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Status - International Space Station (ISS) Crewmembers' Noise Exposures

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ABSTRACT

Environmental noise in space vehicles caused by onboard equipment and noisy activities has generated concerns for crew health and safety since early U.S. space missions. The International Space Station (ISS) provides a unique environment where acoustic conditions can be monitored while crewmembers from the U.S. and their international partners work and live for as long as 6 to 12 consecutive months. This review of acoustic dosimetry data collected to date reveals that the noise exposure limits of NASA's stringent noise constraint flight rule have been exceeded in 41% of these dosimetry measurements since ISS Increment 17 (2008), with undefined impacts to crew. These measurements do not take into account the effects of hearing protection devices worn by the crew. The purpose of this paper is to provide an update on ISS noise exposure monitoring approaches and hearing conservation strategies that include acoustic dosimetry data collected since the ISS Increment 55 mission (April 2018). Future directions and recommendations for the ISS noise exposure monitoring program will also be presented, including research initiatives aimed at better defining the impact of ISS noise on crew health and performance.

1. INTRODUCTION

This paper presents a summary and an assessment of the acoustic dosimetry data collected on the International Space Station (ISS) since Increment 55 mission (April 2018). It includes crew-worn noise exposure monitoring data collected during the daytime (work-period equivalent noise exposure levels, LEQ16) and nighttime (sleep-period equivalent noise exposure levels, LEQ8) periods and environmental noise exposure data, both collected on ISS. Crew-worn and environmental monitoring is performed by the trained crewmembers onboard ISS, with technical support provided by ground personnel. Overview of the ISS noise exposure monitoring and hearing conservation strategies along with details and descriptions of ISS modules have been previously discussed and presented elsewhere[1-5].

Acoustic monitoring measurements made onboard the ISS are used to ensure a safe working and living environment for the crew. This data is used to determine when actions are required in order to

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reduce the noise onboard the ISS. Details of ISS acoustic requirements are briefly explained in the next section and in detail elsewhere[5].

2. REQUIREMENTS

Acoustic monitoring requirements are based on several ISS requirements documents and the ISS Noise Level Constraint Flight Rule (JSC Flight Rule B13-152)[6]. The ISS Noise Level Constraint Flight Rule implements actions, e.g. use of hearing protection, depending on the results of 16-hour crew-worn LEQ16 and 8-hour crew-worn LEQ8 measured by the ISS acoustic dosimeters. The flight rule uses a 3-dB equal exchange rate and the World Health Organization noise guidelines for ground conditions[7]. The Noise Hazard Inventory (NHI) was developed to use with this flight rule. The NHI is an inventory of noise levels and duration of exposures where hearing protective device (HPD) use is recommended or mandated. These are specific ISS locations and scheduled activities where hearing protection use is not already covered under specific crew procedures or operational controls. The NHI has been used since ISS increment 36 (July 2013). The NHI has been reviewed and updated for each subsequent ISS increment.

3. NOISE MONITORING HARDWARE AND CREW TRAINING

3.1 Monitoring Hardware

Acoustic dosimeters (ADs) are instruments used to measure noise exposure over extended periods of time. There are three calibrated ADs onboard ISS at all times. Currently the SV 102A+ Class 1 Dual-Channel Noise Dosimeter manufactured by Svantek is being used on ISS (see Figure 1). Internally, NASA uses the name Acoustic Monitor for this hardware, which has been used since ISS Increment 53 (November 2017). The Acoustic Monitor is a COTS product that meets Type 1 standards for accuracy per international standards for sound level meters (SLMs), IEC 61672-1:2013, allowing it to be used as both an AD and a precision SLM. Detailed hardware descriptions have been previously discussed and presented elsewhere[5].

Figure 1. Svantek SV 102A+ Class 1 Dual-Channel Noise Dosimeter, a.k.a. Acoustic Monitor.

The crewmembers wear the Acoustic Monitor for a continuous 24-hour period to measure typical exposures to noise on ISS. The Acoustic Monitor can be stored in a pocket attached via integrated belt-loop on the back or clipped to the crewmember's clothing via a carrying pouch. The microphone has a separate clip allowing placement on the collar or lapel so that it is in close proximity to the crewmember's ear. The Acoustic Monitor is also deployed at static locations in ISS to collect noise exposure levels in predetermined locations. The data transfer and data download processes are outlined in Figure 2 below. As part of nominal on-orbit operations, the Acoustic Monitor runs for approximately 14-hour periods and therefore requires a battery change-out halfway through the 24-hour crew-worn sessions (typically done right before the sleep-period) and prior to the static location measurements. The Acoustic Monitor is then connected to a Space Station Computer (SSC) via a USB connection and then the data is transferred to an ISS server, where it is then accessed and downlinked by Houston Mission Control Center (H-MCC) and finally passed to the Acoustics Office for analysis, exposure assessment, data interpretation and reporting.

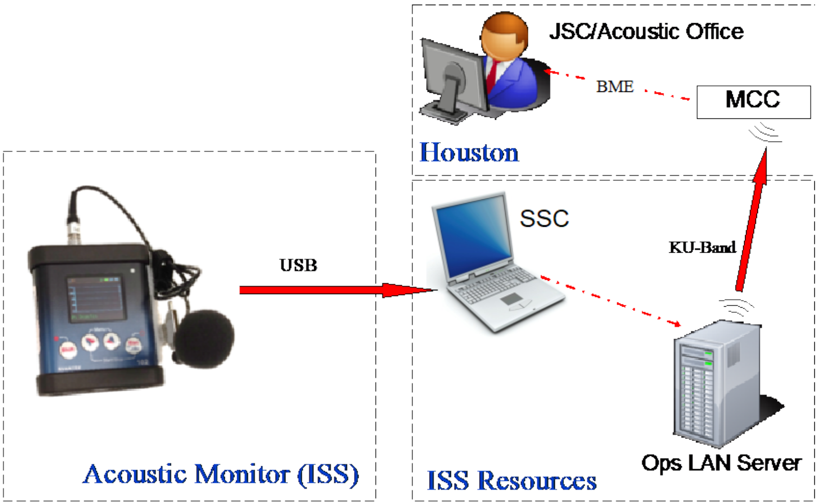

Figure 2. Acoustic Dosimeter Data Download Process.

