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History and variations of Lindsay's wheel of acoustics: From a nested pie chart including words to a drawn acoustics world

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ABSTRACT:
In 1964, Robert Bruce Lindsay introduced "The Science of Acoustics," a graphical representation that has become popular and is often called the Wheel of Acoustics. This communication first recalls the historical context and initial versions of this representation. Adaptations to its original design are then introduced. Some follow the idea of a wheel representation but focus on specific acoustic domains or perceptual descriptions of sound. Other adaptations propose a slightly modified arrangement of the wheel's elements while including icons to illustrate covered topics. We introduce a wheel that blends realistic and iconic representations following a primarily hand-drawn and artistic vision. This visual tool can be used for acoustics teaching and popularization to improve audience engagement and provide more in-depth and concrete examples. The Drawn Acoustics World is provided in English and French versions, and also in a text-free version that can be used to adapt to any language.
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I. INTRODUCTION

Acoustics is an essential field of scientific study that significantly impacts our lives. It helps us understand how sound (in the general sense, including infrasound, ultrasound, and vibration) is generated, propagates, interacts with different structures or materials, and finally affects our environment.[1–4] Audible acoustics is concretely used to design and optimize systems to reduce noise pollution or improve overall acoustic comfort and quality in various industries,[5] including music and film, construction, and transportation (automotive, aerospace, and train).[6] Research in ultrasound[4] has also contributed to developing tools that find applications in industry[7] and medicine,[8] noting that acoustics research on health[9] covers an extensive range of subjects from speech[10] to audiology.[11] Let us not forget underwater sound[12] and bioacoustics, the study of animals' sound production, transmission, and reception in nature.[13] Finally, some of these topics might extend outside Earth's boundaries since Perseverance rover microphone recordings on Mars recently allowed the first characterization of its acoustic environment.[14] Without further examples of its fields and applications, acoustics is quite a wide-ranging and interdisciplinary discipline.

However, this discipline is often seen as mainly grounded in music or architecture (*somebody plays an acoustic instrument—a concert hall has excellent acoustics*). Not only the scope of acoustics can be easily misunderstood by the general public but also by students, science educators, or scientists. This can have adverse effects on the perceived importance of acoustics and also on the way it is taught. On March 12 and 13, 1964, a conference was organized by the Acoustical Society of America whose objective was "to evaluate the role and significance of acoustics in higher education and chart the future of education acoustics." Lindsay and the conference members agreed that one of the main problems was to be able "to publicize the full significance of the discipline" and a solution was to display acoustics' many ramifications.

To help visualize "the tremendous scope of the applications of acoustics," Lindsay proposed "The Science of Acoustics," a graphic description of the main areas and corresponding sub-areas of acoustics. Lindsay's proposal has become quite popular in the acoustics community and is known as the Wheel of Acoustics. It is mainly used as an introduction to acoustics for students or the general public to explain that there are many domains in acoustics and many different kinds of acousticians. Such a discussion and educational support is essential. Indeed, we want to emphasize that most of the issues raised during the 1964 conference are ever-present challenges, underlined in the 2010 Technology for a Quieter America report:[15] first, there is a strong need to educate specialists in acoustics given the shortage of acoustics manpower; second, the multidisciplinary or interdisciplinary nature of acoustics poses challenges for school and university programs, and these latter must be

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improved to meet the required manpower; third, the importance of acoustics has to be better publicized to raise awareness of acoustics importance but also of the offered career opportunities.

To continue efforts in this direction and to promote and perpetuate Lindsay's legacy, this paper first recalls the history and uses of the Wheel of Acoustics, which is done in Sec. II A. Section II B lists uses and adaptations of the original wheel, while Sec. II C briefly introduces perceptual wheels. Section III describes the origin, setup, and contents/formats of a hand-drawn version of the Wheel of Acoustics, called the Drawn Acoustics World. Section IV summarizes key points and suggests a few perspectives.

II. WHEELS OF ACOUSTICS

A. Lindsay's Wheel of Acoustics

The Science of Acoustics was initially introduced in a 1964 publication[16] (Fig. 1), followed by a conference proceeding[17] and an erratum[18] (both published in 1965). The original version indicates *Acoustics* in a subsection of the chart, whereas one should read *Room and Theater Acoustics*. This typo was corrected in the erratum.[18] In a version published in 1968[19] (Fig. 2), Lindsay modified the used font and further discussed this chart's relevance and context in the article's core.

The Science of Acoustics resembles a nested pie chart in which a center circle indicates core themes: fundamental physical acoustics, mechanical radiation in all material media, and phonons. Surrounding the center circle are two annular rings containing wedge-shaped subsections. The wheel's inner part lists the specific fields or topics to which the various disciplines in acoustics could naturally lead. These disciplines, as usually classified by acoustical standards, are listed in the wheel's outer ring, which are areas one may choose to study for a career in acoustics. The wheel is finally divided into four main quadrants (the four broad fields of Arts, Earth Sciences, Engineering, and Life Sciences).

