Vibrations and Museum Collections

Part 2: The Effects of Vibrations from Musical Events and Transportation on Museum Collections

By Arne Johnson and Mohamed ElBatanouny

Introduction

Vibrations from a variety of sources can have a detrimental impact on museum collections. Sources include normal activities inside a museum facility, such as foot traffic and crowd movements, the operation of elevators and heavy doors, the use of carts and lifts to move objects, and activities at loading docks. Even reciprocating mechanical equipment can cause background vibrations. In addition, one-time or occasional sources of vibration include activities associated with construction projects, special events both within and adjacent to museum buildings, and the transportation of art.

Protecting museum collections from vibrations due to human activity and building construction is a recognized concern, and was summarized in Part 1 of this series,[1] whose authors have served as vibration experts for numerous museums during renovation and expansion projects. Following a scientific and practical methodology, customized for each project, art and artifacts can be reliably protected without unduly encumbering designers or contractors.[2]

Two further topics involving vibration and museum collections are starting to receive increasing attention: the vibratory impacts of musical events, and new questions regarding vibrations associated with transportation of museum objects. Increasingly, museums around the world are hosting events, often near art and artifacts, and often including live or recorded music. In other cases, these types of events take place near museum buildings.

Unfortunately, there have been very few systematic studies of the impact of music on art and artifacts, despite reports of adverse effects. Furthermore, since events often recur, and since the impact of exposure to vibrations is cumulative, damage to art and objects may not be immediately observed. Regarding the vibratory impact of the transportation of art, considerable scientific research has been performed and reported, including methods of crate design to mitigate shock and vibration.[3] However, new questions are now being raised about the vibrations that objects experience during transportation, with some reporting that vibrations during transportation are greater than anticipated.

Scientists and professionals involved in collection protection are conducting research into these topics. This article provides an overview of the state of knowledge, as well as research underway to advance the state of the art, focusing particularly on the impact of musical events within or adjacent to museum buildings.

This article also summarizes the findings of a research questionnaire on the current practices and experiences of museums worldwide, in relation to the vibratory impact of musical events and transportation. The questionnaire was administered by an international research group[4] and clearly identified the need for practical guidelines that can

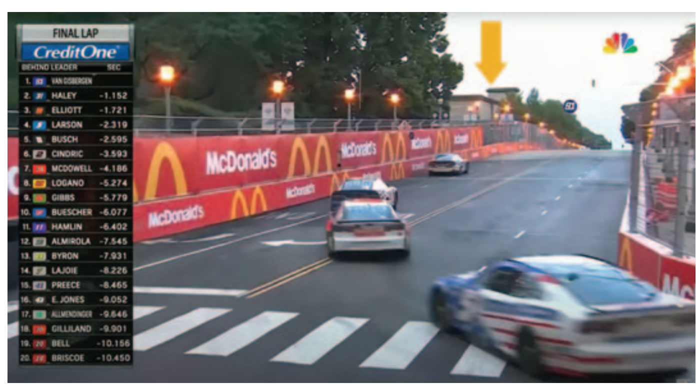

Figure 1. Screen capture from NASCAR Cup Series race, showing lead cars approaching The Art Institute of Chicago (arrow). Source: https://www.youtube.com/watch?v=pjXGWREWS7A.

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[1] Arne Johnson and Mohamed ElBatanouny, "Vibrations and Museum Collections, Part 1: Effects of Human Traffic and Construction on Museum Collections," *Papyrus*, 2019.

[2] See, for example: Arne Johnson, Bob Hannen, and Frank Zuccari, "Vibration Control During Museum Construction Projects," *Journal of the American Institute for Conservation*, Vol. 52 No. 1, 2013, pp. 30-47; Arne Johnson and Robert Hannen, "Vibration Limits for Historic Buildings, Art Collections and Similar Environments," *APT Bulletin, Journal of Preservation Technology*, Vol. 46:2-3, 2015, pp. 66-74; and Arne Johnson and Mark DeMairo, "The Neue Galerie: Targeted Vibration Control During Internal Construction," *Papyrus*, Fall 2017.

[3] For example: Mervin Richard, Marion Mecklenburg, and Ross Merrill, *Art in Transit: Handbook for Packing and Transporting Paintings*, Washington, D.C.: National Gallery of Art, 1991.

[4] "Research Questionnaire Findings: Vibratory Impacts of Musical Event and Transport on Museum Collections," October 2022, report accessible here: https://www.wje.com/knowledge/articles/detail/vibratory-impacts-of-music-and-transport-on-museum-collections; April 2023 webinar in partnership with AIC and ARCS accessible here: https://www.wje.com/knowledge/webinars/detail/findings-of-research-questionnaire-on-vibratory-impacts-of-music-and-transport-on-museum-collections; research group members are Catherine Higgitt, Arne Johnson, Mohamed ElBatanouny, W. (Bill) Wei, Peter Henson, Tomasz Galikowski, Mark Ryan, and JP Brown.

be used in the field. Case studies are also presented, as is a summary of some of the factors that should be considered in museum facility operations to help reduce the risks to museum collections from these sources of vibrations.

Vibrations from Musical Events

In response to a growing number of anecdotal reports on the impact of musical vibrations on art and objects, an international research group designed questionnaire to systematically gather data on the experiences and practices of museums in relation to musical events and transportation. A total of 155 responses from 138 museums in 24 countries were received and summarized in a report[5] and webinar,[6] presented in partnership with the American Institute for Conservation (AIC) and the Association of Registrars and Collection Specialists (ARCS). Key findings regarding musical events were as follows:

- The vast majority (92 percent) of museums indicated that they permit music in or directly adjacent to spaces containing collections (see Figures 2 through 4 for examples). Nearly half have musical events more than once per month, and nearly half host large groups of musicians (e.g., live bands) or DJs with amplified music.
- Control measures primarily include planning with event organizers and musicians, with oversight during the event—typically by security staff, and occasionally by collections staff. Quantitative monitoring during events, if any, is generally limited to taking decibel readings in event spaces, sometimes with decibel limits that are enforced during soundchecks and events.
- Around 60 percent reported effects on collections that have been attributed to music. Effects most commonly reported were vibrations felt in walls, floors, or objects/cases. The next most commonly reported effects from music were the "walking" (lateral travel/sliding) or rattling of objects. Occasionally, physical effects from music were reported, including objects losing support, falling, or visibly shaking (see Figure 5 for details).
- Analyzing the data for trends revealed that the following factors *did not* appear to influence the effects of music:
    - Whether the institution has a sound decibel limit or other sound/vibration limit.
    - The numerical value of any decibel limits being used.
    - The size of the institution.
- The following factors *did* appear to correlate to the effects of music:
    - Type of music allowed (music with more bass and percussion was reported to be more problematic).
    - Regularity of musical events.
    - Whether equalization parameters or filters were applied to the speaker outputs. (Museums that require audio technicians to apply equalization parameters/filters reported fewer effects.)
- Some museums have taken sound or vibration measurements during events, but the vast majority of these have been decibel readings, which, as noted above, did not correlate to observed effects. A few museums reported taking vibration measurements on floors or walls during musical events. None reported taking vibration measurements directly on the surfaces of objects.

