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Assessment and Mitigation of the Effects of Noise on Habitability in Deep Space Environments: Report on Non-Auditory Effects of Noise

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January 2018

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Space Administration

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Acronyms and Definitions

<	less than
~	approximately
ANR	active noise reduction
ARAS	Ascending Reticular Activiating System
dB	decibel
dBA	A-weighted sound level
DSB	Deep Space Gateway
DST	Deep Space Transport
EEG	electroencephalogram
h	hour
HFBP	Human Factors and Behavioral Performance
HPD	hearing protection device
HRP	Human Research Program
HVAC	heating-ventilation-air conditioning system
Hz	Hertz
ISS	International Space Station
kHz	kilohertz (1,000 Hertz)
L_{day}	day equivalent level
L_{den}	day-evening-night equivalent level
L_{dn}	day-night equivalent level
L_{eq}	equivalent continuous sound level
L_{max}	maximum sound level
L_{pk}	instantaneous peak level
ms	millisecond
NASA	National Aeronautics and Space Administration
NBC	balanced noise-criterion curves
NC	noise criteria
NR	noise rating
PNC	preferred noise criteria
RC	room criteria
REM	rapid eye movement
RNC	room noise criteria
RR-measurements	respiration rate
SEL	sound exposure level
SPL	sound pressure level
SWS	slow-wave sleep
WHO	World Health Organization

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1. Application Areas of this Report

This document assesses non-auditory effects of noise relevant to habitable volume requirements in cislunar space. Challenges to NASA's future manned journeys to cislunar space and Mars are described within the Human Exploration and Operations Exploration Objectives document (NASA, 2016). Phase I of the exploration objectives call for a four-person crew to assemble and eventually occupy a module, the 'Orbital ATK cislunar habitat,' by ~2020 as part of the Deep Space Gateway (DSG) in NASA mission EM-3[1]. The objective of Phase II reflects the buildup and shakedown of the Deep Space Transport (DST) vehicle that must also support a four-person crew, up through NASA mission EM-9, by 2028–9. The DSG habitat is planned to evolve over time to a much larger research platform—by ~2024 to include a pair of modules having many of the capabilities required for supporting a human mission to Mars (Gebhardt, 2016; Cichan et al., 2017). Four astronauts are scheduled to occupy a pressurized volume of ~300 m3 for ~30–60 days during Phase I in DSG, and for up to 400 days during Phase II in DST[2].

The general health impacts of long-term habitation on humans within such confined environments have been well documented and researched by NASA (e.g., Connors et al., 1985). In space flight and habitats, the auditory effects of noise can be significant due to long-term exposure and momentary higher levels during launch, abort, and descent. The auditory effects of noise are understood primarily via analysis of crew dosimetry and acoustic measurements from within the International Space Station (ISS) and other space habitats, resulting in robust hearing conservation programs and standards that directly address noise levels known to impact health (Limardo et al., 2017).

Less understood are the non-auditory effects of noise pertinent to sleep quality, psychological well-being, cognitive performance, and team dynamics. Although auditory effects of noise are known to be highly significant, NASA needs to understand which non-auditory effects of noise are significant to mission success, which non-auditory effects have impact on crew performance, the cost-benefit of mitigation strategies, and possible needs for more detailed measurement techniques or additional standards to address significant impacts.

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[1] The Deep Space Gateway and Deep Space Transport plan relates directly to the NASA Transition Authorization Act of 2017. Under the authorization act, NASA's long term goals are: "(1) to expand permanent human presence beyond low-Earth orbit and to do so, where practical, in a manner involving international, academic, and industry partners; (2) crewed missions and progress toward achieving the goal in [paragraph one] to enable the potential for subsequent human exploration and the extension of human presence throughout the solar system; and (3) to enable a capability to extend human presence, including potential human habitation on another celestial body and a thriving space economy in the 21st Century."

[2] The pressurized volume of the DST has yet to be determined.

This document addresses the following non-auditory effects of noise: **performance-teamwork, sleep disturbance,** and **cognitive well-being**, all of which impact crew performance and readiness to perform. It reviews the relevance of research performed on earth to the space environment, the quality of the measurement metrics used, and potentially significant research gaps. Auditory effects of noise are considered to the degree that measurement metrics overlap with non-auditory effects.

The Phase 2 objective of the NASA (2016) objectives document includes the area of crew health within the broader category of "Staying Healthy" within deep space habitation. "Crew health focuses on validating crew health and performance, and mitigation protocols for Mars-class missions." Objective identifier P2-15 and P2-16 concern validating human flight operations crew physiological and psychological well-being on Mars-class missions. Non-auditory effects of noise can include effects on physiological and psychological well-being impacting the key activity periods of work, rest, and sleep. Effective communications are key to successful teamwork that requires performance efficiency and accuracy, rest periods are particularly affected by a sense of well-being, and uninterrupted sleep is a necessary component for success in all activities over the period of a long-term mission.

Two risk–gap areas identified in the Human Research Roadmap of NASA's Human Research Program (HRP) Human Factors and Behavioral Performance Element (HFBP) are addressed by this report.

- Gap HAB-01, *Risk of Incompatible Vehicle/Habitat Design:* "We need to understand how new aspects of the natural and induced environment (vehicle/habitat architecture, acoustics, vibration, lighting) may impact performance, and need to be accommodated in internal vehicle/habitat design."
- Gap BMed7, *Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders:* "We need to identify and validate effective methods for modifying the habitat/vehicle environment to mitigate the negative psychological and behavioral effects of environmental stressors (e.g., isolation, confinement, reduced sensory stimulation) likely to be experienced in the long duration spaceflight environment."

This report addresses the need to "Integrate results to quantify effect sizes and thresholds for vehicle/habitat environmental factors on human performance during long-duration missions" (HAB-01). And while current tasks address environmental aspects of lighting or sensory stimulation (NASA-HRP, 2017a, 2017b, 2017c) it is necessary to address potentially adverse psychological and behavioral effects of the acoustic environment; to review best methods for acoustic measurement; and to assess available mitigation techniques to the degree appropriate to the considered schedule.

The time period of 400 days for occupancy of the cislunar habitat for DST missions is significantly longer than the scheduled period of 60 days for DSG. Psychological and physiological impacts are highly likely to become more significant as mission duration increases. "It seems probable that some degree of performance attenuation will occur among crews isolated for long periods, perhaps owing to decrements in morale and motivation rather than to any cognitive or psychomotor deterioration. Research involving limited environments is certainly warranted in order to explore more fully just how an unchanging environment affects performance under long-term conditions" (Connors et al., 1985). Accordingly, the possible mitigation solutions proposed here apply primarily to DST missions, such as methods for modifying the acoustic environment via adaptive masking, reverberation modification, and active noise control. Research into these promising areas of acoustic development is worthwhile for NASA missions and habitats in the long term, particularly as implementation challenges become minimized.

2. Executive Summary and Recommendations

- This review indicates that for long-term missions, including the DST, there are non-auditory effects of noise potentially significant enough to require additional standards and procedures or review and enhancement of existing standards and procedures such as NASA STD-3001. This includes improved noise measurement techniques and methods for adapting the acoustic environment to enhance performance, sleep, and psychological well-being.

- For short-term missions this review indicates that most non-auditory effects of noise are not significant enough to impact performance or sleep for multi-week missions such as the Orbital ATK cislunar habitat of the DSG planned for ~2020, as long as compliance with NASA STD-3001 is maintained.

- Noise measurement (section 4). Periodic review should be made of NASA standards with respect to the continual evolvement in the scientific literature of how best to measure noise in a manner that corresponds to subjective response. This includes measurement techniques that take into account psychoacoustic factors such as masking level differences and loudness (Moore, 2012; ISO 2017a, 2017b). Ground-based research will be required to assess how psychoacoustic measurements can better predict and quantify the non-auditory effects of noise in space environments.

- Noise measurement (section 4). When using noise criteria specifications, the spectrum of background noise should be adjusted so that is balanced (i.e., without any significant frequency bands that rise above other bands) in line with ANSI standards for measurements of Room Criteria (RC) (ANSI, 2008). The use of RC as opposed to Noise Criteria (NC) measurements should be evaluated in updates to NASA standards to account for low frequencies and tonal components of noise that can impact sleep, performance, and psychological well-being.

- Performance (section 5). There are significant practical challenges for bringing continuous noise levels in spacecraft work areas within the NASA STD-3001 specification of NC levels of NC-50 (Broyan et al., 2010; Allen et al., 2016). Nevertheless, research results indicate that individual and team performance would be enhanced if levels could be further reduced to levels recommended for open-plan offices, NC-40 (GSA, 2011). This allows for a balance between maintaining speech privacy (reduction of irrelevant speech and noise to minimize distraction) and enhancement of team communications.

- Sleep quality (section 6). Ideal noise level limits for sleep conditions are cited as 35 dBA L_{eq} in the literature and are ~10 decibels lower than the current NASA STD-3001 requirement of NC-40 (equivalent to 45 dBA L_{eq}) for sleep quarters. Long-term missions should explore the possibility of additional noise reduction in sleep quarters, to the degree practical. Hearing protection devices (HPDs) such as polyurethane foam earplugs can provide additional attenuation to meet a 35-dBA goal for mid-band and high-band frequencies at the ear. The masking of auditory alerts requiring attention by the use of HPDs should also be considered, including augmentation by tactile-vibratory or lighting cues. Arousal from sleep by alarms is a function both of the depth of sleep and individual differences; multi-sensory alerts may be a more reliable form of arousal compared to purely acoustic alarms (Caddick, 2017).