B. Variations to Lindsay's wheel and extension to other acoustics domains

Most original wheel adaptations imply variations in font type or size, color, and the general arrangement of the wheel's subsections. Some websites include these adaptations; two examples are: (1) Explore Sound! website,[20] and (2) ACOUCOU website, with an online rotating wheel[21,22] (Fig. 3). In Ref. 23, Potel and co-authors introduce a version

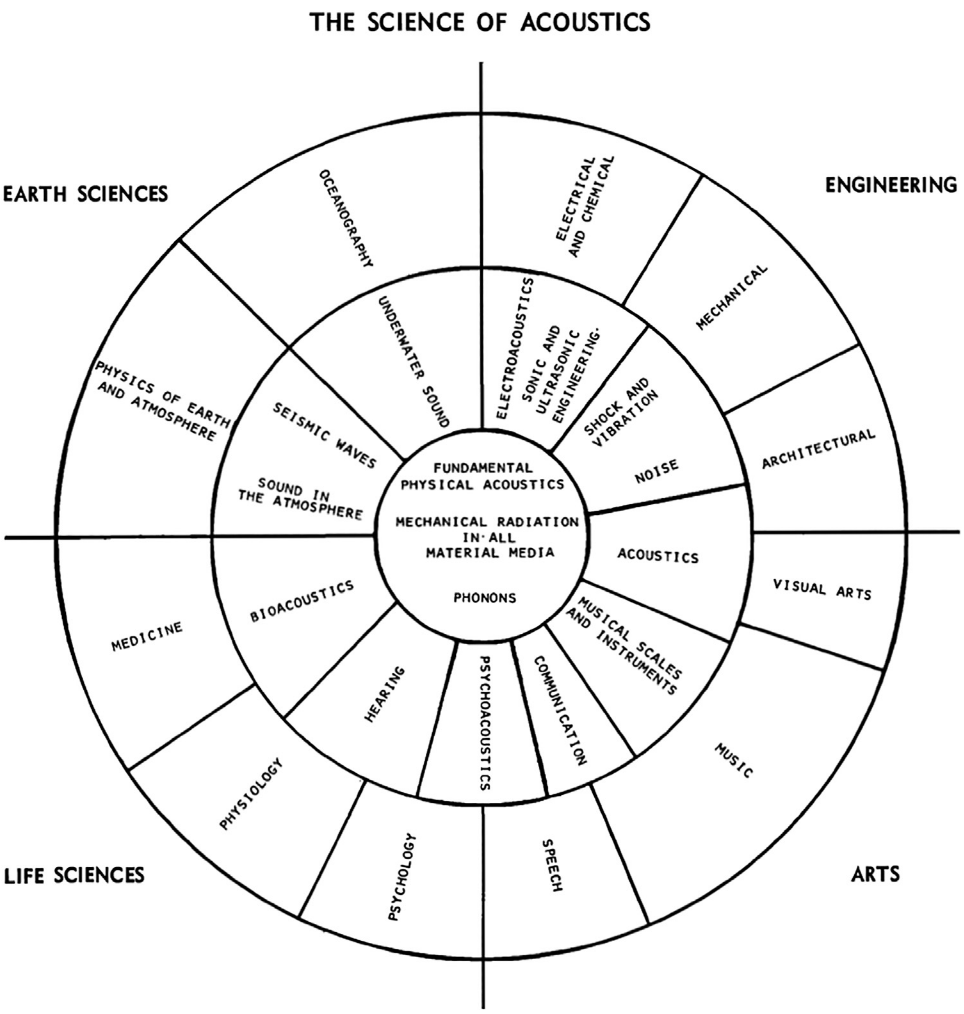

FIG. 1. The original and 1964 version of Lindsay's "The Science of Acoustics." Reproduced with permission from Lindsay, J. Acoust. Soc. Am. **36**, 2241–2243 (1964). Copyright 1964 The Acoustical Society of America (Ref. 16).