The questionnaire findings demonstrate that musical events can significantly affect art and that better means are needed to try and limit their impact. A decibel limit, the most common method reported, does not consistently prevent adverse effects, and very few museums are taking vibration (not just sound) measurements. Furthermore, vibration measurements are not being taken directly on the surfaces of objects—and often cannot be taken—even though sound pressure travels through the air directly to the object. This means that measurements on adjacent walls or floors may not represent vibrations being experienced by the object itself.

The questionnaire demonstrates that institutions need more effective monitoring programs to protect collections during musical events. Members of the international research group are continuing their research towards developing a *Good Practice Guide for Musical Events at Museums*. This includes networking with museums and other experts who are currently developing appropriate monitoring equipment and methods, and conducting laboratory testing on the effects of music. The goal is to recommend practical yet effective methods for evaluating the risk of musical events,

Figure 2. Pitchfork concert event at The Art Institute of Chicago—there are galleries behind the walls.

[5]"Research Questionnaire Findings," Op. cit.
[6]Ibid.

Figure 3. Large party with DJ setup (circle) at the Rijksmuseum—there are galleries behind the walls.

Figure 4. Percussion concert at The Metropolitan Museum of Art—there are paintings on the balcony walls above.

mitigating against such risks and, when necessary, monitoring sound and vibration during events to protect collections.

Unlike construction vibrations that are primarily structurally-borne (i.e. conducted through the solid media of building elements), vibrations from music and sound also travel through the air as sound pressure. When sound pressure impinges on a surface, it can make the surface vibrate. Figure 6 illustrates the three primary paths along which vibration waves can travel to reach art objects during a musical event: 1) sound pressure from a source travels directly (or through reflected paths) to the art object; 2) flanking sound pressure impinges on adjacent cases, floors, or walls, then travels through those elements to the art objects; and 3) structurally-borne vibrations from speaker cabinets and supports travel through structural elements to the art objects.

Monitoring during musical events and understanding the potential impact of vibration from music is complicated

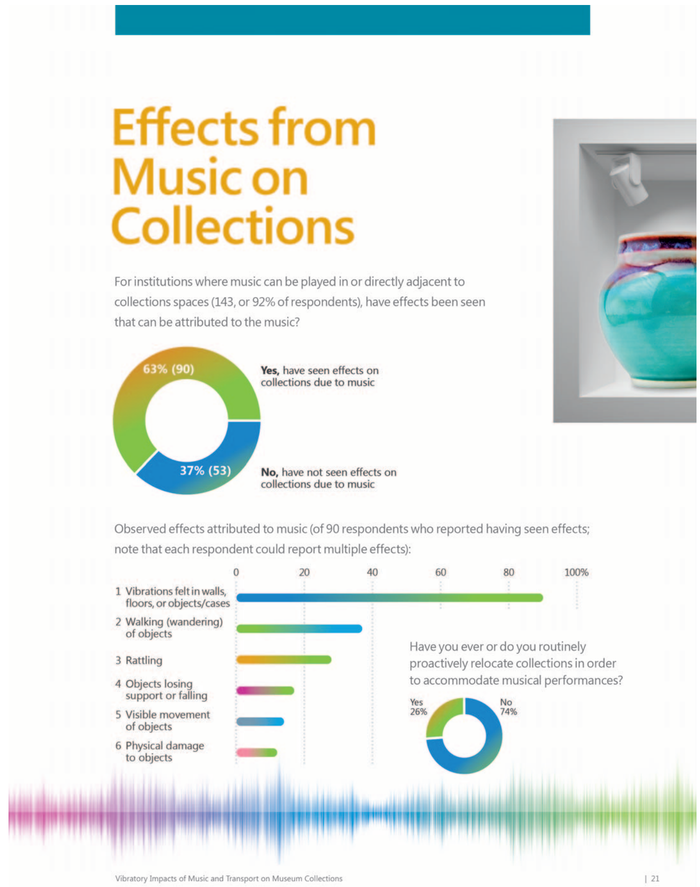


Figure 5. Page 21 from the research questionnaire report, with data on effects observed from music.[7]

by these multiple paths, which all need to be considered. In contrast, monitoring and mitigating construction vibration is simpler, because construction vibration is structurally or ground-borne and can be "intercepted" by monitors or mitigation placed on adjacent floors or walls before it reaches art objects. However, for music played inside a gallery, what is detected on adjacent walls and floors may or may not be related to the vibrations affecting art objects.

The following case studies demonstrate approaches to monitoring and assessing the impact of vibrations from events involving sound/noise, both within and outside museum buildings. In addition to studies based around actual events, members of the research questionnaire team are undertaking laboratory testing to simulate music inside a gallery space. This will help inform practical guidelines being developed for the monitoring and mitigation of vibration.

Preliminary Laboratory Measurements Simulating Music Inside a Gallery

In a limited and preliminary laboratory study, the authors measured the vibratory impact of music on simulated art objects, using a blank canvas painting and two showcases provided by The Art Institute of Chicago. A professional DJ

[7] "Vibratory Impacts of Musical Events and Transport on Museum Collections," October 2022.

