

BMJ Open Noise exposure and auditory thresholds of German airline pilots: a cross-sectional study

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ABSTRACT

Objective The cockpit workplace of airline pilots is a noisy environment. This study examines the hearing thresholds of pilots with respect to ambient noise and communication sound.

Methods The hearing of 487 German pilots was analysed by audiometry in the frequency range of 125 Hz–16 kHz in varying age groups. Cockpit noise (free-field) data and communication sound (acoustic manikin) measurements were evaluated.

Results The ambient noise levels in cockpits were found to be between 74 and 80 dB(A), and the sound pressure levels under the headset were found to be between 84 and 88 dB(A). The left–right threshold differences at 3, 4 and 6 kHz show evidence of impaired hearing at the left ear, which worsens by age. In the age groups <40/≥40 years the mean differences at 3 kHz are 2/3 dB, at 4 kHz 2/4 dB and at 6 kHz 1/6 dB. In the pilot group which used mostly the left ear for communication tasks (43 of 45 are in the older age group) the mean difference at 3 kHz is 6 dB, at 4 kHz 7 dB and at 6 kHz 10 dB. The pilots who used the headset only at the right ear also show worse hearing at the left ear of 2 dB at 3 kHz, 3 dB at 4 kHz and at 6 kHz. The frequency-corrected exposure levels under the headset are 7–11 dB(A) higher than the ambient noise with an averaged signal-to-noise ratio for communication of about 10 dB(A).

Conclusions The left ear seems to be more susceptible to hearing loss than the right ear. Active noise reduction systems allow for a reduced sound level for the communication signal below the upper exposure action value of 85 dB(A) and allow for a more relaxed working environment for pilots.

INTRODUCTION

Civilian airline pilots bear a high responsibility as one wrong decision could lead to disastrous consequences for the entrusted employees and passengers. The demands on the health and performance of pilots are correspondingly high. Communication and the understanding of acoustic information are very important in their occupation and a sufficiently good hearing is one of the fundamental conditions for the profession. Therefore a hearing test at the annual health check-up is mandatory. Nevertheless, sound

Strengths and limitations of this study

- The current study is a large epidemiological study in civilian pilots over a wide age span with acoustic measurements in various airplanes.
- Hearing thresholds include extended high frequencies.
- Multivariate analysis and differential presentation (left–right ear) identified unknown risk factors influencing hearing thresholds.
- A limitation may be the cross-sectional design of the study without the direct development of hearing loss in the individuals.

exposure for pilots and the consequences for their hearing are still being discussed.

Modern jet aircrafts are less noisy than former models. This results in reduced noise exposure in the flight cabin and less annoyance for the affected population. However, the reduced annoyance per flight will be overcompensated by a higher flight frequency. Lindgren *et al*¹, for example, did not find an extended risk to hearing loss in Swedish airline pilots compared with a non-noise exposed population. The upper action values of 85 dB(A) were generally not reached. They also found about 1.2 dB worse thresholds in the left ear when compared with the right ear. Lie *et al*² reported no articles with markedly increased risk to hearing impairment in civilian airline pilots in a review about occupational noise exposure. However, there are hints about an increased susceptibility to hearing loss of the left ear compared with the right, which are independent of the occupation.^{3 4} In studies concerning the hearing of pilots the left–right ear asymmetries are considered only negligible. This subject will be addressed in the present study.

Presbycusis is one main factor for a decreasing hearing ability over age. Therefore, it is desirable to eliminate the age factor from the audiometric data so as to discover other factors like occupational and



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environmental noise exposure of the pilots. This can be done by using existing standards to a suitable age correction. The usefulness of age correction standards will be demonstrated in the present paper.

