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Occupational noise and vibration risks for go-kart instructors in a dynamic track environment

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This study evaluates occupational noise and vibration exposure among nine male go-kart instructors (mean age 25.7 years, mean work experience 6.3 years; 2–12 years) using objective measurements, predictive modelling, and subjective hearing assessments. Daily noise exposure ($L_{EX,8\,h}$) ranged from 75.8 dB to 82.3 dB, with peak levels reaching 109.3 dB. Regression analysis showed that operating more than nine go-karts simultaneously could exceed the 85 dB regulatory threshold, predicting noise levels up to 92.7 dB at full capacity. Whole-body vibration (WBV) exceeded short-term exposure limits in two of four cases (max 3.26 m/s²), while hand-arm vibration (HAV) surpassed limits in three cases, reaching 14.23 m/s². The average score on the Amsterdam Inventory for Auditory Disability and Handicap (AIADH) was 68.1, indicating mild perceived hearing difficulties. Strong negative correlations were found between AIADH scores and both age and work experience. Our findings reveal hidden risks in this recreational occupational setting and underscore the need for more nuanced exposure assessment and preventive measures in non-industrial sectors.

Keywords Occupational noise, Mechanical vibration, Motorsports safety, Occupational risk assessment, Risk of hearing loss

Occupational exposure to noise and mechanical vibration has been extensively studied in various industrial contexts, including mining, construction, and manufacturing[1,2]. In contrast, dynamic non-industrial environments, especially those in the expanding recreational motorsports sector, are often neglected in occupational health frameworks despite similar physical risks. Go-karting, a worldwide popular activity involving small combustion-engine vehicles, creates settings characterised by high-intensity noise and mechanical vibrations. Instructors working at go-karting tracks are constantly exposed to these stressors while supervising races, assisting participants, and maintaining vehicles.

While regulatory thresholds exist (85 dB $L_{Aeq,8\,h}$ for noise, 0.5 m/s² for whole-body vibration (WBV), and 2.5 m/s² for hand-arm vibration (HAV))[3,4], they are primarily applied in heavy industry and rarely enforced in leisure-based occupations. Notably, occupations such as go-kart instructors are not listed in formal risk registers in many countries, including Poland. As a result, systematic environmental monitoring and preventive health measures are seldom implemented. However, measurements from similar environments have recorded A-weighted equivalent continuous noise levels of around 100 dB(A) and mechanical vibrations exceeding the hygienic thresholds defined by ISO and European directives[5]. In peer-reviewed studies, measured A-weighted equivalent continuous noise levels at karting tracks frequently approach or exceed 100 dBA, paralleling or surpassing exposures documented in industrial environments such as metal manufacturing, construction sites, or professional driving roles[6]. For instance, ambient noise levels at outdoor karting circuits and stock car races have been reported at 90–125 dBA, with even higher peak values during acceleration and braking events. Furthermore, occupational vibration exposure among karting instructors has, in specific cases, exceeded short-term limits and approached levels associated with adverse musculoskeletal and neurovascular outcomes observed among professional drivers and taxi operators[7]. These parallels underscore the substantial overlap in risk profiles between recreational motorsports and more traditionally regulated industrial sectors, calling for improved monitoring and focused prevention strategies within leisure environments.

Exposure to high-kurtosis noise, characterised by transient acoustic peaks, is particularly problematic in go-karting. Standard energy-based metrics like L_{Aeq} or $L_{EX,8\,h}$ fail to account for the additional damage caused by such impulsive noise, which has been linked to greater cochlear injury at equivalent average levels. Simultaneously, mechanical vibration from vehicles lacking suspension systems can increase the risk of musculoskeletal disorders and neurovascular dysfunction[8]. Combined exposure to noise and vibration is known

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to exacerbate physiological stress and cognitive fatigue, particularly in roles that require sustained alertness and rapid response[9].

Despite these risks, few if any studies have comprehensively assessed both the physical exposures and health perceptions of go-karting staff. Existing research has primarily focused on motorsport participants or industrial operators, leaving a gap in our understanding of risk in hybrid recreational/occupational environments. Moreover, subjective health complaints, such as tinnitus, difficulty understanding speech in noise, or fatigue, may appear before clinical thresholds are crossed, underscoring the need for integrative approaches that include both objective and self-reported data.

Aim and scope. This pilot study quantifies task-level and daily noise and vibration exposures among go-kart instructors and estimates when predicted $L_{EX,8\,h}$ would exceed 85 dB as the number of active karts increases. Using ISO-1999 projections, susceptibility percentiles for speech-range thresholds (2–4 kHz) across age and tenure scenarios were reported to contextualise risk in this understudied recreational workforce. These preliminary data are intended to guide larger, multi-site studies.

Methods

General characteristics of the study population

The study was conducted at a professional go-kart track located in Wroclaw, Poland. Measurements were performed during regular operation hours in late autumn 2024. The facility includes an outdoor go-karting circuit with adjacent indoor facilities (training room, garage, reception), where instructors perform duties under variable environmental conditions. The test population consisted of nine male go-kart instructors, aged 20 to 33 years (mean age: 25.7), with overall work experience ranging from 2 to 12 years. Their tenure specifically at the go-karting track ranged from 2 months to 9 years. All participants voluntarily participated in the measurements and subjective assessments.

The daily schedule of instructors was categorised into six major task blocks, based on direct observation and interviews with management. These tasks were:

Preparatory and closing activities (30 min)

Tasks include technical inspections of go-karts, such as checking tyres, brakes, pedals, steering, and throttle cables to ensure safety and optimal performance. Instructors also manage refuelling operations and perform post-race vehicle checks, including repositioning tyres and conducting safety verifications before closing the track. These activities ensure karts are race-ready and facilities are secure.