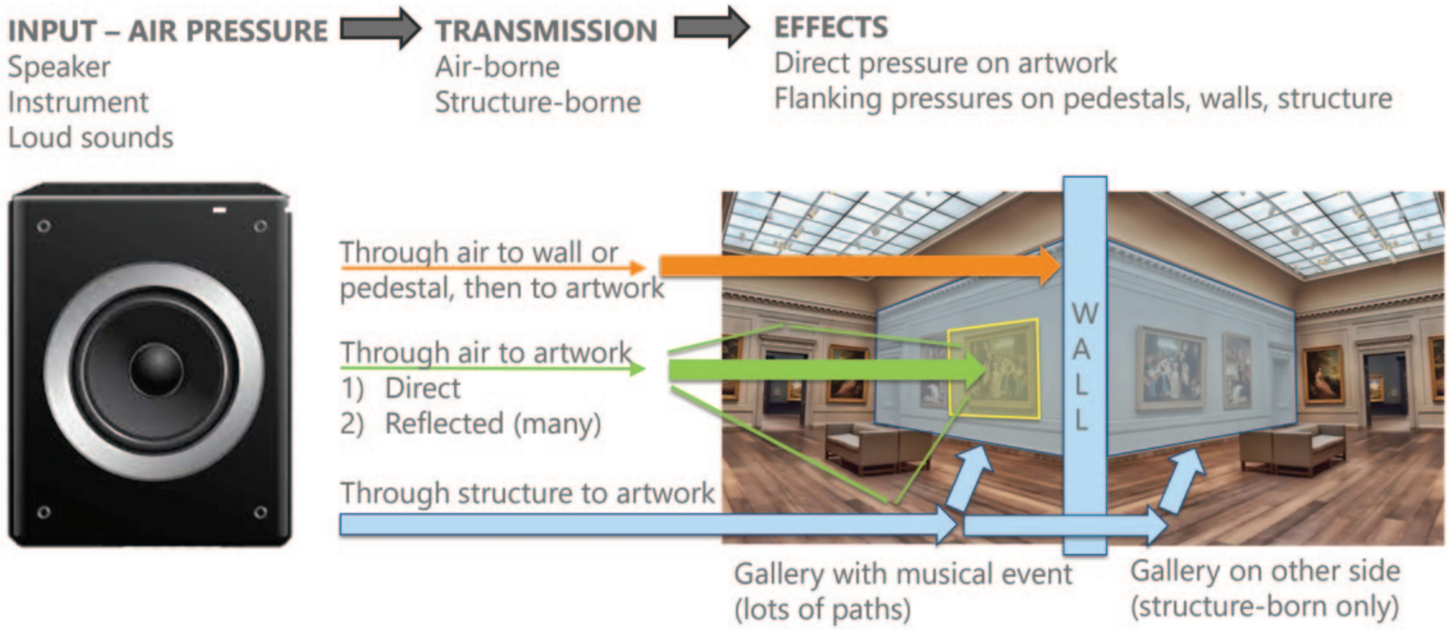


Figure 6. Simplified illustration of potential vibration paths to art objects during a musical event.[8]

played four different genres of music and single tones, at two volume levels, while accelerometers and laser vibrometers measured vibrations in the rooms and on the simulated art objects. The sound system included a mixing board, speakers on stands, and subwoofers on the floor (Figure 7).

Testing was conducted in three different spaces: a small semi-enclosed space with slab-on-grade floor containing objects 12 feet from speakers; a large open space with slab-on-grade floor containing objects 34 feet from speakers; and a large, enclosed space with structurally supported floor containing objects 30 feet from speakers. Equipment included: accelerometers on the showcases, floors, and walls; a laser vibrometer taking readings on the surfaces of the mock painting and vases in the showcases; and two sound meters—one near the speakers, and one near the art objects.

The resulting measurements indicated that, in addition to the volume of the music, other factors contributed to the degree of vibratory response and its impact on the objects, such as the type of music, space, and structure, and the directionality and support of the speaker cabinets. Although useful, these limited measurements indicated that more robust, systematic testing is needed to fully understand the effects.

[8]Concepts credited to Tomasz Galikowski, Associate Acoustic Engineer, Bickerdike Allen Partners, London.

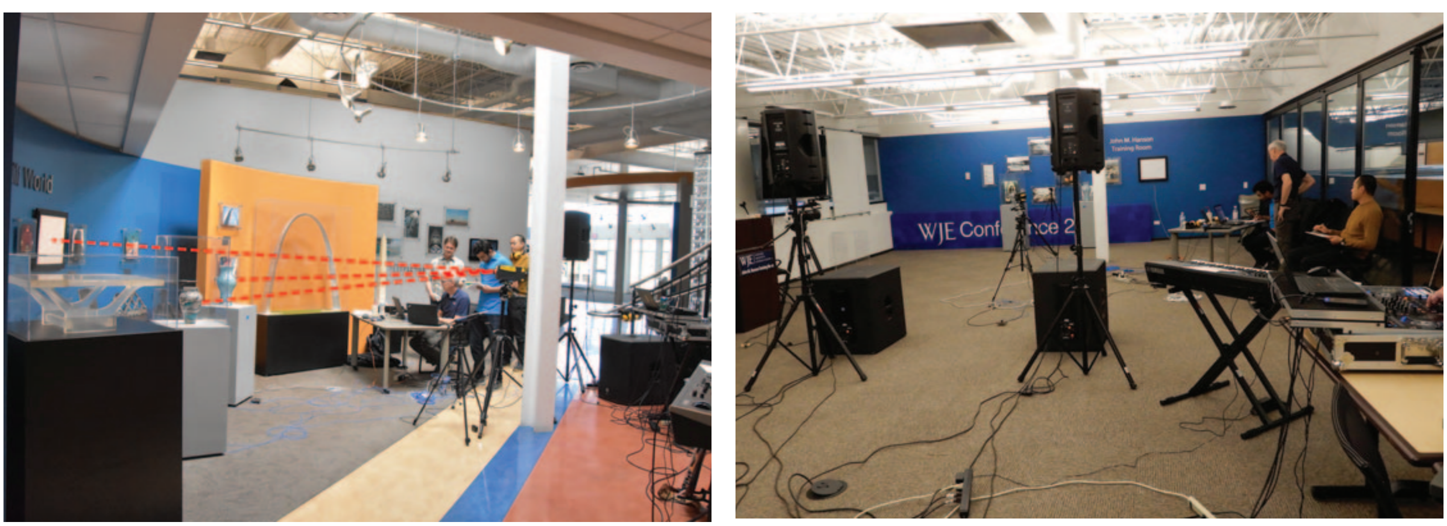


Figure 7. Views of preliminary laboratory testing conducted to study the effects of music on art objects. DJ and sound system (right); mock painting and showcases provided by AIC (left and in distance). Red dashed lines indicate laser vibrometer measurements.