3.2 Acoustic Measurements

Monitoring the acoustic environment is a key task required for all crewmember onboard ISS to ensure a healthy and safe noise environment. On-orbit crew-time is a high demand asset for all operational tasks and because acoustic monitoring tasks can be very time consuming, procedures have been optimized in an effort to minimize crew-time. Each acoustic monitoring task is performed by a trained crewmember. This crewmember either performs hardware set-up/battery change-out and then takes background noise readings in various locations on ISS via a noise survey, deploys hardware for crew-worn measurements or to a static location. Once measurements are completed, the crew member downloads the data from all three Acoustic Monitors as described above and then stows the hardware back into the noise monitoring kit. These activities are generally performed once every other month.

3.3 Hearing Protection

Many different types of HPDs are available to crewmembers onboard ISS, including both passive and active devices. These include disposable foam earplugs, custom (molded) earplugs, and active noise reduction (ANR) headsets[8-10]. Several sizes of the disposable foam earplugs are also provided to and worn by the crewmembers, at their discretion, and then trashed.

4. DATA AND ANALYSIS

4.1 Data Collection

Acoustic data is collected from crew-worn, noise survey and static location measurements over a several-day period. Based on a three-person crew the following schedule would typically be used: (Day 1) crew-worn measurements, (Day 2) brief noise survey measurements immediately followed by static deployment, and (Day 3) data download activity. The frequency of these activities is generally performed every other month, as previously mentioned.

4.1.1 Crew-worn measurement

The crew-worn session includes both, daytime and sleep-time periods (24-hours). For this activity, the crewmember dons the Acoustic Monitor and starts the measurement before breakfast of the day of the planned activity. Just before sleep, a crewmember temporarily collects the dosimeters for a battery change-out and then redeploys to the same crewmembers. The crew-worn session typically concludes in the morning just before normal activities begin for the day. The sessions conclude immediately before post sleep activities on the following day. ISS noise exposure levels are based on a 3-dB time-intensity exchange rate, consistent with criteria recommended by the National Institute of Occupational Safety and Health (NIOSH)[11] and the U.S. Department of Defense, and it has also been adopted internationally for use in hearing conservation programs[12]. In this paper, all data, including the plots, will be presented using the 3-dB exchange rate.

An example of crew-worn dosimetry data can be seen in Figure 3. The graph has been divided into work- (daytime) and sleep- (night-time) periods. The noise hazard level (85 dBA), the 16-hour LEQ limit (72 dBA), above which the crew are – directed to wear HPDs, and the 60 dBA limit, where –

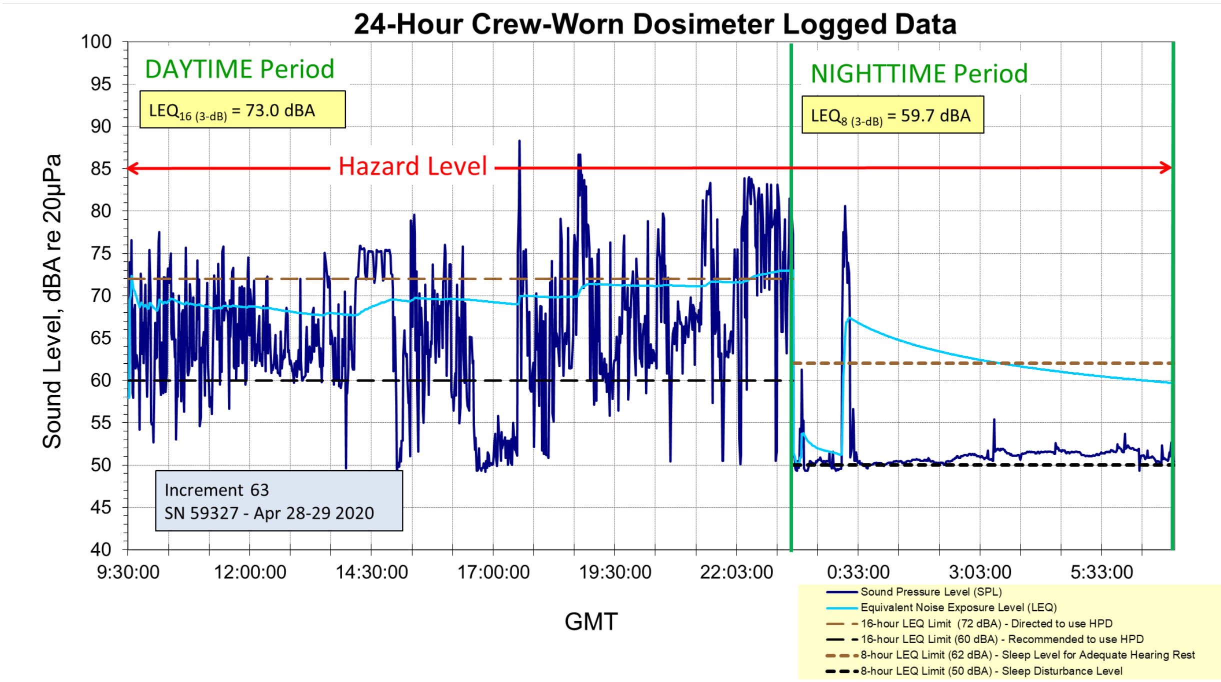

Figure 3. Crew-worn Acoustic Dosimeter Logged Data.
SOURCE: ISS Acoustic dosimeter data collected on April 2020, Increment 63.

crew may be recommended to wear HPDs, depending on the situation, have been identified in the work-day portion of the graph. For this particular dataset, LEQ16 during the daytime was measured at 73.0 dBA. Based on the Noise Level Constraint ISS Flight Rule this crewmember was required to don HPD during noisy activities since the levels were above the 16-hr LEQ limit (72 dBA). However, use of HPDs was also required since the LEQ16 was above the noise hazard level at GMTs 17:32 and 18:47 during the work-time period. The flight surgeon may recommend use of HPDs whenever the levels exceed 60 dBA based on the individual needs of the crewmember and the level and duration of the noise exposure. HPDs are always available to the crewmembers on ISS, if needed or desired. During the nighttime period, LEQ8 was 59.7 dBA, which falls above the established sleep disturbance level (50 dBA) but below the level needed for adequate hearing rest (62 dBA).

