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Evaluation of Ambient Sound, Vibration, and Light in Rodent Housing Rooms

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Excessive sound, vibration, and light are detrimental to rodent welfare, yet these parameters are rarely recorded in vivaria. Whether housing environments exceed the suggested thresholds and which specific factors may alter these parameters is generally unknown. The goal of this study was to determine how environmental factors may alter sound, vibration, and light at the room and cage levels. Measurements were made using an ultrasonic microphone, accelerometer, and light sensor. Measurement sites were 1) in open air at a central location in 64 rooms located in 9 buildings, and 2) inside an empty mouse or rat cage containing chow, water, and bedding and located on an animal transfer station (n = 51) or housing rack (n = 102). Information collected for each transfer station and rack measurement included the year of manufacture, the species on the rack, and the number of cages on the rack. For each location, a baseline measurement was taken with the transfer station turned off, followed by another measurement after the transfer station was turned on. In general, many factors influenced ambient sound, vibration, and light, indicating that values are not uniform across rodent rooms in the same institution or across cages in a single room. Sound peaks capable of startling rodents were measured in association with hallway ultrasonic motion sensors and during cage change. Vibration and light intensity were generally low when cages were located on the rack. In contrast, active transfer stations had more vibration and light intensity, reaching levels that were potentially stressful for rodents. These data reflect the ambient sound, vibration, and light that rodents experience during normal facility operations. These patterns may extend to other locations, but given the variability in all parameters, the data highlight the need for institutions to conduct their own monitoring.

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Introduction

Sound, vibration, and light are extrinsic factors in the research animal housing facility that may affect the validity and reliability of preclinical research data. An animal's hearing range and sensitivity to vibration and light can vary by species and fundamentally differs from that of humans.[31] This is particularly true of rodents. Mice and rats can hear into the ultrasonic range, up to or approaching 100K Hz, whereas humans can perceive sounds only up to a frequency of approximately 20 to 20K Hz.[5] Furthermore, rats can hear a wider range of sound frequencies than mice.[5] Rodents also have extremely sensitive vibrissae and plantar mechanoreceptors that detect slight changes in vibration.[7,34] As crepuscular species, rodents are also sensitive to bright lights that may be present in the laboratory.[11,24,25] These factors should be considered when designing animal facilities, conducting experimental studies, and evaluating animal welfare.

Ambient high frequency sound is common in animal facilities. When considering the hearing range of rodents, blowers on individually ventilated caging (IVC) racks and transfer stations are sources of high frequency sound, along with moving carts, cage changing procedures, building ventilation systems, computer equipment, and even ultrasonic motion sensors. Many motion sensors that control hallway lights function by emitting ultrasonic frequencies and sensing when the sound waves bounce off a moving object (that is, a person walking by).[26] While humans cannot perceive the frequencies given off by these sensors, they fall within rodents' hearing range (23 to 40 kHz).[26] Despite all of these sound sources, limited information is available concerning the acoustic environment of laboratory rodents. One study found that normal background sound in a typical rodent room averages 80 dB, with normal workday activity creating transient sound peaks of 110 to 120 dB.[12] Transfer station use alone can increase sound levels by 10 dB.[12] However, another study showed that mice can perceive only about 30 dB of ambient sound in the housing room, and this is not affected by an active IVC rack blower or transfer station.[21] To the best of our knowledge, only these 2 publications report ambient sound levels, but the variation between these 2 environments is concerning given the wide range of effects that excess sound can have on animals.[12,21] These effects can alter several physiologic measures such as blood pressure and heart rate, levels of stress hormones, sleep/wake cycles, and fertility in research rodents.[19,20,28,29]

Vibration is also common in animal facilities and can occur from IVC rack blowers, transfer stations, cage wash, construction, during transportation on carts, and even nearby structures outside of the building such as a helipad or subway system. While housing guidelines discourage excessive vibrations in general, specific frequency ranges are likely to be most aversive to mice and rats. The resonance frequency range (RFR) is the range of external vibration that is most likely to cause the body or a specific cavity to amplify, rather than absorb, the vibration. These values fall around 30 Hz for mice and around 27 Hz for rats if the animals are in a natural posture.[16,18,32] Vibration acceleration is typically used as a measure of amplitude and is often denoted in g force ($\times g$). One study showed that IVC racks

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produce vibration in a frequency range that is more likely to affect rodents than humans; a functioning rack blower can increase ambient vibration acceleration from 0.024 m/s^2 (0.00245 × *g*) to 0.035 m/s^2 (0.00357 × *g*).[16] The effects of vibration on physiology and behavior are similar to those of excess sound and include increased cardiac measures, stress hormones, and startle behavior, and decreased fertility.[1,4,13,19,22]

Light is an inherent component of research environments, with lighting typically designed with human workers in mind. The eyes of mice and rats are both rod-dominated, making them sensitive to bright lights, and dichromatic, with cones that perceive blue-green and UV wavelengths.[9,14,27] In particular, albino rodents can have heightened sensitivity to bright light[33] and albino rats avoid sleeping areas with light as low as 25 lx.[24] Several examples in the literature show that rats prefer red-tinted enrichments that filter out light in their visible spectrum and also decrease overall light intensity.[23,35] Rats housed in red cages and under reduced light intensity (25 lx) seem to have more positive affect.[10] While most of our knowledge of rodent light preferences comes from rat research, a recent study found that female CD-1 mice generally prefer to gather nesting material and spend more time inactive in red tinted cages (108 ± 21 lx) compared with clear cages (342 ± 85 lx).[3] The only time mice showed equal preference between the 2 cage types was the combination of 32 °C (a temperature near thermoneutrality and considered preferred) and a clear cage. This finding indicates that the dimmer red cage is preferred to the bright-clear cage and that the lighting environment influences these preferences.

Despite these physical and behavioral effects, sound, vibration, and light are seldom measured in the animal facility. Measurements are typically limited to areas of concern for human exposure, such as the cage wash environment. The *Guide for the Care and Use of Laboratory Animals* recognizes that all 3 parameters can be stressors in animal rooms and should be limited.[15] While the *Guide* recommends that light intensity be limited to 325 lx in rodent rooms, it does not give maximum values for sound and vibration.[15] Recently, a threshold of 70 dB for sound, and 0.025 × *g* for vibration was recommended for continuous 24-h exposure.[30] While 70 dB is a practical level to try to achieve, adverse effects may still occur below this level. Nonetheless, given the limited and variable data currently available, how often these thresholds are exceeded and whether they present an immediate concern in the typical animal facility is unknown. Because mice and rats have different sensitivities, unique species needs may further complicate the suitability of housing conditions for rodents. The current study measured baseline values of sound audible to rodents, vibration, and light in rodent rooms across multiple facilities in our academic institution. In addition, we aimed to identify environmental features that could alter those baseline values by evaluating different models of transfer stations and IVC racks, as well as specific locations on individual racks. We hypothesized that these environmental parameters were not uniform across animal rooms or even across locations within a single room. We predicted that sound and vibration would be higher in rooms with IVC racks than in static housing and in rooms with active transfer stations. Further, sound and vibration on IVC racks would be higher in those with older air supply blowers. We also predicted that light would be brighter at the top of racks than at the bottom.

Materials and Methods

Equipment. An ultrasonic microphone (PCB Piezotronics, Depew, NY; preamplifier model 426A11, microphone tip model 377C01, adapter model 079A02), accelerometer (PCB Piezotronics; model 352C33), and light sensor (Yoctopuce, Cartigny, Switzerland, model Yocto-light-V2) were used to measure sound audible to rodents, vibration, and light, respectively. Vibration data represents root mean square data taken on the z-axis. All devices came as a set used in conjunction with a tablet equipped with Sensory Sentinel monitoring software (Turner Scientific, Jacksonville, IL). Measurements were taken in 64 rooms across 9 facilities at Purdue University's main campus (West Lafayette, IN). The sampled rooms include those where rodents were actively housed and where behavioral testing is regularly conducted. Ninety-seven individually ventilated racks and 5 static racks were included for a total of 102 sampled racks, as well as 51 animal transfer stations. For each transfer station and rack air supply blower, the year manufactured, and model number were recorded along with the species housed in the room. Summary data are presented in Tables 1 and 2.

For sound measurements, the microphone was calibrated before sampling in each room. This was done by playing a sample tone at 94 dB and confirming that the correct intensity was detected. A species reference spectrum for rats (250 to 96,000 Hz) or mice (900 to 96,000 Hz) was selected on the device for each room based on which species was present. The reference spectra are designed so only the frequencies that each species can detect are recorded. However, sound data was unweighted. For rooms that housed both rats and mice, measurements were taken twice, one for each species' spectrum. The accelerometer and light sensor had been calibrated by the manufacturer and were guaranteed at the time of measurement.