Case Study: Music/Sound Inside a Gallery—SUE the Dinosaur

Part 1 of this series, and a subsequent publication, looked at vibration mitigation at Chicago's Field Museum in a new gallery for SUE the *T. rex*.[9] The new exhibit includes video animations and a sound show played on six projectors, 17 ceiling speakers, four wall-mounted cabinet speakers, and six ceiling-mounted subwoofers. The museum raised questions about whether the sound show—especially the loud dinosaur growling and roaring segments—would cause detrimental vibrations that would negatively affect the dinosaur bones.

To evaluate these effects, following a vibration-mitigation retrofit of the floor structure, non-contact laser vibrometer measurements were taken (Figure 8) of selected rib and gastralia bones, both during human activities and during the sound show. In addition, vibrations of the floor and the selected bones were measured during the following activities: ambient (no sound or human traffic), floor impact near the specimen using a calibrated heel-drop plate, random walking of three to four people near the specimen, roar segments excerpted from the soundtrack, single low-frequency synthesizer notes, and four genres of music (classical, jazz, rock, and R&B). Measurements were taken while increasing the volume from a normal listening level (70–80 dB) to loud (90–100 dB).

The maximum vibration of the bones due to random walking was approximately 5 to 12 mm/s (0.2 to 0.5 in/s), indicating an amplification of three to eight times the maximum vibrations of the floor from walking (a common amplification range due to the resonant-like behavior of geometric objects supported on a floor). By comparison, the maximum vibration of the same bones due to the roaring segments of the soundtrack was lower, from approximately 0.8 to 5 mm/s (0.03 to 0.2 in/s). The music clips and single notes yielded similar results.

[9]Arne Johnson, Mohamed ElBatanouny and William Simpson, "Vibration Mitigation and Sound Testing in SUE Hall at The Field Museum in Chicago," *APT Bulletin: The Journal of Preservation Technology*, 51:4 2020.

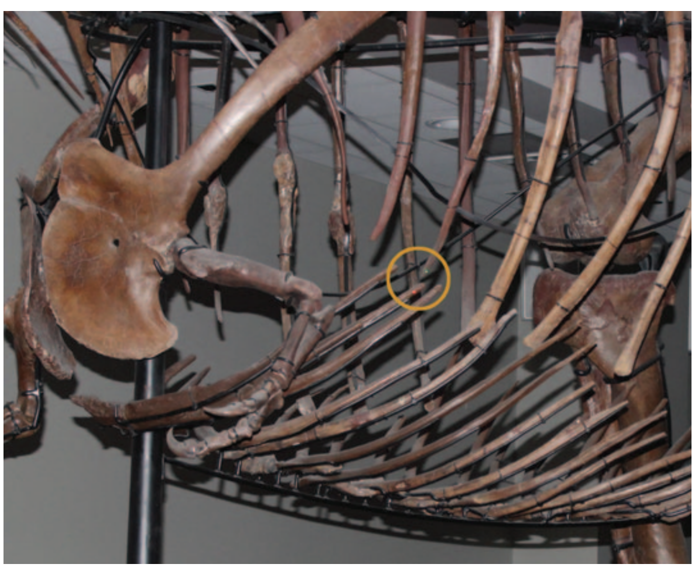


Figure 8. Laser vibrometer measurements on SUE while the exhibit soundtrack and different music genres were played in the gallery (red and green laser points indicated by circle).

In short, vibration of the fossils due to the sound system, although noteworthy, were considerably less than the vibration caused by normal walking on the retrofitted gallery floors. It should be noted that the sound system in the space was not designed to have a large bass response like that of a live band or DJ setup. In addition, this study did not endeavor to distinguish how much vibration was transmitted through the structure, compared to how much, if any, was transmitted through the air directly to the fossils.

Case Study: Music/Sound Outside a Gallery—NASCAR Street Race

The Art Institute of Chicago (AIC) retained the authors' firm to develop and implement a vibration-monitoring program for the first-ever NASCAR Street Race event on July 1–2, 2023. The 12-turn, 3.5-km (2.2-mile) street course included parts of Lake Shore Drive, Michigan Avenue, Columbus Drive, and Jackson Drive, which borders the south side of the AIC campus (Figure 9). Approximately 50,000 fans attended the weekend event, which included multiple concerts and two races, with cars reaching top speeds of nearly 240 kph (150 mph).

Art located near the south wall of the Rice Building fronting Jackson Drive includes works in the Regenstein Hall galleries, which—during the NASCAR event—featured a Van Gogh special exhibition. Fortunately, numerous prior vibration studies by the authors on the AIC campus provided reference data, the most relevant of which was for reconstruction of the Jackson Drive Bridge,

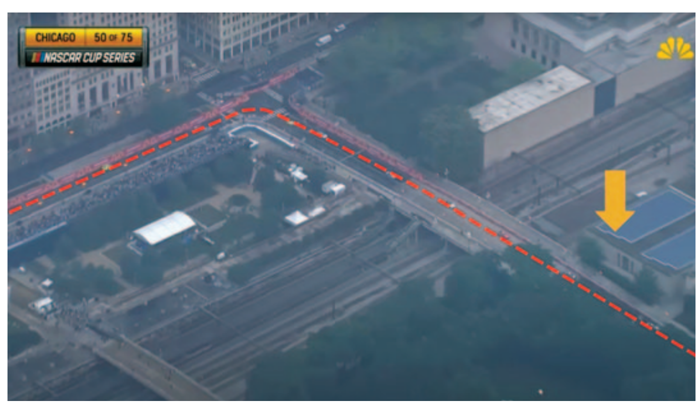


Figure 9. Aerial view of Cup Series race showing course (red dashed line), southern extent of AIC campus (shaded), and Rice Building (arrow).
Source: https://www.youtube.com/watch?v=pjXGWREWS7A

located adjacent to the Rice Building. This study included onsite vibration attenuation testing, which documented the transmission of vibrations into the Rice Building and Regenstein Hall. A network of vibration monitors distributed within the building collected vibration data throughout the bridge reconstruction project.