Crew-worn acoustic dosimetry data on ISS have been collected since November 2001 (Increment 1). To date, the overall noise levels on ISS have improved and decreased from the higher levels first measured during the early years on ISS. However, some ISS increments are noisier than others. For example, as shown in Figure 4; in 2009 (Increments 18-21), in 2010 (Increments 23-25), in 2012 (Increments 30-32), and more recently in 2018 (Increments 54-56) the noise levels are much higher than the other years. These elevated levels can be caused by dust-clogged fans, noisy exercise equipment, experiment hardware, or noisy activities, etc. These high noise levels can increase the risks for degraded voice communications, and habitability (possible disruptions to crew sleep, interference with crew performance, etc.). General improvements in acoustic levels have been observed on ISS due to noise mitigation efforts performed in the Russian Segment, as well as the addition of quieter modules and crew quarters as previously reported and discussed elsewhere[13]. Elevated noise levels in a given segment can often be traced to clogged fans operating outside recommended set-points. After the clogged fans are cleaned, noise levels are seen to returned back to nominal levels as verified during subsequent acoustic measurement activities[1-3]. We have also observed the reduction of high noise levels associated with crewmembers running at high speeds on the treadmill has been reduced with the installation of acoustic blankets in the vicinity of the treadmill.

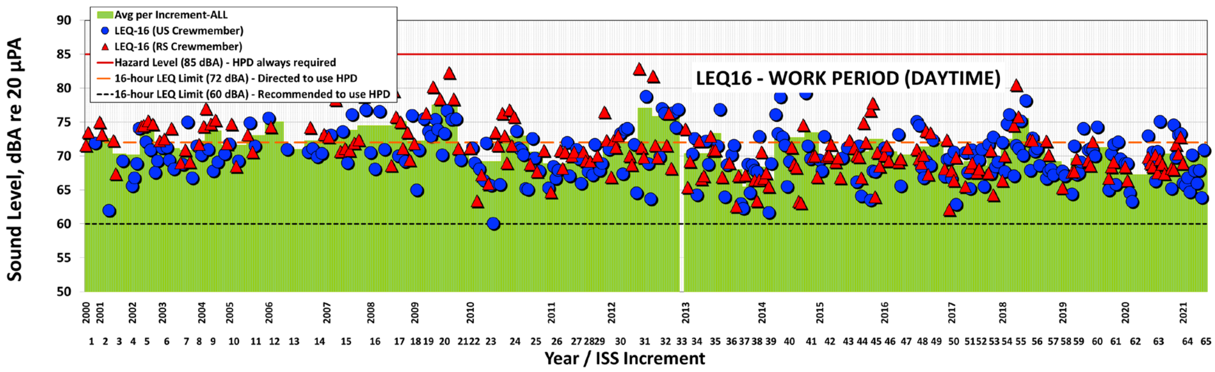

Figure 4. LEQ16 Crew-Worn Acoustic Dosimetry vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

Since the addition of the acoustic blankets in 2016 (Increment 49), crew noise exposure to hazardous levels (>85 dBA) associated with running on the treadmill have been decreased and eliminated. Installing a new T2 treadmill (April 2019) has also helped reduce noise exposure levels. See Figure 5.

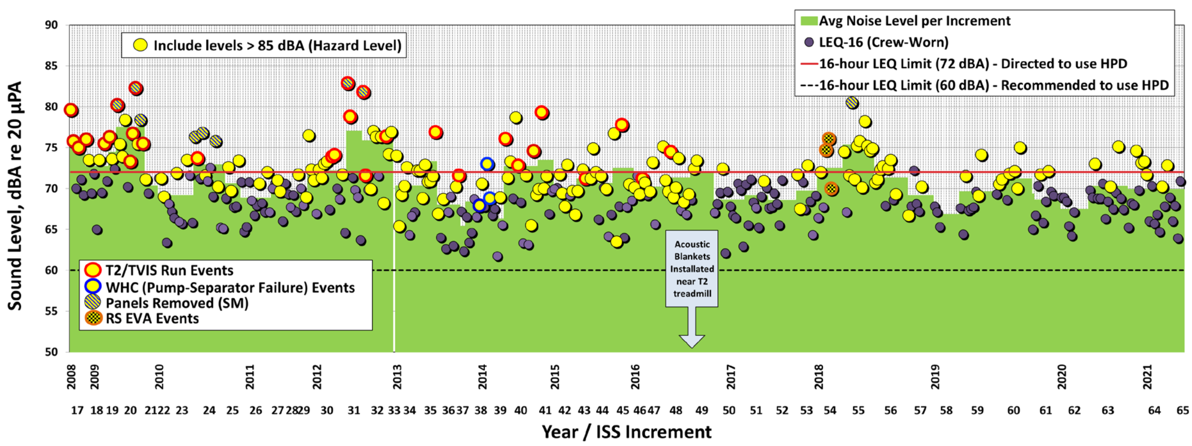

Figure 5. LEQ16 Crew-Worn Acoustic Dosimetry vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2021 (Inc. 64).

The noise exposure level for the work-time period was dependent on where the crewmembers spent most of their working and/or in leisure time, and what activities or tasks they were performing. Crewmembers can either work in the Russian Segment (RS) modules or in the U.S. segment modules. See Figures 6 and 7 for a data distribution of LEQ16 during work hours in the US and RS segments, respectively. As we compare the data distribution (LEQ16) from previous reporting