METHODS

Study population

Civilian pilots of a large German airline were examined during the annual health check-ups within the German occupational safety and health system (health check for pilots are enforced by law) with particular attention to their hearing status. All voluntarily participating pilots were interviewed in a standardised manner about their professional and leisure-related noise exposures. From a total of 542 candidates, 487 male pilots were included in the study. Twelve pilots were excluded, because their questionnaires were lost or incomplete. Further 12 people were excluded, because they did not work in the cockpit and five female pilots were excluded, because the subgroup was too small. Furthermore, 11 pilots were excluded due to sudden hearing loss, 12 due to former ear surgery and 3 because of severe colds. So about 10% of the examined subjects (55 out of 542) were not involved in the analysis. The mean age was 43 years (median: 38 years), with a range from 20 (pilot candidates) to 63 years. Since a strong age dependency of the audiograms was to be expected, the pilots were divided into two age groups. A total of 271 pilots were younger than 40 years old with 11 flight alumni, 209 flight officers, 48 captains and three flight engineers. A total of 216 pilots were 40 years and older with 14 flight officers, 180 captains and 25 flight engineers. The mean age of the younger group was 32.4 years and of the older group was 48.8 years. The mean difference of age, therefore, was 16.4 years. Four age groups with 10-year range were pooled for statistical characteristics (percentiles).

Instrumentation

Pure tone audiometry was performed by experienced audiologist's assistants in a sound proof room of the medical centre of the airline company. The audiometer was a type CA540 from Hortmann (now GN-Otometrics) with circumaural headphones type HDA200 from Sennheiser suitable for tests in the extended high-frequency range up to 16 kHz. The maximum sound levels of the CA540 in combination with the HDA200 are 90 dB HL at 11.2 kHz, 80 dB HL at 12.5 kHz, 70 dB HL at 14 kHz and 60 dB HL at 16 kHz (HL: hearing level according to ISO 389-5 and ISO 389-8).^{5,6} Via the serial interface RS 232 the audiometric data were recorded into a software database Avantgarde 2.0 of the company Nüß (Hamburg).

Acoustic measurements

The acoustic measurements in aircraft cockpits were carried out by the technical service of the aviation company. The measurements were performed with a 0.5-inch free-field microphone and an acoustic manikin (AM) Type 4100 with an artificial middle ear Type 4157 of Brüel &

Kjær (Denmark). In all sound measurements integrating function and an A-filter were used, as it corresponds to the regulations in the EU DIRECTIVE 2003/10/EC.⁷ The free-field microphone was placed beside the pilot near the ear. The AM was placed on a seat just behind the pilot wearing a headset in the same way as the pilot and receives the same signal. The headset was a two-sided supra-aural headphone without active noise attenuation. The middle ear simulator conforms to IEC 60318-4, ANSI 3.25 and ITU-T Rec. P.47. The frequency response and impedance is similar to the real human ear.

Age correction

Presbycusis is the main influence factor in hearing thresholds if the study collective differs widely in age. To analyse other factors it is advisable to eliminate the age factor from the dataset. The success of this procedure depends on the validity of the used age correction tool. The ISO 7029 (2000)⁸ is still valid but a new draft of ISO 7029 (2014) has new correction formulas leading to different results. The usage of age correction tables (examples of database B) in ISO 1999 (2013)⁹ is also not helpful, because the three examples differ more than the two versions of ISO 7029.⁸ The results and their interpretations depend on the decision of which version is used and become arbitrary. In the current study we will demonstrate the difference of both versions of ISO 7029⁸ and renounce on the statistical analysis of age-corrected threshold data. The focus of the paper was placed on individual left–right threshold differences, because they do not require age correction.

Software and statistics

All data were calculated with Excel 2013, in particular the age correction. Simple t-tests were implemented in Excel to get hints for further evaluation. A comprehensive multifactorial analysis of variance (ANOVA) with repeated measures was calculated using SPSS V.20.

RESULTS

Hearing thresholds

The audiometric examinations of jet pilots from a German airline company are presented as average audiograms in age groups, thereby evaluating both ears and the averaged differences between both ears. In **figure 1A**, the averaged thresholds of all pilots in the age groups and both ears are shown and the left–right differences are shown in **figure 1B**. The results are two completely separated curves clearly indicating better hearing for younger pilots. At low frequencies up to 1.5 kHz the curves are parallel with differences between 2 and 4 dB. From 2 kHz up to 14 kHz the differences increase up to about 30 dB. The 16 kHz value in the older group is distorted by missing data caused by the limitations of the audiometer. **Figure 1B** shows small threshold differences ≤ 1 dB between both ears up to 2 kHz. Here, both curves cross the zero level from 'right ear worse' to 'left ear worse' with increasing values. The curve of the younger pilots does not exceed levels