Safety training in the classroom (60 min)

Instructors conduct comprehensive safety briefings covering track rules, behaviour expectations, and emergency procedures. Sessions include detailed explanations of kart controls, proper use of protective gear, and racing etiquette. To reinforce learning, instructors use safety videos that demonstrate correct practices and common hazards, providing visual and auditory cues that enhance participants' understanding and retention.

Pre-race participant check (15 min)

Performing individual safety checks, including seat adjustments, helmet fittings, and ensuring proper fastening of seatbelts and safety harnesses. Instructors verify that participants are medically and physically fit to race and brief them on track etiquette and emergency procedures.

On-track supervision during races (315 min)

Actively monitoring races from various trackside stations, instructors oversee race conduct, ensure compliance with rules, and intervene in incidents or unsafe behaviours. They issue warnings, enforce penalties, and coordinate emergency responses as needed.

Minor vehicle maintenance (30 min)

Handling routine maintenance and minor repairs such as tightening components, adjusting mechanical settings, and transporting karts requiring servicing to the repair area. This includes troubleshooting minor mechanical issues that arise during racing activities to minimise downtime.

Breaks (30 min)

Each task was assigned an estimated duration, resulting in a 480-minute (8-hour) working day. Ambient environmental conditions during measurements were relatively stable across all workstations. The average air temperature was approximately 8 °C, with moderate humidity levels (~ 70%) and slight air movement (~ 0.5 m/s). WBGT values ranged from 5.2 to 7.1, indicating cool thermal conditions. These factors did not significantly interfere with sensor function but may have contributed to worker discomfort during prolonged outdoor tasks.

Noise and vibration measurements

Using the task-based measurement approach, noise exposure was assessed at five instructor workstations in line with ISO 9612:2009[10]. Measurements were conducted using a Svantek SV 971 A Class 1 sound level meter, calibrated before and after each session. The microphone was positioned 10 cm from the ear most exposed to noise. Task-level $L_{Aeq,\,T}$, L_{Amax}, and L_{Cpeak} were recorded at five instructor workstations. For each task, ≥ 3 × 300-s samples were collected (and took additional samples when within-task spread exceeded 3 dB). Values are reported as estimates ± expanded measurement uncertainty U in accordance with ISO 9612 (coverage factor k = 2 ≈ 95% coverage); U is a metrological quantity and not a statistical confidence interval[10].

Mechanical vibration exposure was assessed according to ISO 2631-1:1997[11] (for whole-body vibration, WBV) and ISO 5349-2:2001[12] (for hand-arm vibration, HAV), using Svantek SV 100 A and SV 103 dosimeters, respectively. Measuring instrumentation met the performance and tolerance requirements of ISO 8041-1:2017[13], with verification and in-situ checks as specified. The vibration standards do not require reporting an expanded measurement uncertainty per result (unlike ISO 9612 for noise). For vibration measurements, each instructor underwent five standardised sessions lasting 180 s each. Both setups were designed to capture realistic exposure during typical track activities. WBV measurements were taken by mounting a triaxial accelerometer on the go-kart seat during simulated driving. HAV was assessed using a triaxial accelerometer attached to the palm of the instructor's dominant hand while gripping the steering wheel. Measurements were conducted for four different go-karts, each operated by a different instructor, to capture variation in equipment and working conditions.

For WBV, frequency-weighted root mean square (RMS) accelerations were recorded in three orthogonal axes: X (fore-aft), Y (side-to-side), and Z (vertical). In line with ISO 2631-1:1997[11] and Polish guidelines for seated posture, the final vibration value was determined using the dominant axis method, incorporating directional sensitivity:

$$a = \max\,\{1.4 \cdot\ a_{wx},\ 1{,}4 \cdot\ a_{wy}, a_{wz}\}$$

Frequency-weighted RMS accelerations were calculated for vibration exposures; however, the analysis did not incorporate cumulative daily exposure time as a continuous factor, nor did it compute daily vibration dose. Since total daily exposure did not exceed 30 min, exposures were directly compared with the short-term exposure limits defined in the Polish hygiene standards (3.2 m/s² for WBV and 11.2 m/s² for HAV)[14]. This approach aligns with applicable short-term regulatory exposure limits for daily durations of less than 30 min. Still, it limits the assessment of chronic, long-term vibration-related health risks because it lacks cumulative dose calculations. Future studies with full-shift monitoring and dose-based analyses are warranted.

Additionally, meteorological data (including temperature, humidity, wet bulb globe temperature (WBGT), and air movement) were recorded using a Kestrel 5000 anemometer.

An occupational risk assessment for exposure to noise and mechanical vibration was conducted in accordance with the Polish standard[15]. The selected method evaluates risk based on two parameters: the probability of occurrence and the severity of potential consequences. Based on this assessment, the risk level was categorised as low, medium, or high, in line with the criteria defined in the standard.