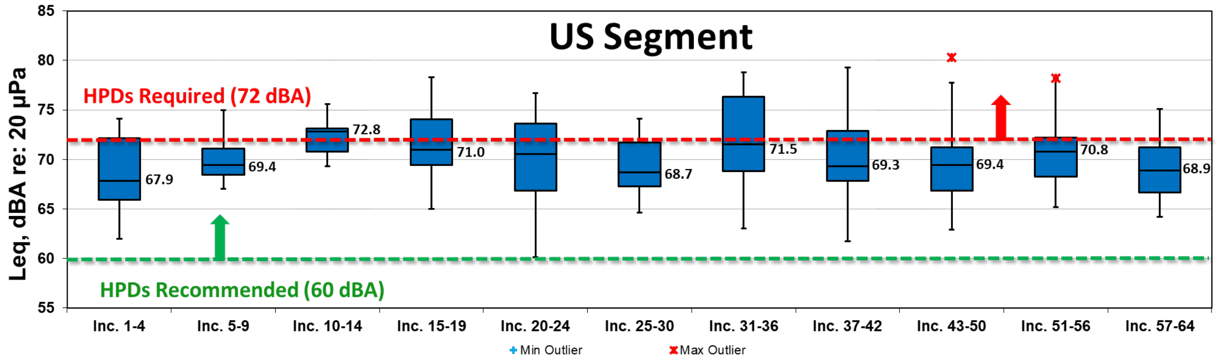

Figure 6. LEQ16 Crew-Worn Acoustic Dosimetry (US Segment) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

years to the current reporting years (ISS increments 57-64), the noise levels experienced by the crewmembers mainly working in the US segment were slightly lower (Figure 6: 70.8 dBA in Increments 51-56 vs. 68.9 dBA in Increments 57-64). The noise levels experienced by the crewmembers mainly working in the RS segment were also slightly lower from the previous reporting year (Figure 7: 69.5 dBA in Increments 51-56 vs. 68.7 dBA in Increments 57-64).

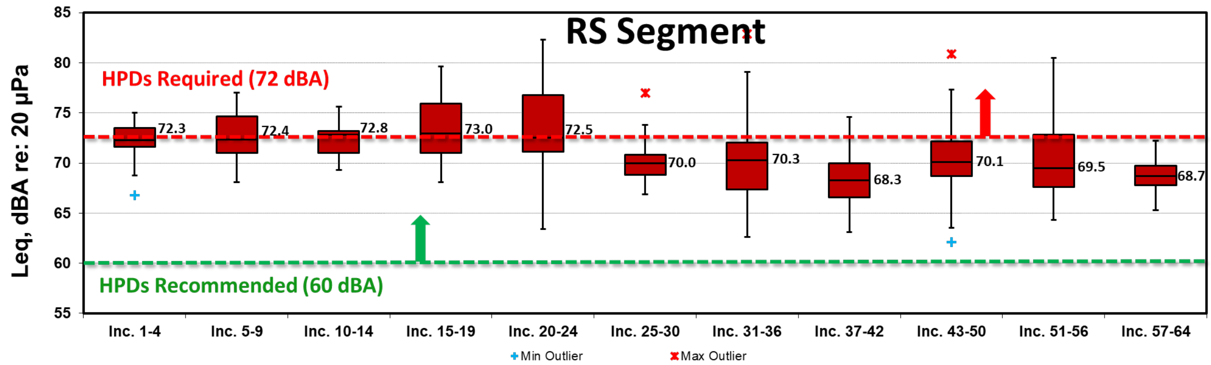

Figure 7. LEQ16 Crew-Worn Acoustic Dosimetry (RS Segment) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

The crew sleep stations in the ISS were designed to provide a personal, private area for a crewmember to rest, sleep, and work and also for personal activities. There is a total of six permanent sleep stations: two Russian sleep stations (kayutas) located in port and starboard locations in the Russian segment's Service Module and the other four sleep stations (crew quarters) are located in the U.S. segment in Node 2. The ISS Crew Quarters (CQs) provide a quiet area for recovery (reduced acoustic stimulus to the ears) from daytime noise exposure levels. Noise levels in the kayutas have previously (early ISS years) been a concern due to high noise levels; see Figure 8. Initially, the kayutas were designed with a porthole and a door, but the doors were removed on-orbit during Increment 1. Doors were later provided and installed to the kayutas, along with other noise control mitigations added to Russian Segment hardware components and the noise levels were reduced in the Service Module. Despite many mitigation efforts, high noise levels are still observed on occasion, some of these being traced to crew personal activities. Some crewmembers tend to sleep with the door opened, others with the fan operating in high speed, etc. When the crew sleep station door

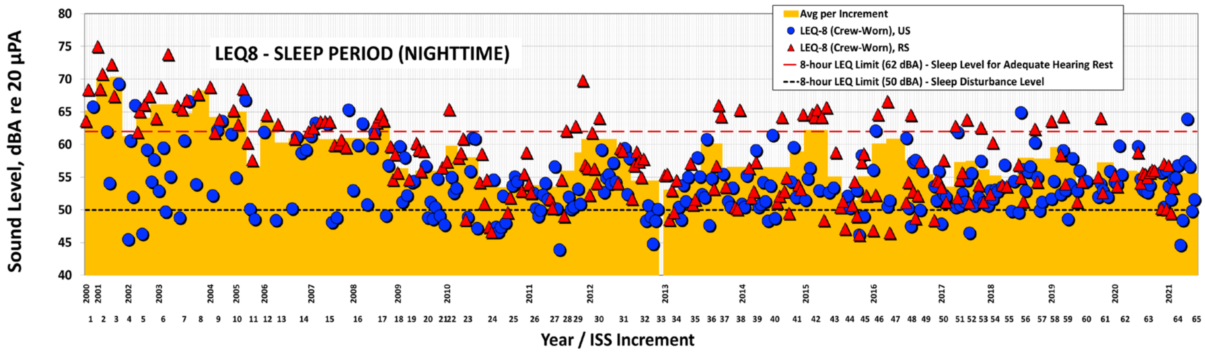

Figure 8. LEQ8 Crew-Worn Acoustic Dosimetry vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

is opened, the module's environmental noise level can increase the levels inside the sleep station (impacting crew noise exposure during the sleep-time period). Different types and sizes of HPDs are always available to crewmembers on ISS, if needed for sleep. The bottom-line is that both, U.S. and Russian sleep stations are adequately quiet when the doors are closed, providing auditory rest, and do not increase the risk for hearing loss. As we compare the data distribution of sleep-time periods (LEQ8) from previous reporting years, the noise levels experienced by the crewmembers sleeping in the US and RS segments were similar to the previous reporting year. No significant differences were noted (Figure 9: 52.5 dBA in Increments 51-56 vs. 53.9 dBA in Increments 57-64) and (Figure 10: 54.6 dBA in Increments 51-56 vs. 55.5 dBA in Increments 57-64).