Room measurements. Baseline measurements at the room level were taken from the center of the room, with the accelerometer taped to the floor, and light meter and microphone approximately 3 ft (91 cm) above the floor for at least 3 s. This was followed by turning the transfer station blower and light, when present, on and taking a subsequent recording for 3 s. Transfer stations were left on for at least 30 s before recording to allow the blower to stabilize.

Transfer station and rack measurements. Next, the sensors were placed inside of an empty rat (Allentown NexGen Rat 900, Allentown, NJ) or mouse (Allentown 75JAG, Allentown, NJ) cage, depending on which species occupied each room. Both cages were made of polysulfone material. The port from the back of an individually ventilated cage was removed to

Table 1. Summary of measured transfer stations

Manufacturer	Model	Manufacture Year	Number measured
Allentown	ATS5 8320005	2008	1
Allentown	Phantom	2011	1
Allentown	Phantom	2014	1
Allentown	Phantom	2016	11
Allentown	Phantom2	2018	2
Allentown	Phantom2	2019	1
Allentown	Safety Cabinet Plus	2020	2
Ancare	ACS-DS4	2010	1
NuAire	NU425-SPEC	2002	1
NuAire	NU 619-400	2011	1
NuAire	NU 619-400	2012	20
NuAire	NU-1307-1300	2013	1
NuAire	NU 619-400	2014	3
NuAire	NU-S101-630	2017	1
NuAire	NU-620-401	2019	3

Table 2. Summary of measured racks

Manufacturer	Air supply model	Manufacture year	Rack type	Species	Number of racks measured
Allentown	EcoFlo	2011	IVC	Mice	10
Allentown	EcoFlo	2012	IVC	Mice	25
Allentown	EcoFlo	2014	IVC	Mice	2
Allentown	EcoFlo	2016	IVC	Mice	13
Allentown	EcoFlo	2017	IVC	Mice	5
Allentown	EcoFlo	2018	IVC	Mice	4
Allentown	EcoFlo	2019	IVC	Mice	4
Allentown	Other	2020	IVC	Mice	2
Allentown	SB4100	2004	IVC	Mice	1
Allentown	SB4100	2007	IVC	Mice	1
Allentown	SB4100	2008	IVC	Mice	9
Allentown	SB4100	2010	IVC	Mice	4
Alternative Design- Other	Other	2014	IVC	Mice	1
NuAire- Other	Other	2020	IVC	Mice	1
Alternative Design- Other	Other	2014	IVC	Mice and Rats	2
Allentown	EcoFlo	2015	IVC	Rats	1
Allentown	EcoFlo	2016	IVC	Rats	1
Allentown	EcoFlo	2018	IVC	Rats	7
Allentown	EcoFlo	2019	IVC	Rats	4
Metro Rack	—	—	static	Mice	4
Metro Rack	—	—	static	Rats	1

"—" signifies irrelevant parameters for static racks

allow the sensor wires to run through it. The mouse cage was complete with corncob bedding, wire bar lid, full food hopper, and full water bottle (Figure 1A and B). The rat cage was equipped similarly but had aspen bedding. This represented the typical bedding used for each species at this university. As seen in Figure 1B, the hole in the back of the mouse cage that contained the sensor wires was not sealed for measurements. A similar hole was present in the rat cage.

The accelerometer was securely taped to the middle of the cage floor, under the bedding. According to consultation with Turner Scientific, securing this accelerometer with tape produces data that are similar to that obtained with more permanent attachment, such as a bolt or adhesive. Before measurements were taken, the accelerometer was checked to ensure the tape was securely fashioned and the device could not move if it or the cord were touched. Tape was reapplied as needed. The microphone was propped up at rodent head level using a folded paper towel, which also simulated enrichment material, and was taped in place. The light meter was taped to the center of the cage floor, resting on top of the bedding next to the microphone.

The assembled cage was placed in the center of the transfer station of each room and data were collected for at least 3 s with the blower and light off. Then the blower and light were turned on and allowed to run for at least 30 s before repeating the measurements. The assembled cage was then carefully placed in 3 cage slots per ventilated rack (top right, center, and lower left). For racks that hold static microisolation cages, the cage was placed on the top, middle, and bottom shelf of each rack. Measurements from each rack location were collected for 30 s each, first with the transfer station off and then again with it on. The filter top was present on the cage for all measurements. We acknowledge that this may underestimate some high frequency sound and light values. We did not evaluate either cages in the transfer station with the lid off or conventional open top cages.

Two IVC racks housed both rat and mouse cages and were sampled using both species' spectra. In total, data were collected from 16 rat racks and 88 mouse racks.

Specific situations of interest. Certain conditions of interest were also evaluated during this study.

1. The room adjacent to the elevator in one building was a focus due to investigator complaints of poor mouse breeding performance. Recordings were taken in an IVC rack on the wall adjacent to the elevator, in a cage slot near the door, for 5 min with the elevator silent, and again for 5 min during which the elevator was continuously triggered. For comparison, the room farthest from the elevator was measured in the same way.
2. In another building, a room directly across from cage wash was sampled for 5 min without cage wash running, and again with the machines operating.
3. One room was recorded for 30 min before cage change, and again for 30 min during cage change. The recordings were taken in a mouse IVC rack adjacent to the rack that was actively being changed.
4. Measurements were taken in hallways newly equipped with ultrasonic motion sensors (Greengate, OAC-DT-MicroSet, Cooper Lighting Solutions, Peachtree City, GA) to assess sound level changes. The microphone was held at shoulder level for 30 s, placed in a cage with the lid on for 30 s, and after removal of the cage lid for 30 s. Based on manufacturer data, this model of motion sensor emits frequencies around 32 kHz. For comparison, the same measurements were taken in a room adjacent to the motion sensor with the door closed.