Based on a review of prior data and consultation with NASCAR about the event, the authors advised AIC that vibrations from racecar traffic should not pose a significant risk to structures, art, or people on the museum's campus. However, as an added layer of precaution, AIC commissioned development of a monitoring plan to continuously measure sound and vibrations in nearby collection spaces during race setup, event activities, and tear-down.

Since NASCAR may repeat this event in future years, the plan included a more comprehensive monitoring program for this first event, including:

- Fifteen seismographs (triaxial vibration monitors recording peak particle velocity) generally positioned along two lines from the race track into the building.
- Six wired and wireless triaxial accelerometers, mounted on various floors and walls inside the galleries,
- Two sound meters (measuring sound pressure in unweighted decibels, dB_Z.): one outside and one inside the double doors in the exterior wall facing the race route.
- A streaming 180° camera positioned on the roof, providing a real-time view of the race route, time-synchronized with the monitoring data.

A summary of vibration amplitudes recorded along one of the lines of monitors in Figures 10 and 11 is shown in Table 1. It reveals that ambient vibration of the gallery floor due to normal human traffic (patrons in the Van Gogh exhibit) was typically up to 1 mm/s (0.04 in/s), with occasional excursions up to 2.5 mm/s (0.10 in/s). Vibrations on the gallery floors during the race (when galleries were vacant) were less, reaching only 0.8 mm/s (0.03 in/s). Figure 15 shows a time history of vibrations recorded at one of the floor monitors on July 2, illustrating graphically that vibrations from approximately 10:00 a.m. to 5:00 p.m., when the galleries were open, were greater than vibrations during the racing from approximately 5:30 to 8:30 p.m., when the galleries were closed. It is noteworthy that race-related activities, especially installing and removing the concrete barriers, caused elevated vibrations near the track of up to 4.8 mm/s (0.19 in/s), but these vibrations were transient (impact) and did not transmit appreciably into the building.

Sound-pressure levels outside the building during the races were very high, reaching 119 dB_Z. However, corresponding sound levels inside the building, although very perceptible as cars passed, only reached 87 dB_Z, owing to high attenuation from the thick masonry cavity wall.

The loud noise and corresponding sound pressure (air-borne vibration) from passing race cars caused out-of-plane vibration of the exterior wall, located only 9 metres (30 feet) from the race route. Figures 12 and 13 illustrate the vibrations in the soil near the route when race cars passed, and Figure 14 illustrates the out-of-plane vibration of the building's exterior wall when multiple cars passed. Vibration of the exterior face of the exterior wall (VM-5) reached 2.5 mm/s (0.10 in/s), but vibrations of the interior face of the wall (GL-4) only reached 1.3 mm/s (0.05 in/s), again owing to the high attenuation of the exterior wall.

Table 1. Summary of Vibration Data Before, During and after NASCAR Event—Maximum Peak Particle Velocity PPV (mm/s)

	Distance from Race Route and into Building						
Activity	**VM-1 (in soil 10 ft from track)**	**VM-4 (terrace outside exterior wall)**	**VM-5 (exterior face of exterior wall)**	**GL-4 (interior face of exterior wall)**	**VM-7 (floor inside exterior wall)**	**VM-9 (gallery floor at first partition wall)**	**GL-2 (partition wall above VM-9)**
Ambient from exterior activities (traffic and concrete barrier removal)	2.0 typical, excursions to 4.8	0.5 typical, excursions to 3.3	—	—	0.8 typical, excursions to 2.3	0.8 typical, excursions to 1.3	0.8
Ambient from human activities inside galleries	—	—	—	—	1.0 typical, excursions to 2.5	1.0	1.8
Xfinity Cars—time trials and race July 1	1.3	0.3	1.0	NA	0.8	0.8	1.5
Cup Series Cars—time trials on July 1 and race on July 2	2.0	0.5	2.5	1.3	0.5	0.5	1.0

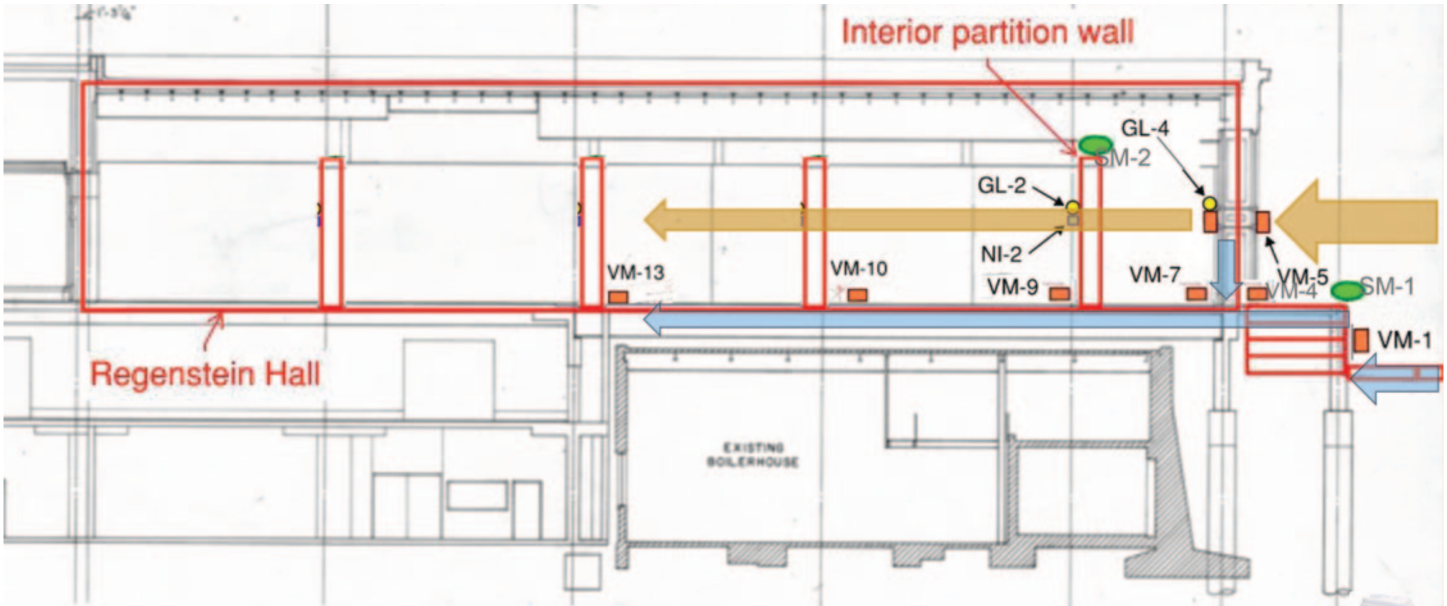


Figure 10. Schematic building cross-section showing layout of one of the lines of vibration/sound monitors from the race route (right side) progressing into the building (left side).