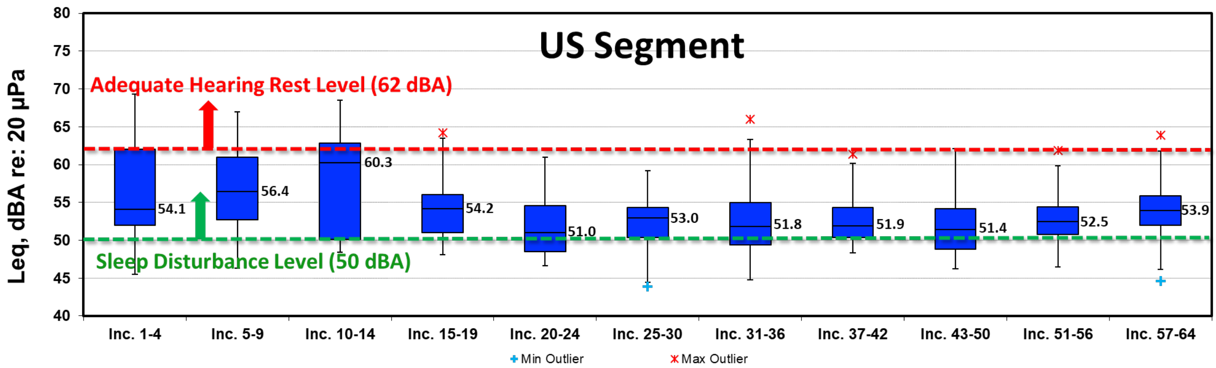

Figure 9. LEQ8 Crew-Worn Acoustic Dosimetry (US) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

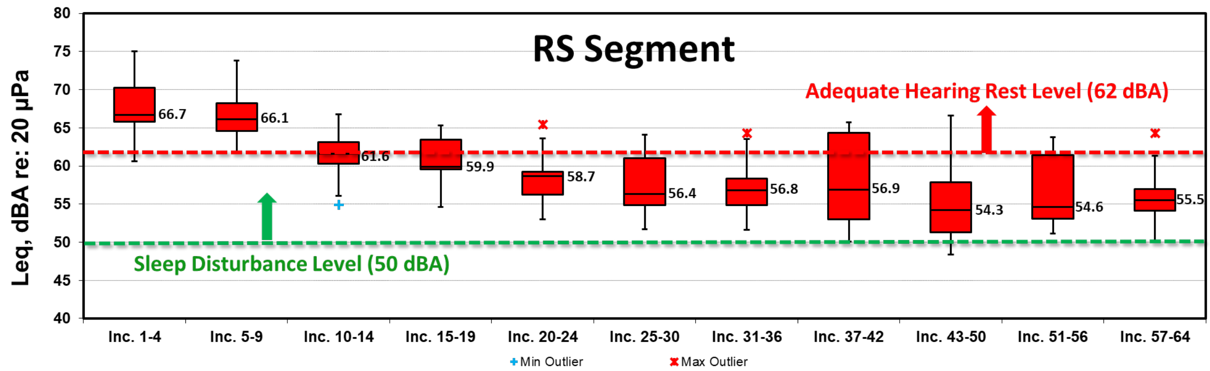

Figure 10. LEQ8 Crew-Worn Acoustic Dosimetry (RS) vs ISS Increment.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

After reviewing the dosimetry data collected on ISS since Increment 1 (2000), it can be seen that the data trend of the average work-time period noise exposure level for the crewmembers working either in the US or RS segments have remained consistently stable and below the 16-hour L_{EQ} limit (72 dBA) since the ISS assembly was completed (after 2011). However, there were several ISS increments (2012: 30-32, 2014: 38-41, and most recently 2018: 54-57) where the average level was slightly above the flight rule limit. See Figure 11. The dosimetry data collected to date also indi-

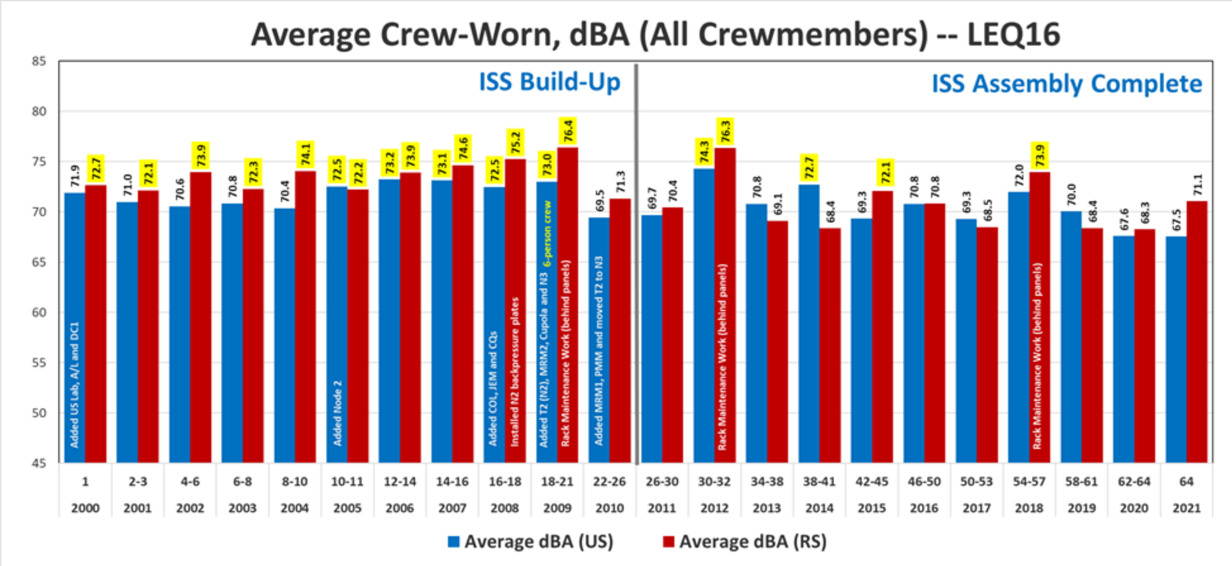

Figure 11. LEQ16 Crew-Worn Acoustic Dosimetry vs ISS Increment and Year.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

cates that the noise hazard limit (85 dBA) has been exceeded approximately 41% of the time since ISS Increment 17 (2008), with undefined impact to crew. This measurement does not consider the effects of any HPDs worn by the crew. See Figure 12.