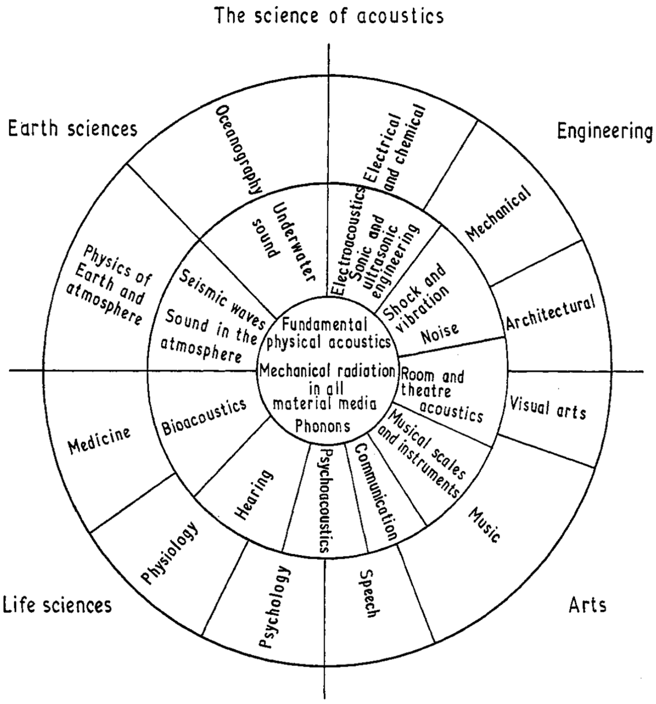

FIG. 2. The 1968 version of Lindsay's "The Science of Acoustics" which has minor font differences from the 1964 version (Ref. 16). Reproduced with permission from Lindsay, Phys. Educ. 3(2), 62–66 (1968). Copyright IOP Publishing (Ref. 19).

FIG. 3. (Color online) The Wheel of Acoustics from the Acoucou.org platform (Ref. 21). This is an adaptation of Lindsay's 1964 wheel (Ref. 16).

of the wheel that integrates icons to illustrate more clearly the areas and applications targeted by the wheel's sub-blocks (Fig. 4). The elements of the original wheel are slightly reordered, and the center circle is redefined. Some examples of fields belonging to each quadrant are given (Human and Social Sciences include Art, Comfort, Architecture, Culture, Environment, Noise pollution, and Telecommunications). The authors of Ref. 23 underline that they use this wheel for a general introduction to acoustics for new students whose acoustics vision is mainly restricted to audible acoustics (music, audio, and room acoustics). This wheel, by including illustrated examples for each specialized area, makes a significant change to the initial proposal and is deemed a relevant tool for an introduction to the global world of acoustics.[23]

Another approach can be found in Kallistratova's publication.[24] In this work, a modified version of Lindsay's wheel is first introduced with alterations to the terms used in the center circle, the annular rings, and the main quadrants (Fig. 5). Still, the author makes the following observation: Atmospheric acoustics occupies a tiny "Sound in atmosphere" sector in the original diagram, but this sector can, in turn, be subdivided into many constituents. This leads the author to propose an analog Wheel of Atmospheric Acoustics. From center to outer, that wheel indicates (1) the branches of physics to which atmospheric acoustics are rooted, (2) the concrete effects of atmospheric phenomena on sound waves, (3) how sound waves respond to these effects, and (4) their use in studies related to the atmosphere (Fig. 6). This idea of a focused-on-a-domain wheel looks exciting but has been little explored. The only other step in this direction that could be identified is the one of Talaske,[25] who suggested applying Lindsay's acoustical wheel to architectural acoustics in a communication proceeding. Still, to our knowledge, no graphical example can be found.

C. Perceptual wheels

Examples given in previous sections should not be confused with perceptual wheels (or sensory wheels). The latter are used to represent a product's perceptual characteristics or a sensory domain and are usually based on an established lexicon[26] or dictionary (see a well-documented example in the case of brewing malt in Ref. 27). Some authors proposed perceptual wheels that are related to acoustics, and worth mentioning, as they offer an exciting avenue for visualizing specific perceptual characteristics. A first example is the Wheel of Concert Hall Acoustics proposed by Kuusinen and Lokki[28] (Fig. 7). The wheel's inner part includes the main perceptual categories for concert hall acoustics, like loudness or clarity, and an "extraneous sounds" category. The outer part of the wheel lists attributes that can be used to qualify each category's different facets. For example, loudness can be further described with the terms "strength, level, volume, body, or dynamic range." Compared with a usual perceptual wheel, these attributes would be equivalent to the "flavor, appearance, or taste" of the related category. A second example of a perceptual wheel applied to acoustics is the Audio Wheel[29] or Sound Wheel proposed by Pedersen and Zacharov[30] (Fig. 8). The Sound Wheel aims to propose a hierarchical visual representation of a perceptual attribute lexicon, highlighting relations between attributes. For