- Psychological well-being (section 7). The current practice of establishing sound isolation for sleeping and crew quarters, combined with the allowance of personal sound devices such as music players and hearing protection devices, will allow astronauts to maintain a sufficient degree of perceived control over their acoustic environment, thereby augmenting cognitive well-being. The types of headphones used for personal sound devices should be considered for their ability to act simultaneously as a HPD. Impacts of personal sound devices on allowable noise dosage should be assessed.

- Psychological well-being (section 7). The monotony of a confined environment with constant background noise can be mitigated via inexpensive, low-power signal processing technologies, particularly for headphone delivery. Customized sound masking systems, circadian sound cueing, entertainment or exercise systems that include virtual sound for increased immersion, and acoustic environment modification are possible technologies that should be explored. The sound quality and wearing comfort of these systems should be specified to insure ease of use.

3. Overview of Non-Auditory Health Effects of Noise

Noise is defined technically either as: 1) a sound with a random frequency content without discernable tones; or 2) a disagreeable or unwanted sound (Harris, 1991). The ‘unwanted’ aspect can be both psychological or with reference to physiological harm. The focus of this report is primarily on unwanted sound (which may or may not include tonal components, speech, and/or random frequencies). Consideration of benign or even advantageous effects of noise will also be considered.

Noise requires special consideration in the confines of space habitats due to limited space, close proximity to other humans, and the need for optimal performance in a high-stress human-machine environment. Even with hearing protection, there is no way to truly ‘escape’ unwanted sound. Strategies and requirements are necessary not only to optimize performance but also to mitigate the psychological effects of annoyance that can impact well-being and have cross-effects on performance and health.

With regards to unwanted sound, laboratory and animal experiments have long indicated the relationship between noise, physiological stress, and hypertension, including long-term effects of disturbance of nighttime rest. When coping capacity is exceeded in the long term, permanent effects on hypertension and other forms of cardiovascular disease can occur.

Figure 1 provides an overview of both auditory and non-auditory effects of noise and human response (Babisch, 2002; Babisch et al., 2010). The direct pathway accounts for hearing loss and the effect of noise as a physiological stressor over long time periods. Substantial research has established correlations between long-term noise exposure and cardiovascular disease, endocrine responses, and psychiatric disorder (Babisch et al., 2010; WHO, 2011).

The indirect pathway of Figure 1 is shown to have areas of cognitive as opposed to physiological response: disturbance of activities, sleep, communication; cognitive and emotional response; and annoyance. These non-auditory effects of noise contribute to overall health as defined by the World Health Organization (WHO): “health is a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity" (WHO, 2009). These factors are also the root causes of decrements in performance-teamwork and sleep disturbance.

The direct and indirect pathways converge towards levels of physiological stress reaction and risk factors associated with the long-term effects of noise. Support for long-term stress-related physiological and cardiovascular effects are typically based on correlational data over a period of several years or decades (WHO, 2011) and are not considered directly relevant to DSG or DST missions.

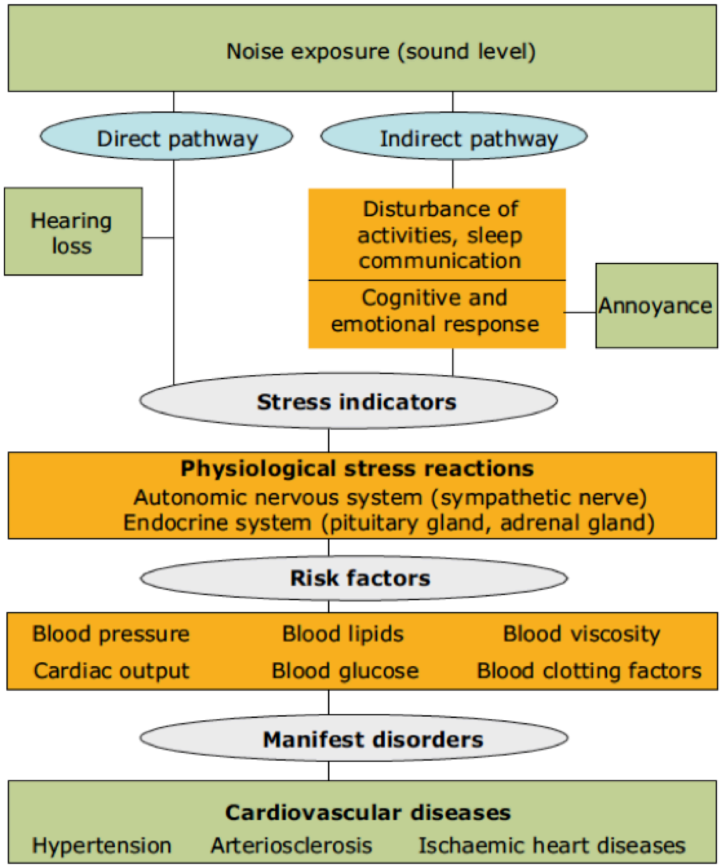

Figure 1. Noise effects and pathways considered in research (Babisch, 2002; Babisch et al., 2010).

Non-auditory effects of noise can impact autonomic function. Figure 2 shows connections between the auditory system and the neural-muscular-glandular systems of the body, including the autonomic system. The connection between neural and sympathetic nervous system below the brain is thought to explain immediate human response to the environment not requiring conscious thought processes. For example, the acoustic startle reflex to a loud unexpected sound can concurrently cause physical reflex actions that include allocation of attention to the source, a 'fight or flight' hormonal reaction, and activation of a stress response in the sympathetic nervous system (Martin et al. 2016). The fact that autonomic reactions to noise can cause psychologically stressful emotions (fear, anger, loss of control) has been demonstrated to require conscious or unconscious cognitive processing.

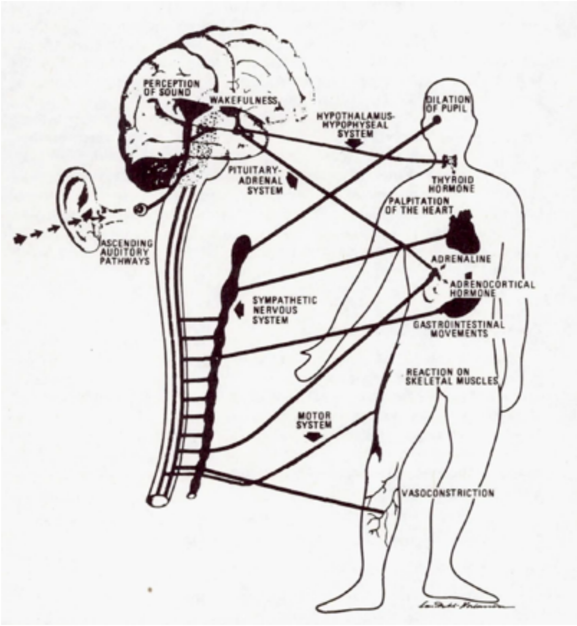

Figure 2. Connections between the auditory system and the neural-muscular-glandular systems (adapted by Kryter, 1984).

Published reviews of non-auditory effects of noise include both animal and human studies that focus on a range of physiological and cognitive effects, including from unusually high levels of noise exposure (Borg, 1981). Other reviews have focused on performance and social effects (e.g., Cohen & Weinstein, 1981). Recent studies have focused more on the role of acoustics and performance in 'healthy buildings' for workplaces and in the general built environment, including open-plan office designs (e.g., GSA, 2011).

Current recommendations and standards for open-plan offices include acoustic mitigations for noise intrusion and diminished speech privacy (GSA, 2014). With the recent popularity of open-plan office design, there has been an increase in research, primarily survey data, of employee satisfaction. Most of these studies rate acoustic factors (speech privacy and noise) as overwhelmingly the most significant area requiring improvement (Salter et al., 2003; Saval, 2016). In one study, the benefits of enhanced 'ease of interaction' were smaller than the penalties of increased noise level and decreased privacy resulting from open-plan office configuration (Kim & de Dear, 2013). Research has also been conducted on diminished cognitive performance and efficiency in noisy work environments as well as effects on overall health such as risk factors for musculoskeletal disorder from diminished postural adjustment (Evans & Johnson, 2000).

In one sense, the shared workspaces of a space habitat present the same acoustical challenges as an open-plan office. The needs for worker communication, privacy, and collaboration are similar but exist in a more confined environment with excessive noise levels. For example, the background noise level specified in NASA STD-3001 or within the International Space Station exceeds that recommended for open-plan offices. Assessment of the impact of non-auditory effects of noise in space habitats can potentially benefit from open-plan office research to assess potential cognitive and performance impacts and recommended noise levels.

4. Noise Measurement and Standards

Acoustical engineering has long established several useful objective measures of sound pressure level as a function of time and frequency content. Such measures can be easily used to measure compliance with ordinances, codes, or standards.

How effective these measurements are at making predictions of human response depends on context and the specificity of the human response to be studied. “From the scientific point of view the best criterion for choosing a noise indicator is its ability to predict an effect” (WHO, 2009). For example, to assess long-term cardiovascular disorders, an average noise exposure over the period of a year may be relevant, while sleep disturbance may be better predicted by exposure to short term impulse levels on the order of 35 ms or less.

Sound pressure level (SPL) is measured in decibels, a logarithmic unit that describes a ratio between a measured level and a reference level (0 decibels). The reference level of 0 decibels corresponds to a sound pressure of 20 micropascals, roughly the threshold of hearing. The threshold of pain and for potential hearing damage is 140 decibels. Normal speech at one meter distance has a level of ~58 decibels and shouted speech has a level of ~88 decibels at the same distance.

It is common in acoustical engineering to evaluate noise as a function of its frequency spectrum, within ranges referred to as “frequency bands.” These bands are typically in ranges of one octave or one-third-octave, where an octave represents a doubling of frequency. Additional background can be found in many texts, including Harris (1991).