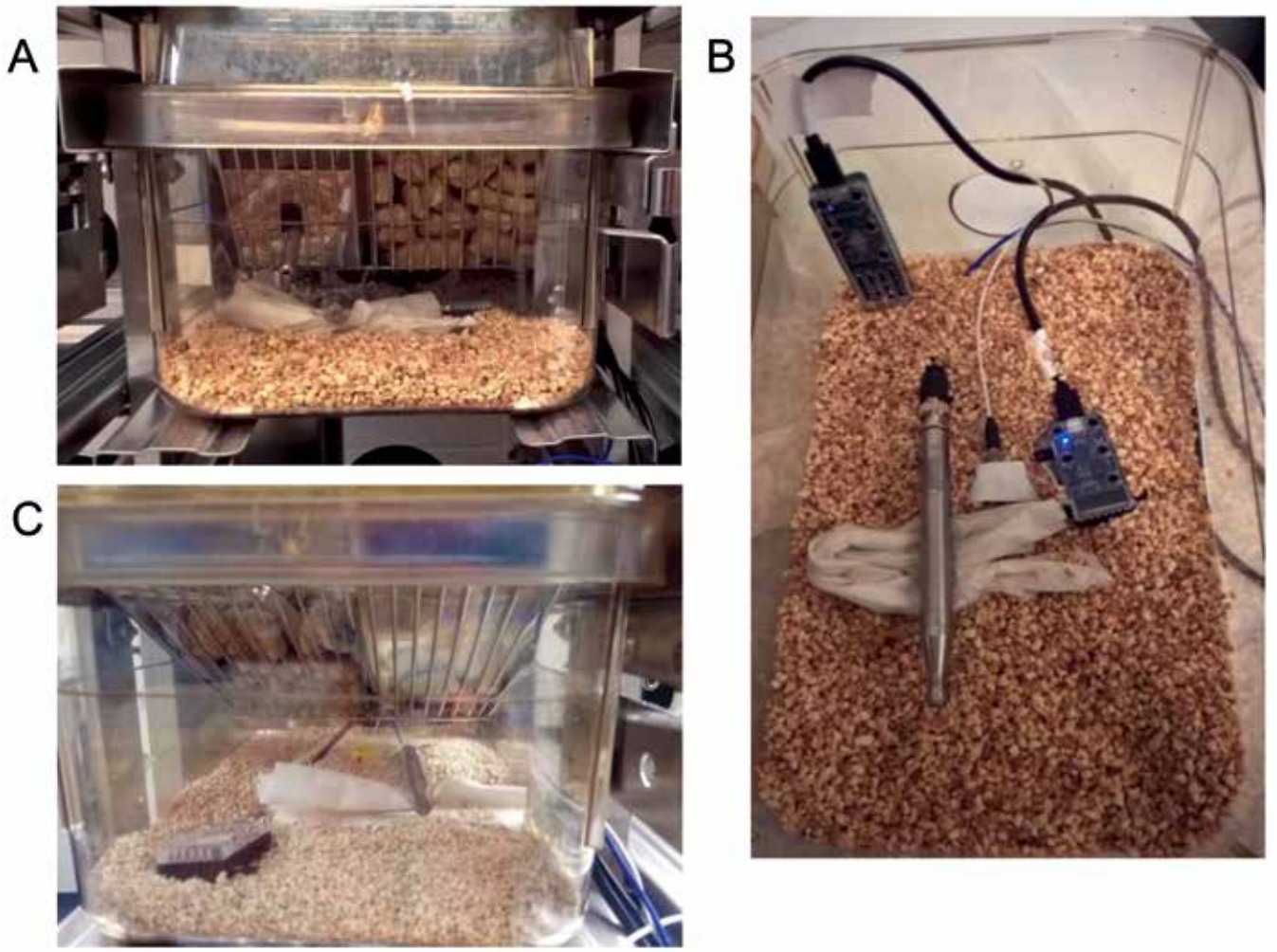

Figure 1. Sensor placement in a mouse cage. (A) Front view and (B) overhead view of the microphone, accelerometer, and light sensor placed in the center of the cage. A temperature/humidity probe is located in the back left corner. (C) Front view of the light sensor placed at the front of the cage for measurements across the top row of a ventilated rack.

5. Measurements were taken for 3 s in each cage slot of the top row of one ventilated rack to assess light intensity differences in cages located directly beneath the blower as compared with those not under the blower. For this, the cage was set up as previously described (light sensor in the center under the food hopper), and a separate measurement was taken with the light sensor placed at the front of the cage (Figure 1C).

Statistics. Because over 85% of the data came from mouse rooms with ventilated racks, only those data points were formally analyzed. Descriptive statistics were calculated for data from rat rooms and from all static racks. Data from the 2 racks that held both mouse and rat cages were excluded. For each parameter at room, transfer station, and IVC rack level, average values were compared based on significant factors identified in the formal mouse models. For example, at the room and transfer station level, data are summarized according to station activity. At the IVC rack level, data are summarized based on row location. All rat IVC racks were the EcoFlo model, and thus comparisons with other models were not possible (Table 2). In addition, descriptive statistics were calculated for the data collected from 'areas of interest,' as each measurement was only conducted in one room and at one time point (that is, $n = 1$).

Formal analyses. Sound, vibration, and light intensity in mouse rooms with ventilated racks were analyzed with repeated measures, general linear mixed models. In all models, transfer station activity ('on' compared with 'off') was included as a fixed effect. Room number and building were included as random effects. The following parameters were also included in the specified models:

- Model number was included as a fixed effect for analyses at the transfer station and IVC rack level. Transfer stations were primarily either Phantom (Allentown) or NU 619-400 (NuAire, Plymouth, MN) models. Other models accounted for less than 10% of the data and were grouped as 'other.' All IVC racks were either EcoFlo (Allentown) or SB4100 (Allentown), except for 4 racks. These other 4 racks were excluded from analysis, such that 78 ventilated mouse racks were formally analyzed.
- Manufacture year was excluded for both transfer stations and ventilated racks due to multicollinearity issues with model and bimodally distributed data. As shown in Tables 1 and 2, most of the older transfer stations were NU 619-400 models and the oldest IVC racks were SB4100.

- In IVC rack models, row location was included as a fixed effect.
- All relevant 2-way interactions were tested and dropped if not significant.
- Room square footage and volume were included as covariates for light intensity at the room level.
- The following covariates were included in the IVC rack models: number of cages on the rack, presence of a cage above the sensors ('yes' compared with 'no'), rack angle relative to light fixtures (light intensity model only), and rack angle relative to the door (sound and vibration models only).
- Blower serial number was included as a random effect in IVC rack models to account for sampling across multiple locations on each rack.

Any significant main effects and interactions were further examined with Tukey post hoc comparisons. Model assumptions were checked post hoc based on comparison of residual and predicted plots and normal Q-Q plots. Transformations were made when necessary to adjust for any violations. Significance was based on $P < 0.05$. Analyses were conducted in JMP Pro (SAS Institute, Cary, NC; version 14.3.0). All data were compared with the relevant recommended sound (70 dB), vibration (0.025 × *g*), and light intensity (325 lx) thresholds.

Results

Formal analyses of mouse rooms. *Sound.* Across all sound readings, the suggested 70 dB threshold was rarely exceeded. In mouse housing rooms, the average sound intensity audible to mice was significantly louder when transfer stations were turned on (LSM: 61.94 ± 0.94 dB) as compared with turned off (LSM: 53.56 ± 0.93 dB, $F_{1,45.42} = 317.29$, $P < 0.0001$, Figure 2A). Significant variation was also found between individual rooms ($P = 0.0133$). Average sound intensity per room ranged from 46.78 to 70.46 dB (IQR: 52.67 to 61.83 dB).

Inside the transfer stations, average sound intensity audible to mice was influenced by the on or off condition ($F_{1,42.93} = 793.77$,

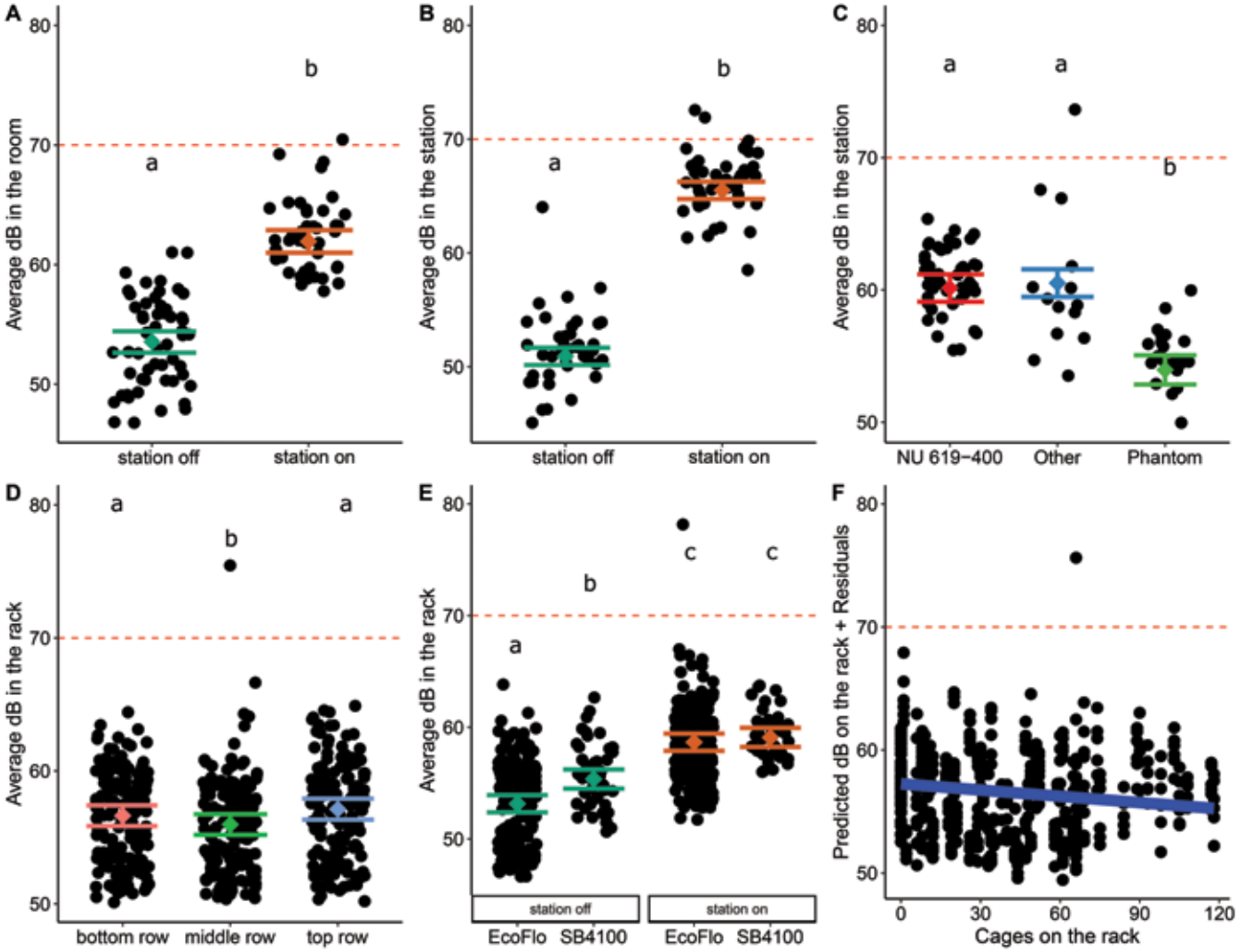

Figure 2. Average sound intensity audible to mice in the general housing room, in cages on the transfer station, and in cages on IVC racks. Use of the transfer station affected sound in (A) the housing room ($P \leq 0.0001$) and (B) the transfer station itself ($P \leq 0.0001$). (C) Sound in the transfer station was affected by station model ($P \leq 0.0001$). On the IVC rack, (D) row location ($P \leq 0.0001$), (E) an interaction between blower model and station activity ($P \leq 0.0005$), and (F) number of cages on the rack ($P \leq 0.05$) affected sound levels. The red dotted line shown the suggested 70 dB threshold in all panels. Panels A through E contain the factor levels LSM ± SE over the scatter of the individual residual points. Any factor with more than 2 levels was tested with post hoc Tukey tests, with significance based on $P < 0.05$. Different letters indicate significant factor level differences. Panel F shows the best fit line over the scatter of residual points.