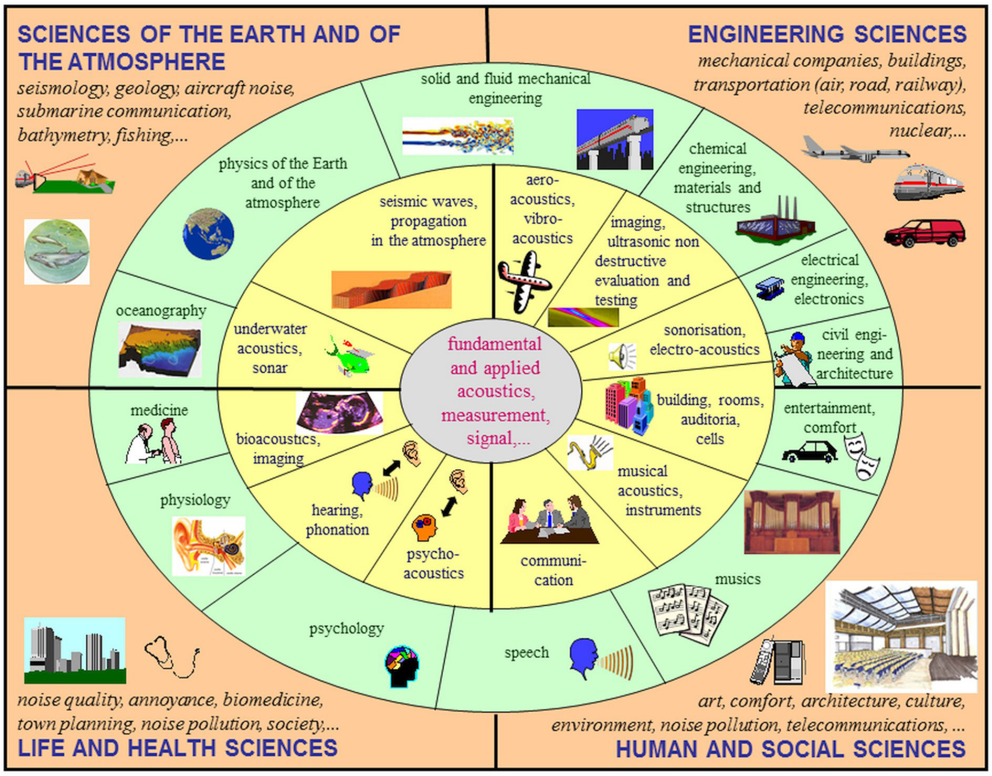

FIG. 4. (Color online) The World of Acoustics, adapted from Lindsay (Ref. 16). Reproduced with permission from Potel *et al.*, J. Acoust. Soc. Am. **151**(2), 1093–1103 (2022). Copyright 2022 Acoustical Society of America (Ref. 23).

example, timbre comprises "Treble, Midrange, Bass, and Timbral balance." The attributes "Treble strength, brilliance, and tinny" can be further used to qualify Treble. Reference 29 precisely details attributes associated with the Audio Wheel or Sound Wheel.

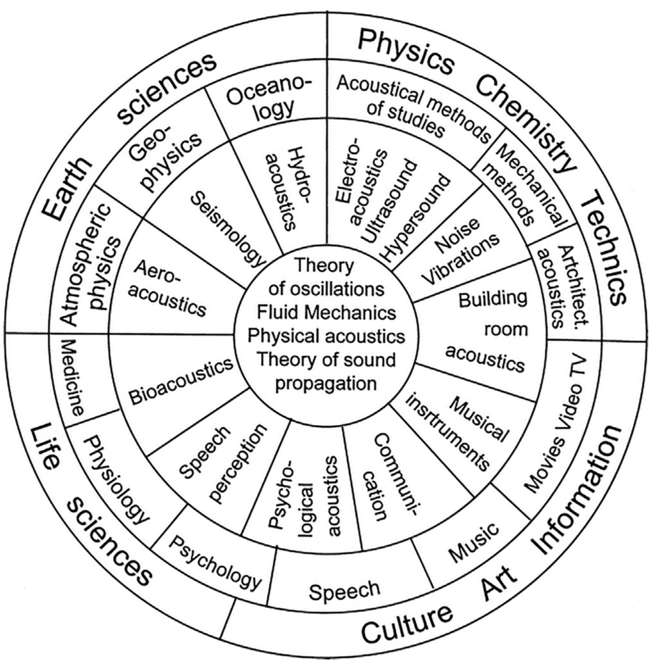

FIG. 5. A modified Wheel of Acoustics. Reproduced with permission from Kallistratova, J. Atmos. Oceanic Technol. **19**, 1139–1150 (2002). Copyright 2022 American Meteorological Society (Ref. 24).

