

COVER PAGE

Document downloaded by @DAEL

Sun Nov 22 06:15:24 2026
For personal use

When automatic English translation is provided, only the original document is authentic.
The EAA cannot be held responsible of any translation error

Bibliographical reference

Investigations Into the Velocity and Distance Perception of Moving Sound Sources, Christoph Pörschmann and Christian Störig, Acta Acustica **vol. 95** (Number 4), 2009, pp. 696-706

DOI
https://doi.org/10.3813/AAA.918198

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 95 (2009) 696 – 706

DOI 10.3813/AAA.918198

Investigations Into the Velocity and Distance Perception of Moving Sound Sources

Christoph Pörschmann, Christian Störig
Institut für Nachrichtentechnik, Cologne University of Applied Sciences, Germany.
Christoph.Poerschmann@fh-koeln.de, Christian.Stoerig@gmx.de

Summary
Temporal loudness changes, binaural cues and Doppler shift can all influence distance perception of moving sound sources. This article will analyze different auditory distance perception cues of moving sound sources. In psychoacoustic experiments, the subjects were presented with dichotic and diotic stimuli of a set of real-life recordings taken from a passing passenger car and then asked to determine the velocity of the object and its minimal distance from the listener. The results of the listening experiments allow us to separate monaural distance perception cues from binaural ones, and thus show that binaural cues contribute significantly to the perception of velocity. For short distances and high velocities, the presentation of binaural cues causes a decrease in the perceived velocity while for long distances and low velocities this causes a clear increase. By estimating the minimal distance from the passing object, one observes a significant difference between dichotic and diotic presentation, which can be explained by an increased loudness of dichotic stimuli due to the binaural masking level difference (BMLD). Furthermore, it is shown that the main parameter for distance determination is the maximum sound pressure level at the listener's position. However, dynamic cues (change of sound pressure level over time, Doppler shift) are of considerable importance for the plausibility of the auditory scene.

PACS no. 43.66.Pn, 43.66.Qp

1. Introduction

It is a well-known fact that the listener's hearing experience dominates the distance perception of stationary sound sources. Commonly both air absorption and sound pressure level are considered the most relevant factors contributing to the perception of medium and large distances. When looking at the perception of non-stationary sound sources, an analysis of the relevant distance perception cues is far more complex than in the static case. Here both temporal changes of the distance cues and Doppler shift take effect. However, the auditory distance perception of moving sound sources is of great importance in many everyday situations; when evaluating the velocity and distance of a passing passenger car, for example. It seems surprising that the distance and velocity perception mechanisms used to evaluate moving sound sources have not yet been considered in great detail. Only a few studies are available in literature, most of them employing artificial signals as stimuli and thus only varying some of the relevant cues.

Grantham [1] simulated moving sound sources by amplitude panning of a 500-Hz tone and found that the perception of velocity corresponded to an angular displacement and was independent of the duration of motion. Rosenblum [2] and Lutfi and Wang [3] investigated the perception of a sound source passing the listener. Having varied Doppler shift, loudness and interaural time differences, they found Doppler shift to be the most relevant cue for the determination of velocity and the amplitude envelope of the signal as most relevant for the moment of closest approach. Strauss [4] investigated the influence of amplitude envelope, Doppler shift and the direction of sound incidence on plausible perception of an auditory virtual environment. He found that all three cues significantly contribute to enhance a plausible perception of the environment.

This article, based on the typical scenario of a passing passenger car (which is familiar to almost anyone), analyzes the different cues contributing to the distance and velocity perception of moving sound sources. Binaural and diotic recordings are presented to the subjects in three psychoacoustic experiments. The following key questions shall be addressed:

- *How do the perceived velocity and the perceived distance correlate to the physical velocity and distance of the sound sources?*
- *How do monaural and binaural cues influence the perception of distance and velocity?*
- *Is the plausibility of the presented scenario reduced if a single cue is altered?*

The first section of this paper analyzes the human distance and velocity perception. It describes the relevant cues and

Received 15 January 2008,
accepted 19 February 2009.

© S. Hirzel Verlag · EAA

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

gives an overview of the literature. Afterwards the recordings of the moving sound sources are described. Subsequently details of three experiments are given, the first one analyzing velocity perception, the second one determining the relevant cues of distance perception, and the last one investigating how discrepancies between the cues influence distance perception.

2. Distance and velocity perception

2.1. Perception of stationary sound sources

Most of the research dealing with distance perception has been performed on stationary sound sources. Estimating the distance from a sound source is a task which seems to be very difficult for the subjects. Several investigations show that, compared to the localization blur, which is below 1° in the horizontal plane, the distance blur is relatively high (e.g. [5, 6, 7]). The following cues are commonly regarded to be relevant for the distance perception of sound sources (e.g. [8, 9]):

Intensity: The sound pressure level decreases with an increasing distance from the sound source. For free-field conditions and point sources (monopoles) the sound pressure level is reduced by 6-dB when the distance is doubled. Listeners determine the distance from a sound source by comparing the loudness of the sound source to their prior listening experience. Familiarity of the sound source properties is thus an important criterion when using intensity cues (e.g. [10]).

Spectrum: For distances larger than 15 m the spectrum of the sound source is significantly modified due to air absorption (e.g. [11]). Higher frequencies are more attenuated than lower frequencies. Thus, when comparing the colorization of the sound source's spectrum to his listening experience, the subject can identify spectral changes and thus estimate the sound source distance.

Direct-to-reverberant energy ratio: In rooms or other environments with sound reflecting surfaces, the ratio between the energy of the direct sound and the energy of the reflections depends on the distance between sound source and listener. With decreasing distance from the sound source the direct sound energy increases, while the diffuse reverberant energy remains nearly unchanged in the room.

Binaural cues: Both interaural level differences (ILD) and interaural time differences (ITD) change when the distance from a sound source is altered. Binaural cues are especially relevant for distance perception in the case of nearby sources. According to Brungart and Rabinowitz [12] and Duda and Martens [13] ILD cues are of more importance than ITD cues in distance perception.

In localization experiments, head movements improved the subject's ability to estimate the direction of sound incidence. However, according to the experiments of Simpson and Stanton [14] head rotations do not improve the accuracy of distance judgements in distance perception.

Zahorik's [9] experiments show that listeners underestimate the true sound source distance from medium to high ranges. For nearby sources, the true distance is overestimated by the listeners. In [15] a systematic overview of the psychoacoustic research regarding the quantification of distance perception was performed, showing that the relationship between the perceived distance d' and the true distance d can be described by a compressive power function.

$$d' = k d^a. \tag{1}$$

The two parameters k and a have been determined by Zahorik *et al.* [15] using the results of 21 previous studies and 84 data sets from literature. Even though the exponent of the power functions varies significantly from 0.15 to 0.7 between the different experiments, the coefficient k has been found to be consistent at about 1.3 for the results of the different experiments. For an extensive overview of research in the field of stationary source distance perception, the reader is referred to [15].

2.2. Perception of non-stationary sound sources

In the case of non-stationary sound sources, additional monaural cues affect distance perception. The sound pressure level and the influence of air absorption become time variant. Moreover, Doppler shift provides additional information for the listener regarding distance perception.