$P < 0.0001$) and the station model ($F_{2,28.98} = 15.20$, $P < 0.0001$). Sound was louder in the station when it was turned on (LSM: 65.51 ± 0.76 dB) than off (LSM: 50.91 ± 0.76 dB, Figure 2B). Sound was also louder in the NU 619-400 model (LSM: 60.15 ± 1.04 dB) and in those models grouped as 'other' (LSM: 60.52 ± 1.04 dB) as compared with Phantom models (LSM: 53.96 ± 1.11 dB, Figure 2C), based on post hoc tests ($P < 0.05$).

In cages on IVC racks, the average sound intensity audible to mice was affected by row location ($F_{2,414.80} = 9.41$, $P = 0.0001$), an interaction between blower model and transfer station activity ($F_{1,395.40} = 13.99$, $P = 0.0002$), the number of cages on the rack ($F_{1,55.31} = 6.51$, $P = 0.0135$), and the presence of a cage immediately above the sensor ($F_{1,381.30} = 8.88$, $P = 0.0031$). Sound intensity was louder in the top (LSM: 57.12 ± 0.79 dB) and bottom (LSM: 56.63 ± 0.78 dB) rack rows as compared with the middle row (LSM: 55.97 ± 0.78 dB, Figure 2D). When the transfer station was off, sound was louder in SB4100 racks (LSM: 55.37 ± 0.86 dB) as compared with EcoFlo racks (LSM: 53.16 ± 0.77 dB). However, with the transfer station on, the sound was similar in both racks and louder than when the station was off (SB4100 LSM: 59.09 ± 0.86 dB, EcoFlo LSM: 58.66 ± 0.77 dB, Figure 2E). As the number of cages on the rack increased, average sound intensity decreased (Figure 2F), and having a cage above the sensors (LSM: 56.10 ± 0.80 dB) reduced sound intensity as compared with the absence of a cage above the sensors (LSM: 57.04 ± 0.77 dB). Furthermore, individual rooms varied significantly ($P < 0.0001$).

Vibration. Average vibration in mouse rooms was not affected by transfer station activity ($F_{1,43} = 0.66$, $P = 0.4210$), but significant variation was detected between rooms ($P = 0.0037$). Overall, average vibration in the room was low (IQR: 0.00022 to 0.00077 × g), with a maximum vibration 0.02347 × g measured at room level.

In the transfer station, average vibration was significantly higher when it was on (LSM: 0.01698 ± 0.00112 × g) as compared with off (LSM: 0.00126 ± 0.00112 × g, $F_{1,39.21} = 687.47$, $P < 0.0001$, Figure 3A). The station model did not have a significant effect on average vibration ($F_{2,33.74} = 3.14$, $P = 0.0560$). However, a significant interaction was detected between station model and station activity in terms of maximum vibration recorded over the sampling periods ($F_{2,60.51} = 3.45$, $P = 0.0380$). When the station

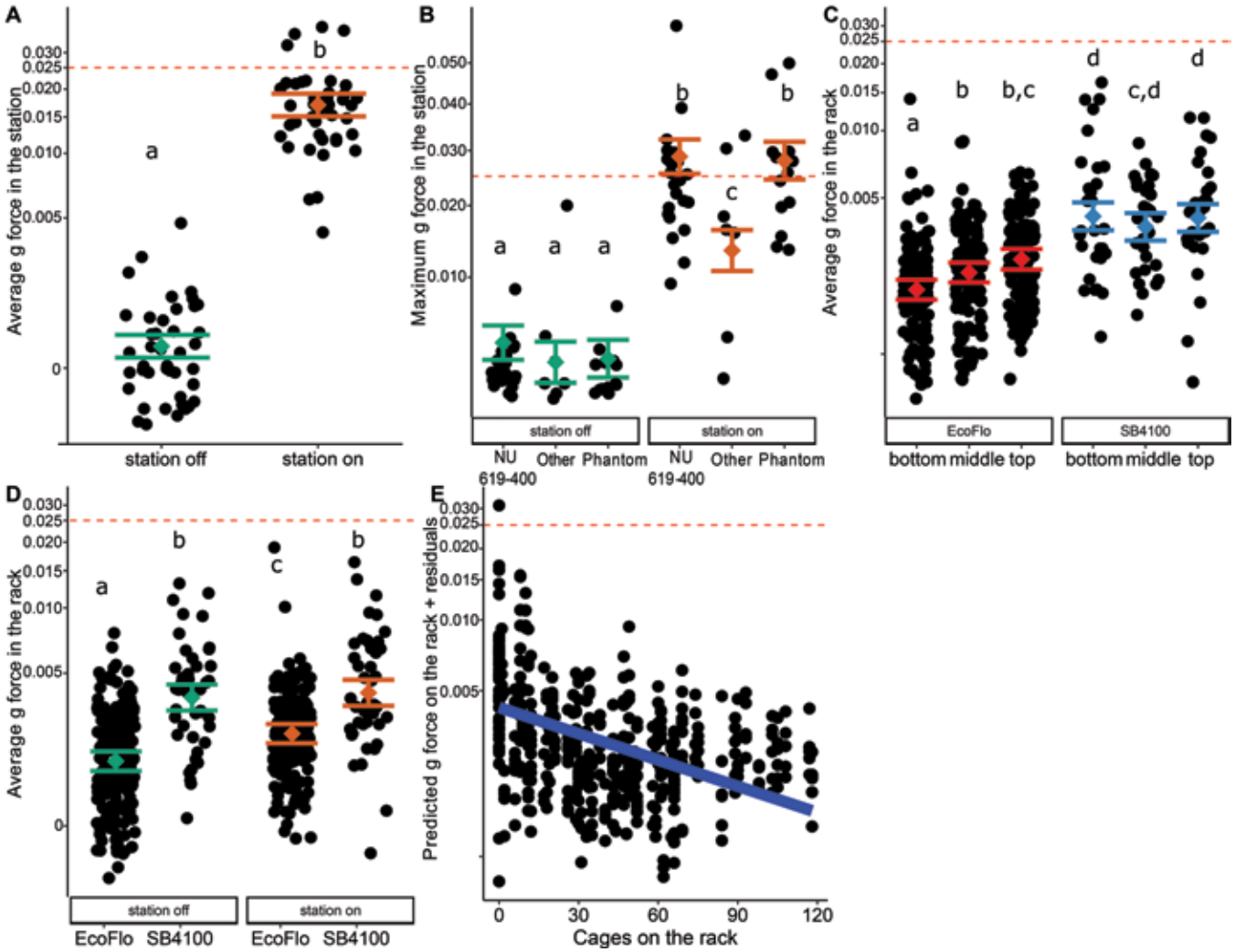

Figure 3. Ambient vibration in cages on the transfer station and on IVC racks. (A) Average vibration in the transfer station was affected by use ($P \leq 0.0001$). (B) Maximum vibration in the transfer station was affected by an interaction between station model and use ($P \leq 0.05$). Vibration in IVC racks was affected by (C) an interaction between blower model and row location ($P \leq 0.0005$), (D) an interaction between blower model and transfer station use ($P \leq 0.0005$), and (E) number of cages on the rack ($P \leq 0.0001$). All panels show the suggested 0.025 × g threshold with a red dotted line. Panels A through D contain the factor levels LSM ± SE over the scatter of the individual residual points. Any factor with more than 2 levels was tested with post hoc Tukey tests, with significance based on $P < 0.05$. Different letters indicate significant factor level differences. Panel E shows the best fit line over the scatter of residual points. Y-axes are shown on a log10 back-transformed scale in panels A, C, D, and E. The Y-axis in panel B is shown on a square root back-transformed scale.

was off, all models had similar levels of maximum vibration. However, when the station was on, NU 619-400 (LSM: 0.02873 ± 0.00010 × *g*) and Phantom (LSM: 0.02788 ± 0.00012 × *g*) models had higher maximum vibration levels than did those grouped as 'other' (LSM: 0.01332 ± 0.00014 × *g*, Figure 3B). Significant variation was also detected in the maximum vibration of the transfer station across rooms ($P = 0.0001$). Maximum vibration of active transfer stations often met the 0.025 × *g* threshold value (20 of 43 stations).