Risk assessment of hearing loss

To estimate the long-term risk of NIHL, calculations were performed using the ISO 1999:2013 methodology[16]. This standard allows for the prediction of permanent threshold shift (PTS) based on several factors, including the daily noise exposure level ($L_{EX,8\,h}$), the duration of exposure in years, the expected hearing loss at specific frequencies (0.5, 1, 2, 3, 4, and 6 kHz), and the age and sex of the worker. A validated calculation tool developed by the Institut für Arbeitsschutz (IFA)[17] was used to simulate hearing-loss scenarios for instructors aged 25–60, assuming exposure durations of 5–40 years in the same occupation. The risk of hearing loss was calculated as the average threshold at 2, 3, and 4 kHz, where hearing impairment due to noise is most noticeable and where early signs of NIHL typically appear[18]. ISO 1999 provides percentiles P10, P50, and P90 that represent variability in susceptibility within the population: P10 corresponds to the most susceptible 10%, P50 is the median hearing loss, and P90 corresponds to the least vulnerable 90%. These percentiles enable estimation of both average and individual differences in hearing loss risk, supporting a comprehensive assessment. The classification of hearing impairment in this study was based on the World Health Organisation (WHO) system, which categorises hearing loss severity. The WHO classification defines hearing impairment as normal (≤ 20 dB HL), mild (21–34 dB HL), moderate (35–49 dB HL), moderately severe (50–64 dB HL), severe (65–79 dB HL), and profound (≥ 80 dB HL)[19]. This standardised framework facilitates consistent classification of hearing loss severity for research and clinical assessment purposes.

Subjective hearing assessment

AIADH was used to assess subjective hearing difficulties[20]. This self-report questionnaire includes 30 items across five domains, which were interpreted by the authors as five basic auditory functions: (i) sound discrimination, (ii) sound localisation, (iii) understanding speech in noise, (iv) understanding speech in quiet, and (v) sound detection. Respondents were asked to indicate how often they were able to hear effectively in each of the described situations. They chose from four response options: "almost never", "occasionally", "frequently", and "almost always." Each response was assigned a score from 0 to 3, with higher scores reflecting fewer perceived hearing difficulties. Following the original scoring protocol, two items (Questions 18 and 30) were excluded from the total and domain score calculations. This results in 28 scored items, yielding a maximum total score of 84 points. Higher values indicate better self-assessed hearing function. While the AIADH does not specify standardised cut-off points, commonly used interpretive thresholds suggest the following: scores ≥ 76 reflect normal or near-normal auditory function, scores between 60 and 75 suggest mild perceived hearing difficulties, and scores < 60 may indicate moderate to severe perceived handicap. These thresholds should be considered indicative rather than diagnostic, providing a useful framework for classifying functional hearing status in everyday life contexts[21,22]. These categories help classify the degree of subjective hearing limitations in everyday life. In addition to the total score, results were also calculated for each of the five domains:

1. Sound discrimination (8 items, maximum 24 points).
2. Sound localisation (5 items, maximum 15 points).
3. Understanding speech in noise (5 items, maximum 15 points).

Workstation No	GK, number	$L_{EX,8\,h}$ ± U [dB]	L_{Amax} ± U [dB]	L_{Cpeak} ± U [dB]	Exceedance coefficient (k)
1	5	80.7 ± 2.0	90.6 ± 2.0	109.3 ± 2.0	0.37
2	2	76.3 ± 2.1	87.5 ± 2.0	105.8 ± 2.0	0.13
3	2	75.8 ± 2.0	85.6 ± 2.0	103.2 ± 2.0	0.12
4	3	78.7 ± 2.0	89.3 ± 2.0	106.1 ± 2.0	0.23
5	7	82.3 ± 2.0	89.6 ± 2.0	106.7 ± 2.0	0.53

Table 1. Summary of noise exposure by workstation. Note. Values are reported as estimates ± expanded measurement uncertainty U in accordance with ISO 9612 (coverage factor k = 2, ≈ 95% coverage). These are not standard deviations and should not be interpreted as statistical confidence intervals. Abbreviations: GK – the number of go-karts operating simultaneously.

GK number	Predicted noise level ($L_{EX,8\,h}$) [dB]	95% CI for mean [dB]	95% PI for single observation [dB]
8	84.0	[81.4, 86.7]	[80.4, 87.6]
9	85.25	[82.1, 88.4]	[81.2, 89.3]
10	86.5	[82.8, 90.2]	[82.0, 91.0]
11	87.74	[83.5, 92.0]	[82.8, 92.7]
12	88.99	[84.2, 93.8]	[83.6, 94.4]
13	90.24	[84.9, 95.7]	[84.3, 96.2]
14	91.49	[85.5, 97.5]	[85.1, 97.9]
15	92.74	[86.2, 99.3]	[85.8, 99.7]

Table 2. Predicted noise level depending on the number of go-karts.

4. Understanding speech in quiet (5 items, maximum 15 points).
5. Sound detection (5 items, maximum 15 points).

Each domain score was calculated by summing the points from the relevant items. Higher domain scores indicate better perceived function in the specific auditory area. This domain-level analysis enables the identification of functional hearing deficits in particular contexts and supports a more nuanced understanding of individual auditory performance beyond the global score.

Statistical analysis

Data were analysed using standard statistical procedures. Continuous variables are summarised as mean ± SD; categorical variables as n (%). Acoustic values in Table 1 are reported as the estimate ± expanded measurement uncertainty U in accordance with ISO 9612 (k = 2 ≈ 95% coverage); U is a metrological quantity and not a statistical confidence interval. The relation between activity and noise was evaluated using a simple ordinary least squares (OLS) model at the workstation-mean level ($n = 5$): LEX,8 h = a + b x (number of go-karts). Reported metrics include the slope b (dB/kart), intercept, R^2, two-tailed p-value, and 95% confidence intervals (CIs) from the t distribution. For forecasts (Table 2), both 95% CIs for the mean prediction and 95% prediction intervals (PIs) for a single observation were computed using standard OLS formulas. Subjective hearing outcomes were displayed as box plots with individual points for each AIADH domain. Associations with the AIADH Total score were assessed using Spearman's rank correlation coefficient (ρ) for bivariate relationships (Age, overall work experience) and partial Spearman correlation for Age adjusted for overall and instructor-specific experience (rank residualisation of both variables on the covariates followed by Pearson correlation of residuals). For these correlations, effect sizes (ρ) with two-tailed p-values and 95% confidence intervals based on the Fisher z transformation are reported. In addition, a concise OLS model of AIADH Total on Age is presented, reporting the unstandardised slope b with 95% CI and the standardised coefficient (β_std) (shown without CI to avoid mixing effect types). The internal consistency of the AIADH Total score (treating the five domain sums as items) was assessed using Cronbach's α (α = 0.95, $n = 9$). All analyses and figures were prepared in Microsoft Excel 365; statistical formulas follow standard references (t-based confidence intervals and OLS prediction formulas). The study was conducted in accordance with the Declaration of Helsinki and received approval from the Ethics Committee of Wroclaw University of Science and Technology. Informed consent was obtained from each participant. All data were anonymised before analysis.