III. A DRAWN ACOUSTICS WORLD

A. Context

An increasingly developed body of research indicates that arts positively impact the transfer of information by

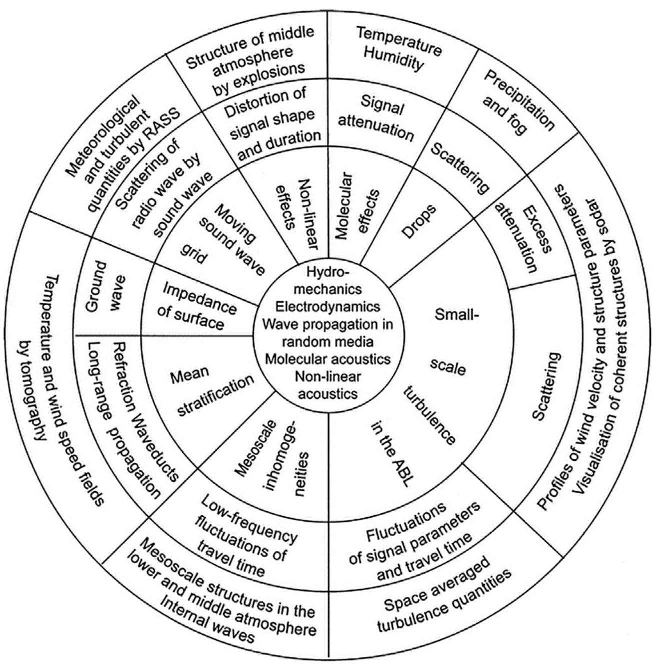

FIG. 6. The Wheel of Atmospheric Acoustics. Reproduced with permission from Kallistratova, J. Atmos. Oceanic Technol. **19**, 1139–1150 (2002). Copyright 2002 American Meteorological Society (Ref. 24). RASS: Radio Acoustic Sounding System; ABL: Atmospheric Boundary Layer.

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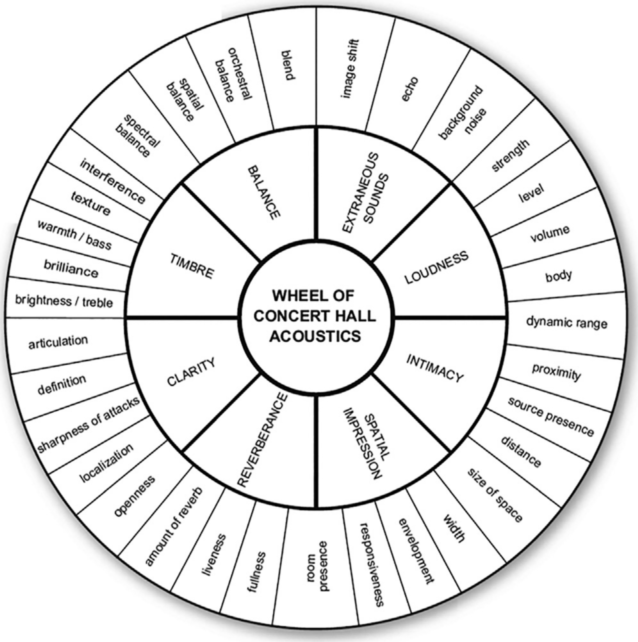

FIG. 7. The Wheel of Concert Hall Acoustics. Reproduced with permission from Kuusinen and Lokki, Acta Acust. united Acust. **103**(2), 185–188 (2017). Copyright 2017 Author(s), licensed under a Creative Commons Attribution 4.0 International License (Ref. 28).

prioritizing the affective domain of learning, rather than the cognitive domain.[32] This corresponds to a focus on emotional engagement and attitude rather than understanding and application, typically emphasized in science education. In other words, art can connect with people in ways other than science alone. Artistic visualizations usually elicit more emotions than scientific visualizations, especially when the audience is not specialized. However, no difference in perceived credibility between artistic and abstract representations was found in a number of studies, even when data regarding polarizing topics like climate change had to be explained.[33] Using different art forms, scientists can make scientific information more understandable, relatable, and engaging to the public.

Given this context, our specific proposal must be further explained to understand our motivations better. This project was initially conceived as part of an exhibition for the general public in the city of Le Mans, France, during the 2022 Biennale du Son (in English, Biennale of Sound; January 22 to February 17, 2022). The proposed exhibition location was a 70 m^2 space in a downtown shopping mall. To help trigger interest from shoppers strolling through the mall and improve their efficient understanding of acoustics, it was decided to set up an exhibition at the crossroads between comics and acoustics, given the documented positive effect