Furthermore, binaural cues gain influence on distance perception, even for large distances. The binaural cues help to create a spatial impression of the scene and to estimate the source's movement angle. These cues are caused by a change of the static ones and will be termed 'dynamic cues' in the following paragraphs, as suggested by Speigle and Loomis [16]. This information is used by the listener and thus enhances the accuracy of the estimate.

There are two applicable ways of categorizing the relevant cues of distance perception. On the one hand, the cues can be categorized as 'binaural' or 'monaural'. On the other hand, it is possible to class them as 'static' or 'dynamic'. Static cues are caused by a specific sound source at one specific distance, while dynamic cues are parameters caused by a movement of the sound source. Dynamic cues either turn into static cues or are irrelevant for stationary sound sources. They influence distance perception for moving sources and are also important for velocity perception. Table I gives an overview of the different cues and their categorization.

In literature only a few psychoacoustic experiments on distance and velocity perception of moving sound sources have been described yet. In the following an overview of the relevant research is given.

One of the first investigations dealing with the perception of a linear moving sound source was conducted by Grantham [1]. Amplitude panning of a 500-Hz tone, radiated between two loudspeakers, produced a simulation of moving sound sources. The results show that the velocity perception of the simulated motion corresponds to a

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

Table I. Categorization of distance cues as monaural and binaural cues versus static and dynamic cues.

	Monaural	Binaural
Static	Sound pressure level, Air absorption (relevant for distant sound sources), Direct-to-Reverberant energy ratio	ITD, ILD (relevant for near sound sources)
Dynamic	Change sound pressure level over time, Doppler shift	Change of incidence direction, ITD(t), ILD(t)

constant angular displacement, which was found to be independent of the duration of motion. Grantham concludes from these experiments that listeners infer velocity from the total distance travelled, rather than estimating velocity directly. This concept of motion detection is known as snapshot hypothesis [3].

The first experiments, which aimed to study the influence of different dynamic cues on the detection of the moment of passing, were carried out by Rosenblum [2]. As stimuli Rosenblum used the sound of a European ambulance siren and presented these stimuli with fixed values for distance ($d = 15$ m) and velocity ($v = 13$ m/s). In his experiments he varied Doppler shift, loudness and interaural time differences independently of one another. The experiments focused on the identification of the most relevant psychoacoustic parameters in order to detect the moment of passing. The results of the investigations show the amplitude envelope of the signal to be the primary factor in determining the moment of closest approach, followed by interaural time differences and finally by Doppler shift.

The experiments of Lutfi and Wang [3] follow a similar principle. In their experiments amplitude envelope, interaural time differences and Doppler shift of the first five harmonics of a 100 Hz tone were modified. According to their results Doppler shift is the primary dominant cue determining the velocity of a sound source moving at a velocity of 10 m/s. The secondary dominant cue differed depending on the subject. The subjects either relied more on interaural time differences or on the amplitude envelope of the signal.

Earlier investigations in this field have been carried out by Speigle and Loomis [16]. The authors performed investigations with moving listeners and a stationary sound source. Here the listeners were able to use binaural cues in order to determine the distance from a sound source. The results of the investigations show a slight reduction of the blur compared to a static listener scenario.

Several investigations on moving sound sources have been carried out in the field of auditory collision detection. Here, moving sound sources are analyzed in order to determine the time of collision with the listener.

Hellmann [17] investigated the way in which loudness influences the perception of non-stationary sound sources. In his experiments, binaural recordings were presented to the subjects via headphones. The sound-radiating objects moved towards the listener and the subjects were asked to determine the time of collision. As a first result the experiments indicate that the time of collision is systematically determined as too early. The subjects underestimate the distance from the sound source. However, the loudness of the sound sources has a significant influence on the estimation of collision as well. Thus the loudness of the object influences distance perception.

In his investigations Hellmann [17] shows that, when sound sources are approaching the listener, two different strategies are used in order to determine the distance from the object. The listener may use the computational strategy, which means that he detects distance and velocity separately from static cues (e.g. loudness) by comparing the cues to his listening experience. Thus, as for the already mentioned snapshot theory, the estimation of velocity is not performed directly, but based on a computation of the results of several cues. A listener also uses the so-called "Tau-strategy". Here, the estimation is directly based on the change of dynamic cues. The listener directly determines the collision time from the change of the stimulus without performing an estimation of distance. A detailed description of the experiments and an analysis of the relevant literature for collision detection and avoidance were performed by Hellmann [18].

Following the investigations of Lutfi and Wang [3], Kaczmarek [19] performed experiments in order to detect the just-noticeable differences (JNDs) for different sound source velocities. The considered velocities were ranged from 10 m/s to 40 m/s. The results show that the differential velocity threshold is independent from the considered velocities, which vary across the range of listeners from 1.5 m/s to 4.6 m/s. Furthermore, Kaczmarek compared the influence of different cues on velocity perception. The experimental results show that the subjects tended to respond mostly to Doppler shift and that they were least sensitive to interaural time differences.

A scenario similar to the one presented here was used in the psychoacoustic investigations of Strauss [4, 8], who integrated moving sound sources into a virtual auditory environment generator. The system was capable of positioning moving sound sources freely in a virtual environment considering Doppler shifts, amplitude envelope and direction of the sound source. With this system he performed a listening test using a passenger car which passes the subjects at a velocity of 100 kph and at a distance of 4 m. The results of this experiment show that a correct amplitude envelope as well as Doppler shift and binaural presentation of the stimuli enhance the plausibility of the scene. However, one cannot conclude from the results of the ex-

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

periments which one of the cues has the most influence on a plausible perception of the considered scene.

Further investigations dealing with the perception of a linear moving sound source were conducted by Neuhoff and McBeath [20] and McBeath and Neuhoff [21]. They discovered that listeners perceive a rise of pitch during the approach of a sound source, even though the signal falls in frequency. Obviously, a dynamic intensity change – depending on the movement of the source – has an influence on the perceived pitch. The observed effect is called "Doppler Illusion". For an extensive overview of the research in the field of auditory motion perception, the reader is referred to Neuhoff [22].

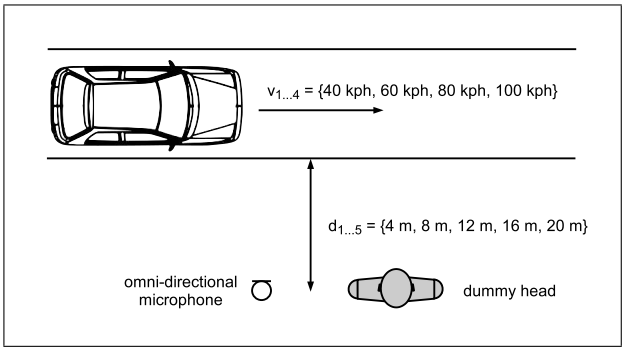


Figure 1. Measuring setup.