Results

The daily routine of a go-kart instructor consists of short, repetitive tasks, described in the Methodological Section. Work schedules vary by contract type and day of the week. Instructors employed on fixed contracts typically work 8-hour shifts, while freelance staff may work 10 to 12 h, especially on weekends. Shifts start at 14:00 (Monday–Thursday), noon (Friday), and 10:00 on weekends, ending at 22:00 each day.

Noise exposure

Measurements conducted at five instructor workstations revealed equivalent A-weighted sound levels ($L_{Aeq,\,T}$) ranging from 75.8 dB to 82.3 dB, depending on task type and proximity to active go-karts. The calculated daily noise exposure levels ($L_{EX,\,8\,h}$) are summarised in Table 1, ranging from 75.8 dB to 82.3 dB. The highest daily exposure level ($L_{EX,8\,h}$) was recorded at workstation 5, with a value of 82.3 dB, corresponding to a risk coefficient k = 0.97, just below the Polish occupational limit of 85 dB. Peak levels (L_{Cpeak}) reached up to 109.3 dB, particularly during go-kart acceleration and skidding events. Although none of the instructors exceeded the permissible $L_{EX,8\,h}$ threshold, several tasks involved brief exposure to high-intensity noise, suggesting a potential risk of cumulative hearing fatigue.

Regardless of the workstation where noise measurements were taken, none of the recorded values exceeded the permissible exposure limits set by Polish occupational health and safety standards. However, at workstation 5, the risk coefficient exceeded 0.5, indicating a moderate yet acceptable level of risk. It is important to note that the number of go-karts on the track varied during measurements due to changes in participant groups. As a result, noise levels should not be interpreted as being strictly linked to a specific workstation but rather to the number of go-karts operating simultaneously.

To quantify the impact of the number of go-karts operating simultaneously on the noise exposure of track personnel, a linear regression analysis was conducted. The number of go-karts was used as the independent variable, while the daily noise exposure level ($L_{EX,8\,h}$) was the dependent variable. The data showed a clear linear relationship, with the regression Eq. (1):

$$L_{ex,8h} = 1.25 \bullet \left(EquationNumber\ of\ go-karts\right) + 74.02 \tag{1}$$

Coefficients shown in the equation are rounded for readability. A linear regression of $L_{EX,8\,h,}$ against the number of simultaneously operating go-karts yielded a slope of 1.249 dB per go-kart (95% CI 0.68–1.82, $p = 0.006$); an intercept of 74.018 dB (95% CI: 71.57–76.45 dB). This model demonstrated a strong fit, as indicated by $R^2 = 0.93$ (see Fig. 1). Analysis of residuals did not reveal any significant violations of the linearity or homoscedasticity assumptions. However, further research should explore potential nonlinear saturation effects at higher go-kart numbers. Because decibels add logarithmically, an approximately linear dB-per-kart slope is consistent with multiplicative source additions at these counts; mild nonlinearity could emerge at higher counts due to shielding/geometry and should be checked with more sites.

As shown, the daily noise exposure level ($L_{EX,\,8\,h}$) would exceed the occupational limit of 85 dB when more than nine go-karts are operating on the track simultaneously. At the maximum observed operational capacity of 15 go-karts, the predicted $L_{EX,8\,h}$ reaches approximately 92.74 dB, clearly surpassing the regulatory threshold (Table 2).

Table 2 lists 95% CIs for the mean and 95% PIs for single-day observations. These findings highlight the significant influence of the number of go-karts on occupational noise exposure and underscore the importance of controlling the number of vehicles in operation to manage noise risks effectively.