The average vibration in cages on IVC racks was affected by the number of cages on the rack ($F_{1,80.94} = 28.78$, $P < 0.0001$), an interaction between rack row location and supply blower model ($F_{2,392.80} = 5.80$, $P = 0.0033$), and an interaction between supply blower model and transfer station activity ($F_{1,390.70} = 8.04$, $P = 0.0048$). On SB4100 racks, average vibration was similar on the bottom (LSM: 0.00417 ± 0.00115 × *g*), middle (LSM: 0.00372 ± 0.00115 × *g*), and top rows (LSM: 0.00407 ± 0.00115 × *g*). On EcoFlo racks, vibration was stronger on the top (LSM: 0.00263 ± 0.00112 × *g*) and middle (LSM: 0.00234 ± 0.00110 × *g*) rows than on the bottom (LSM: 0.00194 ± 0.00110 × *g*, Figure 3C). Across blower models, vibration was higher in all locations of SB4100 racks as compared with the corresponding location on EcoFlo racks (Figure 3C). In SB4100 racks, average vibration was similar whether the transfer station was off (LSM: 0.00387 ± 0.00115 × *g*) or on (LSM: 0.00407 ± 0.00115 × *g*, Figure 3D). In EcoFlo racks, vibration was higher when the transfer station was on (LSM: 0.00264 ± 0.00111 × *g*) as compared with off (LSM: 0.00198 ± 0.00111 × *g*, Figure 3D). All measurements on SB4100 racks were higher than those on EcoFlo racks (Figure 3D). As the number of cages on the rack increased, average vibration decreased (Figure 3E). Significant variation was also detected across rooms ($P = 0.0216$) and individual air supply blowers ($P = 0.0059$). Overall, the 0.025 × *g* threshold was never met on mouse IVC racks.

Light. Average light intensity in the mouse rooms was not impacted by transfer station activity ($F_{1,40.32} = 1.03$, $P = 0.3161$), but did significantly vary across rooms ($P < 0.0001$). Light ranged from 16.63 to 1,471.38 lx across rooms (IQR: 240.97 to 555.36 lx). The lowest readings were found in rooms dedicated to behavioral tests (16 to 32 lx). Considering this

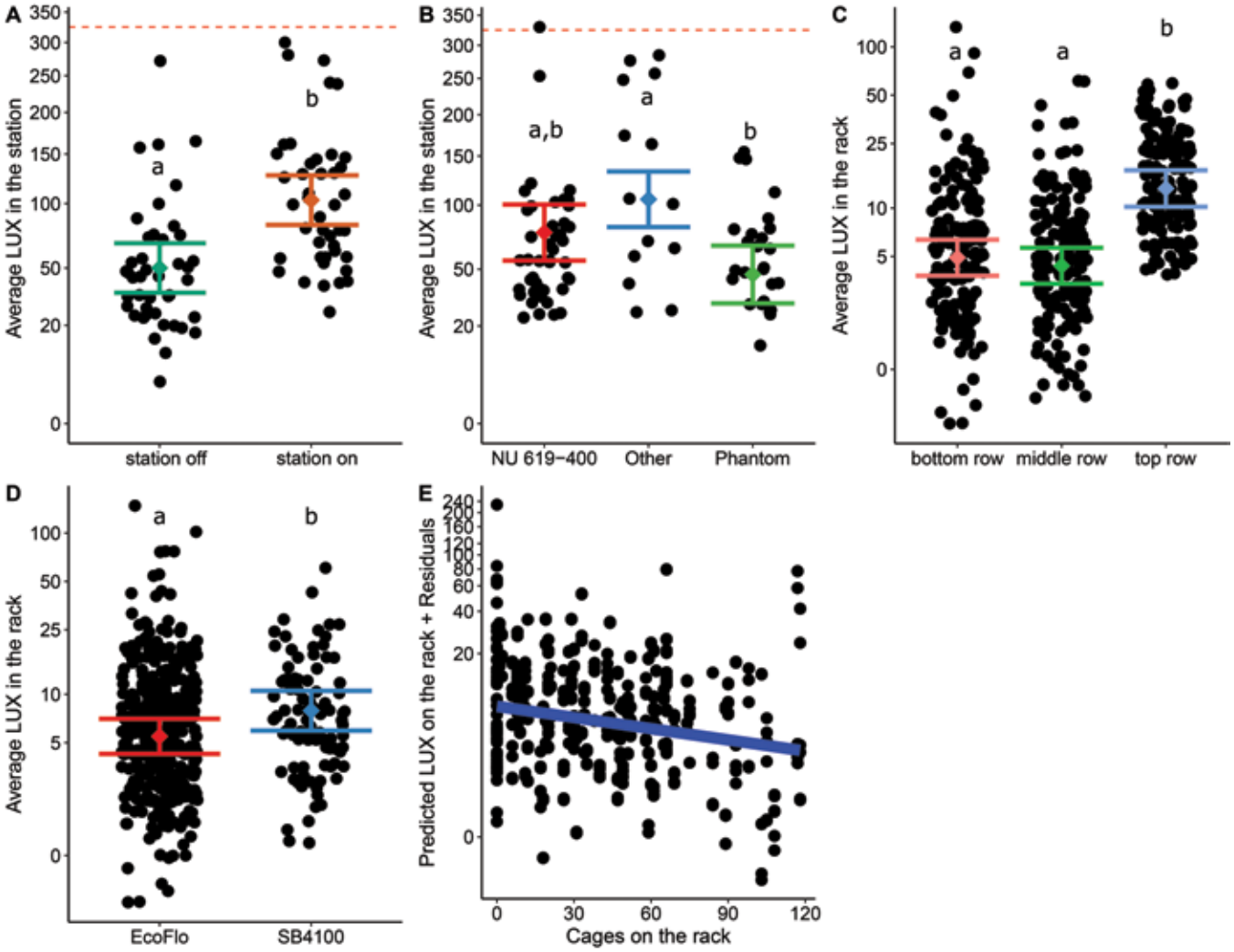

Figure 4. Average light intensity in cages on the transfer station and on IVC racks. (A) Transfer station use ($P \leq 0.0001$) and (B) station model ($P \leq 0.05$) affected light intensity on the station. Light in IVC racks was affected by (C) row location ($P \leq 0.0001$), (D) supply blower model ($P \leq 0.05$), and (E) number of cages on the rack ($P \leq 0.01$). Panels A and B depict the suggested 325-lx threshold with a red dotted line. Panels A through D show the factor levels LSM ± SE over the scatter of the individual residual points. Any factor with more than 2 levels was tested with post hoc Tukey tests, with significance based on $P < 0.05$. Different letters indicate significant factor level differences. Panel E shows the best fit line over the scatter of residual points. Y-axes are shown on a square root back transformed scale in panels A and B. Y-axes in panel C, D, and E are shown on a log10 back transformed scale.

Table 3. Data collected in rooms, transfer stations, and IVC racks containing rats. Data are shown as averages ± SDs across rat rooms. This data were not formally analyzed due to small sample size.

Room level			
Condition	Average dB	Average × *g*	Average lux
Hood off (*n* = 12)	53.01 ± 3.64	0.00057 ± 0.00087	**326.23 ± 181.01**
Hood on (*n* = 6)	68.04 ± 1.80	0.00046 ± 0.00030	**432.55 ± 170.53**
Transfer station level			
Condition	Average dB	Average × *g*	Average lux
Hood off (*n* = 6)	50.87 ± 1.81	0.00084 ± 0.00066	69.95 ± 25.26
Hood on (*n* = 6)	**72.02 ± 0.96**	**0.01715 ± 0.01691**	**438.00 ± 208.77**
Rack level			
Rack location	Average dB	Average × *g*	Average lux
Bottom row (*n* = 13)	59.57 ± 6.36	0.00320 ± 0.00288	40.57 ± 33.63
Middle row (*n* = 13)	59.23 ± 6.31	0.00287 ± 0.00160	52.19 ± 51.97
Top row (*n* = 13)	60.43 ± 5.74	0.00330 ± 0.00180	71.58 ± 57.25

Bold values indicate exceeded thresholds based on reference 30 or *the Guide*.

high variation, an additional evaluation was performed to determine whether the number of functioning bulbs and type of bulb (fluorescent compared with light emitting diode [LED]) influenced lux readings across rooms. Bulb information was obtained for 3 of the largest facilities on campus (*n* = 31 rooms). Both the number and type of bulbs influenced the lux readings. Light intensity increased with the number of functioning bulbs present in the room ($F_{1,28} = 9.62$, $P = 0.0044$) and when LED bulbs were used as compared with fluorescent ($F_{1,28} = 19.89$, $P = 0.0001$). There was no significant interaction between the 2 factors.