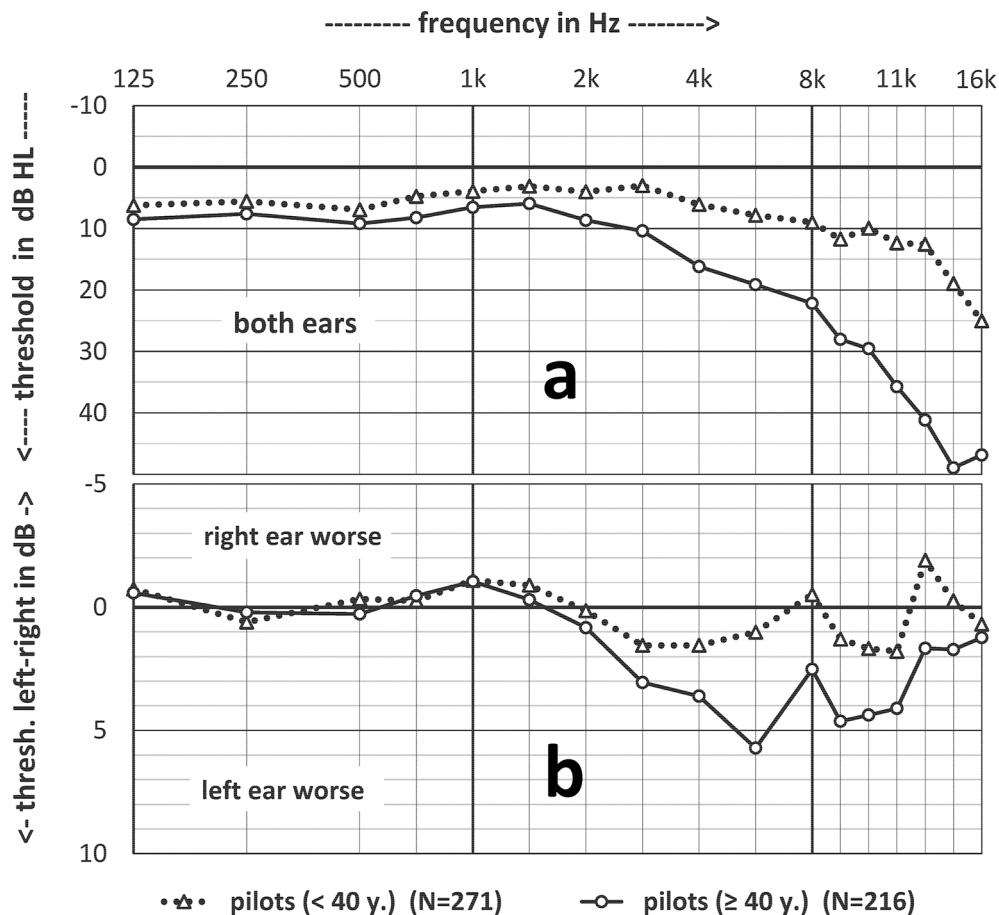


Figure 1 (A) Hearing thresholds of civilian airline pilots in two age groups at both ears averaged from 125 Hz up to 16 kHz. Values are relative to standard ISO 389^{5,6} normal hearing levels (dB HL). (B) The differences between left and right ears in dB.

over ± 2 dB. In the older pilots the threshold difference increases up to 6 dB at 6 kHz. The 8 kHz value seems to be a local minimum in both age groups. In the extended frequency range the differences between right and left ears decrease and approach each other at 16 kHz at about 1 dB.

In table 1 the statistical distribution in the frequencies 3, 4 and 6 kHz is presented in four age groups with a span of 10 years. Six pilots are between 60 and 63 years old and not considered in the distribution.

Age-corrected thresholds

The effect of two different age corrections can be seen in figure 2. The second edition of ISO 7029⁸ is presented in figure 2A and the third draft edition in figure 2B. Frequency range is limited from 125 Hz up to 12.5 kHz, the highest correction proposal in the third draft edition.