Common objective acoustic measures pertinent primarily to sleep effects include the following:

- The *equivalent continuous sound level* (L_{eq}); an *average* level over a stated period of time.
- The *day equivalent level* (L_{day}); an A-weighted, average level, measured over the 12-hour period 0700–1900 hours.
- The *day-night equivalent level* (L_{dn}); an A-weighted average level measured over the 24-hour period, with a 10-dB penalty added to the levels between 2300 and 0700 hours.
- The *day-evening-night equivalent level* (L_{den}); an A-weighted average level measured over the 24-hour period outdoors, with a 10-dB penalty added to the levels between 2300 and 0700 hours and a 5-dB penalty added to the levels between 1900 and 2300 hours to reflect peoples’ extra sensitivity to noise during the night and the evening.
- The *sound exposure level* (SEL); similar to L_{eq} except that the measurement is normalized to reference duration of one second. SEL is the constant sound level that has the same amount of energy in one second as the original noise event.
- The *maximum sound level* (L_{max}); the maximum sound pressure level measured during a specified time period, using a specific frequency and time weighting constant (e.g., 125 milliseconds).
- The *instantaneous peak level* (L_{pk}); the maximum sound pressure level measured in an interval of 40 microseconds or less. This is the preferred method for measurement of impulsive sounds such as explosions or impacts that may cause hearing damage.

Acoustic measures are calculated in terms of frequency and time weighting factors:

- *A-weighting*: sound pressure as a function of frequency adjusted to correlate with human response to loudness at a relatively low level. Indicated specifically as dBA; sound levels reported here can be assumed to be A-weighted unless otherwise indicated.
- *Slow time weighting*: sound pressure values are integrated in intervals of 1 second.
- *Fast time weighting*: sound pressure values are integrated in intervals of 0.125 second.
- *Peak sound pressure*: the maximum instantaneous value within a specified time range.

Figure 3 shows typical temporal characterizations of noise. Steady-state noise (upper left) has a constant level over time. An example is the air turbulence and fan noise of an heating-ventilation-air conditioning (HVAC) system that is constantly running, e.g., in a space flight vehicle. Intermittent noise (upper right) is usually caused by a sound source that switches on for durations of several seconds or minutes and then switches off, leaving intervals of background noise. An example would be a pump or a chiller unit that switches on as needed by the system. Time-varying noise (lower left) is caused by a sound source that changes spectrum and level over its duration. An example would be a motorized grinding tool that progressively pulverizes an object. Impulsive noise (lower right) is characterized by brief duration sounds that are significantly higher than a background level. An example would be a riveting tool, an impact between objects, or the discharge of a halon fire suppression system in spacecraft.

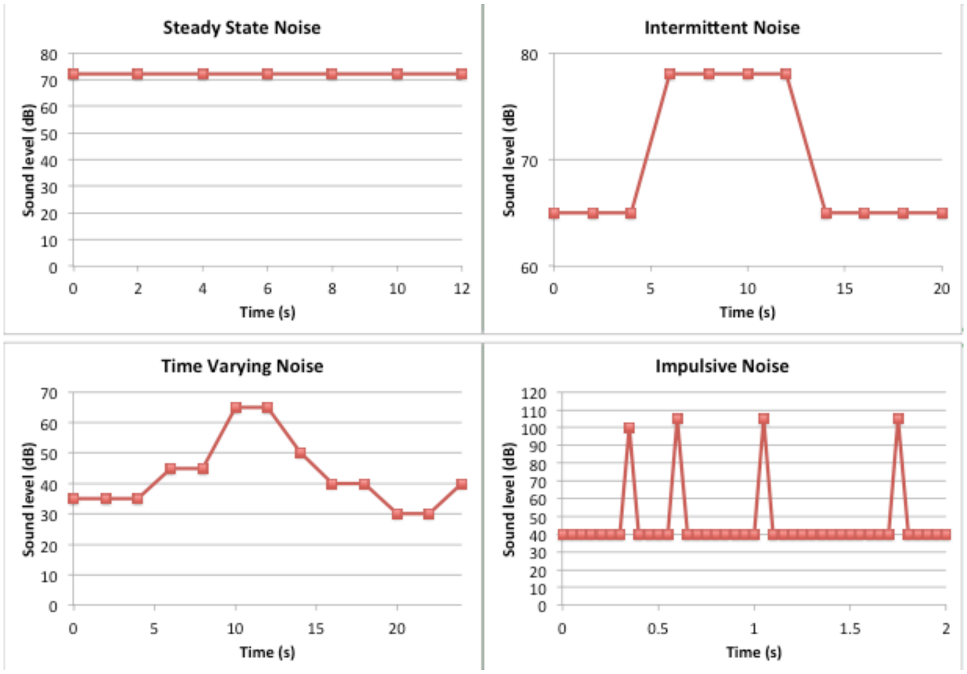

Figure 3. Temporal characterization of noise.

Intermittent noise is defined as a sound level from a source that cycles between minimum and maximum values over a relatively brief period of time, with a period generally longer than one second. The actual time period is not strictly defined but it typically occurs frequently enough so that the cycle is perceivable. An alternative definition is "a significant noise source that exists for a cumulative total of less than 8 h in any 24 h period" (Allen et al., 2016). Very brief duration noises such as impacts or knocking sounds may have intermittent characteristics, but are analyzed as *impulse noise* since they are of brief duration and have particular impacts on auditory health.

The following generalizations have been made regarding the temporal aspects of noise and related psychoacoustic effects (Kryter, 1984): 1) frequency weighted (e.g., dBA) measurements integrated over one second (slow weighting) are good predictors of loudness; 2) loudness of impulsive and non-impulsive sounds do not increase as a function of durations over one second; and 3) the annoyance from impulsive sounds increases beyond one second on an integrated energy basis.

From the standpoint of the non-auditory effects of noise discussed here, human response is not always predictable for a given sound level measurement. Although prediction of sleep disturbance is often cited as correlated to measurements of sound pressure level, individual reactions can vary as a function of habituation and individual sensitivity. To the degree that speech communication is masked by noise, degradations in teamwork can be predicted to some extent, but not individual performance. Cognitive associations with the source of a noise can influence response within a wide range of sound levels.

Significantly, the acoustic measurements listed here do not include significant psychoacoustic measures or considerations of intermittency, in spite of their application to non-auditory noise effects.

- A-weighting accounts for perceived loudness only for specific conditions. It does not account for temporal effects that affect loudness or the non-linear relationship between sound pressure level and loudness as a function of frequency.
- More accurate methods of calculating loudness such as specified in standards ISO 532-1 and ISO 532-2 (ISO 2017a, 2017b) are not typically used in environmental noise analysis, thereby reducing the applicability of findings based strictly on unweighted or A-weighted measurements for habitability considerations.
- The phenomenon of auditory masking is also not accounted for. Masking refers to the process by which the sound pressure level threshold for a particular sound is raised by the presence of another sound (Moore, 2012).
- Recent research on hearing loss cites evidence that intermittent noise, or impulsive sound superimposed on a background of continuous noise, can be more damaging than "pure" Gaussian continuous noise (Suter, 2017). The use of an acoustical kurtosis metric to assess intermittent or impulsive sound levels in consideration of the baseline background noise level is recommended. It is likely that such measures would also better predict non-auditory effects of complex noise as well.

The literature has provided targets for acoustic specifications for various criteria. Table 1 illustrates levels summarized by Babisch et al. (2010). Equivalent average A-weighted noise level recommendations in the literature cite 30–35 dB in sleeping quarters (Marks & Griefahn, 2007; WHO, 2009) and 45 dB for work areas (GSA, 2011).

Table 1. Noise Measurements and Thresholds Associated with Evidence from the Literrature*

Effect	*Dimension*	*Acoustic Indicator*	*Threshold*	*Time Domain*
Annoyance disturbance	Psychosocial quality of life	L_{den}	42	Chronic
Self-reported sleep disturbance	Quality of life, somatic health	L_{night}	42	Chronic
Learning, memory	Performance	L_{eq}	50	Acute, chronic
Stress hormones	Stress indicator	L_{max} L_{eq}	NA	Acute, chronic
Sleep (polysomnographic)	Arousal, motility, sleep quality	$L_{max,\ indoors}$	32	Acute, chronic
Reported awakening	Sleep	$SEL_{indoors}$	53	Acute
Reported health	Wellbeing clinical health	L_{den}	50	Chronic
Hypertension	Physiology somatic health	L_{den}	50	Chronic
Ischaemic heart diseases	Clinical health	L_{den}	60	Chronic

* Pertinent measurements outlined in red. Adapted from Babisch et al. (2010).

NASA standard STD-3001 addresses noise primarily from the standpoint of hearing conservation and speech communication and secondarily from the standpoint of non-auditory acoustic effects (NASA, 2011). Requirements are specified for establishing an acoustic noise plan and verification of requirements via test of flight hardware. Special consideration is given for noise limits for launch entry and abort since these phases of flight can have hazardous levels. Hazardous noise limits for on-orbit, lunar, and extraterrestrial operations are limited to 85 decibels for communications and maintenance activities.

Section 6.6.2.6 “Continuous Noise Limits” of NASA (2011) indicates levels most pertinent to non-auditory effects of noise. The *long-term average* noise level within spacecraft and space habitats during orbit is quantified in terms of its *Noise Criteria* (NC) level. This level is based on a spectral analysis of noise in octave bands spanning from 63 Hz to 8 kHz.

Figure 4 shows noise criteria curves ranging from NC5 to NC65. The level of noise is measured in one-octave or one-third-octave bands; the lowest NC curve that is not exceeded by this spectrum constitutes its NC level rating.

