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The Influence of the Masker on the Localization of the Moving Signal in the Horizontal Plane

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Abstract—The effect of the masker on the localization of the moving signal was investigated in the free field conditions. The experiments were carried out in an anechoic chamber. Sound signals were presented from loudspeakers located on a semicircular arc in the horizontal plane. Bandpass noise bursts (5–18 kHz) were used to create a signal and a masker. The signal and the mask were uncorrelated stimuli and were created from two independent noise bursts. The stationary masker was always on the right at an angle of 15°. The moving signals traveled to or from the masker along two paths located at two places (–86° to –52° and –52° to –18°). The signal and the masker of 1-s duration each were presented either simultaneously or with a delay of the signal onset relative to the masker onset. The delay varied from 1 to 40 ms and 1200 ms. The subjects evaluated the start and end points of the trajectory of the moving sounds. Localization data for a moving signal under masking conditions were compared with spatial estimates of the same signal when presented in isolation (without a masker). Localization of the start and end points of the signal in masking condition was compared with localization of the moving source alone. Results showed that the masker affected the start and end points of the signal trajectory. The shift depended on the direction of movement. The starting points were always shifted in the direction of motion of the signal. The end points were shifted in the opposite direction.

Keywords: masking, localization, moving sound source

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INTRODUCTION

In everyday life, listeners localize the sound source against the background of extraneous interfering sounds. The effect of these interferences depends on the spatial, temporal, and spectral characteristics of the sound signals. In an ordinary room, interfering (masking) sounds are their own reflections of the signal (echo) from the surfaces of the enclosed space. Regardless of extraneous sounds, the auditory system shows the ability to localize the useful signal against the background of interference.

Masking is a phenomenon consisting in the deterioration of the perception of one stimulus (signal) in the presence of another stimulus (masker) [1–3]. A special case of masking is the precedence effect, which is expressed in the listener's ability to localize the signal source against the background of multiple reflections of this signal (reverberation) in the room. It is based on the extraction of directional information from the first sound waves coming directly from the sound source (direct sound) while simultaneously suppressing directional information about reflected sound waves (echo signals) that arrive with some delay [4, 5]. A distinctive feature of the precedence effect is the presence of a cross-correlation of the direct and reflected signals, the degree of which can vary widely in real conditions [6].

A small number of studies are devoted to the analysis of masking for a moving sound source. In [7, 8], the signal detection thresholds under masking conditions were studied. In the study of Ya.A. Altman et al. [7], showed that the masking of a moving signal is noticeably weaker than the masking of a stationary one. At the same time [8], no differences were found in the detection of a moving and stationary signal under masking conditions.

Two other studies were devoted to the study of the localization of a moving signal under masking conditions. The work of E.A. Petropavlovskaya and Ya.A. Altman [9] was carried out under conditions of forward masking upon presentation of a stationary masker (noise) and subsequent presentation of a moving series of clicks through headphones (dichotic stimulation). It is shown that the masking effect manifests itself in the suppression of the initial section of the signal movement, as well as in the displacement of the subjective trajectory of the signal movement. The degree of displacement of the subjective trajectory increased with increasing intensity of the masker.