Average light intensity in transfer stations was affected by the model number ($F_{2,36.15} = 4.65$, $P = 0.0160$) and by whether the station was on or off ($F_{1,43.84} = 125.65$, $P < 0.0001$). Intensity was higher with the station on (LSM: 103.12 ± 1.27 lx) as compared with off (LSM: 50.01 ± 1.27 lx, Figure 4A). Stations grouped as 'other' (LSM: 105.45 ± 1.62 lx) were brighter than Phantom models (LSM: 46.59 ± 1.75 lx, Figure 4B). The recommended 325-lx threshold was rarely reached on transfer stations in cages with the lid on.

Light intensity in cages on IVC racks was influenced by row location ($F_{2,412.80} = 101.81$, $P < 0.0001$), blower model ($F_{1,70.46} = 4.63$, $P = 0.0349$), and number of cages on the rack ($F_{1,72.82} = 7.21$, $P = 0.0090$). Cages in the top row (LSM: 13.21 ± 1.30 lx) were brighter than those in the middle (LSM: 4.39 ± 1.30 lx) or bottom rows (LSM: 4.93 ± 1.75 lx, Figure 4C). Cages were also brighter in SB4100 racks (LSM: 7.91 ± 1.33 lx) than EcoFlo racks (LSM: 5.49 ± 1.28 lx, Figure 4D) and brightness became lower as more cages were placed on the rack (Figure 4E). The recommended 325lx threshold was never met on mouse IVC racks.

Descriptive statistics. ***Rat rooms.*** Only 12 rooms were tested that contained rats, and only 6 of those contained a transfer station. Thirteen IVC racks were sampled from the rat rooms. Sound in the frequency range that rats can perceive spanned a similar intensity range as sound in the frequency range that mice can perceive in their respective rooms (IQR: 51.96 to 66.59 dB). Vibration at the room level was minimal (IQR: 0.00024 to 0.00058 × *g*). Light intensity was similarly variable across rooms, ranging from 141.25 to 793.98 lx (IQR: 207.55 to 495.50 lx).

Recommended sound and vibration thresholds were typically not met in rat rooms or IVC racks. However, the average sound intensity in active transfer stations did exceed 70 dB, and vibration variation suggests that 0.025 × *g* may often be exceeded (Table 3). The recommended light threshold was never met on rat IVC racks, but was often exceeded at the room level and in active transfer stations (Table 3).

Table 4. Values for the 5 sampled static racks. Data are shown as averages ± SDs for each rack. These data were not formally analyzed due to small sample size.

Rack ID	Average dB	Average × *g*	Average lux
Rack 1	47.15 ± 0.16	0.00181 ± 0.00143	36.46 ± 18.69
Rack 2	52.97 ± 5.23	0.00130 ± 0.00077	28.33 ± 28.42
Rack 3*	53.08 ± 0.66	**0.07047 ± 0.06534**	100.58 ± 38.91
Rack 4	**61.64 ± 14.38**	0.00067 ± 0.00046	43.66 ± 31.12
Rack 5	56.14 ± 3.64	0.00221 ± 0.00299	36.50 ± 12.91

*Functioning equipment for metabolic data collection was present on the same rack; bold values indicate exceeded thresholds based on reference 30.

Static racks. Across facilities, only 5 static racks were in use: 4 in mouse rooms and one in a rat room (Table 2). All static racks were in different rooms. Generally, parameter values fell within the ranges observed in mouse rooms with IVC racks, except for one extremely high vibration reading (approximately 0.07047 × *g*, Table 4). This high reading occurred in a room with active metabolic equipment on the rack.

Specific situations of interest. Recordings were taken to assess sound and vibration associated with the elevator, cage wash environment, and cage change activity. In terms of elevator activity, average sound intensity, maximum sound intensity, average vibration, and maximum vibration levels were all similar with and without a running elevator, both in the adjacent room and the one down the hall (Table 5). The room across from the cage wash also had similar readings when the cage wash was off and on (Table 5). However, the maximum sound reading was over 70 dB with the cage wash off. The maximum reading of 79.07 dB was observed for a single second, with the rest of the measurements ranging between 53.80 to 62.21 dB. Sound and vibration levels were numerically higher during cage change compared with before cage change (Table 5). The most notable observations were in maximum sound intensity (over 70 dB during cage change) and vibration (over 3-fold increase in average vibration and 8-fold increase in maximum vibration, Table 5). Sound levels over 70 dB were measured during 6% of the observations.

Sound levels were also taken to assess the effects of hallway motion sensors on sound levels. In the control room, recordings averaged between 48 and 52 dB, which falls within the range

Table 5. Preliminary sound and vibration values for elevator, cage wash, and cage change activity. Data are presented as averages ± SDs. These data were not formally analyzed because each was collected at a single time point.

Condition	Average dB	Maximum dB	Average × *g*	Maximum × *g*
Elevator off (adjacent room)	48.69 ± 0.45	50.76	0.00113 ± 0.00049	0.0058
Elevator on (adjacent room)	49.15 ± 0.77	56.77	0.00163 ± 0.00071	0.00539
Elevator off (down the hall)	54.52 ± 0.54	56.15	0.00625 ± 0.00085	0.00860
Elevator on (down the hall)	54.46 ± 0.51	55.99	0.00613 ± 0.00080	0.00829
Cage wash off	56.15 ± 1.83	**79.07**	0.00410 ± 0.00036	0.00486
Cage wash on	55.82 ± 0.59	57.58	0.00412 ± 0.00033	0.00509
Before cage change	50.32 ± 0.81	57.9	0.00083 ± 0.00028	0.00282
During cage change	59.17 ± 5.83	**79.37**	0.00260 ± 0.00135	0.01751

Bold values indicate exceeded thresholds based on reference 30.

Table 6. Sound values for motion detecting light sensors. Data are presented as averages ± SDs. These data were not formally analyzed because each was collected at a single time point.

Microphone placement	Control room average dB	Under motion sensor average dB
In cage (lid on)	48.55 ± 0.30	**76.08 ± 2.19**
In cage (lid off)	52.21 ± 0.99	**86.10 ± 4.76**
Open air, pointed up	52.16 ± 1.67	**94.56 ± 2.51**

Bold values indicate exceeded thresholds based on reference 30.

Table 7. Light values at each grid location in the top row of a ventilated rack. Data are presented as averages ± SDs. These data were not formally analyzed because each was collected at a single time point.

Grid location	Front of the cage average lux	Under the food hopper average lux
A1: not covered by blower	321.77 ± 0.39	141.46 ± 0.42
B1: not covered by blower	208.81 ± 0.63	201.52 ± 0.35
C1: not covered by blower	**348.01 ± 0.63**	**347.54 ± 0.44**
D1: not covered by blower	**463.48 ± 1.16**	**333.81 ± 0.30**
E1: partially covered by blower	**403.97 ± 0.60**	115.97 ± 0.39
F1: covered by blower	278.33 ± 0.39	53.73 ± 0.10
G1: partially covered by blower	237.00 ± 0.44	35.17 ± 0.08

Bold values indicate exceeded thresholds based on *the Guide*.[16]

described above for mouse housing rooms (Table 6). However, under the motion sensors, sound levels averaged between 76 and 94 dB (Table 6). Recordings in the cage were reduced by approximately 10 dB when the lid was on compared with off, but average sound intensity was still over 70 dB (Table 6).

Measurements taken along the top row of an IVC rack focused on light. In some locations, light intensity was several hundred lux higher at the front of the cage than under the food hopper, and the brightest measurements were found in the middle of the top row of the rack (Table 7, Figure 5).

Discussion

To the best of our knowledge, this is the first comprehensive sampling of ambient sound, vibration, and light across multiple animal facilities in a single centrally-managed institution. This current study is also the first reported formal analysis of how common factors in the facility affect these environmental parameters. Generally speaking, many factors influence the sensory world of rodents used in research, and we show here that the environment can vary based on individual room, activity, and cage location within a room.