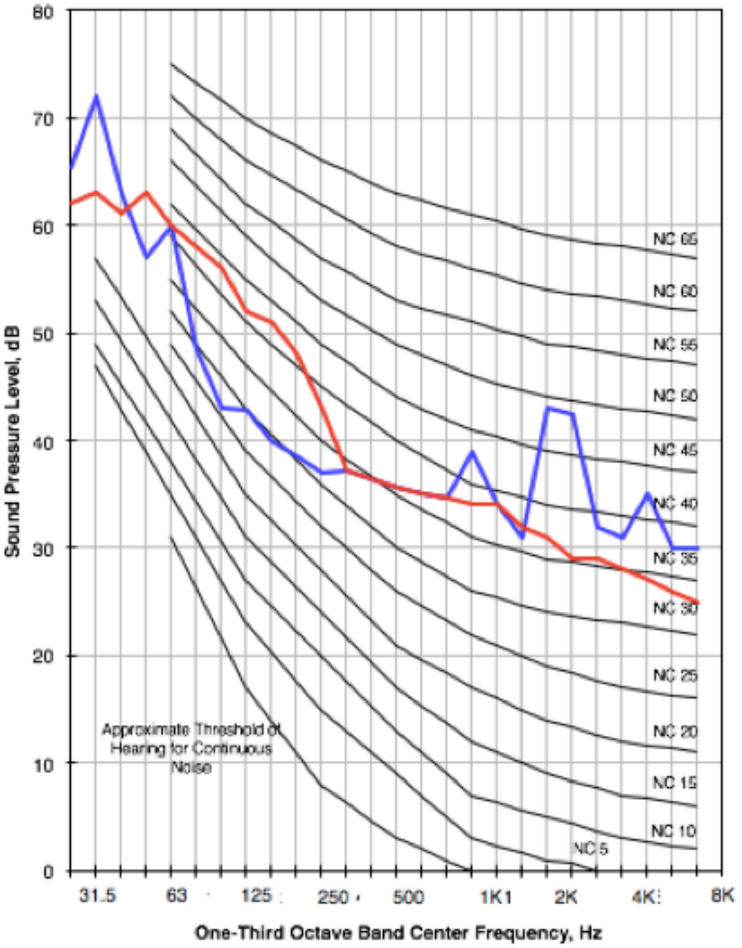

Figure 4. Noise Criteria curves and data. Two noise spectra with value of NC ~48 shown in red and blue.

NASA standard STD-3001 specifies a limit of NC-50 for spacecraft work areas and NC-40 for crew quarters and sleep areas (NASA, 2011). This applies to continuous noise produced by sources such as HVAC systems, and does not apply to communications, alarms, or maintenance activities.

Two examples of a noise spectrum are plotted (in red and blue) that both have a level of approximately NC-48. Both noise spectra would be within the NASA standard specification but would have significantly different subjective reactions. The spectrum plotted in red is typical of HVAC systems in homes; it has a smooth contour and lack of any obvious spectral peaks and therefore would be referred to as a ‘balanced’ spectrum (Harris, 1991; ANSI 2008). The blue spectrum, on the other hand, has a spectral peak in the region of 2 kHz and 31.5 Hz. These peaks would cause noise to be perceived as more disturbing.

Several alternatives have been proposed in the literature as alternatives to NC level that are closer to predicting subjective reaction. These levels include *Noise Rating* (NR) (ISO, 2016); *Room Criteria* (RC) (ANSI 2008); *Room Noise Criteria* (RNC) (ANSI 2008); *Balanced Noise-Criterion Curves* (NCB); and *Preferred Noise Criteria* (PNC). These ratings account for wider frequency ranges and for unbalanced spectra; for instance, the RC rating method would account for 'hiss' (excessive noise in high frequency bands at and above 1000 Hz) for the blue line spectrum shown in Figure 4.

NC-50 is approximately the threshold for normal speech levels for face-to-face communication and would be considered as marginally acceptable for the acoustical design of a factory, but would be in excess of the recommended NC 40–45 level for restaurants or a large public office and NC 30–35 for a private office (Blazier, 1991). There are practical limits to noise control engineering approaches to space habitat noise, driven both by volume and air handling requirements (Allen et al., 2016).

The actual NC level can vary within multi-module space habitats depending on various infrastructure requirements. Figure 5 shows the NC levels throughout various modules (other than sleep quarters) in the International Space Station (Allen et al., 2016). The average level is NC-53 but ranges from NC-42 (in the airlock) to NC-63 (within the MRM-1 "mini research module" of the Russian Orbital Segment).

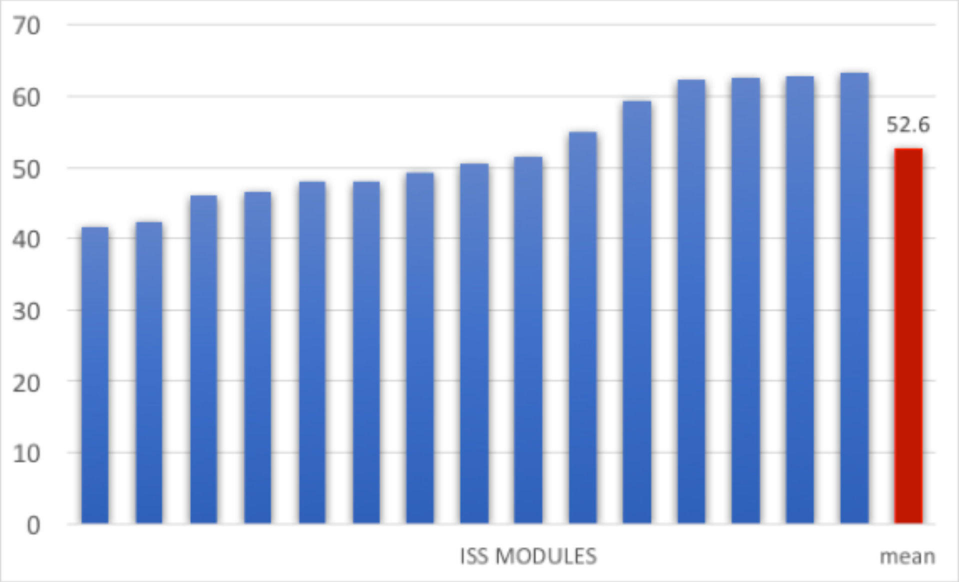

Figure 5. Noise Criteria values within ISS. Adapted from Allen et al., (2016).

NASA standard STD-3001 considers the effect of noise on performance and teamwork principally for speech communication and alarm intelligibility. Exceptions are the "impulse annoyance limit" for sleep and the "narrow-band noise limits" to prevent "irritating and distracting noise conditions, which could affect crew performance." These requirements are itemized as follows:

- 6.6.2.10 Impulse Annoyance Limit [V2 6082]

  With the exception of communications and alarms, the system shall limit impulse noise levels at the crewmember's head location to 10 dB above background noise levels during crew sleep periods.

  Rationale: Impulse noise is to be limited to less than 10 dB above the background noise to avoid waking crewmembers who are sleeping. Communications and alarms are not subject to this requirement.

- 6.6.2.12 Narrow-Band Noise Limits [V2 6084]
  The maximum SPL of narrow-band noise components and tones shall be limited to at least 10 dB less than the broadband SPL of the octave band that contains the component or tone.
  Rationale: Narrow-band noise component and tone levels should be limited to 10 dB below the broadband level to prevent irritating and distracting noise conditions, which could affect crew performance.

These requirements and their stated rationales address important non-auditory effects and could possibly be augmented in the future by other similar requirements as better understanding evolves in the psychoacoustic literature as how best quantify the relationship between noise levels and subjective response. For larger habitats comprised of modules with different defined functions (e.g., exercise, eating, sleeping, lab work, communications) it may also be possible to tailor background noise levels to optimize performance or psychological well-being for the particular function of that module. (Currently, a distinction is made primarily between sleep and non-sleep environments.)

5. Non-Auditory Effects of Noise Pertinent to Individual and Team Performance

Individual performance in the context of noise research is defined in various ways, and can refer to: perceived annoyance that impacts work; changes in perceived workload; degradation or enhancement of cognitive capability; and impacts on collaborative tasks.

Teamwork includes all of these aspects and considers how to optimize collaborative as well as individual performance (Holland, 1999). The nature of teamwork has also been described as ‘collective cognitive work’ that ideally is supported by a system of features that aid awareness, interaction, and collaboration (Heerwagen et al., 2004, 2006).

The challenge for supporting both individuals and teams requires reducing distractions such as speech noise that affect individual performance, without simultaneously affecting the benefits of interaction and communication (GSA, 2011). Both performance and satisfaction are subjectively rated higher in private versus shared spaces for individual tasks (Block & Stokes, 1989). Concurrent teams working on different projects would likely benefit from “privacy” of the individual teams from one another.

In space habitats, the effect of noise must be viewed for both negative and positive effects that can affect a highly motivated crew who must work efficiently and accurately—both individually and in teams. The tasks that must be accomplished include both nominal and off-nominal time-critical situations. The limited space constrains the physical possibility of private spaces other than sleep areas.

5.1 Research Outcomes

The effect of noise on performance is characterized in the literature by studies focusing on specific types of noise and controlled tasks performed in the laboratory. The following itemizes research findings of tasks detrimentally affected by either continuous or intermittent noise:

- Although habituation can minimize the effects of a continuous noise, novel or unexpected changes to the character of a noise interferes with efficiency upon initial presentation, for durations of 2–30 seconds (Jones & Broadbent, 1991).

- Intermittent noise (noise with temporal variations in the noise signal) has a greater effect on performance than continuous noise (Fisher, 1972; Cohen & Weinstein, 1981; Jones & Broadbent, 1991). Definitions and quantification of noise intermittency vary in the literature for both auditory and non-auditory effects (Suter, 2017). Jones & Broadbent (1991) conclude that the change in level of the stimulation (level of noise present versus absent) is the primary effect on performance.