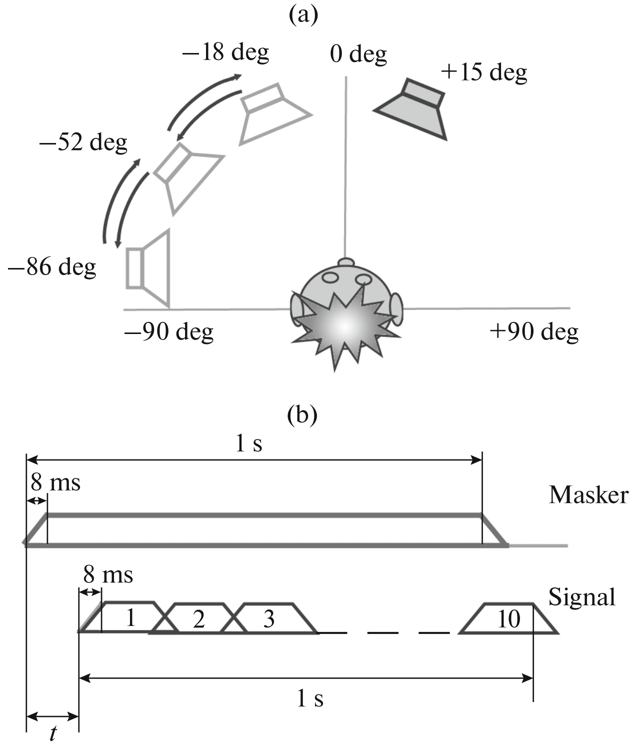

Fig. 1. Schematic representation of sound stimulation. (a) The location of sound sources relative to the test for a moving signal and a stationary masker. The white speakers correspond to the start and end points of the signal movement. The arrows show the direction of movement. The gray loudspeaker on the right is the position of the stationary source of the masker. (b) Masker and signal schematics. The numbers on the signal diagram are noise bursts that create signal movement.

In [10], the localization of a moving signal was considered under the conditions of the precedence effect in a free sound field. To create the precedence effect, the same (fully correlated) noise bursts were used as a signal and a masker. The moving signal was presented with a delay of 0–40 ms relative to the onset of the stationary masker. With short delays up to 3 ms, the subjects could not localize the moving signal with a distinct localization of the masker. At delays greater than 3 ms, a subjective decrease in the signal trajectory was observed, regardless of the direction of movement and the location of the signal trajectory. The decrease in the trajectory arose due to the displacement of the starting points in the direction of movement, and the end points against the direction of movement.

In general, the interaction between the useful signal and the masker under the conditions of localization of a moving sound source remains poorly understood. The purpose of this study was to analyze the effects of masking a moving signal under conditions when the signal and the masker match in amplitude–frequency characteristic (sound the same), but differ in time form. Temporal differences were set by using uncorrelated sound bursts as a signal and a masker. The dependence of the localization characteristics on the spatial separation of the signal and the masker, the time delay between them, and the direction of signal movement was evaluated.

MATERIALS AND METHODS

The experiments were carried out on 10 subjects (9 women and 1 man) with normal hearing, aged 20 to 42 years. Before the experiment, the subjects got a standard tone audiometry procedure. Differences in hearing thresholds, measured for each subject on two ears, did not exceed 5 dB.

The experiments were carried out in an anechoic chamber 3 × 3 × 4.5 m in size. The chamber contained a semicircular turning arc with a radius of 1 m, on which 49 loudspeakers were located (Visaton SC 5.9, Germany) with similar frequency characteristics. The differences in the amplitude–frequency characteristics of the loudspeakers did not exceed ±4 dB in the band 0.2–18 kHz. The angular distance between adjacent loudspeakers was 3.75°. The arc was installed in a horizontal plane.

The subject was positioned in the chair in such a way that the plane of the arc coincided with the interauricular line of the subject (0° in the angle of elevation). The central loudspeaker was located along the midline of the head (0° in azimuth), and the two extreme loudspeakers were directly opposite the right (+90°) and left (–90°) ears of the listener (Fig. 1a). The subject's head was fixed with a special head holder (Philadelphia, Taiwan).

Stimuli. Broadband noise with a bandwidth of 5–18 kHz, digitally synthesized with a sampling frequency of 44.1 kHz, served as an sound signal. Two independent noise bursts were formed (correlation coefficient 0.0003). The messages bursts were delivered to two separate channels, one of which was used to present a stationary masker, and the other to generate a moving signal. The duration of both signals was 1 s.

The stationary masker was presented from a sound source located at an angle of 15° to the right relative to the midline of the subject's head. The moving signal traveled along an arc 34° long. The signal was presented from the left side and moved in two directions: from left to right (approaching the masker) and from right to left (moving away from the masker) along two trajectories. The trajectory closest to the masker was located in the range from –18° to –52°, the far one was from –52° to –86° (Fig. 1a). The work analyzed the localization data for four conditions, which included two signal trajectories and two directions of its movement.

The moving signal was turned on with a delay relative to the turning on of the masker (Fig. 1b). The delay was: 0, 1, 2, 3, 5, 8, 10, 12, 18, 25, 40, and 1200 ms.

