Modeling Recreational Noise-Induced Hearing Loss: A Simulation-Based Approach

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Abstract

Recreational noise-induced hearing loss is a growing issue that affects both young individuals and adults. Constant exposure to recreational noise, such as from personal listening devices or nightclubs, may be a significant contributor to cumulative hearing damage. Due to a lack of detailed data that captures day-to-day noise exposure patterns, this study adopted a simulation-based modeling approach. The methodology consisted of two parts: a mathematical model in the form of a differential equation and a simulated dataset. The differential equation modeled the progression of hearing loss based on the following factors: age-related vulnerability, individual sensitivity, and noise exposure dose. The simulated dataset was created using NIOSH occupational hearing safety guidelines. It consisted of 5000 subjects, whose daily noise exposure and listening times were generated over 365 days. Fitting the simulated data into the mathematical model showed a strong association between that long-term exposure above the 100% NIOSH dose threshold and greater cumulative damage. Additionally, age-related vulnerability and biological sensitivity were found to significantly influence individual susceptibility to hearing loss. This study provides a useful framework for tracking hearing loss progression and assessing potential risks associated with intense listening habits.

Introduction

Noise exposure during leisure activities is a growing concern, especially among teenagers and young adults. According to the World Health Organization (WHO), unsafe listening practices put more than 1 billion young adults at risk of developing permanent hearing loss [1]. Regular exposure to high noise levels during leisure activities, such as nightclubs and live concerts as well as exposure to high sound levels from personal listening devices may be a significant contributor to noise-induced hearing loss [2]. Currently, there is a lack of detailed and consistent data on individual noise exposure and its direct impact on the progression of hearing loss. Numerous studies and research papers have been published on noise-induced hearing loss from recreational activities, each having a unique focus, approach, and results. Some studies did not find a significant relationship between leisure noise exposure and hearing loss, like a study by Degeest et al. [2]. This study consisted of a hearing assessment and a questionnaire, in which 517 individuals aged 18-30 years were surveyed on their leisure noise exposure. Even though a high number of participants reported frequent exposure to leisure noise, this study did not present it as a major cause of hearing loss, suggesting that other factors such as age-related hearing loss may have a greater effect on individuals' hearing. A study by Beach et al. aimed to investigate the relationship between high-noise activities and the potential risks they pose to the hearing of young adults [5]. The study was based on an online survey completed by 1000 young adults aged 18-35 years. Participants were asked to report the frequency of their participation in the five activities and evaluate their overall hearing health. In contrast to the studies mentioned previously, this study did find a link between high-noise recreational activities and an increased risk of hearing damage. It concluded that out of the five activities, nightclubs posed the greatest risk for the development of hearing damage in young adults, while also recognizing that other factors such as occupational, environmental, and recreational noise could contribute to their hearing health. Although the study design proved useful for identifying an overall trend in recreational noise exposure among young adults, it did not capture day-to-day patterns in noise exposure that would make it suitable for computational modeling.

Taken together, these studies demonstrate the difficulty of assessing the role of leisure noise exposure in the progression of hearing loss. Studies mentioned earlier mainly rely on self-reported questionnaires and publicly available data, such as NHANES data on the health status of civilians. Despite the credibility of those sources and their usefulness in identifying population-level trends in hearing loss, they are insufficient for closer tracking of how hearing loss progresses. The lack of detailed hearing loss case studies creates a gap in understanding how repeated, day-to-day exposure to noise may affect hearing health.

This gap presents an opportunity to explore this issue through computational modeling with a simulation study approach. Simulation studies are widely used across different fields to evaluate statistical methods, mathematical models, and other research focuses when empirical data is unavailable or hard to obtain. The process of running a simulation study involves creating artificial data using "pseudo-random sampling" [6], which refers to random values generated by a computer. Even though this approach is sometimes viewed as less direct than an observational study, it can provide valuable insights when properly designed and implemented. In this context, simulation provides a structured way to evaluate how different noise exposure cases may influence the progression of noise-induced hearing loss. This paper presents a simulation study that uses a mathematical model to estimate how different patterns of exposure to high noise may lead to hearing damage over time. By modeling both typical and extreme cases, this study aims to computationally assess the potential risks of excess noise exposure and encourage safe listening practices among individuals.

Methodology

Mathematical Model

A differential equation was constructed to model the progression of hearing loss over time for any given individual. A differential equation is an equation that contains a derivative of a function. It allows us to model how a quantity changes with respect to another quantity.

$$\frac{dD}{dt} = k_{age}(age(t)) \ + k_{sensitivity} \times Dose(t) \quad (1)$$

Where:

- $D(t)$ = cumulative damage (dB HL)
- k_{age} = age-related vulnerability factor (dB HL/day)

  This model assumes that both younger and older individuals are more vulnerable to cumulative hearing damage. For younger individuals, this vulnerability comes from an ongoing physiological development of the auditory system. Since their auditory systems are not fully developed yet, they may be more susceptible to noise compared to fully grown adults [13]. By contrast, older individuals experience a gradual degradation of cochlea (inner year), known as Presbycusis [3, 12], which makes them vulnerable to noise as well. Therefore, an important factor to consider for this mathematical model is age-related vulnerability, which was modeled using a quadratic function:

$$k_{age}(age(t)) \ = \ 0.0003(age(t) \ - \frac{age_{max}}{2})^2 \ + \ 0.001 \quad (2)$$

  The shape of this quadratic assumes that age-related vulnerability is the highest at minimum and maximum points of $age(t)$, and is the lowest towards the middle. Since the main equation is with respect to time, it is a good idea to treat age as a function of time as well:

$$age(t) \ = age_0 + \ t \quad (3)$$

- $k_{sensitivity}$ = individual sensitivity to noise (dB HL/day)

  Apart from age, there are other factors that can influence how an individual responds to noise. These factors include genetics, biological predispositions, pre-existing hearing conditions, and lifestyle factors, among others. A single constant was chosen to represent sensitivity. For each individual, this constant is randomly selected from a uniform distribution, a probability distribution where all outcomes are equally likely to occur [8]. The range of values for the uniform distribution is between 0.005 and 2.