3. Recording moving sound sources

Except for Hellmann [18] all of the investigations already described made use of simulated scenarios or different synthetic sounds. The psychoacoustic experiments presented in this article investigate the perception of distance and velocity by applying a set of real-life measurements of a passing passenger car. This scenario was chosen as it represents a situation which is familiar to all the subjects of the listening experiments. Furthermore, it is one of the typical situations for which the estimation of distance and velocity is of practical importance.

Examination of the influence of the identified distance cues according to Table 1 clearly shows that the applied scenario is not at all suitable for gathering information about the influence of Direct-to-Reverberance energy ratio, as reverberation is negligible in free-field recordings.

Therefore recordings of passing vehicles at different distances between vehicle and listener and at different velocities were performed. Two types of microphones were used for the recordings, one omni-directional microphone (Beyerdynamic MM1) and one artificial head (Head Acoustics HMS III, ID-equalized). The measurements with both types of microphones were performed simultaneously at distances of 4 m, 8 m, 12 m, 16 m and 20 m and velocities of 40 kph, 60 kph, 80 kph and 100 kph. Due to a technical problem with two recordings, the measurements at 40 kph (4 m distance) and at 60 kph (8 m distance) could not be used within the experiments.

The recording data was fed into a PC via a multichannel soundcard (RME-Multiface II) with cardbus interface. The amplifiers were calibrated so that it was possible to reconstruct the same sound pressure level at the listeners' ears in the experiments and in the recording situation.

As sound source a passenger car (Opel Astra, year of manufacture 1997, manual transmission, 1.6 l, OTTO engine) was used. No gearshifts were performed during one recording. However, as in a normal driving situation, the car was driven in different gears for the different recorded velocities.

The recordings were performed on a public road in the broader environment of Cologne, Germany, in the early morning or evening. The recordings therefore include background noise, as well as that of the vehicle. Among others the background noise contains the sounds of other distant vehicles, airplanes taking off and landing at a distant airport and some birds chirping.

No effort was made to eliminate the background noise afterwards, as it was not intended to create laboratory situations within the experiments. However, the difference between the background noise level and the recorded vehicle noise level contains information which might be relevant for distance and velocity perception. Nevertheless, it was certain that there was no danger that the contributions from the background noise should be confused with the vehicle noise. Figure 1 shows the recording setup.

In order to verify the recorded audio signals, a spectrum-analysis of the passing vehicle was applied. As shown in Figure 2, a maximum at a frequency of 1.2 kHz can be observed independently of the velocity. Due to Doppler shift the frequency is slightly changed when the vehicle is approaching or departing. Furthermore, the sound pressure level ($L_{\max}$) was analyzed at the listener's position when the vehicle passed. For the analysis an average time of 125 ms was chosen, which is a typical value for measuring sound pressure levels in pollution control, as for example suggested in the German standard DIN 4109 [23]. Figure 3 shows the dependence of distance and velocity of the vehicle on the sound pressure level at the moment of passing. It can be observed that the sound pressure level does not exactly follow the distance law. This might be caused by the influence of ground reflections, which interfere partly constructively and destructively. Furthermore, due to its directivity and its size, the vehicle cannot be considered as an ideal point source.

4. Psychoacoustic experiments

This article describes three psychoacoustic experiments on distance perception and velocity perception of moving sound sources. The first experiment analyzes the influence of distance from a sound source on velocity perception. Furthermore, in this experiment the contributions of monaural cues (Doppler shift, sound pressure level) and binaural cues (interaural time difference, interaural level difference) to velocity perception are separated from each other. The second experiment investigates the way in

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

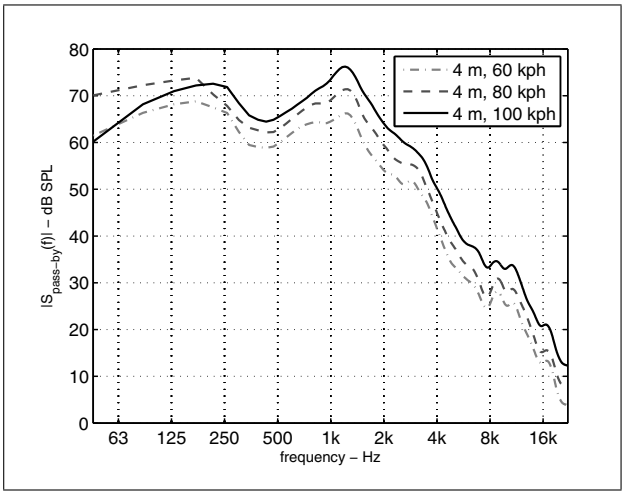


Figure 2. Spectrum of a vehicle when passing at a distance of 4 m for different velocities. The frame had a length of about 750 ms.

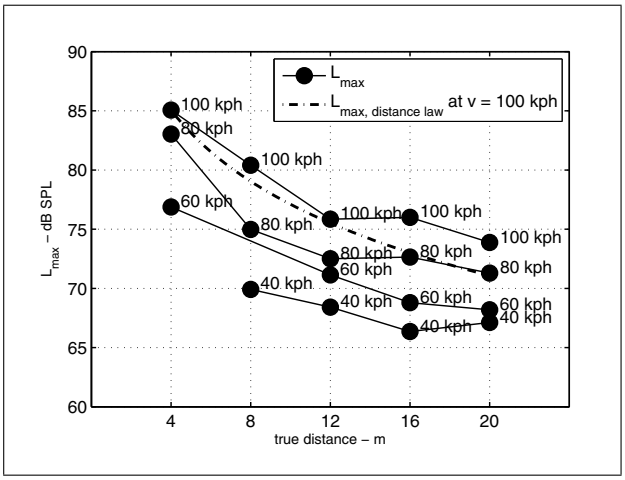


Figure 3. Influence of distance and velocity on the sound pressure level at the moment of passing. Additionally the theoretical curve according to the distance law for 100 kph is shown.

which distance perception in the moment of passing coincides with the physical distance and the degree to which sound source velocity alters distance perception in the moment of passing. Finally, the third experiment analyzes the effect of a manipulated loudness cue while all other cues are kept constant. The aim of this investigation is to find out how modifications of the sound pressure level influence distance and velocity perception and if mismatches between the cues are detected by the listener.

4.1. Experiment 1

According to the investigations of Lutfi and Wang [3], the influence of Doppler shift dominates velocity perception. Interaural time differences and loudness are less important. In general, the experiments show an increased dominance of Doppler shift with higher velocities.

This experiment investigates and compares the influence of monaural cues (Doppler shift, sound pressure level and influence of air absorption) and of binaural cues (interaural time difference, interaural level difference) on velocity perception. The following questions are posed:

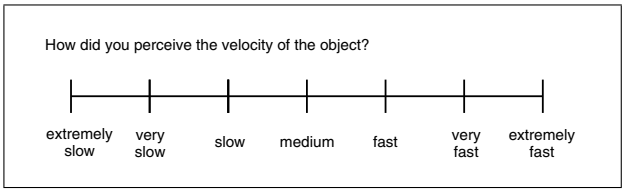


Figure 4. Scale for rating the perceived velocity of the stimulus (the English translation is shown here).