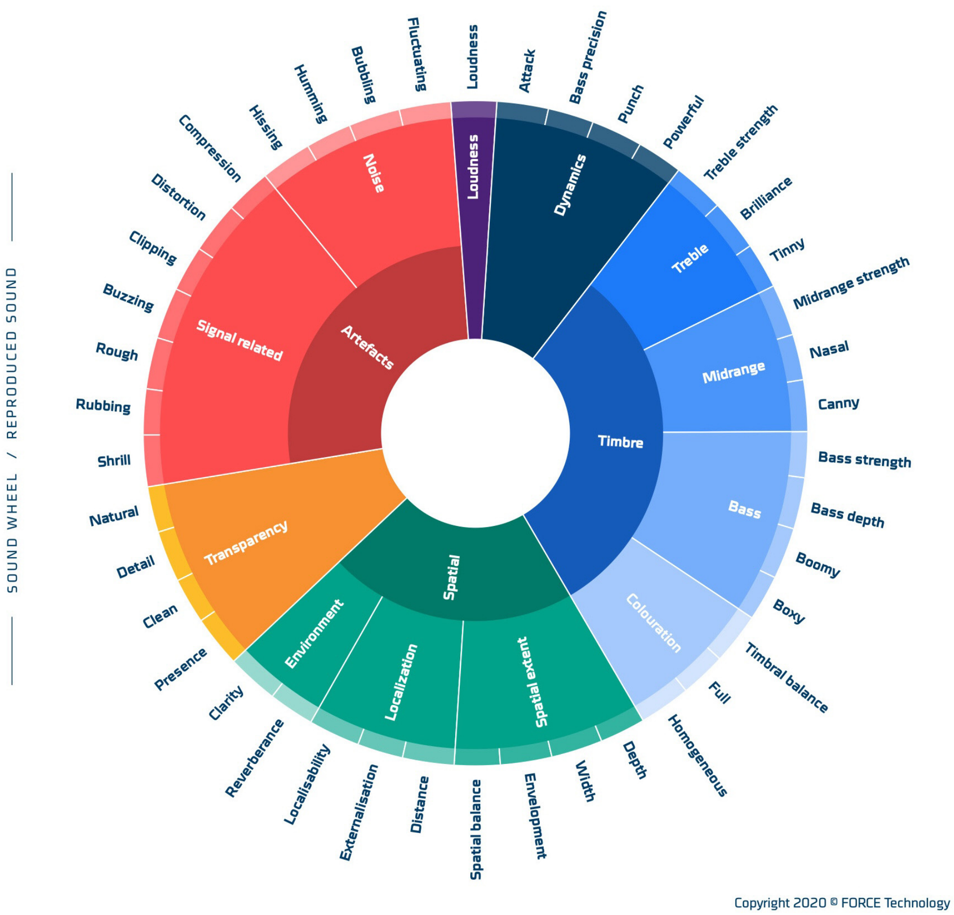

FIG. 8. (Color online) The Sound Wheel (Ref. 31) (an equivalent version can also be found in Ref. 30). Credit: SenseLab department, "Sound wheel for Reproduced Audio," 2021, FORCE Technology, Hørsholm, Denmark.

of arts, and especially comics, in science communication and acoustics teaching.[34–36] (An online version of the exhibition can be found in Ref. 37).

Research artifacts, objects, and expertise were gathered from three laboratories [Laboratoire d'Acoustique de l'Université du Mans (LAUM), UMR CNRS 6613, Le Mans, France; Empa, the Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland; Centre for Research on Acoustics-Signal-Human (CRASH), Sherbrooke, Canada]. Eight comic-like posters were designed to explain various acoustics-related subjects (metamaterials, hearing, vibrations, etc.). In particular, the exhibition organizers thought of an additional visual element that would play the role of an acoustics orientation map at the entrance to the exhibition. The World of Acoustics from Ref. 23 and previous observations on the role of arts in science communication triggered our proposal. It was assumed that a drawn Wheel of Acoustics would provide another aesthetic point of view in the exhibition, enabling people to contemplate and introspect about the fields of acoustics and not only read/locate those fields in the classical version of the Wheel of Acoustics.

B. Development and contents

A researcher/comics writer (O.R.) and an independent artist and comics writer (M.S.) collaborated to elaborate a representative corpus and use it to populate this new version. It includes various illustrations that help the reader connect the research field with practical applications. It was chosen to have smooth visual separations between subsections so that overlapping between domains and applications could occur, just like in real life. A sinc (or sine cardinal) function was included in the center circle to visualize it as a starting point and to include this key mathematical function in signal processing and acoustics. An upper band overlooks the wheel and stands as a possible title placeholder. It features two clarinets, one played by an artificial mouthpiece (upper left) and the other by a human being (upper right).

The upper part of Fig. 9 shows the blank version of the wheel, meaning that it does not include text and only features white rectangles in which descriptions can be further added. We list hereafter some illustrations in no particular order of importance:

- Upper left quadrant: NASA's Perseverance rover on Mars; a twisted bridge resembling the 1940 Tacoma Narrows Bridge that collapsed into Puget Sound; an aircraft generating a supersonic bang.
- Top, middle: The X-15, a hypersonic rocket-powered aircraft that still holds the official world record for the highest speed ever recorded by a crewed, powered aircraft; at the right of the X-15, Captain Archibald Haddock can be noticed making an echo from a corniche road; above the X-15, the bullet train or "Shinkansen," Japan's high-speed train is well present; in front of the Shinkansen, an ice cream vendor links with the field of thermoacoustics.