- $Dose(t)$: noise exposure (dBA)

  Dose percent is the maximum allowed exposure to noise and it is calculated using the following formula, where h represents total hours of noise exposure in one day, and v represents how much time, on average, an individual was exposed to noise per day [10]:

$$Dose = (\frac{h}{8}) \times (2^{\frac{v-85}{3}}) \quad (4)$$

Study Design

Due to a lack of empirical data that captures day-to-day patterns of noise exposure across different individuals, a simulated dataset was constructed using noise exposure guidelines from the National Institute of Occupational Safety and Health (NIOSH). Although originally intended for occupational settings, the NIOSH recommended exposure limit (85 dB(A) for 8 hours) was used as a reference threshold. This threshold was used to approximate average noise exposure among individuals in the simulation. It follows the 3-dB time-intensity tradeoff (see Table 1), also known as the equal-energy rule, which means every time the noise level is increased by 3 dB, the safe listening time for that noise level is reduced by half. Conversely, every time the noise level is decreased by 3 dB, the safe listening time is doubled [10].

Table 1. Recommended safe exposure times for different noise levels based on NIOSH guidelines.

Safe Exposure Time	**Noise Exposure**
16 hours	83 dB(A)
8 hours	85 dB(A)
4 hours	88 dB(A)
2 hours	91 dB(A)
60 minutes	94 dB(A)
30 minutes	97 dB(A)

Source: National Institute for Occupational Safety and Health, Criteria for a Recommended Standard for Occupational Noise Exposure, U.S. Department of Health and Human Services, 1998.

The simulation was run using the Pandas library. It generated a total of 5000 subjects aged 12 to 70 years, each assigned a daily noise exposure time and volume over a period of 365 days. Each subject was randomly assigned a sensitivity constant, which accounted for a possible difference in genetic predispositions and sensitivity levels among different individuals. Randomness was introduced using uniform and normal distribution methods from the Numpy library. Uniform distribution was used for the sensitivity constant ($k_{sensitivity}$) and each subject's average volume and listening time over the year. Based on the NIOSH recommended exposure limit, a range for the average volume for each subject was chosen to be between 70 dB(A) and 90 dB(A). The average listening time was chosen to be between 0 and 10 hours per day. To simulate daily fluctuations and spikes, a normal distribution with a mean of 0 and a standard deviation of 2.5 was added to the average volume, as well as the average listening time. The normal (Gaussian) distribution is a bell-shaped, symmetric probability distribution where values around the mean occur more frequently than values at the extremes. Normal distribution has two main parameters: mean (average) and standard deviation. Standard deviation determines how spread out the values are from the mean [8]. All subjects were put into one of the five age groups: 12-17, 18-24, 25-34, 35-49, and 50-70. Every age group had 1000 subjects.

The degree of hearing loss was chosen as a metric for evaluating the severity of cumulative hearing damage. The degree of hearing loss can be classified into seven categories (see Table 2), from normal hearing up to severe hearing loss. It is measured in dB HL (decibel hearing loss) and serves as the main evaluation metric of cumulative hearing damage $D(t)$ in the differential equation.

Table 2. Degrees of hearing loss and their numerical ranges.

Hearing loss label	**Hearing loss threshold level (dB HL)**
Normal hearing	– 10 to 15
Slight hearing loss	16 to 25
Mild hearing loss	26 to 40
Moderate hearing loss	41 to 55
Moderately severe hearing loss	56 to 70
Severe hearing loss	71 to 90
Profound hearing loss	91+

Source: Clark, J G. "Uses and abuses of hearing loss classification." ASHA vol. 23,7 (1981): 493-500.

The simulation was run on a 2021 MacBook Pro, 16 GB RAM, 512 SSD. Spyder, an open-source python IDE was used through the Anaconda Navigator.

Results

A scatterplot (see Figure 1.) of cumulative hearing damage was plotted, where each data point represents hearing damage of an individual on day 365. We can observe a non-linear, sigmoid-like curve, where cumulative damage rises slowly at lower doses, increases rapidly towards the middle, and reaches a ceiling of 100 dB HL. We can see a clear upward trend, suggesting that higher overall noise exposure is associated with greater hearing damage.

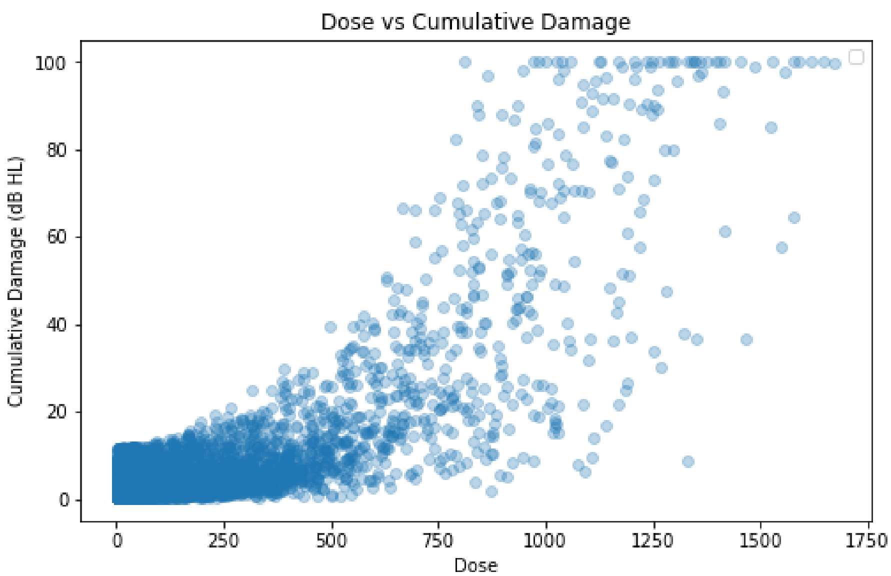


Figure 1. Scatterplot showing the relationship between total dose and cumulative damage for every individual. Each data point represents an individual, specifically their cumulative hearing damage on day 365.