Figure 11. Examples of monitoring equipment in Regenstein Hall galleries. Left: Multiple sensors on floor and wall, with data acquisition system in large enclosure. Right: Stand-alone seismographs in enclosures.

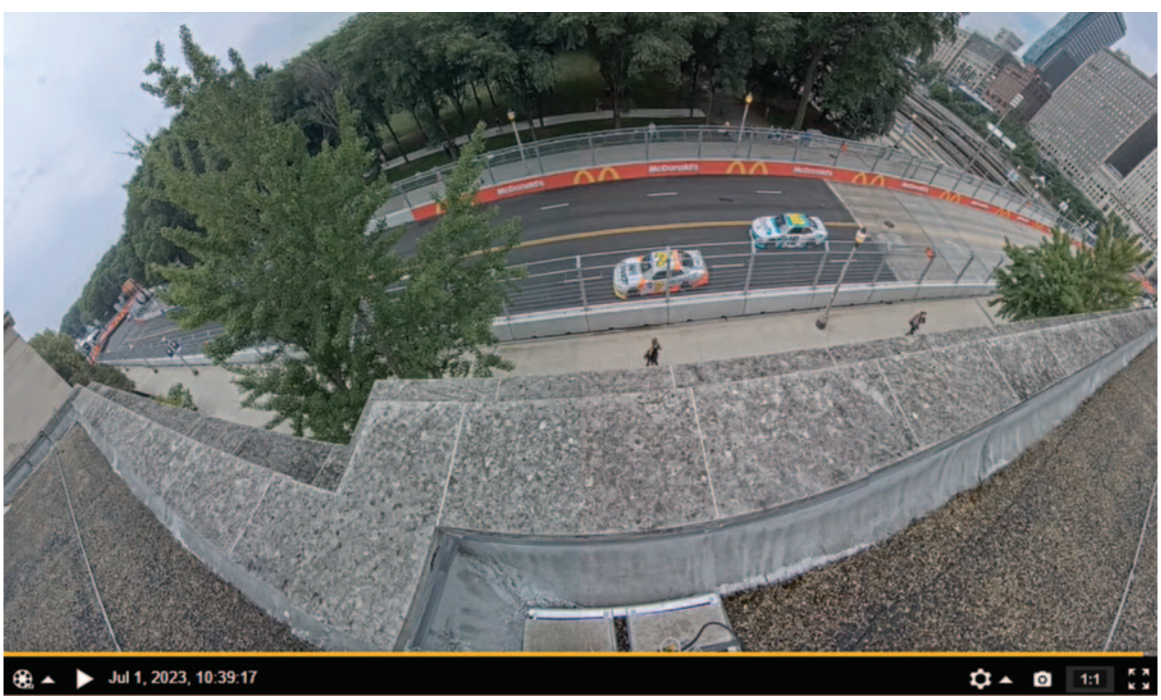


Figure 12. Rice Building roof camera capture at instant of peak recorded vibration amplitude at VM-1.

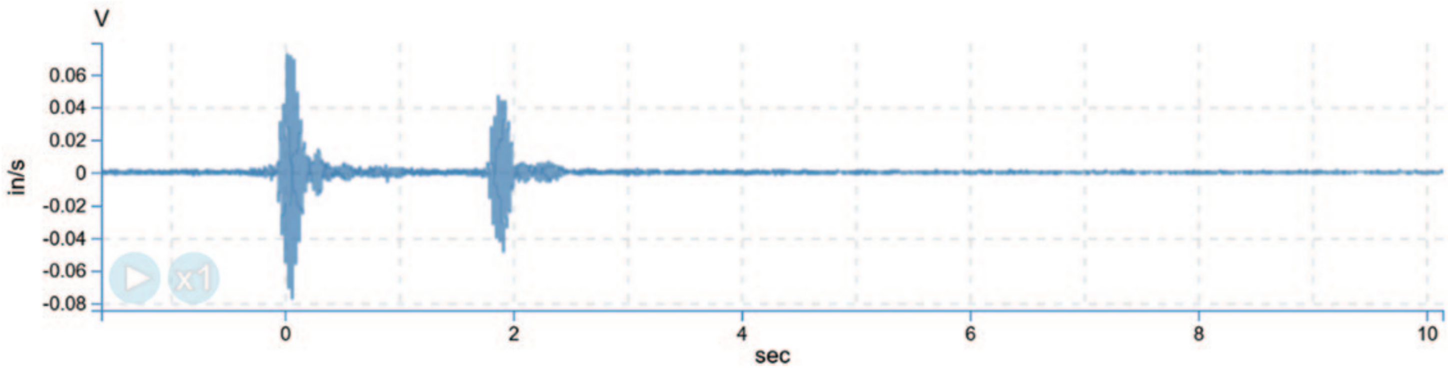


Figure 13. Vertical axis 10-second waveform in PPV (in/s), recorded by VM-1 located 3 metres (10 feet) from race route at instant when two cars passed, as shown in Figure 12.