- *What relationship exists between the distance from a sound source, the velocity of the sound source and the perception of velocity?*
- *What influences do monaural cues (Doppler shift, sound pressure level) and binaural cues (interaural time difference, interaural level difference) have on velocity perception?*

Different psychoacoustic methods can be applied in order to determine the differences between diotic stimuli (recordings with the omni-directional microphone) and dichotic stimuli (binaural recordings). Within a pair comparison these differences are relatively easy to identify. However, a pair comparison does not show the general relationship between distance, velocity of the object and the estimate of velocity. Thus in the experiment the recorded stimuli were presented either diotically or dichotically via headphones and estimates of velocity were rated by the subjects on a category scale. In the evaluation of the experiment the estimates for dichotically and diotically presented recordings will later be compared, thus allowing us to identify the influence of binaural cues. In the first section (experiment 1a) 20 dichotic stimuli were presented to the subjects in a pseudo-randomized order. This order varied among the subjects. Each stimulus was presented twice within the experiment. 24 subjects (4 female, 20 male) aged from 22 to 41 participated in the experiment. All but two subjects reported having normal hearing capabilities. Additionally an audiogram was taken of the subjects in order to prove their hearing capabilities, thus confirming their answers. Thresholds of all subjects were below 20 dB hearing loss for all audiometric frequencies. In the second section (Experiment 1b) 20 diotic stimuli were presented. All other parameters of the experiment remained unchanged. This time 25 subjects (3 female, 22 male) aged 20 to 33 participated. Here, three subjects reported having a hearing loss. For both parts of the experiment the data of the subjects with limited hearing capabilities were not included in the analysis. In the experiment the subjects were asked how they perceived the velocity of the object. A PC-based user interface was used to collect the judgements. The subjects rated the perceived velocity on a seven-point category scale (extrem langsam, sehr langsam, langsam, mittel, schnell, sehr schnell, extrem schnell) which was displayed on the monitor screen by means of setting a slider to the appropriate position (Figure 4). The subjects were also allowed to rate interim values between the given

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

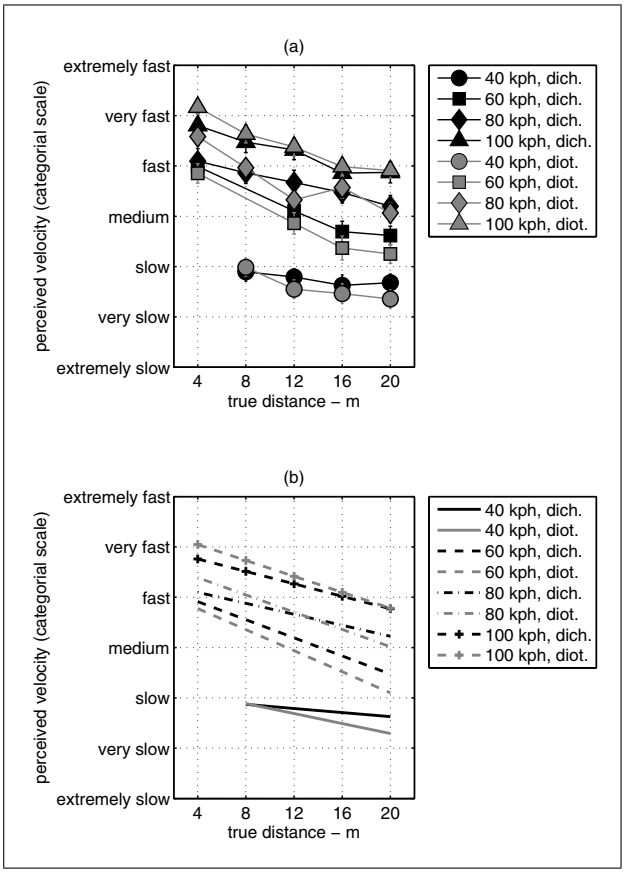


Figure 5. Influence of the distance of the sound source on the perceived velocity. In the upper diagram (a) the average scores as well as the 95% confidence intervals are shown in grey for the diotic stimuli and in black for the dichotic ones. In the lower diagram (b) the results of linear regression analysis are drawn. A downward slope of the regression curve can be observed which seems stronger for the diotic stimuli.

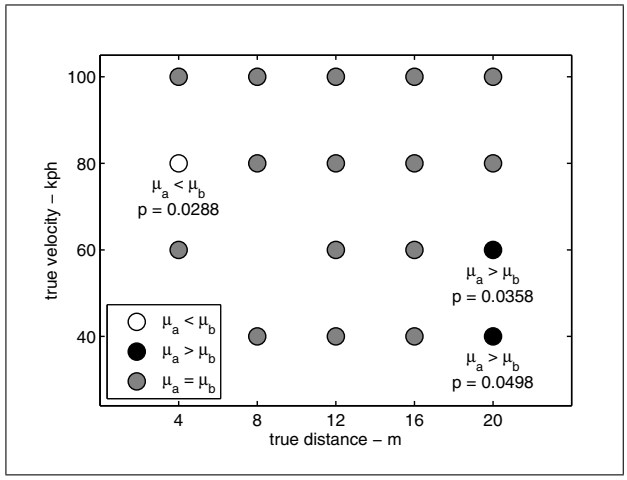


Figure 6. Results of the ANOVA: Differences between the velocity judgments over diotic and dichotic stimuli ($\alpha = 0.95$; μ_a = dichotic, μ_b = diotic). The probabilities are given in addition, in case the Zero-hypothesis H_0 is rejected. It can be observed that for short distances and high velocities the velocity of the diotic stimuli is significantly overestimated while for long distances and low velocities the subjects tend to underestimate the velocity in the diotic case.

categories. The equidistance between the categories was underlined by the visual presentation as shown in Figure 4 as suggested by Bronwen and Mc Manus [24] and Möller [25].

In the initial phase of the experiments the subjects were presented with two 'anchor stimuli' one which was introduced as 'very slow' (stimulus 20 m and 40 kph) and one as 'very fast' (stimulus 4 m and 100 kph). These two conditions represented the ones which in previous informal listening tests were rated as slowest or fastest. However, the subjects were not forced to treat these stimuli as extreme values, because the anchoring stimuli were linked to the second highest and second lowest values on the scale.

Figure 5 shows that the estimation of velocity does not only depend on the velocity of the stimuli but also on the distance from the object. The estimation of velocity greatly depends on the distance from the object, especially in the case of higher velocities. Furthermore, Figure 5 shows a slight difference between the scores for diotic and dichotic presentation. For small and large distances from the sound source the differences are larger than for a distance of 8 m. In order to test the statistical significance of the differences, the velocity factor from the categorical rating was converted into numbers assuming equidistance between the categories. Then an Analysis of Variance (ANOVA) was carried out (e.g. [26]). The tendency of the differences was determined by means of an additional multiple pair comparison (e.g. [27]). The results show that for short distances and high velocities the velocity of the diotic stimuli is overestimated compared to the dichotic case (see Figure 6). On the other hand, for long distances and low velocities the subjects tend to underestimate the velocity in the diotic case.