The distribution of hearing damage was plotted on a histogram for every age group (see Figure 2). We can observe that for individuals aged 12 to 17, most cumulative damage values were concentrated below 10 dB HL. We see a similar pattern for individuals in age groups 18 to 24, 25 to 34, and 35 to 49, where most damage values are close to 0 dB HL. Meanwhile, the 50 to 69 age group shows a wider spread and a higher median value of cumulative damage, with a significant number of individuals accumulating between 10 and 40 dB HL. This trend suggests that hearing damage increases with age.

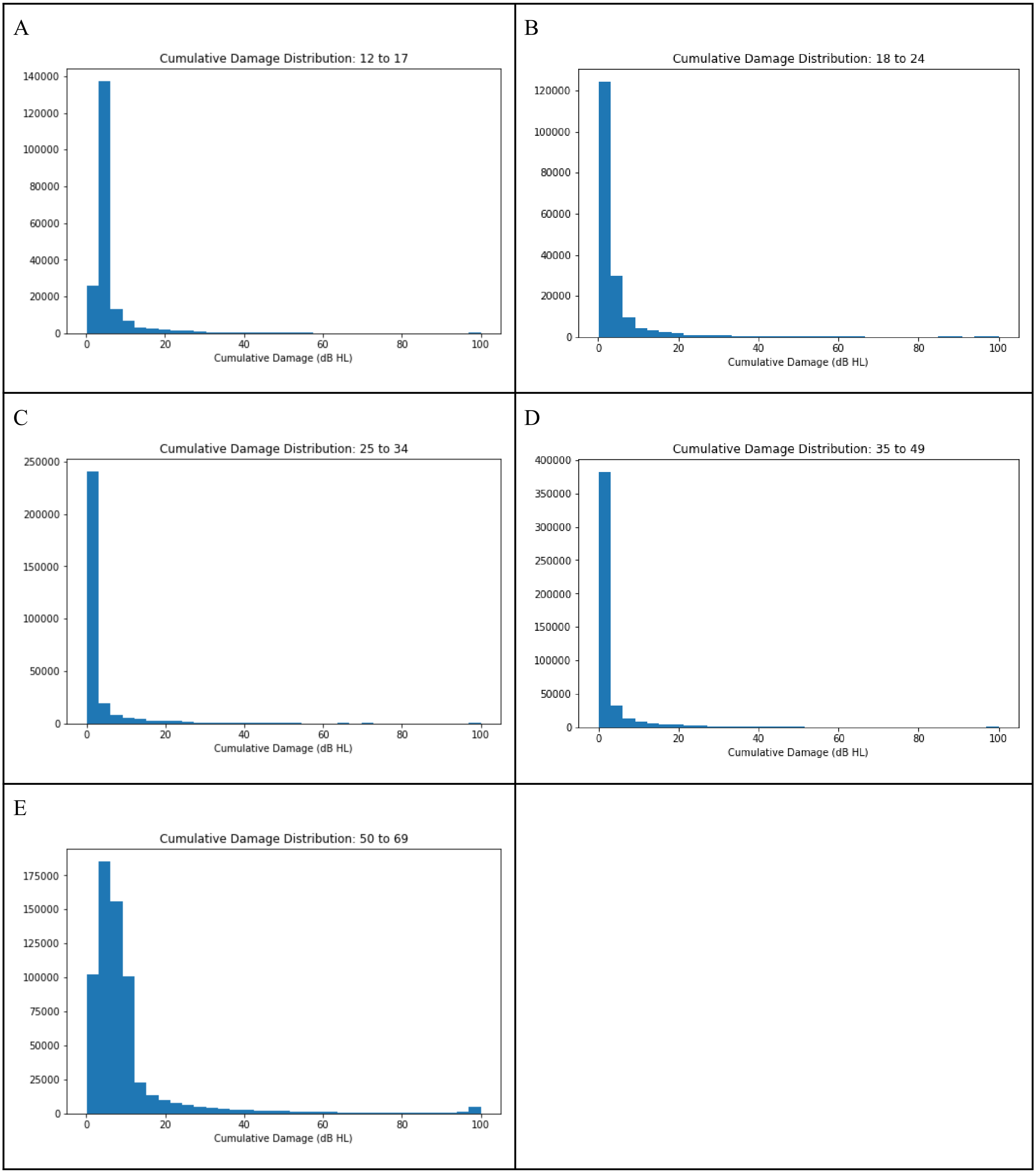

A
Cumulative Damage Distribution: 12 to 17
0
20000
40000
60000
80000
100000
120000
140000
0 20 40 60 80 100
Cumulative Damage (dB HL)
B
Cumulative Damage Distribution: 18 to 24
0
20000
40000
60000
80000
100000
120000
0 20 40 60 80 100
Cumulative Damage (dB HL)
C
Cumulative Damage Distribution: 25 to 34
0
50000
100000
150000
200000
250000
0 20 40 60 80 100
Cumulative Damage (dB HL)
D
Cumulative Damage Distribution: 35 to 49
0
50000
100000
150000
200000
250000
300000
350000
400000
0 20 40 60 80 100
Cumulative Damage (dB HL)
E
Cumulative Damage Distribution: 50 to 69
0
25000
50000
75000
100000
125000
150000
175000
0 20 40 60 80 100
Cumulative Damage (dB HL)

Figure 2. Distribution of cumulative damage by age group. Subplots show simulated cumulative damage in 5 categories: (A) 12-17, (B) 18-24, (C) 25-34, (D) 35-49, (E) 50-69. The x axis represents cumulative damage in dB HL, and the y axis represents the number of individuals within each damage range.