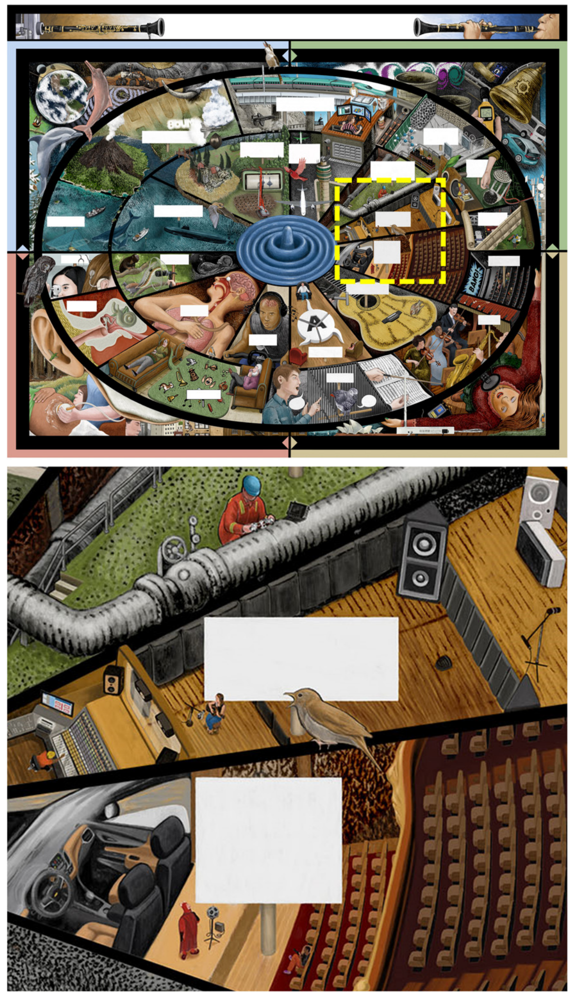

FIG. 9. (Color online) (Upper part) General view of the blank wheel. (Lower part) Zoomed view of the section underlined by a yellow-dotted rectangle.

- Middle, right: A standing wave acoustic levitator; two loudspeakers mounted in a box that includes electronic components used to design frequency filters; people in real-life situations regarding room acoustics, building acoustics, and non-destructive testing.
- Lower right quadrant: Sydney's opera, which became a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site in 2007; a theremin, one of the oldest electronically controlled musical instruments; and a guitar, excited using an impact hammer and depicting Chladni's patterns.

It is, however, irrelevant to list all the elements present. It is more enjoyable to let people discover as they go along the elements that were not immediately seen. Indeed, the wheel provided in the Supplementary Material is a high-resolution file, and many details can be further identified while zooming in using digital tools. The zoom operation can also be conducted with our eyes since the file resolution allowed us to print the Drawn Acoustics World on a panel of 1.5×1 m without losing quality (see it in the online version of the exhibition in Ref. 37). The lower part of Fig. 9

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provides an example of hidden or not immediately visible information. It is a zoomed view of the yellow-dotted area in the upper part of Fig. 9. The considered sections are in between non-destructive testing, building acoustics, room acoustics, and music. From top to bottom, the zoomed version allows one to see someone who is testing a pipe using non-destructive techniques, someone who is playing the guitar while being recorded by someone who would be a sound engineer, a car interior close to a red Mephistopheles singing in a theater indicates that car interior acoustics is close to room acoustics, Mephistopheles being neighbored by a dodecahedral sound source. The first author (O.R.) regularly uses this zoom-in/zoom-out feature during teaching or laboratory visits to focus on a particular subject or talk in general about acoustics.

To help trigger questions or discussions, the wheel can also be seen and used as a search-and-find map (Where is the cicada? Where is the sound level meter? Look at the anatomy of the human ear—Can you name its three parts?). Indeed, M.S., who is especially fond of birds, placed 13 of them in the wheel, emphasizing this search-and-find feature. Figure 10 indicates their positions, while Table I lists their characteristics that are all somewhat related to acoustics.

Finally, Figs. 11–13 correspond to the three versions of the Drawn Acoustics World provided as Supplementary Material, as high-resolution files. The French version (Fig. 11), follows the arrangement and denominations proposed in Ref. 23 for the four main quadrants, the wheel's inner and outer rings, and the central part's text ["Fundamental physical acoustics–Mechanical radiation in all material media–Phonons" in Ref. 16 simplifies to "Fundamental and applied acoustics–Measurements–Signal" (*in French, Acoustique fondamentale et appliquée–Mesure, signal*)].

In the hand-drawn proposal, the sub-domains of each quadrant are listed in an elliptical band to leave more room for illustrations in corners, and the chosen French title is *Les grands domaines de l'acoustique* (in English, The main fields of acoustics). The English version in Fig. 12 is similar to the French version but has an empty head title, center, and elliptical band.