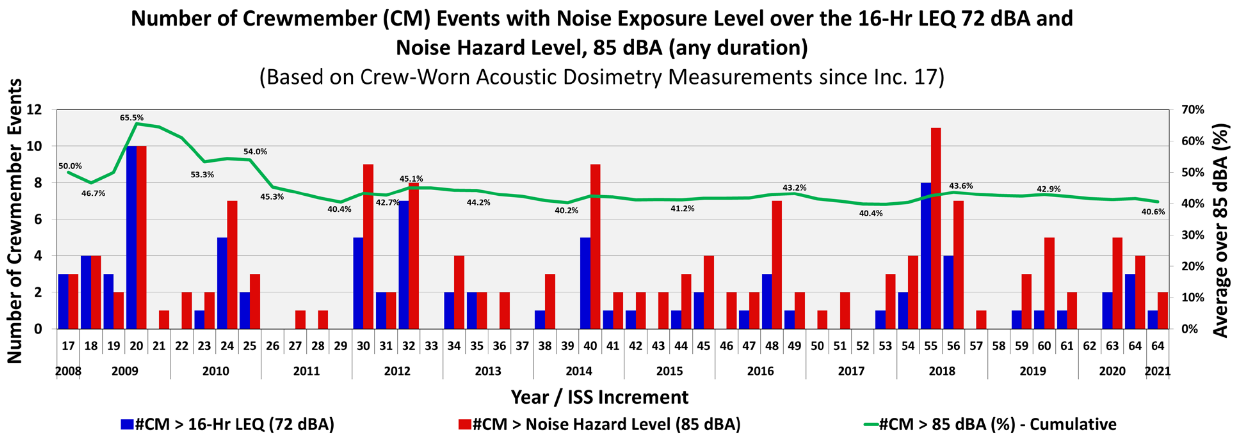

Figure 12. Acoustic Dosimeter Crew-Worn Measurement with Noise Exposure Level over 72 and 85 dBA
SOURCE: Acoustic dosimeter data collected from October 2010 (Inc. 17) through March 2021 (Inc. 64).

After reviewing the work period crew noise exposure data, approximately 93% of the noise sources that were above the noise hazard level (85 dBA) were identified. The identification process was accomplished with the help of the Operations Planning Timeline Integration System (OPTimIS) tool, crew feedback and on-orbit noise surveys. OPTimIS is a software tool used by flight controllers for mission planning and crewmember scheduling using an integrated timeline[14-15]. These events were classified into six categories/activities: operations, maintenance, communications, exercise, crew personal activities and unknown events. See Figure 13. Based on the results, there are more high noise level events related to crew personal activities, such as; mealtime, pre/post sleep activities, morning/afternoon prep work, and a significant number of high noise level activities related to communications, e.g. daily planning conferences (DPC) and public affairs office (PAO) communications. Together, these classifications account for approximately 43% of the hazard level exceedances. However, these events are not considered hazardous, as they are controlled by the crew.

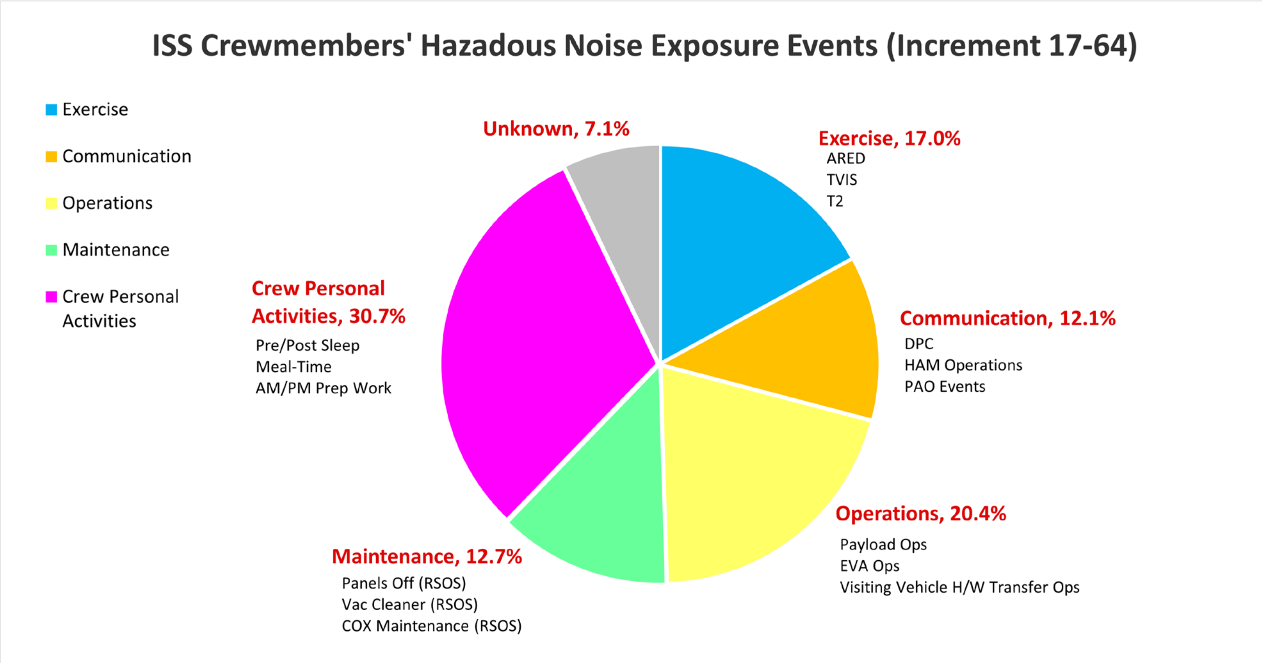

Figure 13. Distribution of noise exposure events during work-period hours (levels above 85 dBA).
SOURCE: Acoustic dosimeter data collected from July 2008 (Inc. 17) through March 2021 (Inc. 64).

The hazard level is meant to control the level of equipment-generated noise, which can increase the risks for degraded voice communications, and reduced habitability, causing the crew to have to talk louder (or increase the volume on music/video entertainment to be heard against the background noise. Further investigations to analyze these events is ongoing.