Signal movement was created by successively switching ten loudspeakers. Each of the loudspeakers was fed a signal with a duration of 100 ms with rise-fall fronts of 8 ms. The sound smoothly passed from one loudspeaker to another without audible breaks due to the simultaneous attenuation of the signal on the previous loudspeaker and its increase on the next one.

The masker intensity was 44 dB sound pressure level (SPL), moving signal, 35 dB SPL. Acoustic measurements were carried out using Bruel and Kjær equipment (Denmark) at the location of the center of the subject's head.

To quantify the effects of masking, two control series of experiments were carried out. In one of them, the subjects determined the position of the initial and final points of the signal trajectory during its isolated presentation (without a masker). In the second experiment, we determined the localization of statiory sound sources located at angles corresponding to the positions of the starting and ending points of the moving signal (–86°, –52°, –18°) and masker position (+15°).

Additional experiments were performed on the same subjects who took part in the masking experiments. The data of the control experiments served as initial data for a comparative analysis of the effects of the interaction between the signal and the masker.

Experiment procedure. Each stimulus, in the main series consisting of a masker and a signal with a certain delay, was presented two times (one trial), after which the response of the subject was recorded. Responses were recorded using a graphics tablet (Genius G-pen 450, Taiwan), on the working surface of which an arc was schematically depicted. After listening to sound stimuli, the subject had to project onto the arc scheme the perceived positions of the starting and ending points of the signal trajectory and then mark them on it. The angular coordinates of the selected points were determined using a specially developed computer program. In the main experimental series, the subjects could hear either the signal and the masker, or only the masker. The subject was asked to mark the position of the second (delayed) signal if he heard it. If the subject heard only the masker, he had to indicate the position of the masker.

At the beginning of each series, a training session was performed during which the subject was presented with stimuli with a wider set of delays: 1, 2, 3, 5, 8, 12, 18, 25, 40, 74, 150, 300, 600, and 1200 ms. Training always started with a maximum delay of 1200 ms. All subjects with this delay heard two successively sounding stimuli: the first, to the right of the midline of the head, and the second, to the left. Then, the delay was successively reduced to 0 ms. After training, they proceeded to the main part of the experiment, in which the time delays were 0, 1, 2, 3, 5, 8, 12, 18, 25, 40, and 1200 ms. Each of the delays used within one series was repeated 12 times. Thus, for each delay, trajectory and direction, 24 trials were conducted for each subject. Stimuli with different delays were alternated in a pseudo-random order. The position of the signal within the same series was not changed.

In the control series, the isolated signal was repeated 20 times in pseudo-random order for each location and direction of movement. The masker was also repeated 20 times in a pseudo-random order for each location.

The experiment consisted of eight main series, two for each location and direction of the test signal, and two control ones. The series order was also pseudo-random.

Data analysis. By analogy with [10], for a quantitative analysis of the spatial effects of the interaction of the signal and the masker, the difference between the localization estimates of the subjects obtained during the joint presentation of the signal and the masker and during isolated presentation was calculated. In order to unify the dimension, the relative units of the trajectory shift due to the start and end points were calculated, since the relative shift does not depend on the length of the subjective trajectory, which could vary for different subjects:

$$\mathrm{X1i} - \mathrm{X2i} = \Delta\mathrm{Xi}, \text{ for the start points,} \quad (1)$$

$$\mathrm{X1f} - \mathrm{X2f} = \Delta\mathrm{Xf}, \text{ for the end points,} \quad (2)$$

where X1 is the localization of the moving signal by the test subjects during its isolated presentation for the start (i) and end (f) points in degrees. X2 is the signal localization in the presence of a masker. ΔX is the shift of the start and end points of the perceived motion of the signal under the action of the masker. The differences were calculated for each trajectory and two directions of movement for each subject separately:

$$\Delta\mathrm{X}/(\mathrm{X1i} - \mathrm{X1f}) = \mathrm{Xo}, \quad (3)$$

where the value of Xo, calculated for the start and end points, shows the severity of the subjective shift relative to the length of the subjective trajectory.