- Under conditions of noise, multiple source tasks cause increase attention towards a primary task but degradation in performance on a secondary task (Boggs & Simon, 1968). A low priority task may be responded to more slowly or missed (Jones & Broadbent, 1991). Loeb & Jones (1978) found that subjects opted for meeting the demands of a simpler task at the expense of a more complex task, with a degradation in target detection and an increased false alarm rate. These results have implications for the phenomenon of attentional tunneling (a.k.a. cognitive fixation), defined as "the allocation of attention to a particular channel of information, diagnostic hypothesis, or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks" (Wickens & Alexander, 2009).

- Speech noise can have a detrimental effect on the processing capability for reading and for the performance of work, even at normal conversational levels (Jones & Broadbent, 1991). Speech noise is more detrimental to complex than simple tasks (Jones & Morris, 1992). Whether or not the speech is intelligible is insignificant, but the detrimental effect exceeds that for an equivalent constant noise (Jones et al., 1990). Research into open-plan offices show that a lack of speech privacy (degree of speech noise from persons other than the workers themselves) causes distractions that cause shifts in attention and reduced focus, increased efforts to concentrate thereby exacerbating stress levels and fatigue, and the need to re-orient, particularly for complex cognitive tasks (Lahlou, 1999; GSA, 2011).

- Tasks involving vigilance, such as detection of a sequence of numbers, can be detrimentally affected at higher levels of noise (80–85 dB), depending on likelihood, training, and the type of signal (Jones & Broadbent, 1991; Smith 1991). Focused attention tasks are affected more than search tasks (Smith, 1991). Noise increases workload due to an increased need for focused attention to cut out irrelevant stimuli (Cohen & Spacapan, 1978) and can alter task completion strategies (Smith & Broadbent, 1981).

- Noise masking of speech communications or acoustic cues from effectors such as switches or controls can have significant effects on performance (Poulton, 1976a, 1976b, 1978). Timely reaction to alarms or communication signals can be impacted by the masking effect of noise.

- The masking of 'internal dialogue' can hamper performance where short-term memory is required (Poulton, 1976b).

- Aftereffects of both intermittent and constant noise on performance following its cessation have been found—similar to the aftereffects of exposure to electric shock, social density, or cold pressor (Cohen, 1980). The ability of subjects to control the source of a noise — including termination, initiation, and choice—helps to mitigate the effect (Sherrod et al., 1977).

- Noise that produces an acoustic startle reflex can impair aeronautic performance under some circumstances for up to 30 seconds without familiarization training (Martin et al., 2016).

The following summarizes main outcomes of the research for tasks that are either unaffected by noise or where performance improves:

- Undemanding tasks under conditions of expected and familiar noise are unaffected (Jones & Broadbent, 1991; Tafalla & Evans, 1993).
- Reaction times and accuracy for easily visible stimuli are unaffected (Jones & Broadbent, 1991).
- Visual tasks depending on acuity, distance judgments, eye movement and focus are unaffected (Cohen & Weinstein, 1981).
- Haptic performance is unaffected (Harris, 1973).
- There is an arousal effect of intermittent or continuous noise that can improve performance or vigilance (Poulton 1976b, 1978).

5.2 Discussion

Heerwagen et al. (2006) describes performance-teamwork in the context of a model of "cognitive workplace" that facilitates "the development, sharing and application of thoughts ideas and knowledge stored in individual minds." They examine the impact of the work environment on attention and point out that a supportive work environment should not only mitigate distractions and interruptions but also provide for relief means to establish attentional recovery. This implies that acoustic environment of space habitats should not only support team interactivity through ease of speech communication but also allow for acoustic privacy.

Poulton (1978) contributed a composite theory on the negative and positive effects of noise on performance. "The four main determinants are: 1) masking, both of acoustic cues and of inner speech; 2) distraction; 3) a beneficial increase in arousal when the noise is first switched on, which gradually lessens, and falls below normal to produce a decrement in performance when the noise is first switched off; and 4) positive and negative transfer from noise to quiet…Negative transfer results from the techniques of performance used in noise to counteract the masking or distraction, when they are not appropriate in quiet." By "masking of inner speech" Poulton refers to interference of short-term verbal working memory, i.e., internal verbalization of words or numbers in a specific task (Kryter, 1984).

The positive or negative effect of noise on task performance (speed or accuracy) depends on the type of task, the level of cognitive load, and its complexity. Generally, the more complex the task the greater the negative effect of noise. The character of the noise (continuous or intermittent), its frequency content, and its meaning to a listener can also differentially affect task performance.

In continuous noise, performance may improve initially because of an increase in arousal. If performance is disrupted by the masking of audible feedback or inner speech, the initial improvement in continuous noise may become a decrement as arousal falls and no longer compensates for the masking. If the noise leaves a detrimental aftereffect, it may be due to a fall in arousal to below normal when the noise is first switched off. In tasks that involve inner speech, asymmetric negative transfer between continuous noise and quiet can be accounted for by the carryover, respectively, of articulatory and echoic rehearsal (Poulton, 1979).

Several reviews of the effect of noise on performance of non-auditory mental and psychomotor tasks have concluded that experimental results are inconsistent when attempting to cite inherent physiological or psychological responses (Kryter, 1984; Borg, 1981; Cohen & Weinstein, 1981; Jones & Broadbent, 1991). In summarizing the state of research at that time, Kryter (1984) stated that conclusions showed that "noise can have a positive effect, no effect, or a negative effect on performance of non-auditory mental and psychomotor tasks," while recognizing that real-world tasks are more complex and usually never strictly auditory as in the reviewed controlled experiments. Meaning or associations of the causation of noise can arouse emotions that create psychological and physiological stresses with consequent adverse effects on work performance. There are also potential positive effects but these appear to be related to personal taste, auditory fatigue, and the particular work task.

One type of meaningful noise with potentially positive or negative effects is music. Music has been suggested for some time in the literature as a facilitating factor for motivation and healing (Burris-Meyer & Cardinell, 1945). Diserens & Vaughn (1931) wrote that music "tends to delay fatigue, speed up voluntary activities, increase the extent of many muscular reflexes...music must set free a certain amount of energy which augments the primary drive involved in concomitant activities." More recent research has found music to improve performance in high-stress situations in the operating room, depending on the preference of the surgeon (Allen & Blascovich, 1994) and the role and specialty of the doctor (Yamasaki, et al., 2015).

The Muzak corporation[3] is well known for its role in creating prevalence of background or 'elevator music' in a variety of commercial spaces to create involuntary emotional reactions. As of 2006 it was estimated to have approximately 100 million daily listeners, most of whom are not directly aware of what they listening to (Owen, 2006). Muzak trademarked the concept of "stimulus progression" for using 15-minute cycles of increasing intensity in its background music to improve worker performance. The modulation of intensity was primarily tied to the pulse rate (tempo) of the music. Much of the internal research underlying claims of improved performance are of questionable scientific validity (Lanza, 2004; Owen, 2006).

The military has long used music as a motivating force in battle, from bagpipes to hard 'metal' rock or other contemporary styles. Alternatively, both police and military agencies have used music or noise as both a positive or negative influence as part of psychological operations. The use of popular songs played at loud volumes include the attempted extraction of Manuel Noriega from the Vatican mission in Panama City in 1989 by the U.S. Army and, more recently, loudspeaker arrays used in the Korean Demilitarized Zone (San-Hun, 2015; Goodman, 2010). Other applications include the use of easy-listening music to soothe suspects or to irritate younger persons who might otherwise loiter at locations such as convenience stores (Vinciguerra, 1997).

The evidence appears to support the fact that personal choice in musical stimuli is fundamentally important and that there are strong personal likes and dislikes for different types of music. Privacy and individual sensitivities can be insured through the use of headphones, as opposed to loudspeaker playback in shared spaces. Caution must be given to the use of music in the confined environment of space habitats in that headsets or 'ear buds' can have a degree of acoustical leakage that might be perceived by other occupants. Also, consideration of the use of music must assess any negative impacts to situational awareness, speech intelligibility, or the total allowable daily noise dose.

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[3] Currently rebranded as Mood Media.

6. Noise Effects on Sleep Quality

Sleep deprivation and degraded sleep quality are understood to have multiple impacts on overall health and performance in space habitats. NASA has examined multiple factors that impact sleep, including the volume of sleep chambers, privacy, temperature, lighting, odor, and noise (Stilwell et al., 1999; Caddick et al., 2017).

Noise can have both positive and negative impacts on sleep. Noise can cause awakenings or, conversely, can provide masking from sounds that could cause a startle effect or a cognitive reaction. The vast majority of research on noise and sleep has been traditionally motivated by studies of community noise disturbance focusing on the impact of ground transportation sources (trains, automobiles, trucks), construction noise, and aircraft flyovers (EPA, 1974). More recently, the effect of noise on sleep quality has been viewed in terms of long-term health effects and learning (WHO, 2009, 2011).

Typical metrics for quantifying environmental noise for compliance with regulations and standards related to sleep disturbance was introduced in section 4, such as L_{den} and L_{night}. The fact that these measures do not account for psychoacoustic phenomena such as masking level differences or loudness was cited in that discussion. As a result, there is only an indirect relationship between objective measures of noise and sleep. For example, L_{max} and SEL measurements given for a specific time period potentially obscure the number of events contributing to awakenings (WHO, 2009).