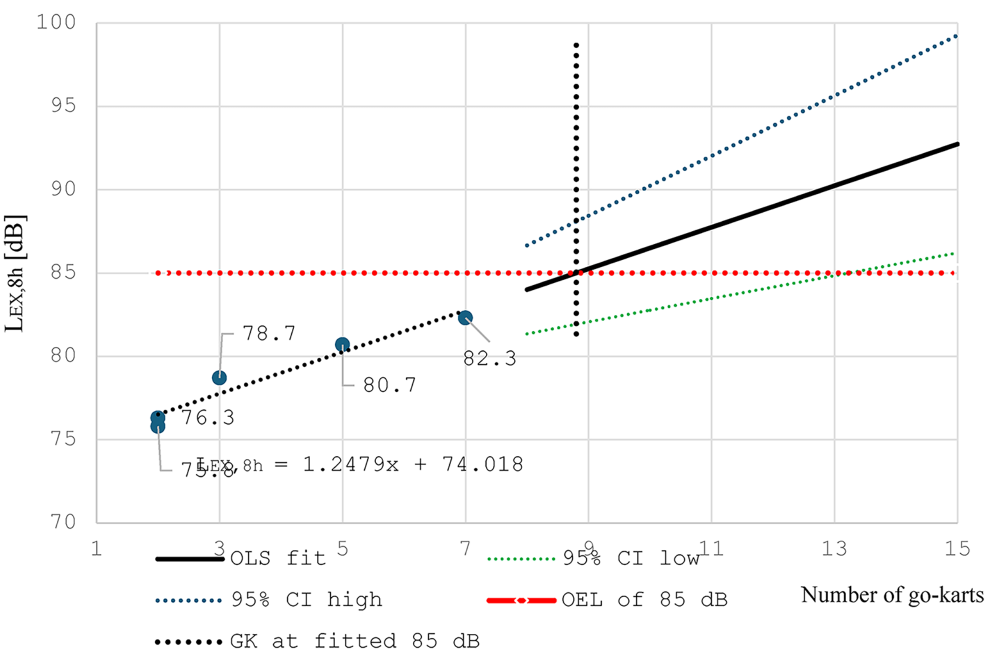

Fig. 1. Actual and predicted noise level ($L_{EX,8\,h}$ [dB]) vs. the number of go-karts simultaneously operating on the track.

Workstation No.	Dominant RMS acceleration [m/s^2]	Exceedance coefficient, k	Risk level	Assessment
1	3.26	1.02	High	Unacceptable
2	3.26	1.02	High	Unacceptable
3	2.48	0.78	Medium	Acceptable
4	2.97	0.93	Medium	Acceptable

Table 3. Evaluation of whole-body vibration exposure and occupational risk level based on exceedance coefficients. Note. Instruments complied with ISO 8041-1; measurements and evaluation followed ISO 2631-1. The vibration standards do not prescribe expanded uncertainty (U) per value; results are therefore presented without "±U".

Workstation No.	Daily exposure level [m/s^2]	Exceedance coefficient, k	Risk level	Assessment
1	14.23	1.27	High	Unacceptable
2	12.48	1.11	High	Unacceptable
3	9.22	0.82	Medium	Acceptable
4	11.99	1.07	High	Unacceptable

Table 4. Evaluation of hand-arm vibration exposure and occupational risk level based on exceedance coefficients. Note. Instruments complied with ISO 8041-1; measurements and evaluation followed ISO 5349-2. The vibration standards do not prescribe expanded uncertainty (U) per value; results are therefore presented without "±U".

Exposure to whole-body and hand-arm vibration

Table 3 presents the evaluation of occupational risk associated with WBV exposure at four go-kart instructor workstations. Workplace 1 and 2 both registered dominant RMS values just above the 3.2 m/s^2 short-term limit for WBV, resulting in $k \approx 1.02$ and classification as high risk/unacceptable. Workplaces 3 and 4 remained below the threshold ($k = 0.78$ and 0.93), classified as medium risk/acceptable.

The HAV exposure results are summarised in Table 4. Daily HAV exposure levels ranged from 9.22 to 14.23 m/s^2, with higher values recorded at workstations 1, 2, and 4 exceeding the Polish short-term exposure limit of 11.2 ms^2. These exceedances indicate significant occupational risk levels at these workplaces. In contrast, workplace 3 exhibited lower HAV exposure, remaining below the limit, suggesting a medium risk level.

Risk of hearing loss among the studied participants

Measured and predicted daily noise exposure ($L_{EX,\ 8\ h}$) from the regression model was used to calculate the pure-tone average (PTA) according to ISO 1999:2013. For each scenario of workers' age and exposure duration, the percentiles of the PTA (2, 3, and 4 kHz). Table 5 presents predicted percentiles (P10, P50, P90) of speech-hearing-loss thresholds depending on the number of go-karts, daily noise exposure level, and scenarios of age/years of experience.

For a lower number of go-karts and shorter exposure durations, most results remain in the normal or mild categories. As a go-kart number, noise exposure level, age and work experience increase, more results transition to moderate or moderately severe HL. P10 values indicate the HL for the most susceptible segment of the population. As can be seen, this group of workers begins to cross "mild HL" in mid-career, even at levels below 85 dB. This more susceptible tail is predicted to exhibit clinically meaningful speech-range loss that worsens with longer tenure and higher exposure levels. For the median worker (P50), the expected speech-frequency PTA_{234} remains within the normal range at younger ages and increases gradually with both age and noise exposure. At $L_{EX,8\ h} \approx 84–85$ dB (go-karts number 8–9), the median PTA_{234} is approximately 8–12 dB at 40–45 years, rising to about 15–19 dB at 50–55 years. At $L_{EX,8\ h} \approx 87.7$ dB (11 go-karts), the median reaches ~ 18 dB at age 50 with 30 years of experience, ~ 22 dB at 55/35, and ~ 26 dB at 60/40, consistent with mild hearing loss. By contrast, the resistant subgroup (P90) shows minimal predicted change—often near 0 dB in early career—rising by only a few decibels at older ages even under higher exposures.

Subjective hearing assessment

The results of the Amsterdam Inventory for Auditory Disability and Handicap (AIADH) indicated an average subjective hearing score of 68.1 among go-karting instructors (range: 55–83). While most participants scored in the mild difficulty range, individual results varied. Associations between the AIADH total score and age/experience were analysed using bivariate Spearman correlations with bootstrap 95% confidence intervals, partial Spearman correlations adjusting for the other experience measures, and standardised OLS (HC3); results are summarised in Table 6.