Statistical evaluation of the data was carried out using a four-factor analysis of variance with factors: *Direction of travel* (to the masker, away from the masker), *Localization* (start, end points), *Trajectory* (nearest to the masker, farthest from the masker), *Delay* (0, 1, 2, 3, 5, 8, 12, 18, 25, 40, and 1200 ms).

Statistical evaluation of the data was carried out using a three-factor analysis of variance for echo signals and a two-factor analysis for a direct signal with a significance level of $p < 0.05$.

RESULTS

Under conditions of masking, the responses of the subjects were grouped mainly in the area of the signal and rarely in the area of the masker. Six out of ten sub-

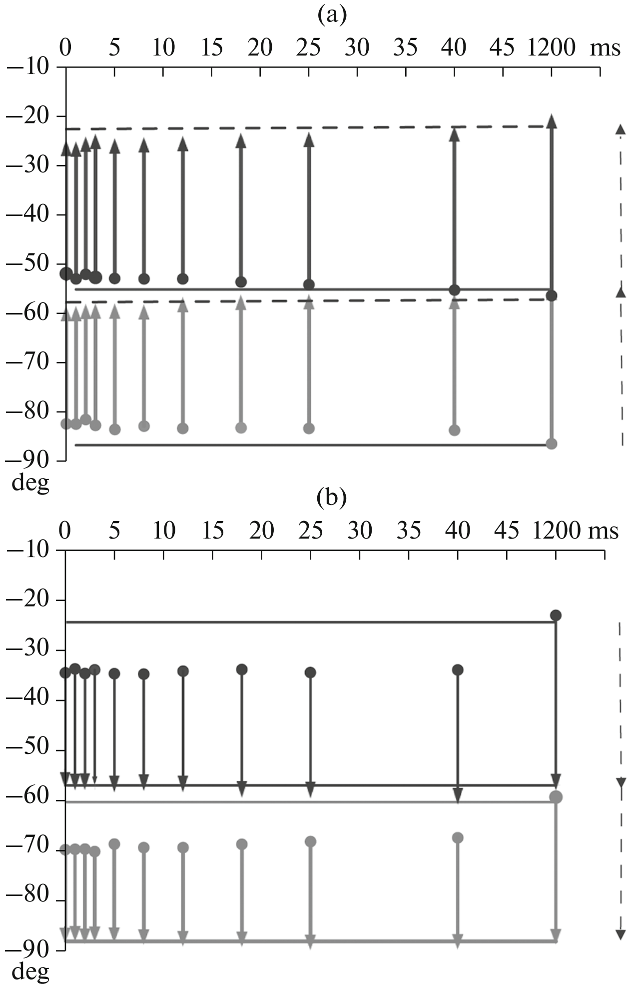

Fig. 2. Perceived signal trajectory during masking. (a) Signal movement to the masker. (b) Movement of the signal from the masker. Black lines—signal movement along the trajectory closest to the masker (from −52° to −18°), gray lines – movement along the far trajectory (from −86° to −52°). Horizontal solid lines are the perceived position of the beginning of the motion trajectory for isolated signal presentation, dotted lines are the position of the end of the motion trajectory of the isolated signal. Vertical dotted lines with arrows are the physical trajectory of the signal. On the *ordinate*-axis, the localization of the signal in deg. The abscissa axis shows the delay value in ms.

jects clearly localized the beginning and end of the moving signal. Four other subjects in separate tests at short delays (up to 18 ms) perceived the signal and the masker as a single sound image, localized in the area where the masker is located.

An estimate of the signal localization probability showed that even at the shortest delays between the signal and the masker, the signal localization remains quite high (above 80%). As the delay increased, the number of trials in which listeners could locate the moving signal gradually increased. At delays of more than 25 ms, all subjects demonstrated 100% signal localization.

Figure 2 shows average-group data on the localization of the start and end points of the signal movement trajectory for two directions of signal movement (indicated by arrows) and two trajectories, near and far. For comparison, Fig. 2 shows the localization of the start and end points of a moving signal during its isolated presentation (lines). As can be seen from Fig. 2b when the signal moves away from the masker, a narrowing of the trajectory is observed due to a strong shift of the starting points in the direction of movement. The shift of the initial points did not exceed 10° on average. The shift of the endpoints was insignificant and was observed at short delays up to 8 ms. At delays greater than 8 ms, the endpoints were localized close to the same values as in the isolated the moving signal. When the signal moves towards the masker, a slight narrowing of the trajectory is observed due to a slight shift of the starting points in the direction of signal movement and a slight shift of the end points against the direction of movement.