Altogether the new version of the ISO 7029 indicates a smaller influence of ageing on hearing thresholds, especially in the frequency range from 3 to 6 kHz where the influence of noise (ISO 1999) is most pronounced. The threshold levels of the younger pilots differed only a little (≤ 2 dB) while in the older pilots the thresholds increased to 3.5 dB at 4 kHz, 6 dB at 4 kHz, 5 dB at 6 kHz and 7 dB at 8 kHz. The better hearing in older pilots in figure 2A

shifts to a worse hearing in figure 2B by different age correcting factors according to ISO 7029.⁸

Cockpit noise and communication sound

For nine jet models of a German airline, free-field noise measurements were carried out in the cockpit¹⁰, which were supplemented by AM measurements. The free-field measurements yielded values between 74 dB(A) for the B767 and 80 dB(A) for B747 jets. The sound pressure levels for communication are higher than the ambient noise for a clear understanding of the messages. These sound pressure levels were measured with an AM under the headset to estimate effects on hearing. In table 2, these measurement data are presented with measurement times and the time portion with communication (air traffic control, ATC) in minutes. In contrast to the uniformly ambient noise the communication signal fluctuates and contains impulsive parts of sound. Therefore, the measurements with time constant 'fast' (125 ms) were supplemented by measurements with the time constant 'impulse' (attack time 35 ms, release time 1.5 s).

The differences between 'impulse' and 'fast' measurements with the AM ($AM_{i_{Ft}} - AM_{Ft}$) are between 5 and 6 dB indicating an impulsive character of the communication sound. With the time period of ATC compared with the

Table 1 Distribution of hearing levels averaged across left and right ears (dB HL) in four age groups

Frequency	Centile	Age (years)			
		20–29	30–39	40–49	50–59
3 kHz	10	-5.0	-2.5	0.0	2.5
	25	0.0	0.0	2.5	7.5
	Median	0.0	2.5	7.5	11.3
	75	5.0	5.0	12.5	17.5
	90	10.0	10.0	20.0	25.8
4 kHz	10	0.0	0.0	3.3	7.5
	25	0.0	2.5	7.5	12.5
	Median	5.0	5.0	12.5	17.5
	75	10.0	10.0	19.4	26.9
	90	17.5	15.0	27.5	35.0
6 kHz	10	0.0	0.0	5.0	7.5
	25	5.0	5.0	10.0	12.5
	Median	10.0	7.5	13.8	21.3
	75	15.0	12.5	22.5	29.4
	90	20.0	17.5	35.0	37.5
n		74	197	133	77

total flight time the equivalent sound exposure of the pilots during communication can be estimated after a spectral correction according to ISO 11904-2.¹¹ This was done in the column AMc_{ATC} . The difference between AMc_{ATC} and the ambient noise (AN_{Ft}) is the signal-to-noise ratio (SNR) for communication. This value varies between minimal 7 dB and maximal 11 dB. The average is about 10 dB.

The free-field measured ambient noise in airline cockpits does not reach the lower exposure action values of 80 dB(A) of the⁷ EU DIRECTIVE 2003/10/EC if the flight time is below 8 hours. The corrected sound pressure levels of communication sound AMc_{ATC} exceed the upper exposure action value of the directive of 85 dB(A) in six cases for flight times of 8 hours and more. The minimum communication sound level was calculated to 83.5 dB(A) in the Airbus A320-200 and the maximum level to 88.1 dB(A) in the Airbus A310-300. Only in intercontinental flights the flight time reaches or exceeds 8 hours.

Statistics

With a multifactorial ANOVA with repeated measures, the left–right differences in the threshold data were statistically evaluated for possible influencing factors (see table 3). In addition to the age group, four other dichotomous factors were selected, which suggests an