The results of the first experiment can be summarized as follows: The perceived velocity depends strongly on the distance from the sound source. An increase of distance results in a decrease of the perceived velocity. Furthermore, for the considered distances and velocities binaural effects influence the estimation of velocity. At short distances between sound source and listener they cause a decrease in the perceived velocity, while at greater distances binaural cues cause an increase in the perceived velocity.

4.2. Experiment 2

This experiment investigates the way in which the distance of an object passing a listener is determined. Different scenarios were therefore presented to the subjects and their estimates of distance were evaluated. The scenarios varied with regards to the distance of the passing object and the velocity of the object. The following questions were posed in the course of this experiment:

- *How does the perceived distance correlate to the physical values of the scenario?*
- *To what extent do monaural cues (Doppler shift, sound pressure level) and binaural cues (interaural time dif-*

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

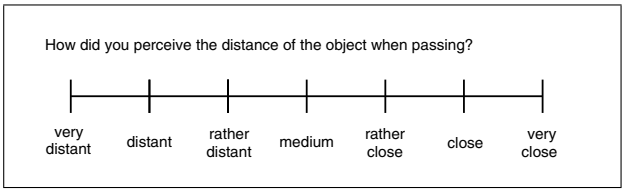


Figure 7. Scale for rating the perceived distance when passing (the English translation is shown here).

ference, interaural level difference) influence distance perception?

- *To what extent does the velocity of the object influence the perceived distance?*

Again the recorded stimuli were conveyed via headphones. Both dichotic and diotic stimuli were presented to the subjects. Thus the stimuli were the same as in the first experiment. In the dichotic case 33 subjects (3 female, 30 male) aged 22 to 38 years participated. The diotic listening situation was presented to 14 subjects (3 female, 11 male) aged from 23 to 37 years.

All subjects, with the exception of two, reported having normal hearing capabilities. Only the data of the normal hearing subjects was used in the following analysis. In the experiment the subjects were asked how they perceived the distance from the object at the moment when the object passes the listener. By means of the described PC-based user interface the subjects rated the perceived distance on a seven-point category scale (sehr weit entfernt, weit entfernt, eher weit entfernt, mittel, eher nah, nah, sehr nah) as shown in Figure 7.

The subjects were presented with two 'anchor stimuli' in the introductory phase. The stimulus of 4 m distance and 60 kph was introduced as close, while the stimulus of 20 m and 60 kph was introduced as being distant.

Figure 8 shows that the determined distance significantly depends on the velocity of the object. An increase of velocity causes the listeners to perceive the vehicle passing at a shorter distance. Towards longer distances and lower velocities the human perception of distance from a sound source seems to follow a compressive power function. Here a similar result can be observed for dynamic sound sources as well as for static sound sources [15].

Figure 9 shows that the perceived distance between sound source and listener depends on velocity. On the one hand the velocity of the moving vehicle influences dynamic cues, but on the other hand the vehicle's increased velocity necessitates an increase in its sound emissions. This results in a higher maximum sound pressure level at the listener's position and thus in an increased loudness.

In order to discriminate these two effects, dynamic cues were separated from static cues. Therefore, the sound pressure level at the moment of passing ($L_{\max}$) was determined from the recordings and compared to the distance judgements. The perceived distances depending on the maximum sound pressure levels are shown in Figure 10.

The figure shows that the main parameter for the determination of distance is the maximum sound pressure level

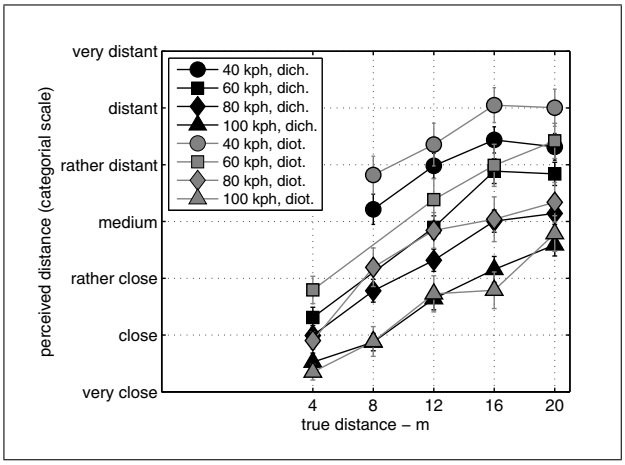


Figure 8. Perceived distance depending on the physical distance when passing. Shown are the average values of the judgments as well as the 95% confidence intervals in black for the dichotic stimuli and in grey for the diotic ones.

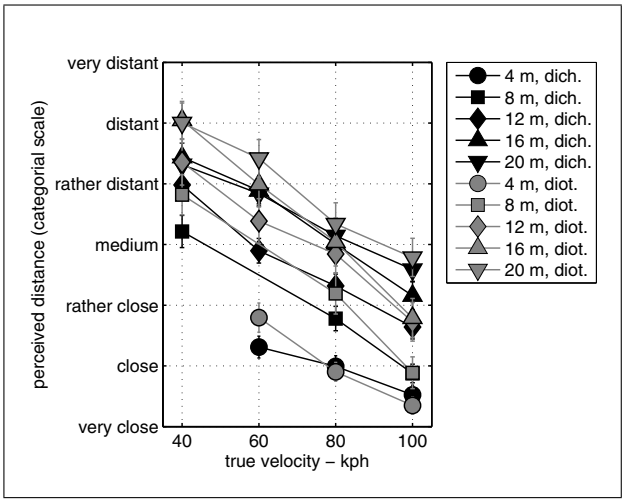


Figure 9. Perceived distance when passing the listener depending on the velocity of the object. Shown are the average values of the judgments as well as the 95% confidence intervals (grey: diotic stimuli; black: dichotic stimuli).

at the listener's position. It was not possible to prove that the dynamic cues have a statistical significance for the perceived distance in the course of this experiment.

However, differences between diotic and dichotic presentation can be observed. As the loudness of the signal increases, the loudness difference between diotic and dichotic stimuli seems to decrease.

By comparing the results of the diotic presentation to the ones of the dichotic presentation, as shown in Figure 8, an interesting result can be observed: Some of the dichotically presented stimuli are perceived as being closer to the listener. The results of a one-way ANOVA for the dichotic and diotic group are shown in Figure 11.

The differences in distance perception between diotic and dichotic presentation of the stimuli cannot be directly explained by the out-of-the-head localization as this would result in an increase of the perceived distance for the di-

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

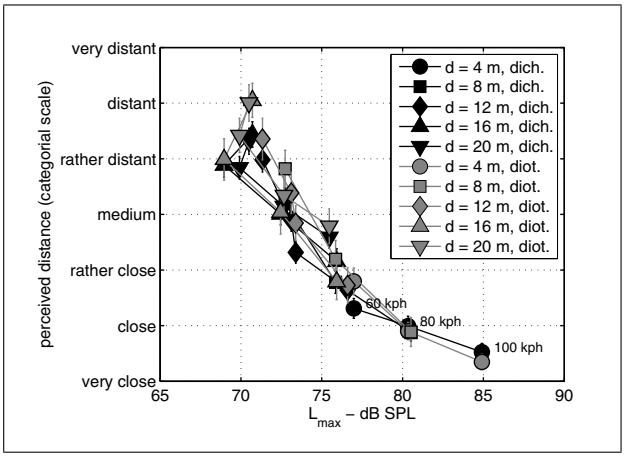


Figure 10. Perceived distance when passing the listener depending on the maximum sound pressure levels at the position of the listener (average values and 95% confidence intervals). The dichotic stimuli are marked black and the diotic ones grey.