Internal consistency for the AIADH Total score was $\alpha = 0.95$ ($n = 9$), indicating excellent reliability of the composite. To better understand which auditory functions were most affected, a more detailed analysis of each domain was provided. As shown in Fig. 2, the highest scores were observed in the "sound discrimination" domain (median 20; mean 19.6, 95% CI 17.3–21.8), indicating that instructors generally experienced few difficulties in

GK number	$L_{EX,8h}$ [dB]	Percentile	Scenarios of age/years of experience							
			25/5	30/10	35/15	40/20	45/25	50/30	55/35	60/40
3	78.7	P10	11.3	13.0	15.3	19.3	23.3	29.0	35.0	42.3
		P50	0.3	2.0	3.3	5.7	8.7	12.0	16.3	20.3
		P90	-7.7	-7.0	-4.0	-5.0	-3.3	-1.3	1.0	3.0
5	80.7	P10	11.7	13.7	16.0	20.0	24.0	29.7	35.7	43.0
		P50	1.0	2.3	4.0	6.0	9.0	12.7	16.7	21.0
		P90	-7.3	-6.7	-5.6	-4.3	-3.0	-0.7	1.3	3.7
7	82.3	P10	12.0	14.3	17.0	20.7	25.0	30.7	36.7	43.7
		P50	1.7	3.0	4.7	7.3	10.0	13.0	17.3	22.0
		P90	-7.0	-6.0	-5.0	-3.7	-2.0	0.0	2.0	4.7
8	84.0	P10	13.7	15.7	18.3	22.3	26.3	31.7	38.3	44.7
		P50	2.3	3.7	6.0	8.0	11.0	14.7	18.3	22.7
		P90	-7.0	-6.0	-4.3	-3.0	-0.3	0.7	2.7	5.7
9	85.25	P10	14.3	16.7	20.0	23.3	28.0	33.3	39.0	46.0
		P50	3.0	5.0	6.7	9.3	11.7	15.7	19.3	24.0
		P90	-6.7	-5.3	-4.0	-2.3	0.7	1.3	3.7	6.3
10	86.5	P10	15.3	18.0	21.0	24.7	29.3	34.7	40.3	47.0
		P50	3.7	5.7	7.7	10.3	13.3	16.3	20.7	25.3
		P90	-6.3	-5.0	-3.3	-1.7	0.7	2.3	4.3	7.3
11	87.74	P10	16.3	19.7	22.7	26.7	31.3	36.3	42.3	48.7
		P50	4.3	6.3	9.0	11.3	14.3	18.0	22.0	26.3
		P90	-6.3	-4.3	-2.7	0.7	1.3	3.3	5.7	8.3
12	88.99	P10	18.0	21.3	24.3	28.3	33.0	38.0	44.0	50.0
		P50	5.3	7.7	10.3	13.0	16.0	19.3	23.3	28.0
		P90	-5.7	-3.7	-1.7	0.3	2.3	4.3	7.0	10.0
13	90.24	P10	19.3	23.0	27.0	31.0	35.0	40.3	46.0	52.3
		P50	6.0	9.0	11.7	14.7	17.7	21.0	25.0	29.7
		P90	-5.7	-3.0	-0.7	1.3	3.7	6.0	8.7	11.0
14	91.49	P10	21.0	25.3	29.0	33.3	37.7	42.7	48.3	54.3
		P50	7.0	10.7	13.3	16.3	19.7	23.0	27.0	31.7
		P90	-5.3	-2.3	0.3	2.7	5.0	7.7	10.0	12.7
15	92.74	P10	23.0	27.3	31.3	37.0	40.3	45.0	50.7	56.7
		P50	8.3	12.0	15.0	18.3	21.3	25.0	29.0	33.3
		P90	-4.7	-1.7	1.3	4.0	6.7	9.0	11.7	14.3

Table 5. Predicted speech-hearing-loss percentiles of the averaged air-conduction thresholds at 2, 3, and 4 kHz (PTA_{234}), depending on noise exposure ($L_{EX,8\,h}$) and age.Cells are colour-coded by predicted $PTAL_{234}$ severity band: green = ≤20 dB HL (within normal limits), yellow = 21- 34 dB HL (mild hearing loss), red = 35-49 dB HL (moderate HL), and purple = 50-64 dB HL (moderately severe HL). GK number denotes the number of go-karts operating simultaneously, which determines the corresponding $L_{EX,8\,h}$ exposure shown in the left column.

Analysis	Predictor	Effect	95% CI	p (two-tailed)
Bivariate Spearman	Age	$p = -0.83$	[-0.96, -0.37]	0.005
Bivariate Spearman	WorkExp (overall)	$p = -0.60$	[-0.90, 0.11]	0.088
Partial Spearman (covariates)	Age/WorkExp, GkExp	p = -0.47	[-0.87, 0.28]	0.204
OLS (HC3)	Age	b = -1.28	[-3.12, 0.56]	0.13
		βstd = -0.63	-	0.13

Table 6. Associations between AIADH total and age/experience ($n = 9$). Notes: Spearman CIs via nonparametric bootstrap (1,500 resamples); Abbreviations: WorkExp – total work experience; GkExp – go-kart experience;

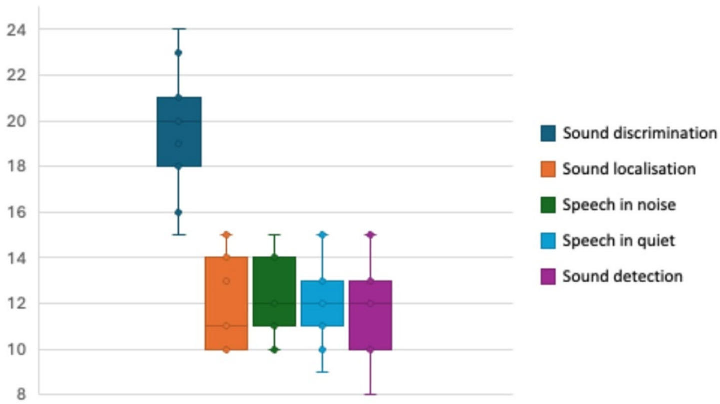

Fig. 2. AIADH domain scores: box plots with individual observations among go-karting instructors (y-axis scaled to observed range (8–24) for readability).

differentiating sounds. Conversely, lower scores appeared in "sound localisation" (median 11; mean 12, 95% CI 10.28–13.72), "sound detection" (median 12; mean 12, 95% CI 10.20–13.80), and both speech comprehension domains, showing that participants encountered more frequent challenges in accurately pinpointing sound sources and understanding speech, whether in quiet (median 12; mean 12.22, 95% CI 10.65–13.80), or noisy (median 12; mean 12.33, 95% CI 10.84–13.82) environments.