Table 2 summarizes both short- and long-term effects of sleep deprivation (WHO, 2009). Most of the short-term behavioral and cognitive effects listed in the second column are pertinent to the Orbital ATK cislunar habitat. This includes behavioral effects of sleepiness, mood changes, irritability-nervousness, and impairment of cognitive function that can further impact performance and psychological well-being in space habitats. The neurological, biochemical, and immune function impairments from long-term effects of noise are not considered relevant for short-term missions.

Table 2. Short-Term and Long-Term Effects of Sleep Disruption

Type	*Short-Term*	*Long-Term*
Behavioural	• Sleepiness • Mood changes • Irritability and nervousness	• Depression/mania • Violence
Cognitive	• Impairment of function	• Difficulty in learning new skills • Short-term memory problems • Difficulty with complex tasks • Slow reaction times
Neurological	• Mild and quickly reversible effects	• Cerebellar ataxia, nystagmus, tremor, ptosis, slurred speech, increased reflexes, increased sensitivity to pain
Biochemical	• Increased metabolic rate • Increased thyroid activity • Insulin resistance	• Decreased weight despite increased caloric intake (in animals) • Diabetes, obesity (in humans)
Others	• Hypothermia • Immune function impairment	• Susceptibility to viral illness

Humans react and evaluate sound even while asleep, likely as a survival mechanism (Basner, 2012). Figure 6 gives a simplified description of human reaction to external stimuli such as noise. This is understood to be an arousal function of the body's Ascending Reticular Activating System (ARAS). Auditory information is relayed through the thalamus, which gates information to the cortex based on sensory and central nervous system input. When acoustic information is passed on to the cortex, a cortical arousal can occur that can change or disturb sleep. Arousals can include a sleep stage shift, conscious awakening, or vegetative arousals such as increase in heart rate or blood pressure.

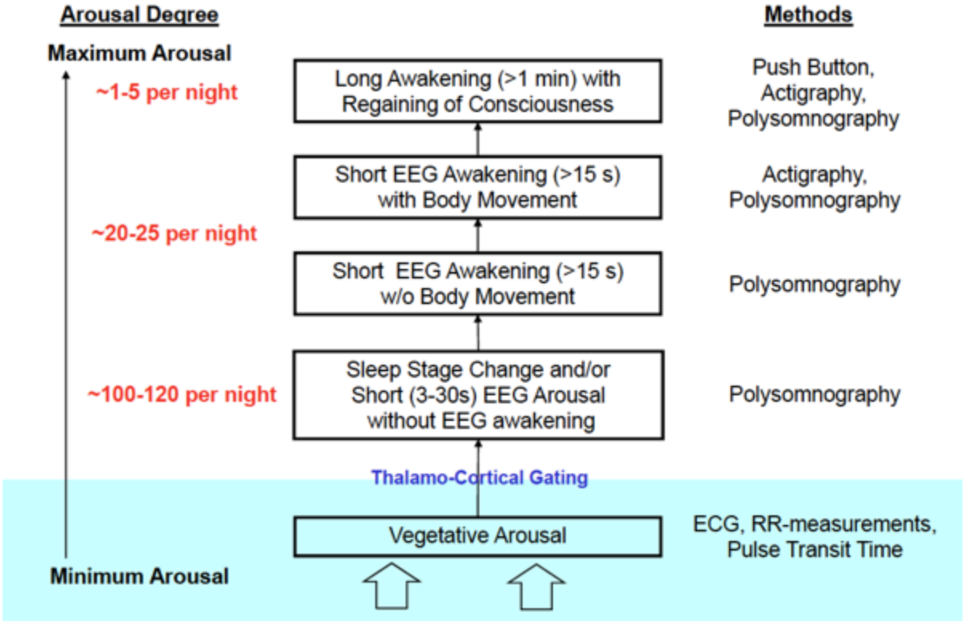

Figure 6. Short-term and long-term effects of sleep disruption and methods of measurement. Basner (2012a).

Two basic effects of noise on sleep are as follows:

- The concept of 'sleep quality' is typically referenced in terms of a proper balance of different sleep epochs (stages 1–2 sleep, slow-wave sleep, and rapid eye movement sleep). Noise is influential in that it can cause transitions in sleep epochs and awakenings. Objective criteria defining normal sleep include latency, total sleep time, efficiency, and the number of awakenings, including cortical arousals. All of these parameters can be affected by age, gender, and individual differences (WHO, 2009).
- The concept of 'entrainment' relates to physiological rhythms and oscillations that are tied to environmental phases. Circadian rhythms are tied to oscillations between day and night and are influential to sleep quality. The effect of circadian desynchronization due to space flight is a recognized risk by NASA HRP. Noise affects circadian rhythm not only by awakenings but also through cognitive association with its meaning.

Both the spectrum and intensity of light (photic factors) are well-known quantities that affect entrainment and sleep quality (e.g., simulation of daylight can interrupt circadian rhythms responsible for sleep). The current NASA Human Research Roadmap includes testing of lighting countermeasures to improve circadian adaptation and sleep (NASA-HRP, 2017a). Non-photic factors affecting circadian rhythm include feeding, exercise, social cycles, and human core temperature (non-photic factors). Evidence has also been found for a non-photic effect of meaningful noise that can affect human circadian rhythm. Goel (2006) found that musically-enhanced bird song stimuli delayed circadian rhythm when presented in the early subjective night phase of sleep. Examination of acoustic analogues to modifications of light spectrum and intensity over the course of a circadian day is a ripe area for future research described in section 7.

The impact of noise on the restorative function of sleep will directly impact performance and cognitive well-being during waking periods. Figure 7 illustrates the relationships in terms of day (awake) and night (sleep) periods. For example, performance in the space environment will be influenced by capacity for *explicit memory*, the conscious, intentional recollection of factual information, concepts, and experiences. Research indicates that explicit memory is most affected by interruptions of slow-wave sleep (SWS) periods that precede rapid eye movement (REM) sleep (Gais & Born, 2004; Drosopoulos et al., 2005). This suggests that noise intrusion during both early and late phases of sleep can impact performance during waking hours.

A committee formed to examine the effect of degraded sleep on performance for public policy included the NASA *Challenger* disaster as an example (Mitler et al., 1988). Persons made errors in judgment in the early morning hours with insufficient sleep (through partial night work) for several days prior to the launch.

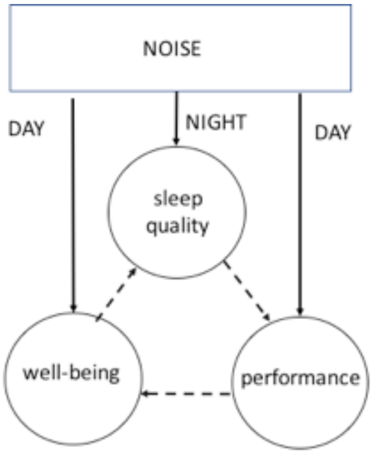

Figure 7. Indirect and direct impacts to well-being and performance via degraded sleep quality.

Caddick et al. (2017) point out “the auditory arousal threshold that causes a transition from sleep to wake has significant implications both for development of countermeasure strategies to protect against noise-related sleep disruption and for the design of alarms sufficient to cause awakenings during emergency situations.” Research indicates that arousal for an alarm depends on the depth of sleep at a given moment and also to individual differences. The use of vibro-tactile or lighting cues to augment acoustic cues for alarms is therefore recommended in sleep quarters.

6.1 Research Outcomes

- Laboratory sleep studies have been shown to increase noise sensitivity of individuals compared to home sleeping conditions, demonstrating a habituation (sensory adaptation) component for acoustic stimuli (Stevenson & McCeller, 1989).
- Noise levels should be 35 dB or less in sleeping quarters (Marks & Griefahn, 2007; WHO, 2009). This recommendation is less than current NASA standards for NC-40 (~45 dB) for crew quarters and sleep areas.

  Figure 8 shows a summary of NC levels from various sleep modules within the International Space Station. The levels range from 47–59 dB, averaging 50 dB. All levels are in excess of the NC-40 standard.

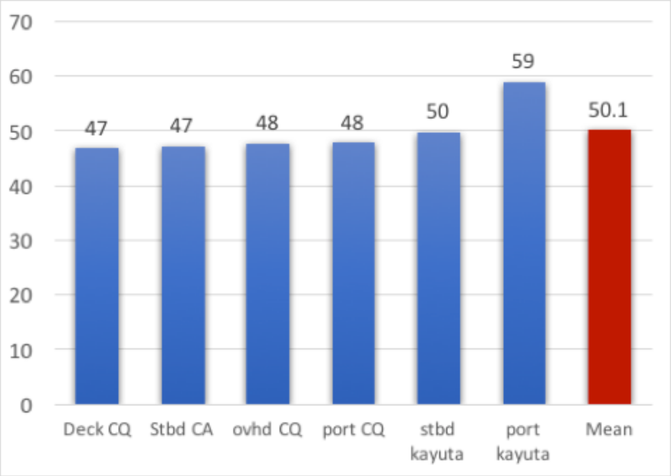

Figure 8. NC levels in various sleep modules of the International Space Station. Adapted from Allen et al. (2016).

- The use of intentionally-designed electronic noise masking can be positive for attributes such as speech privacy and sleep, but only with background noise levels of NC-40 or less (GSA, 2011, 2014). At sound levels up to 35 dB, there is no effect of continuous white noise on sleep compared to a reference condition without noise; at levels higher than this, sleep is significantly disrupted (Namba et al., 2004). NASA standards indicate a NC-40 target for sleeping quarters; therefore, the use electronic noise masking is not recommended (NASA, 2011; GSA 2011, 2014).