In terms of sound audible to rodents, past work is limited, with extreme variation across studies in the sound intensity that is audible to mice in their housing rooms.[12,21] In the current assessment, sound levels were relatively consistent in the open-air environment of rodent housing rooms. Predicted values for

Figure 5. Visualization of the sampled locations across the top row of a ventilated rack to assess light variation.

mice ranged between 50 to 55 dB. Most averages (not formally analyzed) from rat rooms and static racks fell within this range. However, a functioning animal transfer station generates a considerable amount of added sound, as most predicted and raw average sound values exceeded 60 dB. The average sound intensity for rats in a functioning transfer station exceeded 70 dB. While 70 dB is the recommended threshold for 24-h exposure,[30] the World Health Organization recommends that sound not exceed 45 dB to prevent sleep disruption in humans.[2]

Sound audible to rodents on IVC racks was similar to what was measured in the open-air environment. Although mouse IVC racks showed significant differences based on row location, station activity, rack blower model, and number of cages on the rack, all sound intensity values fell between 50 to 60 dB. IVC racks are often considered a major source of sound pollution for rodents,[30] but the current data are similar to previous work showing that IVC racks cause just a small sound increase.[21] In this study, sound from IVC racks was similar in intensity to that of the main building ventilation system. However, the racks measured in the current study were primarily from a single manufacturer, and sound levels may vary in a wider range of rack models. Furthermore, our study aimed to record baseline sound levels in rooms with no additional functioning equipment. If computers or other devices with a blower are used, the associated sound and length of use should be considered.

In terms of the targeted area measurements, 2 notable sound observations were made. First, the ultrasonic motion detectors in the hallway of one facility produced high values of sound intensity. Based on manufacturer specifications, the sound intensity due to motion detectors is likely due to frequencies of approximately 32 kHz, which are in the rodent hearing range.[5] Values measured in cages ranged from 76 dB (with the plastic filter top on) to 86 dB (with the filter top off). As stated above, 70 dB is the recommended maximum for 24-h exposure for rodents[31] and OSHA recommends limiting human exposure to 85 dB for an 8-h workday. While instantaneous exposure to sound from this specific sensor model will likely not be damaging, it could startle animals, as the rodent startle response can be triggered at 75 to 80 dB.[8,17] Our measurements are based on a limited sample window, but a filter top blocked some of the added sound when a cage was under the sensor. Filter tops or even the use of solid lids could reduce stress if cages must be placed in a facility with ultrasonic motion sensors. Second, maximum sound intensity reached 79 dB in the housing room during cage change. Again, these measurements reflect acute sound exposure that could nonetheless evoke startle responses (75 to 80 dB).[8,17] Researchers should be aware of a room cage change schedule when planning procedures as rodents could have been exposed to stressful sound levels.

Past work is also limited for vibration measures and reports that total ambient vibration in the mouse room, as taken from a mouse cage on a rack, is approximately 0.00245 × g.[16] In our study, most vibration measurements taken from the floor of each room or in an inactive transfer station were low (< 0.002 × g). However, the highest value detected at the room level was 0.02347 × g. Upon consultation with husbandry staff who monitor that particular room, we learned that at the time of the measurement, several dairy cows were receiving health checks in an adjacent room. This suggests that vibration in rodent rooms can be easily affected by seemingly unrelated events. Similarly, vibration on the measured static racks was low, except for one rack. The average vibration on one static rack was approximately 0.0705 × g with extremely high variability. This was likely due to the active metabolic equipment located on that rack. While this measurement is from a limited time window, it highlights how additional study equipment can produce extreme vibration increases, well above 0.025 × g.[30]

On IVC racks, vibration was significantly affected by several factors: row location, blower model, transfer station activity, and number of cages on the rack. However, readings taken on the IVC racks generally ranged from 0.001 to 0.005 × g. These values are consistent with a previous report showing an average vibration from functioning IVC racks of 0.00357 × g.[16]

Of greater concern is the large increase in vibration associated with active transfer stations. On average, vibration readings on an active transfer station averaged 0.01698 × g, with maximum values often exceeding 0.025 × g. This threshold was determined based on 24-h exposure, but may nonetheless be a conservative estimate as fear behavior can be triggered by vibration as low as 0.010 × g.[4] Furthermore, the relative increase in vibration in a transfer station as compared with the IVC racks is concerning. Vibration on IVC racks was typically 0.001 to 0.005 × g, so placing cages on a surface that averages 0.01698 × g results in an exponential increase in vibration exposure of the rodents, which could be startling. Because excess vibration can increase the stress response (for example, higher corticosterone, startle behavior, heart rate, and blood pressure[1,4,13,19,22]), future work should focus on how rodents react to this increase in vibration and whether they habituate with repeated exposure. These findings are highly relevant to performing animal procedures on any kind of transfer station, fume hood, or biologic safety cabinet. In addition, a greater range of transfer station models should be tested, as the models grouped as 'other' in our study had a lower maximum reading than Phantom or NU 619-400 stations. Some models may be better for animal work than others in terms of how much vibration they produce.

Vibration during cage change also peaked at 0.01751 × g. These vibration peaks combined with the sound peaks discussed above suggest that cage change is an alarming situation for rodents. Our measurements were taken on a rack adjacent to the one that was actively being changed. Sound and vibration peaks during cage change were detected in a rack that was simply present in the room while another rack was being changed. Determining whether modifications in cage change work practices could lower maximum sound and vibration levels (for example, quiet placement of caging supplies) could be useful. Anecdotally, we noted that measurements peaked when the technician placed caging supplies in the station or on a cart in the room.

Light measurements from mouse IVC racks differed statistically based on row location, blower model, and the number of cages on the rack. However, in general, values were low (< 10 lx), which was surprising given the large range of values seen at the room level. Even measurements on the rat IVC racks and static racks typically did not exceed 100 lx. This suggests that most rodent housing accommodates their inherent light sensitivity.[9,14] The lower values in the mouse cage compared with the rat cage are likely a product of placing the light sensor in the center of the cage, which was directly under the food hopper. Measurements from the top row were taken from the same location. The preliminary readings across the top row of a mouse IVC rack show considerable variation across both cage location and sensor location in the cage. However, these light readings are meaningful because the mice could choose to be in darker areas of the cage. Both rats and mice prefer environments that are darker than typical cage conditions.[3,23,35] Mice also naturally build nests, and if nests are complex enough to form an enclosed dome, light will certainly be blocked by the material.[6,11] Nonetheless, further measurements across cage

locations within a rack would document the true extent of light variability. While evidence in mice is lacking, research in rats shows that changes in light wave frequency can alter various hormone pathways.[35,36] However, to the best of our knowledge, the physiologic consequences of exposure to different light intensities (for example 10 lx compared with 100 lx compared with 500 lx) during the light cycle is unknown.

The large increase in light intensity that occurs when cages are removed from the rack for a procedure during the light cycle is another source of concern. Light measurements in this study showed extreme variation at the room level, with many rooms exceeding the recommended 325 lx.[15] This extreme variation in light intensity could potentially impact data collected from behavioral tests (for example, light/dark box, elevated plus maze, open field test). Animals may remain in darker areas of the testing arena due to optical discomfort, rather than anxiety or unwillingness to explore. This could suggest that cages and testing areas should be shielded from higher light intensities when not on a housing rack, or that testing should be done during the dark cycle, so the animals would not experience such drastic changes in light. Furthermore, higher light intensity was associated with more functioning bulbs in the room and with LED bulbs compared with fluorescent. Perhaps fluorescent bulbs are more appropriate for rodent light intensity needs; the number of bulbs in the room could also be reduced. Based on the data obtained here, animal facility managers at our institution are currently working with maintenance crews to remove bulbs in rooms with high light levels and will regularly monitor rooms with a light meter. Efforts are also being made to install light dimmers in facilities with LED bulbs.

In addition, in the active transfer station, light in the rat cage exceeded 325 lx on average. While light values in the mouse cage typically did not exceed 100 lx in an active transfer station, this could be due to the light sensor's location under the food hopper. Consequently, light readings in the mouse cage may not reflect the true intensity that the mice experience in the transfer station because cage lids are typically removed.

Conclusions

In general, this study provided a comprehensive sample of understudied and underreported environmental parameters in a single large university. While these data only represent a brief snapshot of each rodent room, they provide a general picture of the experiences of research rodents. Our data also highlight areas of potential concern in terms of sound, vibration, and light intensity. These areas may extend to other institutions that house rodents, but individual facilities may have their own unique challenges. Therefore, we recommend that other institutions perform their own environmental monitoring to identify specific areas that require modification.