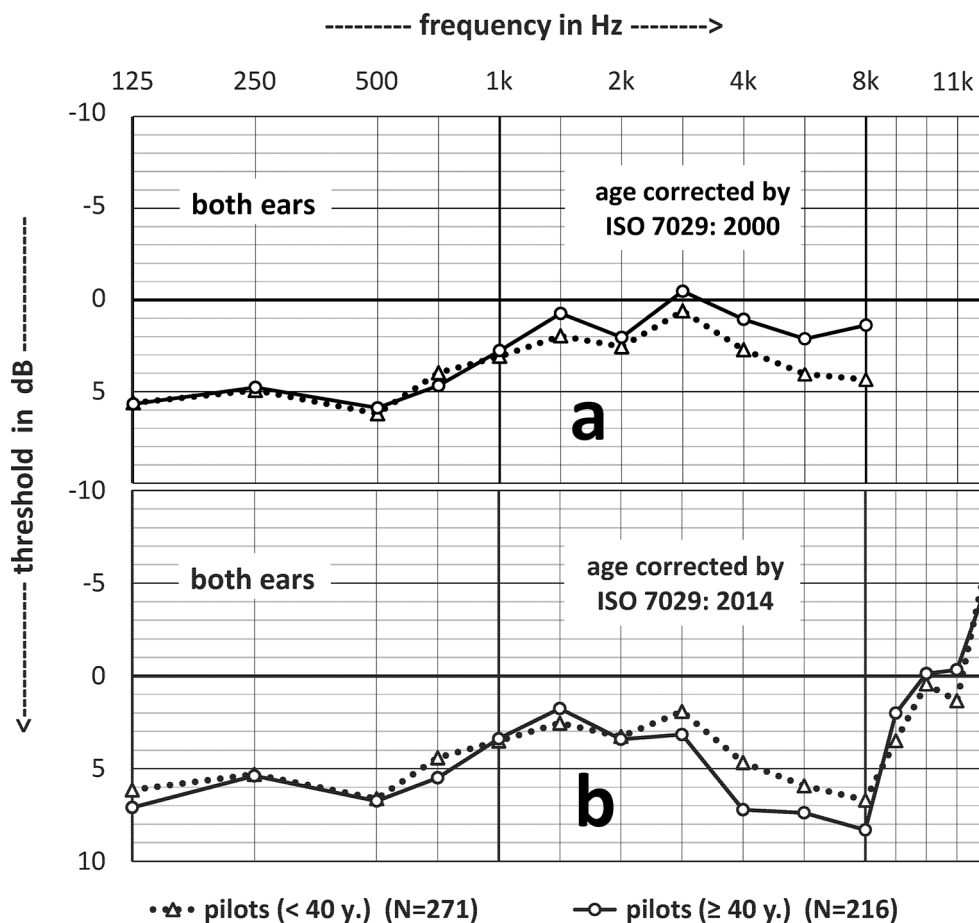


Figure 2 Hearing thresholds of civilian airline pilots in two age groups at both ears. Values are age corrected according to standard ISO 7029⁸ in two editions: second (A) and third draft (B).

Table 2 Sound pressure level measurements in nine different jet cockpits.

Jet data		Sound pressure data					
Type	Flight time (min)	ATC time (min)	AN _{Ft} dB(A)f	AM _{Ft} dB(A)f	AM _{Ft} ⁱ dB(A)i	AM _{ATC} dB(A)f	SNR dB(A)
A310-200	162	70	74.9	81.9	87.9	83.5	8.6
A310-300	460	208	76.7	86.7	92.7	88.1	11.4
B737-200	221	81	76.8	81.4	87.4	83.8	7.0
B737-300	137	28	77.3	80.9	85.9	85.8	8.5
B747	1144	344	79.9	84.8	89.9	88.0	8.1
B757	357	134	75.1	83.7	89.9	86.0	10.9
B767	294	112	74.4	81.6	87.9	83.8	9.4
DC10	116	50	76.8	85.9	91.2	87.6	10.8
MD11	153	73	75.0	84.6	90.3	85.8	10.8

AM, acoustic manikin; AM_{ATC}, spectral-corrected values of AM_{Ft} by ISO 11904-2 and calculated to the ATC time; AN, free-field ambient noise; ATC, air traffic control; dB(A)f, sound pressure level with A-weighting and time constant: fast; dB(A)i, with time constant: impulse; Ft, flight time; SNR, signal-to-noise ratio.

AN_{Ft} measurement data during flight time are presented as well as data from an AM. Measurement data from Hoffmann.¹⁰ AM_{ATC} are calculated values by using the ISO 11904-2 (11) and the ATC time.

impact on the development of noise-induced hearing deteriorations: acoustic shocks, military service, attending discos and the use of hearing protectors at noisy leisure activities. The usage of the headset for communication has three options: right ear, left ear or both ears.