- Speech noise or noise with meaning to the listener can disrupt sleep at levels lower than random noise (Griefahn, 2002; Namba et al., 2004). This is due to the fact that humans evaluate and react to sound during sleep. As a result, isolation of sleep quarters from common area noise is important for space habitats (Caddick, et al., 2017).
- Intermittent noise is more disruptive to sleep than continuous noise. Sensory adaptation (habituation) is such that intermittent sounds are more likely to disrupt sleep due to interpretation of such sounds in terms of environmental change. Intermittency is more significant for sleep disruption than variations in the frequency content or level of noise, relative to a reference quiet condition. The effect of intermittent noise on sleep involves a

transition from deeper to lighter sleep levels and increased frequency of sleep stage transitions and arousals (Marks & Griefahn, 2007).

Continuous noise can aid in reducing arousals from intermittent noise (Stanchina et al., 2005). The probable HVAC noise levels in space habitats provides continuous noise that will mask intermittent sounds at or below the background level.

- Figure 9 shows a probability of sleep state changes as a function of L_{max} (Babisch et al., 2010). The graph predicts a ~10% probability of sleep state change for space habitat sleep quarters, assuming (conservatively) that the steady state level of 45 dB is equivalent to L_{max}.

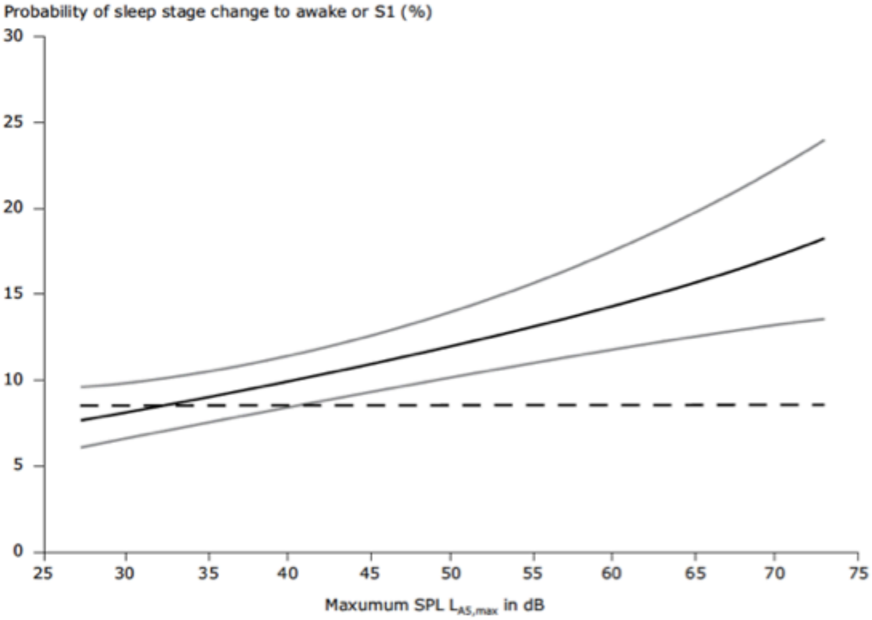

Figure 9. Probability of sleep state change as a function of L_{max}*. Babisch et al. (2010).*

- Low frequency sound has also been shown to have an impact on sleep quality (Waye et al., 2004). Results showed that subjects were more tired and felt less socially orientated in the morning after nights with low-frequency noise compared to a control condition. Mood was negatively affected in the evening after nights with low-frequency noise.

The human auditory system is less sensitive to low frequency sound (63 Hz and lower) compared to mid-band frequencies such as comprised by speech (200–8000 Hz). NASA STD-3001 addresses low frequencies for constant noise in the 63 Hz octave band, which ranges from 44–88 Hz. Limits are given of 71 dB for work areas and 64 dB for sleeping areas.

Although NASA standard STD-3001 does not explicitly address frequencies between 20 and 44 Hz, this range is roughly that of the 31.5 Hz octave band (22–44 Hz). In many cases, the source of a low-frequency noise will also produce vibration that is sensed by the body via tactile and/or kinesthetic cueing. Infrasonic sound pressure levels for frequencies from 1–20 Hz are addressed by the standard, with a specified limit of less than 150 dB at the crewmember's head, based on data from the National Safety Council (ACGIH). Separate whole-body vibration limits are given for lower frequencies (0.1–0.5 Hz) based on frequency-weighted accelerations (section 6.7.1 of NASA, 2011).

7. Noise and Cognitive Well-Being

The effect of noise on cognitive well-being concerns annoyance, the degree to which humans feel in control of the acoustic environment, and perceived speech privacy. These factors overlap in many ways with perceived impacts on performance or sleep.

7.1 Research Outcomes

- Noise annoyance is a subjective quantity that correlates well with acoustic measures for most persons but not certain sensitive groups. Most research on noise annoyance has been applied in community noise research for transportation noise, in particular for aircraft flyovers. The literature focuses on acoustic measures such as L_{dn} and its correlation to survey data, where subjective impressions might be gathered on a 5-point scale ranging from "no disturbance" to "extremely annoying." Reactions to aircraft flyovers vary depending on attitudes of those exposed (a family employed at a nearby airport may be less disturbed than a family who has no connection to the airport). Noise annoyance is therefore a subjective sensation based on a combination of reactions that may be influenced by factors other than sound level, e.g., attitudes towards the origin of the source that have nothing to with acoustics[4].

  As an example, Figure 10 from Kryter (1984) summarizes data from several studies of aircraft flyovers at Heathrow Airport. At even the lowest level of L_{dn} evaluated, there are 8% of "super-sensitive" persons who will respond they are extremely or very annoyed. This level of subjective annoyance is independent of effects on sleep, speech intelligibility, or performance. Noise annoyance would likely occur so long as the sound itself is detectable. This result would apply not only to aircraft flyovers but also to any sound that is equated with a negative outcome or disturbance to a listener, e.g., annoyance from a colleague in close proximity who talks or makes noises to themselves.

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[4] The subjective nature of what qualifies as 'noise' and human response is evident in development of regulations for noise intrusion in multi-family housing and civic government. For example, community noise ordinances frequently contain special rules regarding 'amplified sound' from public address systems or music, e.g., in public parks. 'Time, place, and manner' regulations attempt to strike a balance between first amendment free speech rights and the rights of individuals to a level of acoustic privacy.

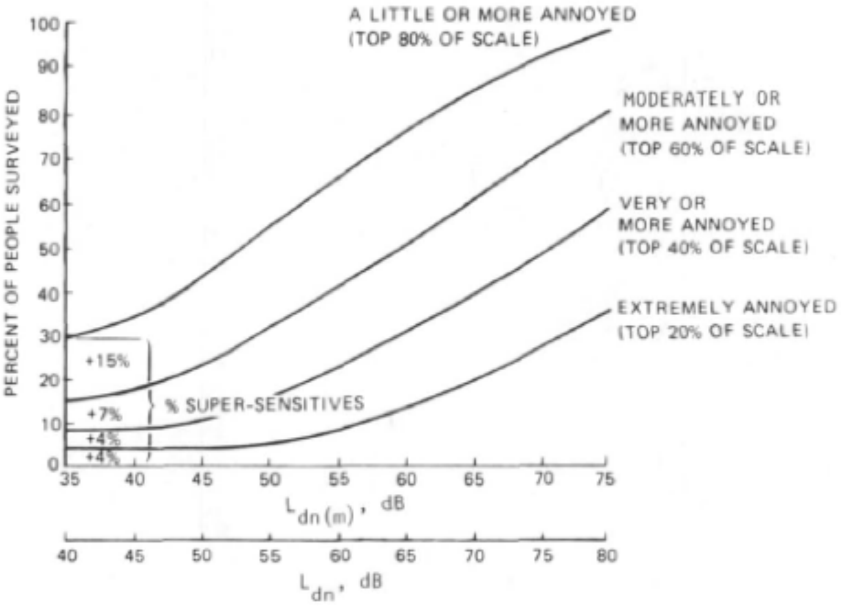

Figure 10. Survey responses to aircraft noise disturbance as a function of L_{dn}.

- <u>Habituation to noise annoyance as a coping mechanism.</u> In space habitats, habituation is necessary for a variety of human factors issues and likely occurs for different types of noise due to motivation for mission success and an understanding that certain types of noise are a necessary condition of the specialized environment. Habituation has been shown experimentally to work as a coping mechanism for noise pollution; "active coping with noise may be sufficient to mitigate any ill effects" of annoyance, sleep, and cognitive performance (Stansfeld & Matheson, 2003).

  Support for the notion of coping strategies for noise is supported in part by a study by Schreiber & Kahnerman (2000) who found that global assessments of aversive sounds were based on the average of the experiences as opposed to the maximum of two singular moments. Evaluation of a loud noise was improved by following it with a period of diminishing annoyance: the experience of 16 seconds of an annoying sound at 78 dB, for example, was rated worse overall than the same experience followed by 8 extra seconds at 66 dB.

  Hartig (2004) discusses the need for restorative environments from stressors such as noise in order to improve coping capacity. In space habitats, the ability to use hearing protection devices or sound masking may provide a restorative effect from the psychological impacts of noise.

- <u>Psychosocial effects.</u> Noise can have impacts on social behavior that result less awareness or concern for others, including as an aftereffect (Cohen & Weinstein, 1981). There may be an attentional tunneling aspect to the coping mechanism for noise that limits situational awareness to immediate tasks and diminishes capacity for altruism (Sherrod and Downs, 1974). Donnerstein & Wilson (1976) found that angered subjects exposed to noise for which they lacked control were more aggressive to a confederate than those subjects who had perceived control over the termination of a noise.