Looking at the dosimetry data for the nighttime period, in Figure 14, it can be seen that the data trend of the average LEQ8 for the crewmembers sleeping in either the US or RS segments have remained stable and below the Sleep Level for Adequate Hearing Rest Level (62 dBA) since ISS assembly complete. Sleep noise exposure levels have been above the Sleep Disturbance Level (50 dBA), however, crew surgeons have been informed of this situation, and discuss any issues with getting restful sleep with the individual crew members during private medical conferences. The sleep-time noise exposure levels for US crewmembers are shown to have been lower than the levels experienced by the RS crewmembers. However, in Increment 64, sleep-time noise exposure levels in the US segment have been elevated. This is a result of increasing the speed of the Node 2 cabin fan, needed for temperature controllability with visiting crew and cargo vehicles attached to the Node 2 ports. See Figure 14.

4.1.2 Static location measurement

After completing the 24-hour crew-worn measurements for all crewmembers, the dosimeters are then deployed at predetermined locations for approximately 16-18 hours for area monitoring. Acoustic Monitors deployment locations are selected based on notably noisy areas, such as areas near exercise equipment, fans, etc. Measurements in these locations specifically help identify high noise levels which can affect crew noise exposure and provide better understanding of the ISS acoustic environment. These locations are defined in a “static-deploy plan” provided by the JSC

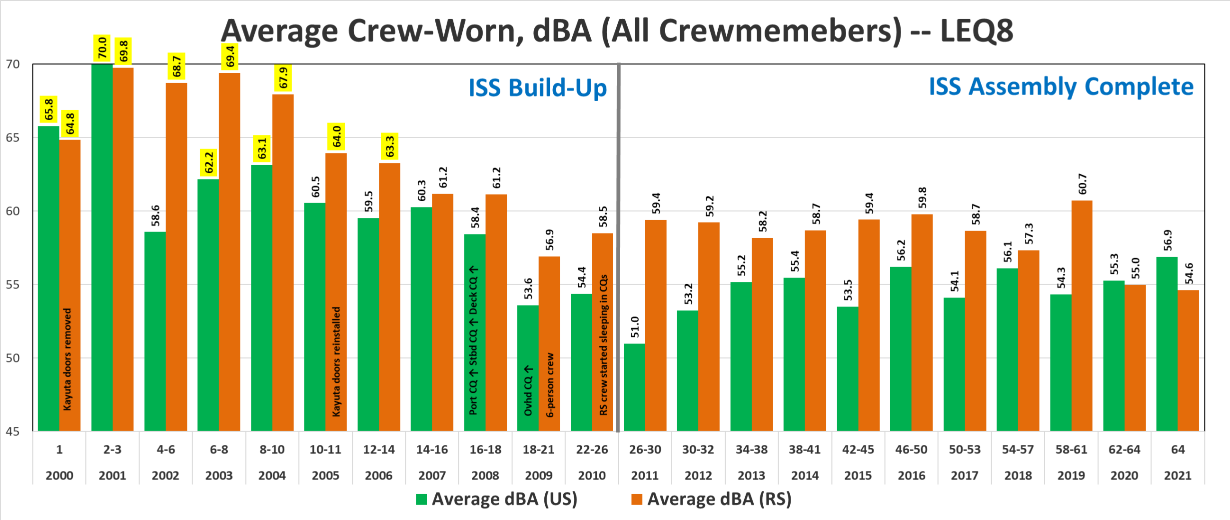

Figure 14. LEQ8 Crew-Worn Acoustic Dosimetry vs ISS Increment and Year.
SOURCE: Acoustic dosimeter data collected from November 2001 (Inc. 1) through March 2021 (Inc. 64).

Acoustics Office and uplinked to the crew on ISS before the activity is performed. Measurements have been recorded in various locations throughout both the US and Russian segments.

The data from static deploy are an effective tool in assessing and evaluating continuous and intermittent ISS environmental noise sources. Evaluating time-stamped acoustic data helps with assessment of changes in the ISS acoustic environment over time. These static measurements can help alert our office if crew activities or tasks that exceeds 72 dBA and are not documented in the crew procedure. When this happens, these newly identified operations can be added to the NHI, and applicable hearing protection requirements will be documented for future crew task or activities.

5. CONCLUSIONS

This paper describes the ISS noise exposure monitoring program and provides an updated assessment of acoustic data collected since April 2018 (Inc. 55) up through March 2021 (Inc. 64). These data provide trending information with regards to the acoustic environment experienced by the ISS crewmembers during the work and sleep-time periods. Overall, there has been a substantial improvement in the acoustical environment on ISS since Increment 55 (2018). The measurements collected to date are highly dependent on the activities/tasks the crew was performing during their stay on ISS, whether occupational or leisure, as well as environmental conditions on ISS. The identification of the hazardous noise events has also provided valuable information with regards to the crew's noise exposure assessment. This information will help with the identification of activities or hardware performance that will require further investigation. The ISS crewmembers have several modules in which they can spend time working during the day and sleeping during the night. As we continue to use OPTimIS and gain better insight and understanding of the crewmember's timeline with regards to completed activities, we will improve our ability to associate measured acoustic data with the actual crew activities and provide a better noise exposure assessment for our crewmembers. With the understanding that crew personal activities and communications makes a significant portion of measured hazard level exceedances, and since these activities are not themselves considered hazardous, the number of hazardous noise events are significantly reduced. Future attention will be focus on the hazardous events caused by equipment-generated noise.

6. FUTURE DIRECTION

Future acoustics research for long-term exploration missions should aim at relating ISS noise exposures to both, auditory and also non-auditory effects of noise, especially how acoustic conditions can affect hearing sensitivity, human performance, sleep and crew health on the ISS. Better understanding is needed as to how to consider measuring noise in ISS for measuring subjective human responses, such as masking level differences and loudness[16]. Non-auditory health effects have been addressed as possible disruptions to crew sleep, interference with speech and communications, possible interference with crew task performance, and possible reduction in alarm audibility. However, these factors have not been formally investigated on ISS, with the exception of speech intelligibility and alarm audibility for which controls on ISS are in place to minimize the risk for adverse outcomes. Further investigation is needed to determine if there are quantifiable non-auditory effects detected by the ISS crewmembers who live and work in space for up to 6-12 consecutive months and to see how these findings can be adapted to future long-term exploration missions. To reiterate, non-auditory health effects are defined as "all those effects on health and well-being which are caused by exposure to noise with the exclusion of effects on the hearing organ"[17]. The following sections briefly highlight some findings from research studies indicating how noise can be associated with sleep disturbance, annoyance and human performance.