Discussion

This study offers new insights into occupational exposures in recreational motorsports—an area often overlooked in occupational health research. Despite relatively short exposure durations, go-kart instructors experienced noise and vibration levels that frequently approached or exceeded regulatory short-term limits. While these findings echo those observed in industrial and driving occupations characterised by intermittent exposures, it is essential to note that our discussion on the interaction between noise and vibration is exploratory. Emerging studies highlight that concurrent exposure to noise and hand-transmitted vibration can adversely affect auditory and cognitive functions as well as muscle fatigue[9,23]. Interpretations of combined noise–vibration effects remain tentative because our study lacked direct cognitive/physiological outcomes.

Our findings of WBV exceeding 3.2 m/s^2 and HAV reaching 14.2 m/s^2 are noteworthy. Comparable studies in commercial drivers report WBV A(8) values of 0.8–1.5 m/s^2, which are significantly lower than the short-term levels measured here[24]. Yet even in these lower ranges, associations with musculoskeletal disorders, especially low-back pain, are well established[25]. Our data suggest that instructors may experience episodic but intense vibration loads, particularly from unsuspended vehicles, which, over time, could lead to cumulative physical strain.

The HAV findings are especially concerning. Exposure exceeded the Polish limit of 11.2 m/s^2 in three of three cases, a range strongly associated with the development of hand-arm vibration syndrome (HAVS). For instance, Gerhardson et al. reported that a daily HAV of 2.2 m/s^2 leads to a 10% prevalence of VWF within ~ 15 years[26], and recent studies show elevated vibration perception thresholds even at levels below the action value of 2.5 m/s^2 A(8)[27]. Thus, our findings suggest a high risk of long-term vascular and neurological damage among go-kart instructors, particularly at higher exposure levels. Though less common in motorised transport research, studies on vibration-induced conditions (such as HAVS) consistently show that prolonged or frequent HAV exposure, even below short-term limits, can lead to vascular and neurological damage.

Although go-kart handlers may experience lower frequencies than power-tool users, repeated grip pressure combined with exposure exceeding the daily limit remains concerning from a health perspective.

These results indicate that, under the measured exposure conditions, the age-related component of hearing loss dominates over noise-induced threshold shifts. This supports the conclusion that go-kart instructors working under current noise conditions may not be at immediate risk of clinically significant NIHL. However, underestimation could occur in environments with high-kurtosis impulsive noise that the energy-based ISO 1999 model does not fully represent.

While the measured A-weighted equivalent noise levels (L_{Aeq}) at instructor workstations remained below regulatory limits in most cases (Table 1), these metrics reflect only the average energy of the noise. They do not account for temporal structure, such as bursts, peaks, and sudden variations in sound pressure, which are typical of motorsport settings. In this context, the concept of noise kurtosis becomes critical.

Kurtosis is a statistical measure that quantifies how "peaky" or impulsive a noise signal is. Noise environments with high kurtosis contain transient, high-energy bursts, for example, sudden engine revs or skidding sounds, which are more damaging to hearing than continuous noise of the same average level. This occurs because go-kart engines rev quickly and irregularly as drivers accelerate, decelerate, and corner. These rapid changes in engine speed (revolutions per minute, RPM) cause sharp fluctuations in sound pressure. Instead of producing a smooth, continuous hum like a fan or highway car, go-karts generate sudden "spikes" in noise levels – short, loud bursts that last fractions of a second. These spikes are not well reflected in average noise measurements (such as L_{Aeq}), but they significantly contribute to hearing damage. Unlike Gaussian (steady-state) noise, high-kurtosis noise causes greater cochlear damage at equivalent energy doses. A study on stock car racing and go-kart dromes in Italy reported sharp peaks during pass-bys and braking, strong, sudden noise events that suggest impulsive characteristics similar to high-kurtosis noise[5].

Although no published studies have directly quantified the kurtosis of go-kart engine noise, the observed peak levels (L_{Cpeak} up to 109.3 dB) and the irregular, transient bursts during acceleration and braking suggest an environment with moderate impulsive noise characteristics. This pattern is comparable to dynamic, engine-driven settings such as motorsport pit crews and construction machinery operations, where noise is marked not by steady levels but by frequent, short-duration peaks. While specific kurtosis data from motorsport environments are limited, observational reports and related research highlight their non-Gaussian, impulsive nature[28]. Similarly, studies conducted by Zhang et al. (2021) in industrial and by Liu et al. (2023) in metalworking environments show that noise with elevated kurtosis values ($\beta \geq 10$) significantly increases the risk of high-frequency hearing loss compared to steady-state exposures, even when the average sound level is similar[29,30]. These findings raise the possibility that traditional ISO 1999 predictions may underestimate actual hearing risk in environments like go-kart tracks, where high-kurtosis, transient acoustic events are likely. Future studies should directly measure kurtosis to assess whether kurtosis-adjusted risk models provide a more accurate reflection of the auditory hazard in such settings.