- <u>Personal control.</u> The ability to obtain visual and aural privacy as needed, and to have freedom of movement between interaction and solitude, is a basic human need and is recognized in current trends for design of healthy workplaces (Heerwagen, 2017). Supportive work environments should not only mitigate distractions and interruptions but also provide for relief to establish attentional recovery through acoustic contexts that can enhance attention. The ability to personally control when these attentional recovery periods occur in workplaces is consistent with studies of personal control of ventilation and temperature. "The research…shows that key threats to individual cognition are distractions, interruptions and stressors that reduce attentional capacity, or create illness symptoms or psycho-physiological arousal that is detrimental to the specific task" (Heerwagen, 2006).

  Jones & Broadbent (1991) stated "the degree to which a person feels in control of the noise dictates the extent to which performance declines and depression increases after the noise has been switched off...the attitude of the person toward the noise, as well as the work, determines its effect on performance." Sherrod et al. (1977) conducted experiments examining performance under conditions where control over the initiation and termination of noise improved performance in a response-time task. The results were explained with reference to the concept of "learned helplessness" and personal causation that influences motivation. Glass and Singer (1972) conducted experiments where the presence of noise caused giving up quickly on difficult tasks or degraded their ability in proofreading but the presence of control, even if not utilized, improves persistence in accomplishing tasks. The effects of noise are reduced if subjects believe they can control the noise, whether true or not (Cohen & Weinstein, 1981).

  Averill (1973) distinguished between three type of personal control: 1) behavioral (direct action on the environment); 2) cognitive (the interpretation of events); and 3) decisional (having a choice among alternative courses of action), concluding that "the relationship of personal control to stress is primarily a function of the meaning of the control response for the individual, i.e., the stress-inducing or stress-reducing properties of personal control depend upon the nature of the response and the context in which it is embedded and not just upon its effectiveness in preventing or mitigating the impact of a potentially harmful stimulus."

  Intermittency of noise and its concurrent unpredictability appear related to diminished sensation of control and diminished ability for noise habituation. Studies have examined the effect of noise aftereffects (post-stimulation effects) such as occur with intermittent noise or changes in the character or type of noise (Cohen, 1980).

- <u>Increasing personal control of the acoustic environment in space habitats.</u> The personal control offered by headphones over the auditory environment in space habitats is significant and made accessible due to small-profile, low-power music or video playback devices. The availability of semi-isolated sleeping compartments in space habitats also allows for acoustic refuge and isolation in a controllable manner. There may be benefit in allowing alert signals such as alarms to be presented via an alternative modality (e.g., tactile) depending on the current activity of the astronaut. Future technologies include adaptive noise masking or sound cancellation for noises such as snoring that could offer additional levels of controls in long-term missions.

- <u>Speech Privacy.</u> Speech privacy concerns the surveys from open-plan office research that cites intrusion from speech noise as a primary factor affecting perceived work quality (Kim & de Dear, 2013). Measurements have been proposed to quantify speech privacy for some time (Cavanaugh, 1962) and a standard method of measurement was recently established (ASTM, 2015). The ideal solution in offices is to implement an electronic noise generator that acts as a speech masking system at a level that is not directly discernable but that causes surrounding speech to be less intelligible or overwhelmed. However, the background noise levels currently specified in NASA-STD 3001 are already at the maximum levels recommended for noise masking systems (NASA, 2011; GSA 2011, 2014).

7.2 Technologies for Personal Control of the Acoustic Environment

The confined environment of a space habitat, combined with constant background noise from air handling equipment and intermittent sounds from occupants and machinery, can be both monotonous and a source of stress. The acoustic influences on psychological well-being can be mitigated by masking of the existing sound environment with sounds that are under user control, using inexpensive, low-power acoustic signal processing technologies and headphone delivery. Possible mitigation strategies could include adaptive sound masking systems, circadian sound cueing, virtual sound for increased immersion, and acoustic environment modification.

The following are promising areas of acoustic development that could augment psychological well-being in long-term habitats such as DST, particularly as implementation challenges such as power requirements and weight are minimized through improved design. The sound quality and wearing comfort of headphone systems should be specified to insure ease of use and enable the full potential of immersion cues (e.g., bandwidth, noise and distortion levels akin to entertainment systems as opposed to speech communication systems).

- Active noise control. Active noise control is a technique where a second sound is added to an undesired sound in such a manner as to reduce or cancel its level. This is accomplished conceptually by adding an out-of-phase version of the second sound to the first sound; the addition of the two sounds ideally results in cancellation of energy. Practically speaking, sound energy is only reduced but not cancelled. The technique is used in some situations for control of HVAC duct noise and is commercially familiar from active noise reduction (ANR) headsets. Several applications have been proposed for NASA ISS to reduce HVAC noise (e.g., Bushnell, et al., 1997). Challenges include: the fact that electronic-based systems must continually adapt to the noise profile; there are significant challenges to actuator placement; and of the three-dimensional aspects of the sound field (Elliot & Nelson, 1993). In ANR headphone applications it is important to recognize that only low frequency content (< 200 Hz) is adequately minimized.
- Adaptive sound masking systems. Sound masking refers to the level at which a signal within a particular frequency band cannot be detected above a background noise level. Current sound masking systems adapt to an overall level of background noise, such as dB(A). Possible developments for such systems could include adaptation to noises that are specifically annoying to a particular listener at a particular location. For example, time-varying noise from exercise equipment might be masked by noise that is spectrally matched to the specific phase of the activity. Another type of sound masking involves "circadian sound cueing," the manipulation of background environmental sound in a manner analogous to the manipulation of light for circadian entrainment.
- Reverberation modification. Commercially-available reverberation modification systems are currently in use to increase the perceived size or dimensions of an acoustic space. First used in concert halls or music practice rooms, reverberation modification systems are

increasingly used for social spaces such as restaurants and workspaces (Ellison & Schwenke, 2010; Ross, 2015). In confined environments it may be possible to modify auditory distance perception of the location of sound sources, such as colleagues or equipment, through electronic modification of reverberation. Distance perception is affected by both level and the direct-to-reverberant sound ratio (Blauert, 1997). A noise source could be modified to be at a greater perceptual distance from a listener even though the physical location and overall level is the same in order to mitigate the sensation of confinement (Begault, 1994). Microphones mounted externally on a headphone earpiece can pass signals through low-power digital signal processors to simulate reverberation of different rooms and then pass that signal to the headphone transducer. This can be combined with active noise reduction, specialized alerting systems, or other communications. Creating the illusion of differentiated private spaces for sleeping, working, or entertainment might be combined with processing of light cues for sleep cycle entrainment and for mood improvement, per NASA Human Research Program roadmap goals (NASA-HRP, 2017a, 2017b).

- Virtual acoustic cueing from instruments and machinery. Providing virtual acoustic 'sonification' can be used to enable both data visualization and auditory feedback for scientific or medical tasks involving instruments (Kramer, 1994). Manual interaction with devices such as docking systems can also be augmented using acoustic cues. Similarly, a subtle but important component to interaction with exercise devices is acoustic feedback from components of the mechanical apparatus (flywheel noise, weight contact, cable noise, etc.). It is possible to adapt exercise machinery to transmit acoustic cues to a headphone user to simulate the mechanical status of different types of machines; to exaggerate cues related to resistance of weights; and to augment mechanical cues with other types of sound such as speech feedback regarding performance. The acoustic cues from standard gym devices could be implemented for machines such as the Advanced Resistive Exercise Device or even simple resistance devices. Allowing for a variety of sounds or feedback under astronaut control could increase motivation and possibly performance through the use of virtual acoustic cues, in line with the NASA Human Research Program roadmap goal of using virtual reality to enhance behavioral health through exercise (NASA-HRP, 2017c).

8. Summary

The non-auditory effects of noise in future long-term space habitats such as the DST are likely to be impactful on team and individual performance, sleep, and cognitive well-being. This report has provided several recommendations for future standards and procedures for long-term space flight habitats. Table 3 summarizes these impacts, along with recommendations for NASA's Human Research Program in support of DST mission success.

Table 3. Impact of Non-Auditory Noise in Long-Term Space Habitats

Findings	*Recommendations*
To best assess subjective response, noise should be measured and specified using best available psychoacoustic-based measures.	Implement noise measurement methods that take into account loudness and masking level differences. Adapt future NASA standards to use Room Criteria (RC) metric in place of Noise Criteria metrics. Conduct research to define what aspects of intermittent noise are impactful.
To facilitate individual and team performance, background noise levels in habitat workspaces should reflect a balance between maintaining speech privacy (reduction of irrelevant speech and noise to minimize distraction) and enhancement of team communications.	To the degree practicable, implement design criteria in future NASA standards to meet NC-40 (~45 dB L_{eq}), in line with recommendations for open plan offices.
To facilitate sleep quality, background noise levels should be minimized to levels in line with existing research recommendations. Familiar sounds from common areas such as speech or equipment and intermittent sounds should be minimized. Background noise levels should correspond to earth-based research recommendations. Entrainment can be effected through sensory augmentation.	To the degree practicable, implement design criteria in future NASA standards to meet NC-30 (~35 dB L_{eq}), in line with research recommendations for sleep quality. To the degree practicable, separate sleep quarters to be non-adjacent to common areas and from intermittent sounds. Provide means for sound isolation (HPDs, headphones). Utilize acoustic cues for their potential in sleep cycle entrainment.
Arousal from sleep using only acoustic alarms is unreliable due to individual differences and depth of sleep, and the use of HPDs.	For sleep quarters, future NASA standards should include multi-sensory alerting methods.
Psychological well-being is impacted by confined space, lack of privacy, and monotonous acoustic conditions, for which the crew member has no control.	Provide virtual acoustic methods to allow crew members to control their acoustic environment. Acoustic sensory augmentation of instruments, tools and machinery allows 'useful' sounds to mask the noise environment. Research should be conducted to determine useful approaches and designs, including adaptive noise cancellation. Headphone signal playback quality and comfort should be specified in future NASA standards.

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