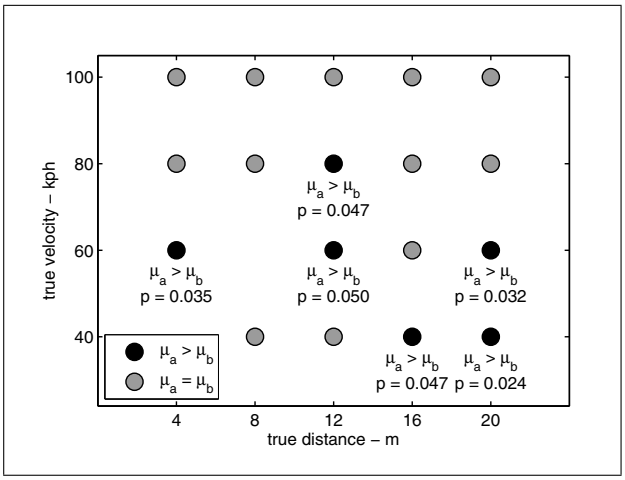


Figure 11. Results of a one-way ANOVA: Differences between the distance judgments over diotic and dichotic stimuli ($\alpha = 0.95$; μ_a = dichotic, μ_b = diotic). If the Zero-Hypothesis can be rejected, the p-values are shown additionally. It can be observed that some of the dichotic stimuli are observed significantly closer to the listener than the diotic ones.

chotic stimuli. Another explanation which applies the binaural masking level difference (BMLD) seems to be more sensible. Soderquist and Shilling [28] performed psychoacoustic experiments which show that the loudness of dichotically presented stimuli is significantly higher than that of diotically presented stimuli. With regard to this experiment, this means that the car sound is perceived louder for a dichotic presentation than for the diotic presentation. As shown above, increased loudness results in a nearer perception of the sound source (Figure 10), which directly explains the differences in distance perception.

Furthermore, the investigations of Soderquist and Shilling [28] show that the strength of this effect depends on the level difference between the stimuli and the masking threshold. According to the authors the effect diminishes when the signals are 20 dB or more over the mask-

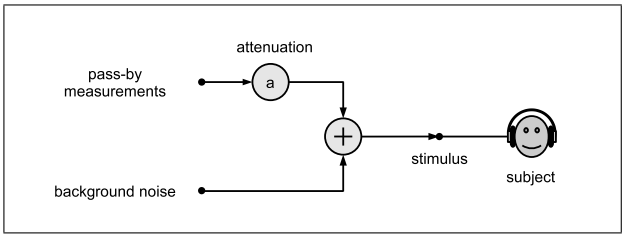


Figure 12. Method of creating attenuated stimuli. The background signal was kept constant by adding a section of background signal properly to the attenuated signal.

ing threshold. This coincides with the results of the listening experiments performed here. The background noise included in the recordings could be regarded as a masking signal. For higher velocities and shorter distances one does not observe an increased loudness of dichotic stimuli compared to diotic ones and thus cannot infer differences in distance perception.

The results of this experiment show that, while the maximum sound pressure level determines the distance, distance perception is different for a dichotic and for a diotic presentation of the stimuli. The question whether other cues (dynamic cues) also have a significant influence on the perception remains unanswered.

4.3. Experiment 3

In this experiment the influence of the sound pressure level at the listener's position, which has proved to be the most important static cue, is separated from other cues. The following questions shall be analyzed:

- *How does the sound pressure level at the listener's position influence the perceived distance?*
- *To what extent are mismatches between the cues detected by the listener?*

The binaural recordings were artificially attenuated and then presented to the subjects. In order not to change the level of the background noise the method shown in Figure 12 was applied. Thus an appropriate signal of pure background noise was added to the attenuated signal. This prevents the subjects from detecting the manipulations of the signal level due to the unnaturally reduced background level.

The attenuation was performed for a set of binaural recordings at $v = 60$ kph in the distances of 4 m, 12 m, 16 m and 20 m. The signals were attenuated by L_a ranging from 0 dB to 21 dB in steps of 3 dB. 21 subjects, all male and aged between 19 and 37, participated in this experiment. Apart from two (whose answers were not considered in the statistical analysis) all of them had normal hearing capabilities. The listeners' statements were checked by applying an audiogram. The subjects were asked to rate the distance from the vehicle as it passed the listener on a seven-point category scale. Additionally, the subjects rated the plausibility of the presented scenarios on a scale ranging from very plausible to very implausible on a seven-point category scale.

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

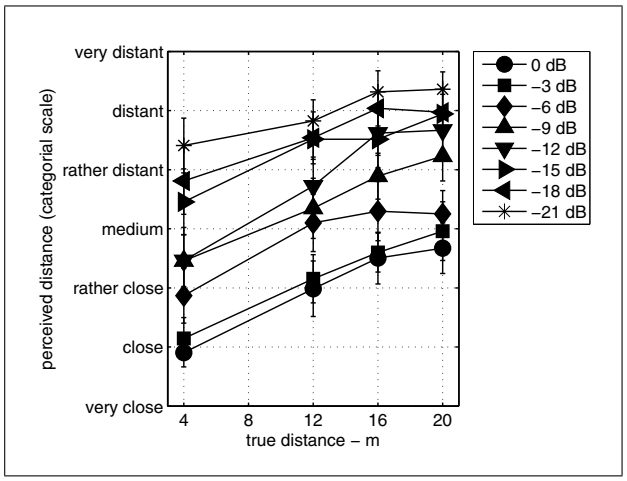


Figure 13. Influence of stimuli attenuation on the perceived distance. The mean values and the 95% confidence intervals are shown. The other parameter on the x-axis is the physical minimal distance of the recorded scenario.

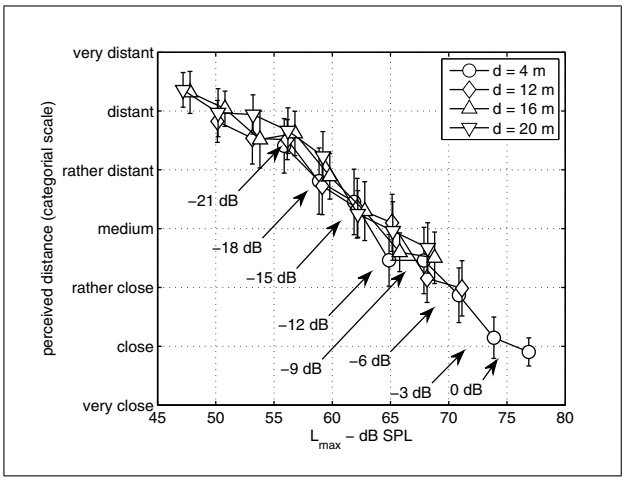


Figure 14. Influence of the perceived distance of the sound sources on $L_{\max}$. Given are the mean values and the 95% confidence intervals. For the results corresponding to the measurements in 4 m distance the attenuation factors are noted as well.