The boxplots on Figure 3 allow us to compare the damage distributions by age groups more closely. Age groups with individuals above 50 years old have a higher median, Q1, and Q3 damage values compared to other age groups. The cumulative damage range and interquartile range (IQR) for the 50-69 age group are also wider than other age groups.

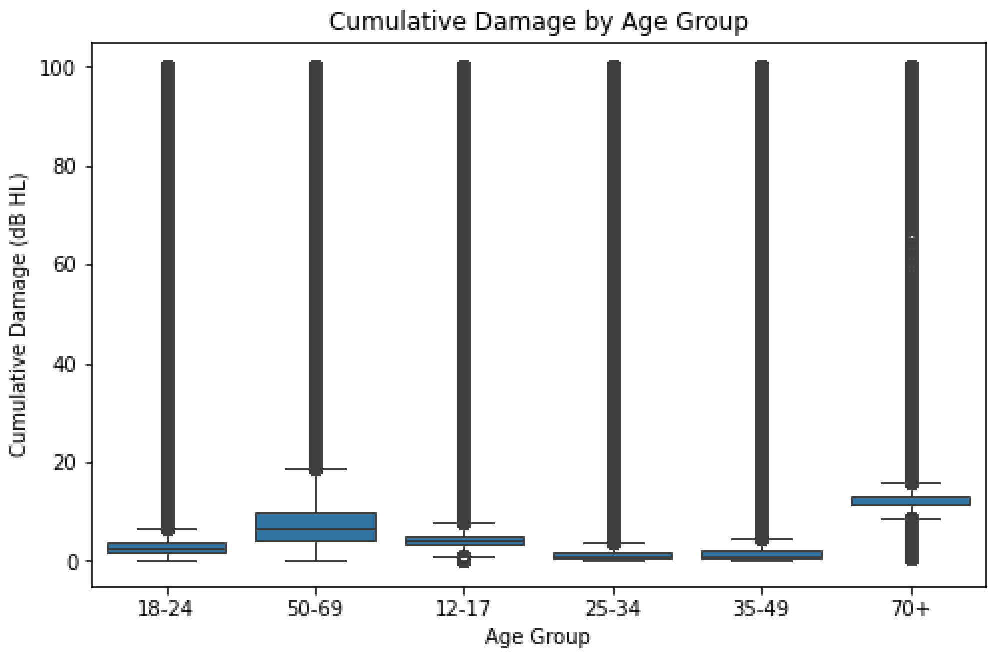


Figure 3. Boxplots showing cumulative damage by age group. Black dots show outliers of cumulative damage for every age group, which can also be seen on Fig 2. as tails of the distributions. The boxplots show the range, interquartile range, and the median of cumulative damage of each age group.

To see how leisure noise alone affects the progression of hearing loss, we need to temporarily remove k_{age} from the differential equation $\frac{dD}{dt}$. To achieve this, a sample of five individuals of the same age was taken from two age categories: a sample of five 20 year olds, and a sample of five fifty year olds. The progression of hearing loss, i.e. the solution to the main differential equation, was plotted for every individual, and their sensitivity, average exposed noise volume, and average time of exposure was also displayed (see Figure 4).