The factor age group shows significant increasing differences between both ears, and the factor headset ear shows a significant effect ($p < 0.001$) on the worse hearing of the left ear.

The within-subjects factor contains the three frequencies 3, 4 and 6 kHz, which have the strongest effect of noise according to ISO 1999⁹ and is significant at $p = 0.02$. Only two-way interactions between frequency and the other main factors were determined. With the exception

of 'frequency×age group' all interactions are not significant and are not listed in table 3.

Headset

The dominant part of noise exposures results from communication sound as seen in table 2. More than half of the pilots ($n = 276$) use the headset on both ears, while the others prefer to use only one ear for radio communication.

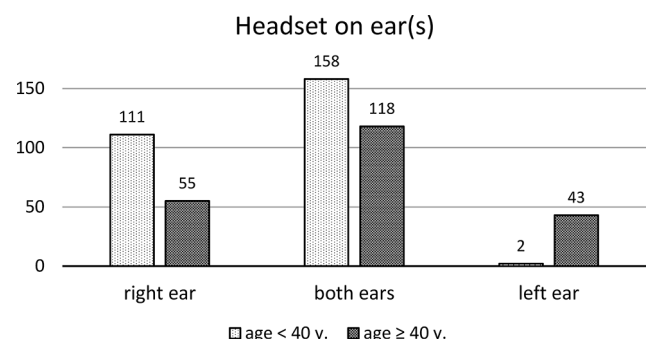
The preferred headset usage in the age groups is presented in figure 3. More than half of the pilots (57%) used both ears for radio communications. About a third (34%) preferred to use only the right ear and 9% only the left ear. The pilots with left ear preference were all captains sitting on the left seat with the right ear free for normal cockpit communication. Forty-three of these captains were older than 40 years and only two of them younger.

In figure 4 the effects of this different behaviour on the threshold differences between the ears are presented. Between pilots with the headset on both ears and the right ear the curves are close together. Only at 4 kHz the difference exceeds 1 dB in the standard frequency range

Table 3 Statistical analysis. Analysis of variance concerning threshold differences (left–right) with six between-groups factors: age group, acoustic shocks, military service, disco visits, use of ear protectors and use of the communication headset.

	df	F	p
<i>Between groups</i>			
Age group	1	8.711	0.003
Acoustic shock	1	1.838	0.160
Military service	1	0.142	0.707
Disco visits	1	0.672	0.413
Ear protection	1	1.654	0.199
Headset Ear	2	8.685	<0.001
<i>Within groups</i>			
Frequency	2	5.473	0.020
Freq×Age group	2	6.111	0.014

Significant factors and interactions (x) are expressed in bold. One within-groups factor is the frequency. Analysed were 3, 4 and 6 kHz, which are predominantly affected by noise.


Figure 3 Age groups and preferred headset usage.

