiorentini, A., and Bisti, S., "Neural correlates of perceptual adaptation to gratings," *Science*, **182**, 1036–1038 (1973), https://doi.org/10.1126/science.182.4116.1036.

McFadden, D. and Pasanen, E. G., "Binaural beats at high frequencies," *Science*, **190**, No. 4212, 394–396 (1975), https://doi.org/10.1126/science.1179219.

Mills, A. W., "Lateralization of high-frequency tones," *JASA*, **32**, 132–134 (1960).

Movshon, J. A. and Lennie, P., "Pattern-selective adaptation in visual cortical neurons," *Nature*, **278**, 850852 (1979), https://doi.org/10.1038/278850a0.

Perrott, D. R. and Musicant, A. D., "Rotating tones and binaural beats," *J. Acoust. Soc. Am.*, **61**, No. 5, 1288–1292 (1977), https://doi.org/10.1121/1.381430.

Perrott, D. R. and Nelson, M. A., "Limits for the detection of binaural beats," *J. Acoust. Soc. Am.*, **46**, No. 6, 1477–1481 (1969), https://doi.org/10.1121/1.1911890.

Petropavlovskaia, E. A., Shestopalova, L. B., and Vaitulevich, S. F., "Predictive ability of the auditory system during smooth and abrupt movements of low-intensity sound images," *Zh. Vyssh. Nerv. Deyat.*, **61**, No. 3, 293–305 (2011).

Saberi, K., "Lateralization of comodulated complex waveforms," *J. Acoust. Soc. Am.*, **98**, 3146–3156 (1995), https://doi.org/10.1121/1.413804.

Salikova, D. A., Petropavlovskaia, E. A., and Shestopalova, L. B., "Distortion of subjective space in a dynamic acoustic environment," *Integr. Physiol.*, **4**, No. 2, 198–212 (2023), https://doi.org/10.33910/2687-1270-2023-4-2-198212.

Salminen, N. H., Tiitinen, H., and May, P. J., "Auditory spatial processing in the human cortex," *Neuroscientist*, **18**, No. 6, 602–612 (2012), https://doi.org/10.1177/1073858411434209.

Shestopalova, L. B., Salikova, D. A., and Petropavlovskaia, E. A., "Auditory aftereffect: influence of a stationary adapter on the perception of a moving stimulus," *Zh. Vyssh. Nerv. Deyat.*, **73**, No. 2, 256–270 (2023), https://doi.org/10.31857/S0044467723020107.

Shestopalova, L., Petropavlovskaia, E., Semenova, V., and Nikitin, N., "Brain oscillations evoked by sound motion," *Brain Res.*, **1752**, 147232 (2021), https://doi.org/10.1016/j.brainres.2020.147232.

Shestopalova, L., Petropavlovskaia, E., Vaitulevich, S., et al., "Discrimination of auditory motion patterns: mismatch negativity study," *Neuropsychologia*, **50**, 2720–2729 (2012), https://doi.org/10.1016/j.neuropsychologia.2012.07.043.