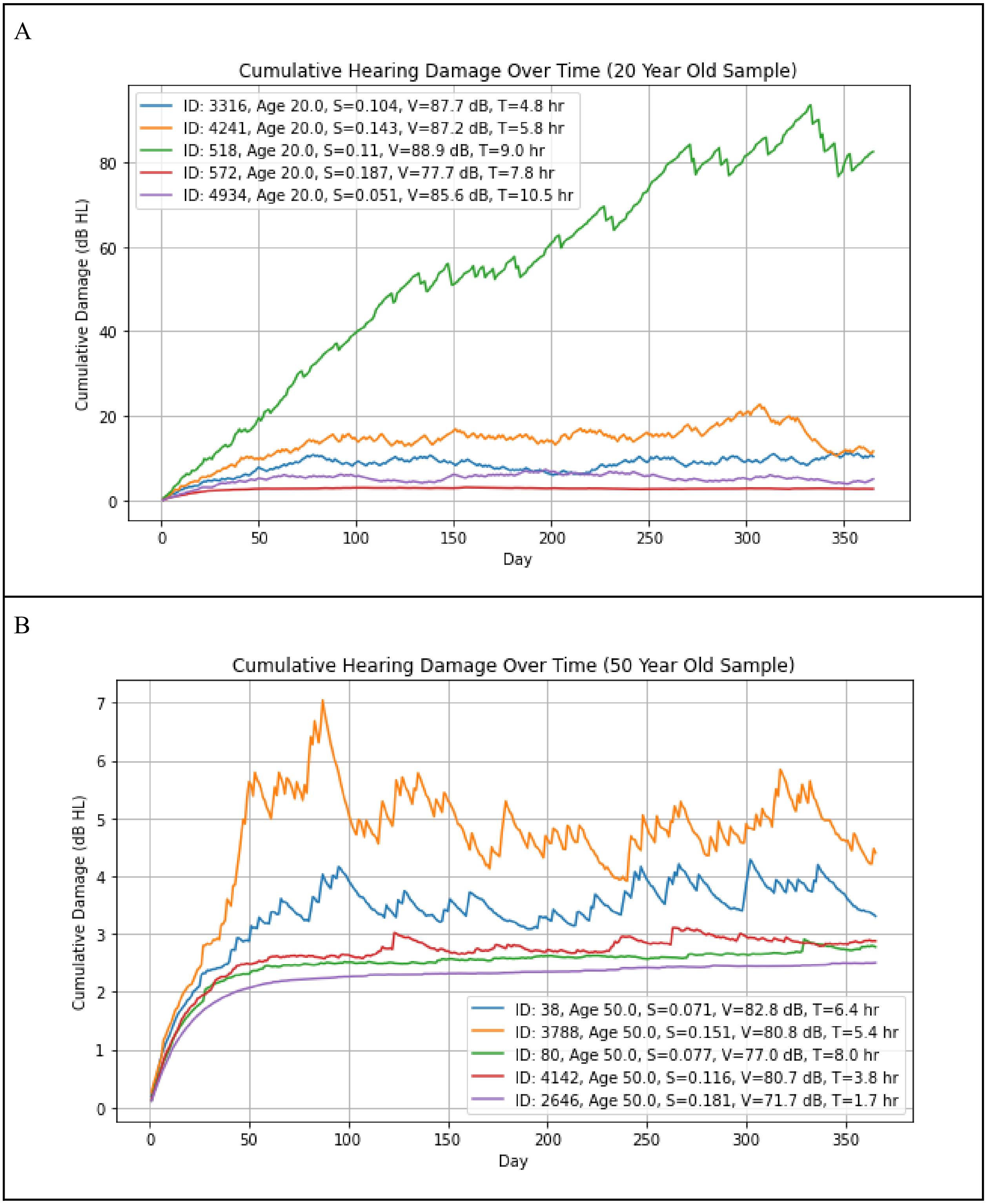
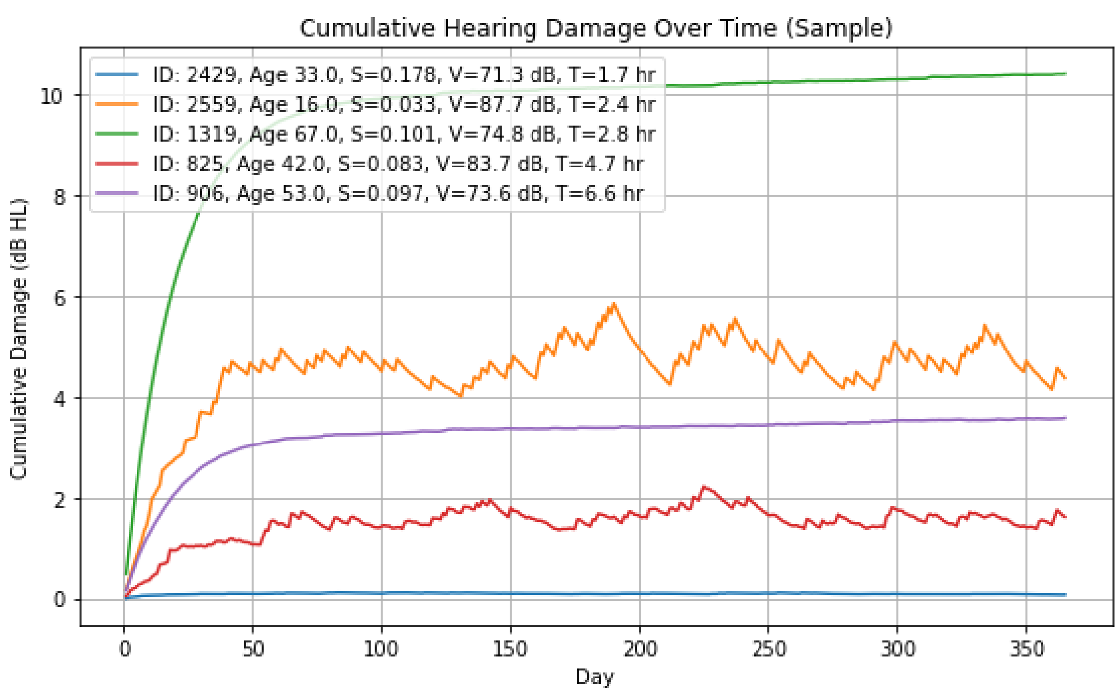


Figure 4. Hearing damage trajectories for individuals aged (A) 20 and (B) 50.

We can observe that individuals with higher exposure times and volumes tend to obtain more hearing damage. For instance, as seen on Figure 4. (A), individual #518 averaged 9.0 hours of exposure time at 88.9 dB, and showed the highest cumulative damage value in the sample. Another interesting result is the effect of the sensitivity factor on hearing damage. As seen in Fig. 5, individual 3788 averaged 5.4 hours of exposure time at 80.8 dB and had a greater cumulative damage than individual 38, who averaged 6.4 hours of exposure time at 82.8 dB. This result occurred due to a drastic difference in their sensitivity values, which was 0.151 for individual #3788, and 0.071 for individual #38.

To observe what cumulative damage progression looks like with k_{age} , a sample size of five individuals was randomly drawn from the simulated dataset. Cumulative damage trajectory of each individual over 365 days was plotted, and each individual's age, sensitivity constant, average exposure volume and average exposure time was displayed. To make accurate inferences, this process was repeated three times (see Figure 5).