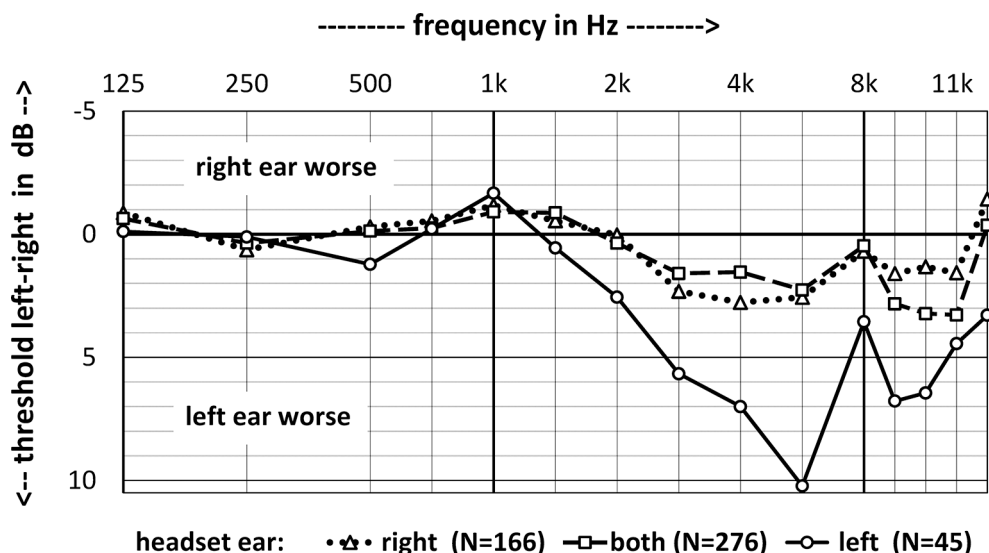


Figure 4 Averaged threshold differences (left ear-right ear) according to the preferred headset usage from 125 Hz up to 12.5 kHz.

up to 8 kHz. The pilots who prefer to use the left ear for communication tasks show a conspicuous worse hearing at the left ear in the analysed frequencies with more than 7 dB at 6 kHz. At 8 kHz the effect is noticeably smaller and increases in the extended high range between 9 and 11 kHz. The 12.5 kHz threshold difference decreases to a value of about 3 dB.

DISCUSSION

As expected, the age of the pilots is the main influence factor on the hearing ability. [Figure 1A](#) shows a clear separation of the two age group curves. At frequencies above 2 kHz the age-dependent differences increase. The course at 14 and 16 kHz is affected by lack of measurements in older pilots by the limited sound pressure level of the audiometer at these frequencies. The threshold differences between left and right ears ([figure 1B](#)) show a clear tendency to worse hearing of the left ear. This tendency is most pronounced at frequencies 3–6 kHz and 9–11 kHz in both age groups and much stronger in the older pilots. At lower frequencies (<3 kHz) the difference values oscillate around the zero line within a ± 1 dB range. At 1 kHz both age groups show better hearing by 1 dB of the left ear and no dependence on age.

Age adjustment in accordance with ISO 7029⁸ should eliminate the age-related effects from the data. [Figure 2](#) shows the results of two versions of ISO 7029.⁸ The second edition in [figure 2A](#) from 2000 shows a stronger dependence of the age than the new draft edition in [figure 2B](#) from 2014. In the case of our dataset we get reverse results in the interesting frequency range 3–6 kHz. Age corrected with the second edition the older pilots hear better and a positive influence of the noise situation would be concluded. With the third edition the younger pilots hear better and we recognise hearing loss. While the third edition represents a draft and the second edition is still

valid we recognise the closer outcomes of our study with the new ISO 7029⁸ version.

In [table 1](#) the distribution of threshold measurements is presented. Compared with the screened dataset of Engdahl *et al*¹² the percentiles of our data are lower on an average of 4.5 dB and the 80% span in our dataset is smaller on an average of 9 dB.

The free-field sound data of Hoffmann¹⁰ [table 2](#) in aircraft cockpits show sound pressure levels between 74 and 80 dB(A). Lindgren *et al*¹ published lower values between 71 and 76 dB(A). Begault¹³ described higher values between 75 dB(A) for the Airbus A310 and 84 dB(A) for the Boeing B727. The ambient noise in cockpits reported by Lower and Bagshaw¹⁴ had levels between 71 and 79 dB(A). The values of Hoffmann¹⁰ are in between this measurement data sets from literature. None of the free-field sound pressure levels of the ambient noise reach the upper exposure action value of 85 dB(A). If we take into account, that noise with impulsive character is more harmful than pure continuous noise, for noise exposure levels by communication the ‘impulse’ weighted exposure levels could be used. In all cases the upper exposure action values then would be reached during communication. As the ATC time is mostly shorter than half of the total flight time and never 8 hours, the higher exposure levels will be compensated approximately by the shorter exposure time. The equivalent exposure levels of our pilots are then around the upper exposure action value of 85 dB(A) in 8 hours.

Gassaway¹⁵ has identified significantly higher values in cockpits of propeller aircraft from an average of 95 dB(A) and strongly recommended the use of hearing protection. Military aircraft are usually even louder. Overall, these measurements are not directly comparable, since the measured aircraft are not the same and certainly also vary in the cockpit design and the measurement set-up.