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References

1. **Atanasov NA, Sargent JL, Parmigiani JP, Palme R, Diggs HE.** 2015. Characterization of train-induced vibration and its effect on fecal corticosterone metabolites in mice. J Am Assoc Lab Anim Sci **54**:737–744.
2. **Berglund B, Lindvall T, Schwela D.** 1999. Guidelines for community noise.
3. **Davis HJ, Barabas AJ, Gaskill BN.** 2022. Titrating the preferences of altered lighting against temperature in female CD-1 laboratory mice, *Mus musculus*. Appl Anim Behav Sci **246**:105541. https://doi.org/10.1016/j.applanim.2021.105541.
4. **Garner AM, Norton JN, Kinard WL, Kissling GE, Reynolds RP.** 2018. Vibration-induced behavioral responses and response threshold in female C57BL/6 mice. J Am Assoc Lab Anim Sci **57**:447–455. https://doi.org/10.30802/AALAS-JAALAS-17-00092.
5. **Heffner HE, Heffner RS.** 2007. Hearing ranges of laboratory animals. J Am Assoc Lab Anim Sci **46**:20–22.
6. **Hess SE, Rohr S, Dufour BD, Gaskill BN, Pajor EA, Garner JP.** 2008. Home improvement: C57BL/6J mice given more naturalistic nesting materials build better nests. J Am Assoc Lab Anim Sci **47**:25–31.
7. **Hutson KA, Masterton RB.** 1986. The sensory contribution of a single vibrissa's cortical barrel. J Neurophysiol **56**:1196–1223. https://doi.org/10.1152/jn.1986.56.4.1196.
8. **Ison JR, Allen PD.** 2003. Low-frequency tone pips elicit exaggerated startle reflexes in C57BL/6J mice with hearing loss. J Assoc Res Otolaryngol **4**:495–504. https://doi.org/10.1007/s10162-002-3046-2.
9. **Jacobs GH, Fenwick JA, Williams GA.** 2001. Cone-based vision of rats for ultraviolet and visible lights. J Exp Biol **204**:2439–2446. https://doi.org/10.1242/jeb.204.14.2439.
10. **LaFollette MR, Swan MP, Smith RK, Hickman DL, Gaskill BN.** 2019. The effects of cage color and light intensity on rat affect during heterospecific play. Appl Anim Behav Sci **219**:104834. https://doi.org/10.1016/j.applanim.2019.104834.
11. **Latham N, Mason G.** 2004. From house mouse to mouse house: The behavioural biology of free-living *Mus musculus* and its implications in the laboratory. Appl Anim Behav Sci **86**:261–289. https://doi.org/10.1016/j.applanim.2004.02.006.
12. **Lauer AM, May BJ, Hao ZJ, Watson J.** 2009. Analysis of environmental sound levels in modern rodent housing rooms. Lab Anim (NY) **38**:154–160. https://doi.org/10.1038/laban0509-154.
13. **Li Y, Rabey KN, Schmitt D, Norton JN, Reynolds RP.** 2015. Characteristics of vibration that alter cardiovascular parameters in mice. J Am Assoc Lab Anim Sci **54**:372–377.
14. **Naarendorp F, Esdaille TM, Banden SM, Andrews-Labenski J, Gross OP, Pugh EN.** 2010. Dark light, rod saturation, and the absolute and incremental sensitivity of mouse cone vision. J Neurosci **30**:12495–12507. https://doi.org/10.1523/JNEUROSCI.2186-10.2010.
15. National Research Council. 2011. Guide for the care and use of laboratory animals. 8th ed. Washington (DC): The National Academies Press.
16. **Norton JN, Kinard WL, Reynolds RP.** 2011. Comparative vibration levels perceived among species in a laboratory animal facility. J Am Assoc Lab Anim Sci **50**:653–659.
17. **Popelář J, Díaz Gómez M, Lindovskỳ J, Rybalko N, Burianová J, Oohashi T, Syka J.** 2017. The absence of brain-specific link protein Bral2 in perineuronal nets hampers auditory temporal resolution and neural adaptation in mice. Physiol Res **66**:867–880. https://doi.org/10.33549/physiolres.933605.
18. **Rabey KN, Li Y, Norton JN, Reynolds RP, Schmitt D.** 2015. Vibrating frequency thresholds in mice and rats: Implications for the effects of vibrations on animal health. Ann Biomed Eng **43**:1957–1964. https://doi.org/10.1007/s10439-014-1226-y.
19. **Raff H, Bruder ED, Cullinan WE, Ziegler DR, Cohen EP.** 2011. Effect of animal facility construction on basal hypothalamic-pituitary-adrenal and renin-aldosterone activity in the rat. Endocrinology **152**:1218–1221. https://doi.org/10.1210/en.2010-1432.

20. **Rasmussen S, Miller MM, Filipski SB, Tolwani RJ.** 2011. Cage change influences serum corticosterone and anxiety-like behaviors in the mouse. J Am Assoc Lab Anim Sci **50**:479–483.
21. **Reynolds RP, Kinard WL, Degraff JJ, Leverage N, Norton JN.** 2010. Noise in a laboratory animal facility from the human and mouse perspectives. J Am Assoc Lab Anim Sci **49**:592–597.
22. **Reynolds RP, Li Y, Garner A, Norton JN.** 2018. Vibration in mice: A review of comparative effects and use in translational research. Animal Model Exp Med **1**:116–124. https://doi.org/10.1002/ame2.12024.
23. **Rowan AN.** 1990. Refinement of animal research technique and validity of research data. Fundam Appl Toxicol **15**:25–32. https://doi.org/10.1093/toxsci/15.1.25.
24. **Schlingmann F, De Rijk SHLM, Pereboom WJ, Remie R.** 1993. Avoidance as a behavioural parameter in the determination of distress amongst albino and pigmented rats at various light intensities. Anim Technol **44**:87–96.
25. **Schlingmann F, De Rijk SHLM, Pereboom WJ, Remie R.** 1993. Light intensity in animal rooms and cages in relationship to the care and management of albino rats. Anim Technol **44**: 97–107.
26. **Stolshek JD, Koehring PA.** 1984. Ultrasonic Technology Provides for Control of Lighting. IEEE Trans Ind Appl **IA-20**:1564–1572. https://doi.org/10.1109/TIA.1984.4504642.
27. **Szél A, Röhlich P, Caffé AR, Juliusson B, Aguirre G, Van Veen T.** 1992. Unique topographic separation of two spectral classes of cones in the mouse retina. J Comp Neurol **325**:327–342. https://doi.org/10.1002/cne.903250302.
28. **Turner JG, Bauer CA, Rybak LP.** 2007. Noise in animal facilities: Why it matters. J Am Assoc Lab Anim Sci **46**:10–13.
29. **Turner JG, Parrish JL, Hughes LF, Toth LA, Caspary DM.** 2005. Hearing in laboratory animals: Strain differences and nonauditory effects of noise. Comp Med **55**:12–23.
30. **Turner JG.** 2020. Noise and vibration in the vivarium: Recommendations for developing a measurement plan. J Am Assoc Lab Anim Sci **59**:665–672. https://doi.org/10.30802/AALAS-JAALAS-19-000131.
31. **Von Uexküll J.** 1909. Umwelt und Innenwelt der Tiere. [Book in German]. Berlin: Springer.
32. **Ushakov IB, Soloshenko NV, Koslovskij AP.** 1983. The examination of resonance frequencies of vibration in rats. Kosm Biol Aviakosm Med **17**:65–68.
33. **La Vail MM, Gorrin GM, Repaci MA.** 1987. Strain differences in sensitivity to light-induced photoreceptor degeneration in albino mice. Curr Eye Res **6**:825–834. https://doi.org/10.3109/02713688709034850.
34. **Walcher J, Ojeda-Alonso J, Haseleu J, Oosthuizen MK, Rowe AH, Bennett NC, Lewin GR.** 2018. Specialized mechanoreceptor systems in rodent glabrous skin. J Physiol **596**:4995–5016. https://doi.org/10.1113/JP276608.
35. **Wren-Dail MA, Dauchy RT, Ooms TG, Baker KC, Blask DE, Hill SM, Dupepe LM, Bohm RP.** 2016. Effects of colored enrichment devices on circadian metabolism and physiology in male Sprague-Dawley rats. Comp Med **66**:384–391.
36. **Wren MA, Dauchy RT, Hanifin JP, Jablonski MR, Warfield B, Brainard GC, Blask DE, Hill SM, Ooms TG, Bohm RP.** 2014. Effect of different spectral transmittances through tinted animal cages on circadian metabolism and physiology in sprague-dawley rats. J Am Assoc Lab Anim Sci **53**:44–51.