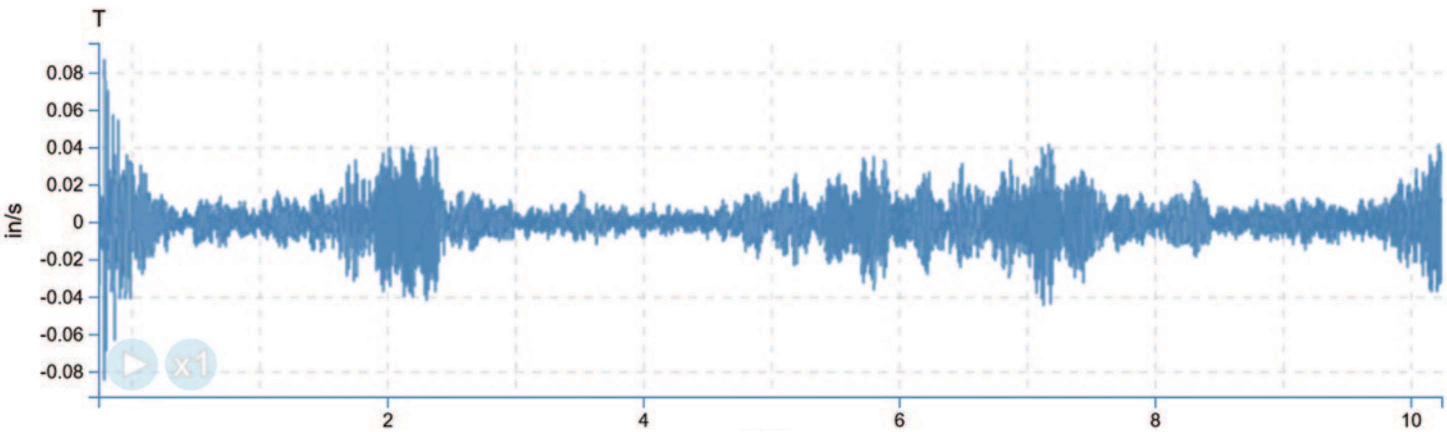


Figure 14. Ten-second waveform showing out-of-plane vibration in PPV (in/s) of exterior wall, as recorded by VM-5 when multiple cars passed by.

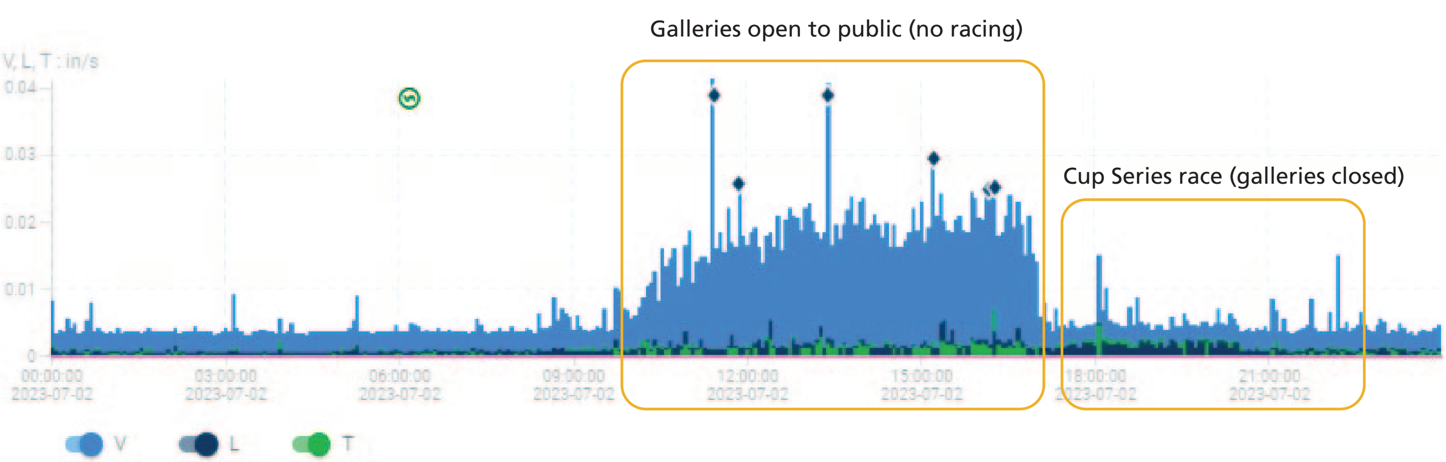


Figure 15. Vibration time-history for July 2 at vibration monitor in PPV (in/s) on floor of gallery next to second partition wall into gallery; lesser vibration amplitudes during racing than normal gallery activities.

Vibrations from the Transportation of Museum Objects

The transportation of museum objects, whether they are being shipped to another location or handled and moved within a museum building, is another concern for collections exposed to vibrations. This extends to the design of transport cases, equipment for moving objects inside museums (e.g., trolleys, dollies, carts, and lifts), and storage units (e.g., painting racks/roller racking, mobile storage units, or drawers). This is an area of active research across the heritage sector.

According to the questionnaire,[10] museums that ship collection objects report that transport-related damage is rare. However, 59 percent of museums indicated that they have at some point observed damage attributed to shock or vibration during transport. The types of damage reported were usually minor, such as small particles of debris found on the floors of crates. Sometimes, however, they were more severe, including cracks in the paint of works on canvas or the breakage of brittle objects.

About one-third of museums said they use data loggers in some of their shipments, depending on the perceived sensitivity of materials, value, loans, and sometimes transportation distance. Of those who use data loggers, more than half place the devices inside crates, with more than 30 different devices being used, and nearly all reportedly capable of measuring environmental conditions, approximately half shock, and approximately one-third vibration. The capabilities of these devices to accurately characterize vibrations varies considerably. The use of a range of devices makes it challenging to determine the impact of transportation on objects, as there are corresponding variations in measurement units, often with limited understanding of vibrational frequencies. This complicates the assessment of risk and the design of mitigation methods.

Only about 15 percent of the museums that responded have quantitative limits and enforcement on shock or vibration during transportation. For those with limits, the nature of these limits varies widely. Notable challenges in measuring vibrations during transportation included limited storage capacity and battery life of devices during long-distance trips. Several museums indicated that they have collected, or are currently collecting vibration measurements during transportation, and will be publishing the results soon.

To illustrate transportation-related vibrations, the authors performed a live demonstration using a mock painting inside a travelling crate.[11] During the demonstration, the crate and painting frame were instrumented with three different types of vibration sensors: an MSR 165, a Lansmont Saver 9x30, and a custom accelerometer system connected to an external laptop via WiFi (Figure 16). Art handlers then loaded the crate, which was rolled around the auditorium while vibrations streamed on the screen. The results showed significant levels of vibration and shock on the crate, with considerable vibrational impact on the frame as well.

Implications and Practical Suggestions for Museum Facility Operations

In summary, vibrations caused by musical events within or adjacent to museums, and the transportation of art objects, can have a significant impact on collections. More research needs to be done to address a number of questions and develop practical guidelines for use in the field. In the meantime, the following points and practical suggestions are worth considering when managing museum facility operations.