The noise exposure level caused by the radio communication exceeds the ambient cockpit noise, because the messages have to be understood completely. In tests for speech-in-noise recognition mostly a 50% criterion is used to determine the normal skill.¹⁶ At sound pressure levels of 83 dB SPL Killion *et al.*¹⁷ found a word recognition score of 50% at a corresponding SNR of about 2 dB. Pilots need full understanding of the messages at much higher SNR values. The largely standardised communication in aviation has a high redundancy in the transferred messages, which reduces the required SNRs. In the current study the average SNR used by the pilots was at 10 dB, obviously enough for a recognition rate of about 100%. Lower and Bagshaw¹⁴ measured spectral-corrected sound levels for communication between 80 and 88 dB(A). Compared with the corresponding ambient noise levels SNR values between 6 and 13 dB(A) can be calculated with an average of about 10 dB(A) like in our dataset.

Circumaural headsets with passive sound attenuation can be helpful to reduce the communication sound levels, but they impede the communication between the crew as the attenuation at high frequencies is much better than at low frequencies in those earphones. Headsets with active noise reduction systems are now commonly installed, which reduces predominantly the masking low-frequency noise of the cockpit.^{18 19} The sound pressure level of the radio communication can substantially be reduced to a level below the lower exposure action value of 80 dB(A). The pilots of the current study did not use any hearing protection systems. The protective effect depends on wearing the headset on both ears. Open headsets with low frequency noise reduction may allow communication between captain and flight officer as the masking effects are reduced.

A total of 211 of the 487 pilots had a preference to use the communications headset mostly on only one ear. This subgroup is suited to analyse the effect of radio communication on hearing. A total of 166 pilots preferred the right ear, 45 pilots the left ear and 276 used both ears. Figure 4 shows significant differences between these groups. The differences between pilots who use both ears and predominantly the right ear for communication are quite small (max. at 4 kHz 1.3 dB). The left ear, however, shows significant greater differences with more than 7 dB at 6 kHz. In table 1 this fact can be seen as the strongest effect of the ANOVA for headset usage with $p < 0.001$. With the exception of two pilots all of these pilots are in the older age group. This asymmetry can be recognised in figure 1B in the older age group to a lesser degree as in figure 4 where the subgroup with left ear preference is particularly striking.

The right ear seems to be more resistant against the effects of noise than the left ear, because the pilots with headset at the right ear almost do not differ significantly from those with headset at both ears. Left-right ear threshold asymmetries are described by Pirilä *et al.*³ In the frequency range between 3 and 6 kHz these authors found higher thresholds on the left ear and concluded a greater susceptibility to noise-induced hearing loss of the left ear as a biological effect. Influences like handedness and the audiometric

test procedure with learning and fatigue effects could be excluded.²⁰⁻²² This effect was also present in females to a lesser degree, because they are in general less exposed to noise. The higher left-right differences in Cruickshanks *et al.*⁴ may result from not excluding the users of firearms from their dataset.

The pilot group who used both ears for communication tasks show no increased damaging effect at the left ear, although both ears had the same sound exposure level. A possible explanation of this result could be the advantage of the binaural hearing²³ with the squelch-effect (summation of interesting sound and unmasking of the noise) what leads to reduced communication sound levels at a given ambient noise.

Based on the present findings, it can be concluded that the pilots of civil aviation have a good hearing ability compared with other industrial workers with comparable noise exposure levels. The left ear shows markedly higher risk of hearing damage than the right ear. If this effect is age dependent, it cannot clearly be answered with the current dataset based on the cross-sectional design of the study without the development of hearing loss in the individuals. The use of headsets with active or passive noise reduction at both ears can solve this last problem and may eliminate any risk for hearing loss in pilots during their normal occupational activity. It may also be helpful to advise pilots to use both ears for communication over headset.

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Contributors RM: administrative support; provision of study materials and patients; collection and assembly of data. RM, JS: Conception and design; data analysis and interpretation; manuscript writing; final approval of manuscript.

Competing interests None declared.

Ethics approval The data collection in this non-interventional study was part of the annual health check-up's within the German occupational safety and health system (health check for pilots enforced by law). As individuals participated voluntarily in the study and all data were analysed anonymously, no ethical approval was required, in accordance with German guidelines.

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Data sharing statement No additional data available.

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