A



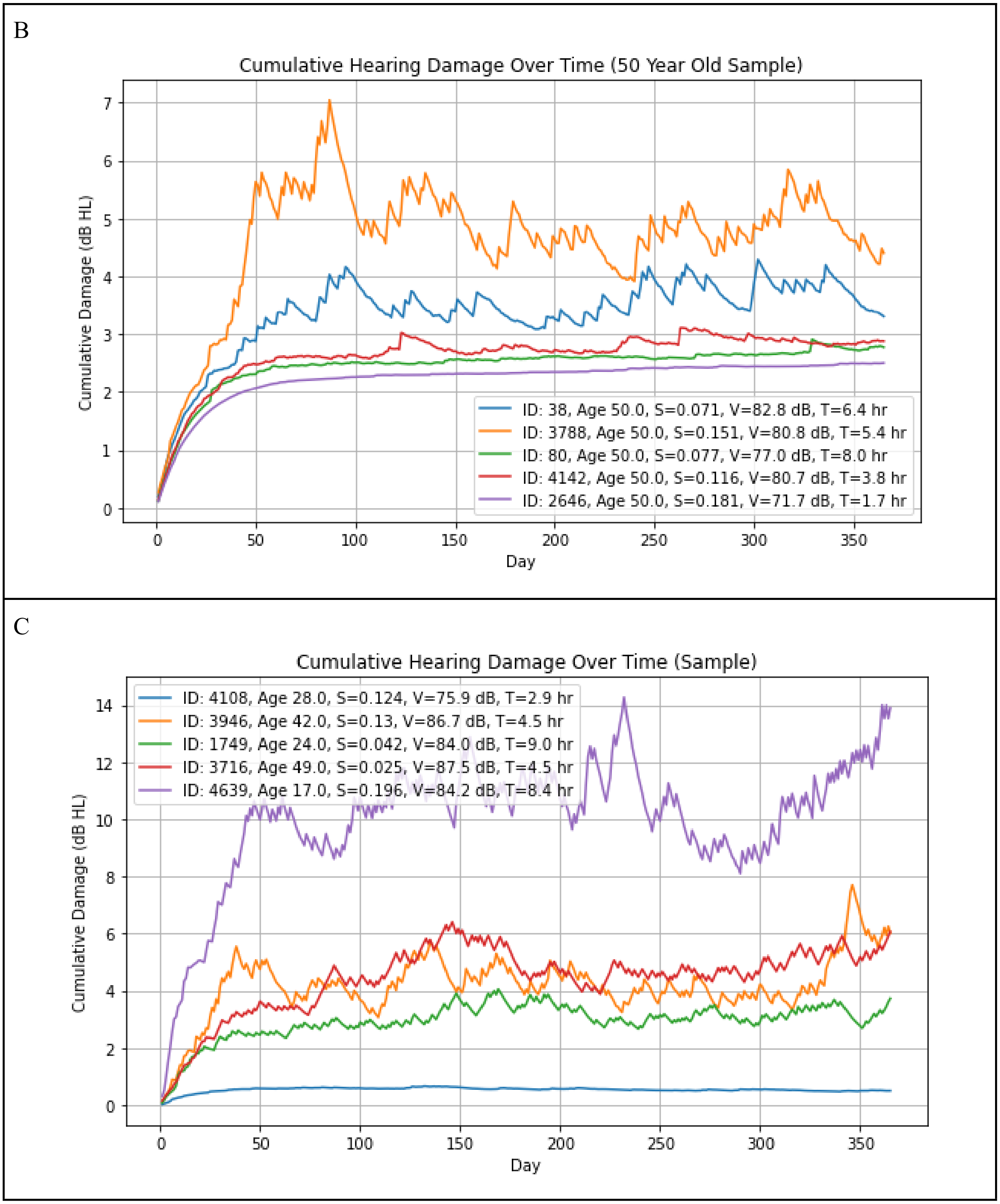


Figure 5. Hearing damage trajectories for three randomly drawn samples. Each sample consists of 5 individuals of different ages.

Discussion

Analysis

This study aimed to simulate the progression of recreational noise-induced hearing loss using a mathematical model, in which factors such as individual noise exposure, age-related hearing loss, and individual sensitivity were considered. The results showed a clear trend: cumulative damage increased with a higher dose and age, suggesting that both more severe noise exposure and age contribute to the progression of hearing damage. As seen in Figure 1, most values of cumulative damage were concentrated between 0 to 12 dB HL, which according to Clark, J G [11], falls under the normal hearing category. A possible explanation for such a high concentration of data points in that area is that extreme hearing loss cases are rare, which is reflective of the real world. As we move towards data points with higher total dose values, we can see a rapid spike in cumulative hearing damage with noticeably fewer data points. Such a low concentration confirms our previous assumption that cases with extreme hearing damage are far less frequent than cases with minimal hearing damage. The sigmoid-like shape of this scatterplot suggests that long-term, greater, and more frequent noise exposure may be significantly more harmful than short-term exposure.

Looking at the two five-individual samples and their plots, we can observe a strong correlation between intensity of noise exposure and cumulative damage, that is, the higher average exposure time and volume, the greater the cumulative hearing damage. For instance, individual #572 averaged 7.8 hours of exposure time at 77.7 dB, and their cumulative damage was slightly above 0 dB HL, which is relatively low compared to other individuals in the sample. By contrast, individual #518 averaged 9.0 hours of exposure time at 88.9 dB, and their cumulative damage was above 80 dB HL, which is much higher than those of other individuals in the sample and is considered severe hearing loss. These results suggest that in isolation, excessive recreational noise exposure is the prime factor of hearing damage. The sample of fifty year old individuals showed a similarly strong relationship between noise exposure and the occurring hearing damage. These results are expected considering that both samples contained individuals of the same age. What can also be noticed is how sensitivity plays a substantial role in shaping the trajectory of the damage. Since sensitivity values of the 20 year old individuals were closer to each other, the results we observed were expected. Looking at the sample of 50 year olds, however, we can see how individual sensitivity skewed the expected results.