For quantitative analysis and unification of dimensions, the relative displacements of the localization of the initial start and final end points of the moving signal were calculated in comparison with the length of the subjective trajectory. In Figs. 3a and 3b are mean-group data showing the shift in the perceived position of the start and end points in relative units. As can be seen from Fig. 3a when the signal moved away from the masker, the shift of the initial points was 30–40% of the length of the signal trajectory. As the delay increased to 40 ms, the shift slightly decreased. At a delay of 1200 ms, when the signal was turned on 200 ms after the masker was turned off, the offset did not exceed 4%. When the signal moved towards the masker, the shift of the initial points was 10–20% of the trajectory value. As in the case of moving the signal away from the masker, the offset changed slightly up to a delay of 25 ms, and then gradually decreased. At the maximum delay (1200 ms), the displacement of the localization of the start of movement did not exceed 4%.

In Fig. 3b, the displacement of the endpoints is shown. For the end points, the offset displacement value when the signal moves towards the masker is slightly larger and amounts to 10% of the movement trajectory, and when moving away from the masker, it does not exceed 5%. Before a delay of 12 ms, the curves run almost parallel, and then converge, and at a delay of 1200 ms, regardless of the direction of movement, all curves show a shift towards the masker.

Comparison of the magnitude of displacement was assessed by a four-way analysis of variance. The analysis showed a significant influence of the factor *Direction of travel* ($F(1, 814) = 153.47$, $p < 0.01$) and *Localization* ($F(1, 814) = 26.9$, $p = 0.01$), as well as a significant interaction of these factors ($F(1, 814) = 256.5$,

$p < 0.01$). The value of the displacementof the start points was greater when the signal moved from the masker, and the end points when moving in the opposite direction. The direction of the shift in the localization of the start points coincided with the direction of movement. For the end points, the reverse pattern was observed: they were displaced against the direction of movement. A significant interaction of factors was revealed between *Localization* and *Direction of travel* with *Trajectory* ($F(1, 814) = 4.462$, $p < 0.05$). Pairwise comparisons show that the magnitude of the shift of the start points was significantly different from the shift of the end points for each direction and each trajectory of movement ($p < 0.05$).

The shift of both start and end points for the far trajectory (in Figs. 3a and 3b, gray lines) when moving towards the masker was significantly different ($p < 0.05$) from shift when moving away from the masker. For the near trajectory of motion (Figs. 3a and 3b, black lines), significant differences depending on the direction of movement were obtained only for the start points ($p < 0.05$). When moving away from the masker, the magnitude of shifts for the far and near trajectory did not differ significantly for both the start and end points of the motion ($p > 0.05$). The movement from the masker in Figs. 3a and 3b are indicated by solid lines. For the end points, the lines practically coincide (Fig. 3b), for start points (Fig. 3a) the curves are close or intersect. When the signal moved in the opposite direction (toward the masker), differences were observed only for the start points (Figs. 3a, dotted curves).

Also, a significant interaction was obtained for factors *Localization* and *Direction of travel* with factor *Delay* ($F(1, 814) = 4.462$, $p < 0.05$). When the signal moved to the masker for delays of 25, 40, and 1200 ms, no significant differences were found between the start and end points ($p > 0.05$), and when moving away from the masker, only for a delay of 1200 ms. For other delays, the start and end points were significantly different ($p < 0.05$).

The results generally show that the decrease in the trajectory of movement occurred due to the displacement of the start points in the direction of movement, regardless of the location of the trajectory, and the end points, against the direction of movement. The value of the shift of the start points of the subjective trajectory of the signal was significantly different from the shift of the end points for delays less than 25 ms ($p < 0.05$).

DISCUSSION

As the study showed, under masking conditions, different subjects may show different abilities to localize a moving sound signal. Some are able to localize the signal over the entire range of delays between the masker and the signal. Others show a reduction in this ability in the low latency region. At delays longer than 18–25 ms, the subjects do not differ and show a 100% probability of signal localization.