Figure 13 shows the influence of the stimuli's attenuation on the perceived distance. It can be observed that the perceived distance greatly depends on the stimuli's sound pressure level at the listener's position. These results agree with the findings of Hellmann [17] who showed that loudness is the main cue for estimating the distance of moving sources.

In order to analyze the influence of loudness more effectively, the maximum level at the listener's position was calculated for each stimulus ($L_{\max}$). As shown in Figure 14, the perceived distance of the sound sources depends on $L_{\max}$. The difference between the maximum level of the recording and attenuation corresponds to the level of the presentation in the psychoacoustic experiment.

It is obvious that the level of the presented stimuli mainly influences distance perception in this experiment. It can be observed that a line of best fit matches nearly all of the 95% confidence intervals.

The results on the plausibility show that, even though sound pressure level is the main cue for distance perception, other cues have to be considered as well. Here the subjects were asked to rate the plausibility of the presented scenarios. As shown in Figure 15 plausibility decreases with increasing distance. Very close sound sources create a more plausible perception than more distant sources. This may result from the fact that all investigated distance cues (binaural cues, Doppler shift, change of sound pressure level over time) are stronger for nearby sound sources. Furthermore, as previous informal psychoacoustic investigations have shown, it can be observed that louder stimuli are often perceived as being more plausible.

Figure 15 shows that an increased discrepancy between sound pressure level and other cues results in a reduced plausibility. Due to the design of this experiment the manipulated stimuli all have a reduced level compared to the original ones. Thus stimuli with lower maximum sound pressure levels tend to be judged as less plausible.

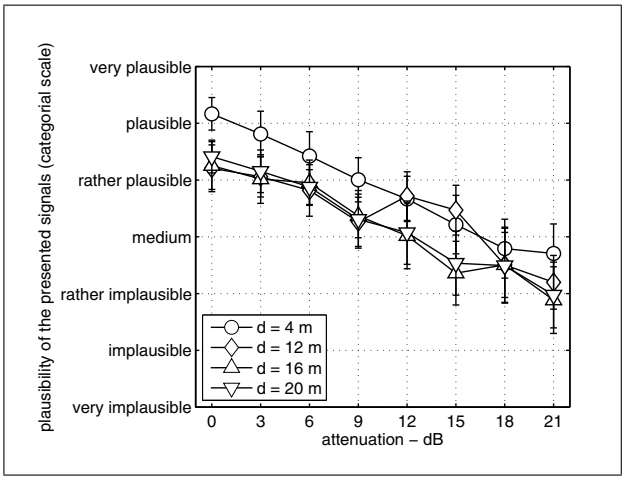


Figure 15. Influence of the attenuation factor of the stimuli on the perceived plausibility. The mean values and the 95% confidence intervals are shown. Another factor is the distance of the vehicle in the recording situation.

To investigate the role of attenuation in plausibility, the influence of the maximum sound pressure level is shown in Figure 16. It can be observed that for one specific maximum sound pressure level $L_{\max}$ the stimulus with the highest attenuation has been rated with the lowest plausibility. For example, three stimuli had an $L_{\max}$ of about 62 dB (4 m distance and 15 dB attenuation, 12 m distance and 9-dB, 20 m distance and 6 dB attenuation). Here a significant difference in the plausibility of the presentation can be observed. The plausibility not only depends on the level of the signal but also on the consistency between the different cues. A mismatch between the most significant cue (sound pressure level) and other cues, that are relevant for distance perception, is detectable by humans and thus leads to a less realistic hearing impression. However, when judging the sound source distance, a mismatch between loudness and other cues is suppressed by the human auditory system.

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

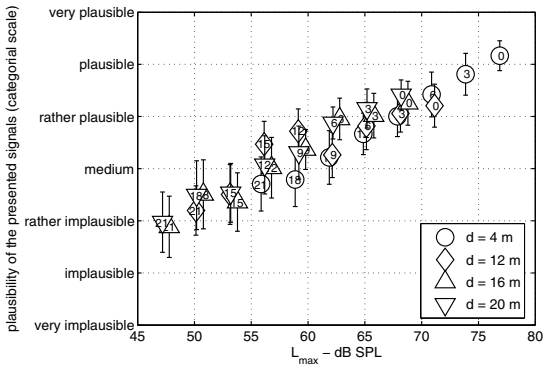


Figure 16. Influence of the maximum sound pressure level $L_{\max}$ on the plausibility of the perception. Given are the mean values and the 95% confidence intervals. The distance and the attenuation factors (in dB) are given as additional information.

Similar effects can be observed within other fields of auditory perception. For example, by localizing static sources the ILDs and the ITDs determine the lateralization of a sound source. Wightman and Kistler [29] performed an experiment with unrealistic ITD or ILD cues and found out that the judgements were always based on the realistic cue, and that the listeners ignored the unrealistic one. However, in order to create a plausible presentation of an externalized sound source more cues need to be considered. In particular the frequency-dependent influences of the head's and outer ear's shadowing need to be appropriately adapted to the respective ILD and ITD as well [11].

5. Summary and conclusion

Three different experiments were carried out in order to understand distance perception and velocity perception of moving sound sources. The sound sources were moved on a line and passed the listener at a specific distance. The subjects were asked to determine both the velocity of the object (experiment 1) and the minimal distance from the listener (experiments 2 and 3).

The results of experiment 1 show that in the near field binaural cues contribute to the perception of velocity. At short distances between sound source and listener binaural effects cause a decrease in the perceived velocity, while at greater distances they cause an increase in the perceived velocity.

Experiment 2 analyzed the parameters relevant for distance perception of moving sound sources. It was shown that the main parameter for the determination of distance is the maximum sound pressure level at the listener's position. Furthermore, for some stimuli dichotic presented sound sources are perceived to be closer than sound sources in the corresponding diotic situation. This might be explained by the binaural masking level difference (BMLD) which increases the loudness of the dichotically presented stimuli.

With regard to the perceived distance between sound source and listener, it was shown that there is a significant dependence on the velocity of the object. A decrease in the vehicle's velocity means that it is perceived as passing the listener at a greater distance. This can be explained by the fact that the sound emissions of the passing vehicles, and thus the sound pressure level at the position of the listener, increase towards higher velocities.

Apart from sound pressure level at the listener's position no statistical significance of other dynamic cues on the perceived distance and velocity could be proved. In experiment 3 the loudness of the stimuli was artificially altered. Again it has been shown that the distance perception of a sound source passing a listener is determined by the loudness of the sound source. However, although dynamic cues have no significant influence on distance perception they are important for the plausibility of the auditory scene.

The results of these experiments are useful for many applications in the field of virtual auditory environments. Distance perception of moving sound sources plays an important role in the creation of virtual environments in which the listener and the sound-radiating objects can move freely [4], for example in driving simulators. The results of experiment 1 may be useful for auralizing moving sound sources. When the auralization takes place diotically, an adaptation of monaural cues is required in order to give the listener the same velocity and distance impression as in a corresponding real-life or binaural auralization situation.