The age-related factor was another focus of this study. Age is a major contributor to hearing loss according to the study by Degeest et al. discussed earlier in this paper [2]. As shown in Fig 3, individuals aged 50 to 69 experienced the highest proportion of mild to moderate hearing loss, while groups with younger individuals largely remained within a normal hearing range. This aligns with the main mathematical model where k_{age} is more profound for individuals above the age of 50. To assess the effects of age-related factors in combination with leisure noise exposure, three hearing damage trajectory plots were made for three samples consisting of five randomly selected individuals. Compared to Figure 4 where all individuals are the same age, Figure 5 shows that age becomes a deciding factor in hearing loss development. For instance, on Figure 5 (A) we can see that individual #1319, who is 67 years old, has accumulated significantly less hearing damage compared to individual #825, who is 42 years old, despite having lower noise exposure over the course of 365 days. We can observe a similar pattern in plot Figure 5 (B), in which older individuals had higher values of cumulative damage compared to the rest of the sample. Another interesting observation is the difference in cumulative damage of individual #1749, who is 24 years old, and individual #4639, who is 17 years old. Despite having similar average noise exposure values, individual #4639 has accumulated more damage, because according to the quadratic k_{age}, younger individuals are more vulnerable to noise. Overall, these results confirm the notion that age-related vulnerability is a major factor of hearing loss.

Limitations

This study made several assumptions to run the simulation. First, it was assumed that biological sensitivity remains constant throughout the simulation period, when in reality, it can vary based on events that an individual experiences. For example, if an individual experiences physiological changes or goes through an illness, their sensitivity might change over time. Second, hearing damage is treated as linearly accumulating day by day with limited recovery and no compounding effect. While some degree of recovery is assumed if dose does not reach 100%, it is largely not representative of how recovery affects the progression of hearing loss in real life. The model also assumes that daily damage contributes to cumulative damage independently, when in reality prior damage can make an individual more vulnerable in the future. Third, the age-related factor is modeled as a quadratic function, where younger individuals and individuals above the age of 50 may experience a more rapid progression of cumulative damage. Although a quadratic computationally makes sense in this study, it is naturally limiting of variability that can occur across different age groups. These assumptions were necessary to construct a traceable and mathematically plausible simulation. While these assumptions simplify real-world biological processes, they are necessary to ensure a model produces clear and interpretable results. With too many biological factors to consider, it would be difficult to investigate the relationship between recreational noise exposure and cumulative damage.

Another thing to keep in mind is that a simulated study is significantly different from a study based on questionnaires or collected datasets. Even though the simulation was run based on real-world statistics and guidelines, it is important to recognize that the data was entirely simulated and therefore should not be compared to publicly available data. That said, the results should not be interpreted as representative of real-world populations, but rather as a computational approximation intended to explore patterns in recreational noise-induced hearing loss.

Another important thing to consider is factors such as environmental and occupational noise, which can greatly influence how recreational noise contributes to hearing loss [4, 9].

While occupational and environmental noise can be contributing factors, this study does not include them to focus on the effects of leisure noise alone. However, we should acknowledge that in real-world contexts, there are other sources of noise that can contribute to hearing loss. Because this model only focuses on leisure noise exposure, age, and biological sensitivity, it may be misinterpreted in other contexts. For instance, an individual who lives in a noisy city and works in a noisy environment may experience more hearing damage than an individual who lives in the suburbs and works from home, assuming that both individuals are the same age and are exposed to similar levels of recreational noise. Despite these limitations, this study offers a useful framework for visualizing how different noise exposure patterns might influence long-term hearing health and assess potential risks of frequent and intense noise exposure. Future research could focus on developing an extension to the mathematical model that includes both environmental and occupational noise to see how those factors influence the progression of noise-induced hearing loss along the factors discussed in this study.

Conclusion

Recreational noise-induced hearing loss is a growing concern, especially among the younger population. Due to a lack of appropriate real-world data for tracking day-to-day listening patterns, this study adopted a simulation study approach. By developing a simulation-based model, this study aimed to understand how hearing damage from noise exposure evolves over time. The simulation was run based on the NIOSH exposure limit guidelines, which state that for every 3 dB increase in volume, the allowable exposure time is cut in half. Dose percent was used as a metric for the allowable volume and listening time per day. Although this simulation-based approach cannot be compared to a real data-driven study, it was largely successful for identifying general trends in hearing loss across different exposure levels. The findings of this study identified a trend in hearing loss progression: intense and frequent exposure to recreational noise, alongside individual sensitivity and age-related hearing loss, can pose a great risk to hearing health.

As personal listening device use becomes more common and long-term effects are still poorly understood, this work emphasizes the importance of safe listening practices. While short-term spikes in recreational noise exposure may be insignificant, long-term persistent exposure should be avoided to minimize potential damage to hearing health. Public health campaigns, educational organizations, and individuals who have interest in the topic of noise-induced hearing loss could benefit from insights of this study. Future research could build upon this work by integrating real-world data and adding additional factors to the model, such as a recovery, occupational and environmental hearing loss, and frequency-specific damage.