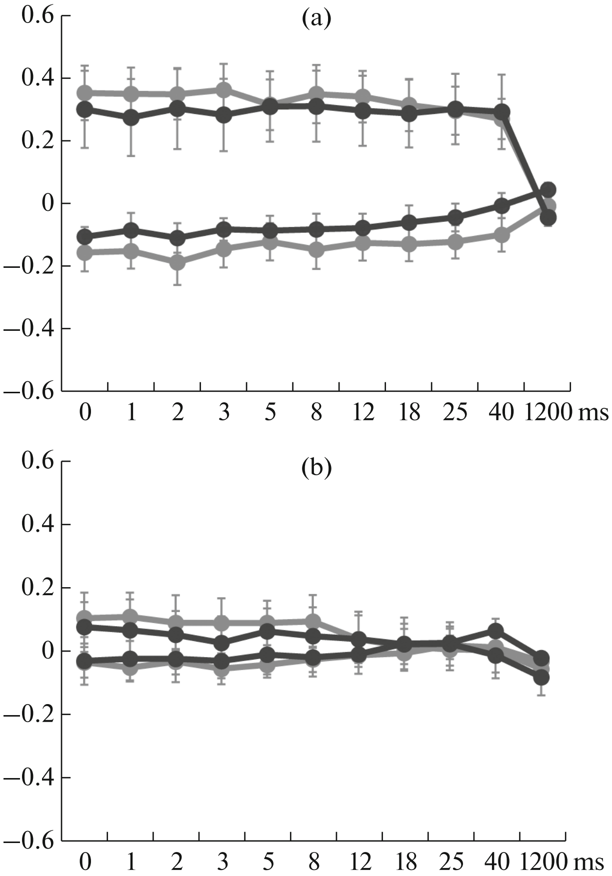

Fig. 3. Relative shifts in the localization of the start and end points of signal movement during masking. (a) Starting points (b) end points. Solid lines are signals moving away from the masker, dotted lines are approaching the masker. Black lines are the near signal trajectory, gray lines are the far one. On the *ordinate* -axis, the relative shift in fractions of the length of the signal's trajectory. Negative values—shift of the start and end points of the signal movement towards the masker, positive values— shift in the opposite direction (away from the masker). Vertical lines are standard error. The abscissa axis shows the delay value in ms.

In contrast to moving signals, the probability of localization of stationary signals during masking depends on both the spatial and temporal characteristics of sound stimulation [11].

Stationary signals are poorly localized at short delays between the masker and the signal, and only at delays of more than 18 ms does the probability of signal localization reach a 100% level. In this case, the lowest probability of localizing the signal source is observed at the signal location closest to the masker, and the highest, at the remote location of the signal source.

Comparison of the data of the cited and present studies allows us to conclude that the movement of the signal, accompanied by temporal changes in the localization features of the signal, can serve as a factor contributing to the unmasking of the signal. Indirectly, this is evidenced by the results of a study demonstrating the dependence of the effect of liberation from masking on the speed of the signal [7].

The data of this study using uncorrelated stimuli show a certain similarity with the results of our previous study, in which the signal and masker were identical (correlated) [10]. In both studies, there was a shift of the initial points of the subjective trajectory in the direction of movement, and the end points in the opposite direction (Fig. 3). In this case, the shift of the initial points when the signal moved from the masker was stronger than when the signal moved towards the masker (Figs. 2 and 3a). The data obtained confirm the earlier assumption that such a picture reflects the interaction of temporal and spatial masking [10]. The action of temporary masking appears at the beginning of the action of signals and does not depend on the direction of movement and the location of the movement trajectory relative to the masker. The subjects begin to perceive the beginning of the movement of the signal after the real signal has already shifted. A similar shift of start points was observed in the study of E.A. Petropavlovskaya and Ya.A. Altman [9], where the phenomenon of masking the initial section of the signal trajectory was shown. In [9], forward masking was used under the conditions of presentation of sound stimuli through headphones. Thus, the masking of the initial segment of signal movement is a general characteristic of masking for different methods of sound stimulation and temporal organization of stimuli.