6.1 Noise and Sleep Disturbance

Research studies have shown that noise exposure has physiological effects, such as disruption to normal sleep cycle (longer to fall asleep, shortens deep and REM stages, daytime fatigue, insomnia, etc.), as well as next day after-effects (excessive daytime sleepiness, tiredness, reduced productivity, poor job performance, and possible risk of accidents, etc.)[18-22]. Sleep disturbance is influenced by characteristics of the noise itself (low-frequency, intermittent or even tonal) and also on the individual being exposed, such as age (as people get older, they spend less time in the deep sleep, Stages III-IV). Shiftwork is also a risk factor for sleep disturbance and other health effects. The biggest industrial catastrophes, such as the Three Mile Island, Bhopal, Chernobyl and Exxon Valdez disasters, have occurred during the night shift. The shift schedules, fatigue and sleepiness were cited as major contributing factors to each incident[23]. The equivalent LEQ8 experienced by the ISS crewmembers during the sleep time period ranged from 42 to 75 dBA, as seen in Figure 8. The sympathetic nervous system (vegetative arousal) is activated within 45-55 dBA and the awakening threshold is around 60 dBA, which is consistent with the noise levels experienced by the ISS crewmembers.

6.2 Noise and Annoyance

Guski has proposed that noise annoyance is partly due to acoustic factors and partly due to personal and social moderating variables. Annoyance brings feelings of disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, and nuisance, discomfort, etc., some of which combine to produce the adverse reaction[24]. According to the literature, annoyance is a response to noise rather than an auditory perception of it. It is mentioned that noise is more likely to be annoying if it's random in nature, high pitched, and it occurs during the sleep time period. Annoyance is classified as subjective; noise is likely to be an annoyance if perceived to be unnecessary. Data suggest that the threshold for acoustic annoyance is from 50-55 dBA. The background work-time period noise levels experienced by the crewmembers on ISS are way above the threshold level for annoyance. According to Persson-Waye et al., prevalence of annoyance and disturbed concentration and rest was significantly higher among the persons exposed to low-frequency noise as compared to controls[25-26]. Similarly, low-frequency noise was rated as significantly more annoying than broadband noise at the comparable A-weighted sound pressure levels[27]. Likewise, loudness and tonality both have a significant influence on noise-induced annoyance[28]. Noise sensitivity as compared to personal factors, had the most significant role to noise annoyance[25-26, 29-30]. Melamed et al. also reported that use of hearing protection devices was related to noise exposure level, but more so to high noise annoyance[31].

6.3 Noise and Human Performance

The effects of noise on human performance depends on the actual task which is being performed by the worker and it can affect each worker in a different way. This effect can be explained by the "Inverted-U Model" also known as the Yerkes-Dodson Law, where peak performance is achieved when workers experienced a moderate level of pressure. But when they experience too much or too little, their performance declines[32]. In this model, noise is considered to act as a biological stressor. The nature of the noise: sound level, spectrum, temporal (continuous or intermittent), speech intelligibility, etc. also effects human performance; as well as personal/individual factors of the worker. The effects on human performance can be perceived in tasks that require reading comprehension, attention span, problem solving, memorization, communication with co-workers and alarm audibility. Several studies have been performed where the nature of the noise has affected human performance and productivity. For example, Kyriakides and Leventhall reported that low-frequency noise can affect productivity, and Persson-Waye et al. and Bengtsson et al. also reported that low-frequency noise can interfere with proof-reading tasks[33-36]. It was also found that intermittent and treble noise reduces human performance[37-38]. With regards to background speech intelligibility and noises from human activities, researchers have found that it impairs short-term memory, working memory tasks, and reasoning ability, and also disrupt tasks representing office work[39-46].

Most of these non-auditory health effects discussed above can be described in a stress model as shown in Figure 15. This figure shows the principal reaction scheme used in epidemiological noise research for hypothesis testing[47]. It simplifies the cause–effect chain, that is: sound – annoyance (noise) – physiological arousal (stress indicators) – (biological) risk factors – disease – and mortality (the latter

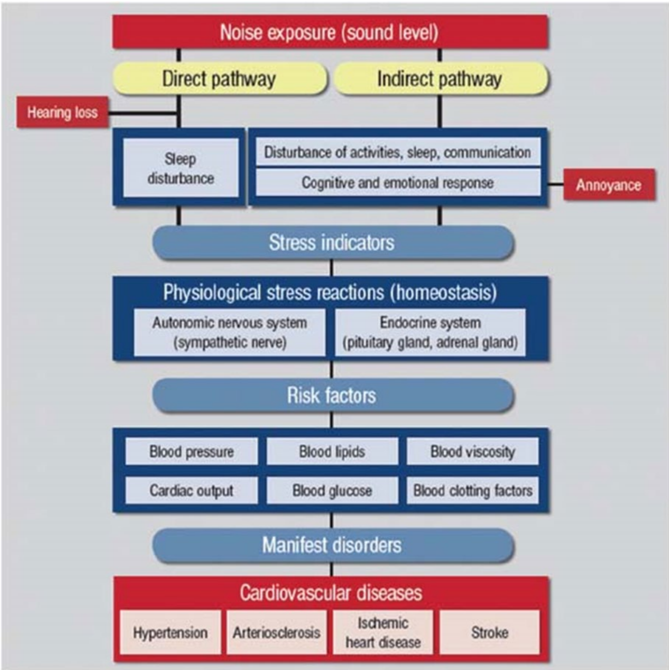

Figure 15. Noise Effects Reaction Scheme.
SOURCE: Adapted from Babisch, 2002.

is not explicitly considered in the graph). The mechanism works "directly" through synaptic nervous interactions and "indirectly" through the emotional and the cognitive perception of the sound. It should be noted that the "direct" pathway is relevant even at low sound levels particularly during sleep, when the organism is at its nadir of arousal. The objective noise exposure (sound level) and the subjective noise "exposure" (e.g. annoyance) may serve independently as exposure variables in the statistical analyses of the relationship between noise and health end points. There is a need to systematically assess causal factors, so that recommendations can be provided to mission planners, habitat designers, and trainers for exploration missions. Such a review could contribute to our understanding of whether noise exposure is a causal factor or an environmental contributor to non-auditory health effects during long-duration space missions.

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