The results presented in Table 5 illustrate a clear relationship between increasing noise exposure, driven by a higher number of simultaneously operating go-karts, and elevated hearing loss risk across different population percentiles. The predicted hearing thresholds at 2, 3, and 4 kHz increase with both the duration of exposure and the number of go-karts, suggesting cumulative damage over time and higher noise intensity. Particularly noteworthy is the progressive shift from normal hearing to mild, moderate, and moderately severe hearing loss as noise exposure intensifies and workers age, with the most susceptible individuals (P10) being disproportionately affected. These findings align with established occupational health research highlighting noise exposure as a primary risk factor for irreversible hearing threshold shifts and emphasise the need for stringent noise control measures in high-exposure settings[31]. The colour-coded severity classifications further underscore the importance of tailored hearing conservation programs, especially in environments with elevated noise levels that could lead to moderate to severe hearing impairment over extended periods[19].

Despite average $L_{EX,8\ h}$ values below 85 dB, AIADH scores indicated mild perceived hearing difficulties, particularly in domains such as sound localisation and speech comprehension. These functions are often among the first to deteriorate due to early auditory stress. Strong negative correlations between AIADH scores, age, and work experience suggest that cumulative exposure, even within "safe" limits, can result in perceptible deficits. These findings reinforce calls to include subjective assessments in occupational health protocols, as they may detect functional decline before clinical thresholds are reached. These results point to specific auditory functions that may be more sensitive to occupational exposure or early signs of auditory strain, even in the absence of significant hearing loss in audiometric testing.

The interaction between noise and vibration exposure deserves more attention. Literature suggests that concurrent exposure can amplify physiological stress, impair attention, and accelerate auditory fatigue[7]. Given that go-kart instructors must maintain high situational awareness under these stressors, this combined burden could reduce alertness and increase safety risks for both instructors and participants.

Therefore, the research showed that go-kart instructors experienced intermittent, sometimes impulsive noise, with predicted LEX,8 h levels exceeding 85 dB when more karts were operated simultaneously. Several whole-body vibration (WBV) and hand-arm vibration (HAV) measurements approached or exceeded short-term exposure limits. Practical control measures identified included limiting the number of karts running simultaneously, implementing staff rotation, and applying engineering solutions to reduce noise and vibration.

Limitations

This pilot study faces several constraints. First, although peak sound pressure levels were recorded, kurtosis and high-resolution time-domain analyses were not performed; thus, any assertions about impulsive or non-Gaussian noise are inferential and should be approached cautiously. Second, with a small sample size ($n = 9$) from a single facility, external validity is limited; station-level averages were used for modelling, reducing pseudoreplication but also lowering degrees of freedom. The smallest detectable effect at $\alpha = 0.05$ (two-tailed) with five station means (df = 3) is $r \approx 0.88$, equating to a slope of about 1.13 dB per kart; our estimate (~ 1.25 dB/kart) exceeds this. For AIADH associations ($n = 9$), the nominal two-tailed threshold is $|\rho| \approx 0.67$, but with rank-based methods and Holm correction across five domains, effects smaller than $|\rho| \approx 0.75–0.80$ might go unnoticed.

Third, AIADH scores are self-reported and not a substitute for clinical audiometry or electrophysiology. Fourth, vibration was measured within limited task windows; daily and lifetime exposure were not modelled, so findings may not represent full-shift variability. Future studies should incorporate larger, multi-site cohorts, longitudinal follow-up, clinical hearing tests, time-domain acoustic metrics (including kurtosis), and comprehensive full-shift vibration dose modelling.

Future research should involve multi-site cohort studies to better understand exposure differences across locations. Implementing full-shift logging will allow detailed measurements, including L10, L50, and L90 noise levels, time histories, and kurtosis analysis, to more accurately characterise the complexity of noise exposure. Clinical audiometry should be complemented by assessments from the AIADH to provide a comprehensive evaluation of hearing effects. Moreover, the linear relationship between decibel levels and the number of karts at higher counts needs to be validated to ensure accurate exposure predictions in more intense operational scenarios.

Conclusion

To reduce occupational risks for go-kart instructors, several preventive measures are recommended. Noise exposure can be managed by limiting the number of active go-karts to no more than nine. A hearing conservation programme should include mandatory use of protective devices and regular hearing assessments, especially for older or long-serving staff. To address vibration hazards, rotating tasks, scheduling breaks, and maintaining equipment are essential. Ergonomic solutions such as anti-vibration gloves and cushioned seats can help lessen strain. Instructors should also be trained on the risks of impulsive, high-kurtosis noise, which can cause hearing damage even when average levels seem acceptable. From a policy perspective, this study highlights a regulatory oversight. Although go-kart instructors fall under general worker protection frameworks, their profession is not explicitly recognised in national or EU occupational classifications, which means they require targeted assessments for harmful physical factors. Consequently, systematic monitoring and tailored preventive measures are often lacking. These findings support the inclusion of this occupational group in formal risk registers to ensure appropriate oversight in this growing sector of the motorsport and leisure industry.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

IIM conceptualised the study design, noise measurements, statistical modelling, interpretation of data and manuscript writing. KP performed subjective assessment coordination, conducted a literature review, and edited the manuscript. DK performed vibration analysis, conducted a literature review, and edited the manuscript. All authors have approved the submitted version (and any substantially modified version involving their contributions) and agree to be personally accountable for their contributions and to ensure that any issues related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The authors wrote this manuscript based on original research and data. ChatGPT (OpenAI) was used solely to assist with language formulation and clarity. All scientific content, data interpretation, and conclusions were developed and reviewed by the authors. No artificial intelligence tools were used to generate figures or graphical materials.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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