Spatial masking is valid throughout the entire signal and depends on the distance between the masker and the signal. The smaller the distance between stimuli, the greater the interaction between them [12, 13]. In our study, significant differences in the magnitude of the shift were obtained only when the signal approached the masker: a larger shift was observed for the far trajectory of motion (Fig. 3a). In addition, the shifts of the start and end points when the signal moved to the masker differed significantly in magnitude from the corresponding shifts of these points when the signal moved in the opposite direction. Based on our data, we can conclude that the effect of spatial masking caused a shift in the perceived trajectory of the moving signal in the direction opposite to the location of the masker. If the signal was moving away from the masker, then the spatial and temporal maskings acted unidirectionally, while when the signal approached the masker, their action became differently directed. The shift of the perceived trajectory in the direction opposite to the location of the masker is shown in [9]. The magnitude of the displacement effect increased with increasing masker intensity.

When uncorrelated stimuli are used as a signal and a masker, the shift in the start and end points of a moving signal is noticeably smaller than when correlated stimuli are presented [10]. Thus, the maximum shift of the start points of a moving stimulus, observed when the signal moved along a distant trajectory, for uncorrelated stimuli was 35% (Fig. 3a), then for correlated stimuli it reached values of 60% and higher. For uncorrelated stimuli, the magnitude of the shift in the starting point of signal movement was weakly dependent on the delay between the masker and the signal. For correlated stimuli, this shift revealed a pronounced delay dependence [10]. The presence of a correlation between the masker and the signal causes a strong interaction between them and, as a result, makes it difficult to separate them in the auditory system. With an increase in the delay between the masker and the signal, the degree of their cross-correlation decreases, which contributes to the weakening of the interaction between them and the strengthening of their perceptual separation. For this reason, the delay between stimuli has a pronounced effect on masking under the conditions of the precedence effect, when the masked signal correlates with the masker. For uncorrelated stimuli, this effect is much weaker. From a practical point of view, this means that in a closed room, characterized by the presence of correlated sound reflections (echoes), the localization of the sound source is worse than in open space.

When uncorrelated stimuli are presented, as in the case of their mutual correlation, the effect of shifting the end points of the moving signal to the side opposite to the direction of its movement is observed. The presence of this effect can be explained from the point of view of a "time window" integrating successive events in the auditory system in time [10]. If the end part of the signal, together with the end section of the masker, enters the window, then the spatial estimation of their position will depend on the weight ratio of the signal and the masker. As the delay increases, the degree of temporal overlap between the signal and the masker decreases and the weight of the signal increases. As a result, the endpoints of the perceived signal trajectory are shifted towards the physical location of the signal. The data obtained show that for both correlated and uncorrelated stimuli, the end point of the subjective trajectory of the signal movement reaches its limiting value, corresponding to the physical localization of the isolated signal, at delays of about 18 ms.

CONCLUSIONS

The effects of masking a moving signal upon presentation of uncorrelated stimuli can manifest itself in a decrease in the probability of signal localization and in a shift in the start and end points of the perceived signal movement trajectory. Regardless of the direction of signal movement, the starting points of the subjective trajectory are displaced in the direction of signal movement, and the end points are in the opposite direction. Compared to the masking effects observed under conditions of correlation between the masker and the signal, uncorrelated stimuli are characterized by a weak dependence of the shift in the starting point of the perceived movement of the signal on the magnitude of the delay between the masker and the signal. When masking a moving signal, the probability of its localization is higher than when localizing a stationary signal. Based on this, we can conclude that the movement of the stimulus can serve as a factor contributing to the improvement of signal localization against the background of interference.

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COMPLIANCE WITH ETHICAL STANDARDS

Ethics approval. All studies were carried out in accordance with the principles of biomedical ethics formulated in the Declaration of Helsinki of 1964 and its subsequent updates and approved by the local bioethical committee of the Institute of Physiology, Russian Academy of Sciences (St. Petersburg) (No. 22-03, dated July 4, 2022).

Informed consent. Each participant in the study provided a voluntary written informed consent signed by him after explaining to him the potential risks and benefits, as well as the nature of the upcoming study.

Conflict of interest. The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.

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