As shown in experiment 2, human perception of distance from a sound source seems to follow a compressive power function. Thus very distant sound sources are often underestimated. When setting up virtual environments and auralizing distant passing sound sources, it should be taken into consideration that this underestimation is compensated for by an artificial enhancement of the sound source distance. Finally, the results of experiment 3 show that the distance between a moving object and the listener can be controlled by a simple adaptation of the sound pressure level. However, a significant decrease in the plausibility is obtained by a manipulation of the sound pressure level compared to a scenario where other dynamic and static cues are adapted as well. With regard to an implementation for a virtual reality application it has to be considered whether the quality of the presentation is still sufficient [30].

Acknowledgements

The recordings and experiments have been carried out within several diploma theses at the Cologne University of Applied Sciences. The authors would like to thank Nicolas Ritschel who contributed to this paper by performing some of the psychoacoustic experiments within his diploma thesis. Finally, the authors would like to thank the anonymous reviewers for the comments which helped a lot in improving the article.

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only

References

[1] D. W. Grantham: Detection and discrimination of simulated motion of auditory targets in the horizontal plane. J. Acoust. Soc. Am. **79** (1986) 1939–1949.

[2] L. D. Rosenblum: Relative effectiveness of three stimulus variables for locating a moving sound source. Perception **16** (1987) 175–186.

[3] R. A. Lutfi, W. Wang: Correlational analysis of acoustic cues for the discrimination of auditory motion. J. Acoust. Soc. Am. **106** (1999) 919–928.

[4] H. Strauss: Implementing Doppler shifts for virtual auditory environments. 104th AES Convention, 1998, preprint no. 4687.

[5] G. von Békésy: The moon illusion and similar auditory phenomena. Am. J. Psychol. **62** (1949) 540–552.

[6] P. D. Coleman: Dual role of frequency spectrum in determination of auditory distance. J. Acoust. Soc. Am. **44** (1968) 631–634.

[7] D. H. Mershon, W. L. Ballenger, A. D. Little, P. L. Murtry, J. L. Buchanan: Effects of room reflectance and background noise on perceived auditory distance. Perception **18** (1989) 403–416.

[8] H. Strauss: Simulation instationärer Schallfelder für auditive virtuelle Umgebungen. VDI-Verlag, Düsseldorf, 2000.

[9] P. Zahorik: Assessing auditory distance perception using virtual acoustics. J. Acoust. Soc. Am. **111** (2002) 1832–1846.

[10] P. D. Coleman: Failure to localize the source distance of an unfamiliar sound. J. Acoust. Soc. Am. **34** (1962) 345–346.

[11] J. Blauert: Spatial hearing - The psychophysics of human sound localization. MIT Press, Cambridge, Massachusetts, 1997.

[12] D. S. Brungart, W. M. Rabinowitz: Auditory localization of nearby sources. Head-related transfer functions. J. Acoust. Soc. Am. **106** (1999) 1465–1479.

[13] R. O. Duda, W. L. Martens: Range dependence of the response of a spherical head model. J. Acoust. Soc. Am. **104** (1998) 3048–3058.

[14] W. E. Simpson, L. D. Stanton: Head movement does not facilitate perception of the distance of a source of sound. American Journal of Psychology **86** (1973) 151–159.

[15] P. Zahorik, D. S. Brungart, A. W. Bronkhorst: Auditory distance perception in humans: A summary of past and present research. Acta Acustica united with Acustica **91** (2005) 409–420.

[16] J. M. Speigle, J. M. Loomis: Auditory distance perception by translating observers. Proceedings of the IEEE Symposium on Research Frontiers in Virtual Reality, New York, NY, USA, 1993, 92–95.

[17] A. Hellmann: Auditive Kollisionwahrnehmung: Schallquellen, die sich auf den Hörer zubewegen. Fortschritte der Akustik - DAGA 1994, DEGA e.V., Bad Honnef, 1994, 1149–1152.

[18] A. Hellmann: Auditory perception of approaching sound sources, and time-of-arrival judgements. Dissertation, Ruhr-Universität Bochum, Fakultät für Psychologie, 1996.

[19] T. Kaczmarek: Auditory perception of sound source velocity. J. Acoust. Soc. Am. **117** (2005) 3149–3156.

[20] J. G. Neuhoff, M. K. McBeath: The Doppler illusion: The influence of dynamic intensity change on perceived pitch. Journal of Experimental Psychology: Human Perception and Performance **22** (1996) 970–985.

[21] M. K. McBeath, J. G. Neuhoff: The Doppler effect is not what you think it is: Dramatic pitch change due to dynamic intensity change. Psychonomic Bulletin & Review **9** (2002) 306–313.

[22] J. G. Neuhoff: Auditory motion perception and localization. – In: Ecological Psychoacoustics. J. G. Neuhoff (ed.). Elsevier Academic Press, San Diego, CA, 2004.

[23] DIN 4109: Schallschutz im Hochbau. Beuth Verlag, Berlin, 1989.

[24] L. J. Bronwen, P. R. Mc Manus: Graphic scaling of quantitative terms. Society of Motion Picture and Television Engineers (SMPTE) Journal **95** (1986) 1166–1171.

[25] S. Möller: Assessment and prediction of speech quality in telecommunications. Kluwer Academic Publ., Boston MA, 2000.

[26] J. Hartung et al.: Lehr- und Handbuch der angewandten Statistik. R. Oldenbourg Verlag GmbH, München, 1991.

[27] O. Beucher: Wahrscheinlichkeitsrechnung und Statistik mit MATLAB: Anwendungsorientierte Einführung für Ingenieure und Naturwissenschaftler. Springer Verlag GmbH, Berlin, 2007.

[28] D. R. Soderquist, R. D. Shilling: Loudness and the binaural masking level difference. Bulletin of the Psychonomic Society **28** (1990) 553–555.

[29] F. L. Wightman, D. J. Kistler: Factors affecting the relative salience of sound localization cues. – In: Binaural and Spatial Hearing in Real and Virtual Environments. R. H. Gilkey, T. R. Anderson (eds.). Lawrence Erlbaum Associates Inc., 1997, 1–23.

[30] R. S. Pellegrini: Quality assessments of auditory virtual environments. Proceedings of the 2001 International Conference on Auditory Display, Espoo, Finland, 2001, 161–168.

[31] M. Bodden: Binaurale Signalverarbeitung: Modellierung der Richtungserkennung und des Cocktail-Party-Effektes. VDI-Verlag GmbH, Düsseldorf, 1992.

[32] ISO 362-1: Measurement of noise emitted by accelerating road vehicles - Engineering method. International Organization for Standardization, Geneva, Switzerland, 2007.

[33] C. Störig, C. Pörschmann: Psychoakustische Experimente zur Untersuchung der Wahrnehmung Doppler-behafteter Signale. Fortschritte der Akustik - DAGA 2007, DEGA e.V., Oldenburg, 2007, 377–378.

Document downloaded by @DAEL, 2026-11-22 06:15:26 - personal use only