Transportation Outside a Museum

- Improvements in crate design to mitigate vibration and shock are ongoing. The levels/types of vibration may depend on the method of transport, and it is often truck transport and the loading/unloading of crates that produces the most vibration and shock.

[10]"Vibratory Impacts of Musical Events and Transport on Museum Collections," October 2022.
[11]Vibration Symposium: Strains of Art and Cultural Property through Mechanical Vibrations and Shocks, Kunsthalle Mannheim, Mannheim, Germany, June 29–30, 2018.

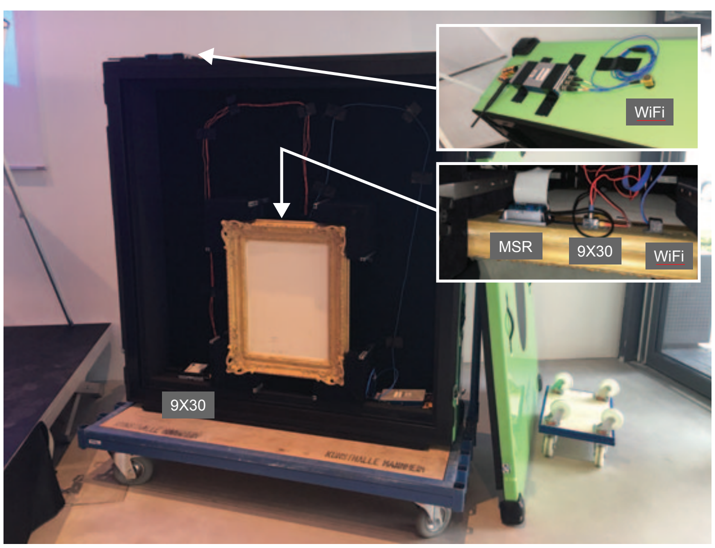
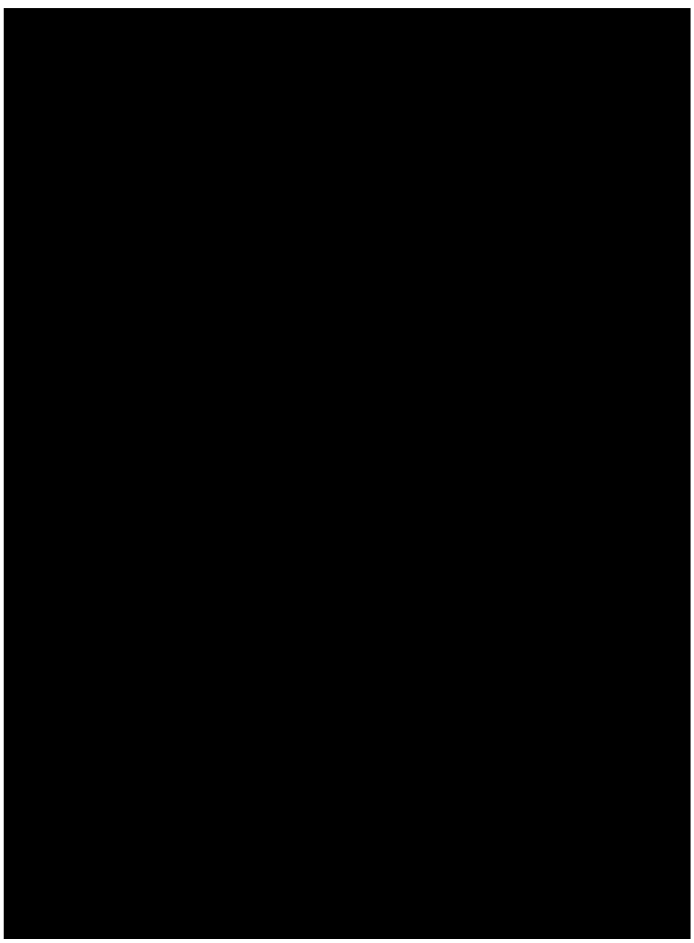


Figure 16. Instrumented crate and painting, and display of vibrations on painting frame in real time as art handlers moved the crate around the auditorium during a symposium in Mannheim, Germany.

- Several publications by researchers of art in transit are reportedly forthcoming, and a symposium focused on the transportation of art is scheduled for the American Institute for Conservation's 2024 annual conference.

Transportation Inside a Museum

- Handling and moving art objects inside facilities can expose them to significant levels of vibration. It may be useful to consider avoiding unnecessary movement and, when it is necessary to move art and objects, to consider reducing the impact of vibration by utilizing smooth-operating carts, dollies, lifts, and similar equipment.
- When art and objects are moved, transportation paths matter. Avoid rolling transport equipment over rough surfaces or sharp door thresholds, and use elevators that operate smoothly, without jerking or other types of impact.
- Moveable art storage devices, such as painting racks, compact storage systems, and flat file drawers can expose stored art objects to vibration when operated. Maintaining or replacing old equipment to ensure that it operates smoothly may be beneficial.



Musical Events

- Raising awareness among facilities staff that music's vibrational impact on art objects can cause adverse effects, and that simple decibel limits may not be sufficient to avoid this impact, is important. Vibrations from music are more complicated than those from construction and other sources because the sound pressure can travel through the air directly to the objects, or to immediately adjacent walls or casework.
- Partnering with event planning, registration, and conservation staff in planning an event can be helpful in mitigating vibratory effects from music. Working with sound technicians to filter or limit low frequencies at the sound board or speaker outputs may also be beneficial. A *Good Practice Guide for Musical Events at Museums*, planned for publication in 2024 by the authors and other members of the international research group, is intended to outline more effective planning, mitigation, and monitoring methods.
- The effects of vibration associated with music are heavily dependent upon factors including the type and sensitivity of the collection and how it is stored/displayed; the building type, room shape and size; the positioning of the musicians/speakers; and the musical genre. It may be beneficial to isolate speakers from the building structure and/or mounts within display cases.
- It may be necessary to seek support from an engineering expert experienced in musical events at museums, who can perform a room-specific and possibly event-specific study to evaluate the potential adverse effects of the planned musical event(s) on artwork.

Vibration remains a cause of concern for museums and their collections worldwide. In addition to ongoing research aimed at mitigating the impact of vibration, awareness and proactive responses from facility managers, museum staff and the wider community will help to ensure that our shared material history endures for generations to come. 🏛

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