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Appendix

Code for the simulation

```
import numpy as np
import pandas as pd

n_days = 365
n_individuals = 5000
age_min, age_max = 12, 70

def k_age(age):
    return 0.0005 * (age - (age_max / 2)) ** 2 + 0.002

def calculate_dose(hours, volume):
    return (hours / 8) * (2 ** ((volume - 85) / 3))

def get_age_group(age):
    if age < 18:
        return '12-17'
    elif age < 24:
        return '18-24'
    elif age < 34:
        return '25-34'
    elif age < 49:
        return '35-49'
    elif age < 69:
        return '50-69'
    else:
        return '70+'

results = []

for person_id in range(1, n_individuals + 1):
    age0 = np.random.randint(age_min, age_max)
    k_sensitivity = np.random.uniform(0.005, 0.2)
    avg_volume = np.random.uniform(70, 90)
    avg_listening_time = np.random.uniform(0, 10)
    age_group = get_age_group(age0)
```

```
    total_dose = 0
    cumulative_damage = 0
    for day in range(1, n_days + 1):
        current_age = age0 + day / 365
        daily_volume = np.clip(avg_volume + np.random.normal(0, 2.5),
60, 95)
        daily_listening_time = max(avg_listening_time +
np.random.normal(0, 2.5), 0)

        dose = calculate_dose(daily_listening_time, daily_volume)
        daily_damage = k_age(current_age) + k_sensitivity * dose

        total_dose += dose
        cumulative_damage += daily_damage

        cumulative_damage = min(cumulative_damage, 100)

        if dose < 1:
            cumulative_damage *= 0.95

        results.append({
            "ID": person_id,
            "Day": day,
            "Age": current_age,
            "Age Group": age_group,
            "Sensitivity": k_sensitivity,
            "Daily Volume (dBA)": daily_volume,
            "Daily Listening Time (hrs)": daily_listening_time,
            "Daily Dose": dose,
            "Total Dose": total_dose,
            "Daily Damage Increase": daily_damage,
            "Cumulative Damage": cumulative_damage
        })

df = pd.DataFrame(results)

df.to_csv("simulated_hearing_loss_data.csv", index=False)
```

Code for visualizations

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns

df = pd.read_csv("simulated_hearing_loss_data.csv")

plt.figure(figsize=(8, 5))
plt.title('Cumulative Damage Distribution: 12 to 17')
plt.xlabel('Cumulative Damage (dB HL)')
plt.hist(df[df['Age Group'] == '12-17']['Cumulative Damage'],
bins=33)

plt.figure(figsize=(8, 5))
plt.title('Cumulative Damage Distribution: 18 to 24')
plt.xlabel('Cumulative Damage (dB HL)')
plt.hist(df[df['Age Group'] == '18-24']['Cumulative Damage'],
bins=33)

plt.figure(figsize=(8, 5))
plt.title('Cumulative Damage Distribution: 25 to 34')
plt.xlabel('Cumulative Damage (dB HL)')
plt.hist(df[df['Age Group'] == '25-34']['Cumulative Damage'],
bins=33)

plt.figure(figsize=(8, 5))
plt.title('Cumulative Damage Distribution: 35 to 49')
plt.xlabel('Cumulative Damage (dB HL)')
plt.hist(df[df['Age Group'] == '35-49']['Cumulative Damage'],
bins=33)

plt.figure(figsize=(8, 5))
plt.title('Cumulative Damage Distribution: 50 to 69')
plt.xlabel('Cumulative Damage (dB HL)')
plt.hist(df[df['Age Group'] == '50-69']['Cumulative Damage'],
bins=33)
```

```
plt.figure(figsize=(8, 5))
plt.title('Cumulative Damage by Age Group')
plt.xlabel('Age Group')
plt.ylabel('Cumulative Damage (dB HL)')
sns.boxplot(x='Age Group', y='Cumulative Damage', data=df)

total_dose_day_365 = df[df['Day'] == 365]['Total Dose']
total_damage_day_365 = df[df['Day'] == 365]['Cumulative Damage']
plt.figure(figsize=(8, 5))
plt.title('Dose vs Cumulative Damage')
plt.xlabel('Dose')
plt.ylabel('Cumulative Damage (dB HL)')
plt.scatter(total_dose_day_365, total_damage_day_365, alpha=0.3)


unique_ids = df['ID'].unique()
sample_ids = np.random.choice(unique_ids, size=5, replace=False)

plt.figure(figsize=(8,5))
plt.title('Cumulative Hearing Damage Over Time (Sample)')
plt.xlabel('Day')
plt.ylabel('Cumulative Damage (dB HL)')

for person_id in sample_ids:
    person_df = df[df['ID'] == person_id]
    age = np.round(person_df['Age'].iloc[0], decimals=0)
    sensitivity = np.round(person_df['Sensitivity'].iloc[0],
decimals=3)
    mean_volume = np.round(person_df['Daily Volume (dBA)'].mean(),
decimals=1)
    mean_time = np.round(person_df['Daily Listening Time
(hrs)'].mean(), decimals=1)

    label = f"ID: {person_id}, Age {age}, S={sensitivity},
V={mean_volume} dB, T={mean_time} hr"

    plt.plot(df[df['ID'] == person_id]['Day'],
             df[df['ID'] == person_id]['Cumulative Damage'],
```

```
              label=label)

df_20 = df[np.floor(df['Age']) == 20]

age_ids_20 = df_20['ID'].unique()

sample_ids_20 = np.random.choice(age_ids_20, size=5, replace=False)

plt.figure(figsize=(8, 5))
plt.figure(figsize=(8,5))
plt.title('Cumulative Hearing Damage Over Time (20 Year Old Sample)')
plt.xlabel('Day')
plt.ylabel('Cumulative Damage (dB HL)')

for person_id_20 in sample_ids_20:
    person_df = df_20[df_20['ID'] == person_id_20]
    age = np.round(person_df['Age'].iloc[0], decimals=0)
    sensitivity = np.round(person_df['Sensitivity'].iloc[0],
decimals=3)
    mean_volume = np.round(person_df['Daily Volume (dBA)'].mean(),
decimals=1)
    mean_time = np.round(person_df['Daily Listening Time
(hrs)'].mean(), decimals=1)

    label = f"ID: {person_id_20}, Age {age}, S={sensitivity},
V={mean_volume} dB, T={mean_time} hr"

    plt.plot(df[df['ID'] == person_id_20]['Day'],
             df[df['ID'] == person_id_20]['Cumulative Damage'],
             label=label)

plt.grid(True)
plt.tight_layout()

plt.legend()
plt.show()
```