Finally, Fig. 13 is a blank text version that can be easily adapted to any language. Indeed, even if English is recognized as the standard and international language of science, using a single language can also limit the scope of discourse.[38] With that blank version, our proposal can be adapted to societies where English is not the native language and include culturally relevant context through the language. Even if an adaptation of drawings would be needed to adapt to any culture, this can improve understanding and support of acoustics at a larger scale, facilitate the dissemination of knowledge across international and cultural boundaries, and increase the scope of our proposal.

IV. DISCUSSION

Even if it is hard to imagine a representation that would do full justice to all acoustics' vast and interdisciplinary ramifications, The Science of Acoustics has proved its relevance and effectiveness. This communication overviews variations from Lindsay's original proposal. All these examples can be used within a wide range of objectives, including (1) the teaching of acoustics at all levels, (2) the classification of acoustics-related jobs/professions, (3) the

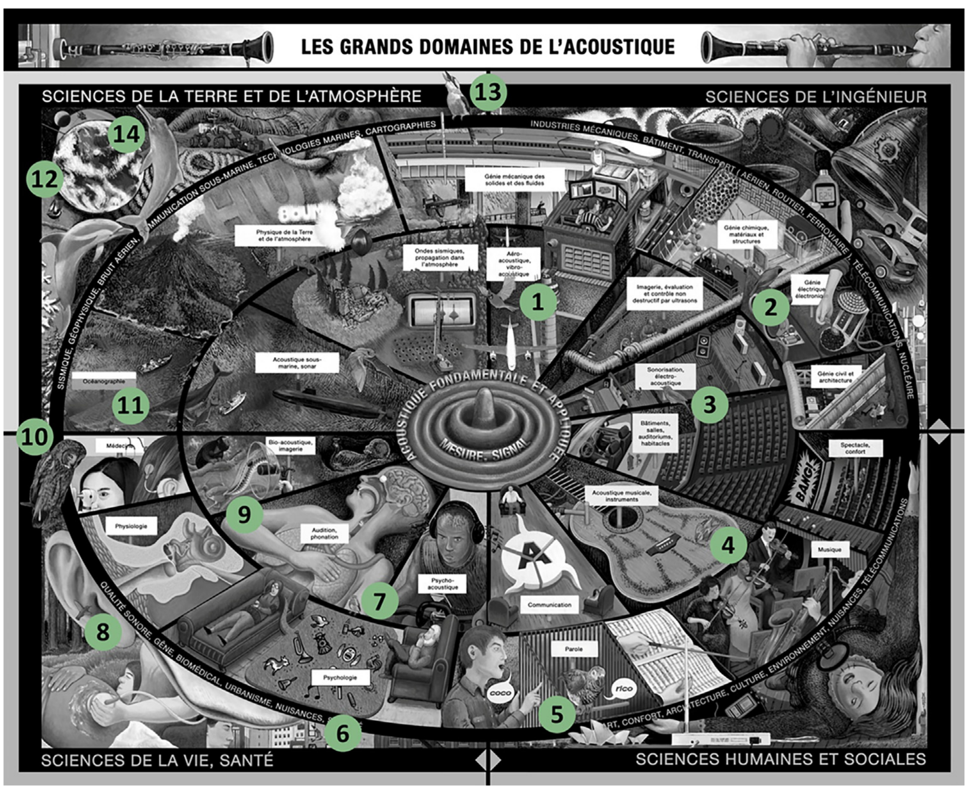

FIG. 10. (Color online) Location of birds and animals in the Drawn Acoustics World (see Table I for details).

TABLE I. List of birds and animals included in the Drawn World of Acoustics.

#	Common name	Scientific (binomial) name	Distribution	Link to sound/acoustics
1	Northern cardinal	*Cardinalis cardinalis*	North and Central America	Related to nearby sinc function
2	Greater green leafbird	*Chloropsis sonnerati*	Brunei, Indonesia, Malaysia, Myanmar, Singapore, and Thailand.	Melodic call
3	Common nightingale	*Luscinia megarhynchos*	Europe, Asia and North Africa	Known for its powerful and beautiful song
4	Chipping sparrow	*Spizella passerina*	North America	One of the most common songbirds in North America
5	Grey parrot	*Psittacus erithacus*	West Africa	Known as the best talking birds, i.e., that can mimic human speech
6	Common nighthawk	*Chordeiles minor*	North and South America	Call typical of the evening since it is only heard after sunset; also generates booming or whooshing sounds
7	European robin	*Erithacus rubecula*	Europe, continental Eurasia, and North Africa	Melodic call
8	Ruby-throated hummingbird	*Archilochus colubris*	North and Central America America	Characteristic sound during flight
9	Superb lyrebird	*Menura novaehollandiae*	Southeastern Australia	One of the world's largest songbirds, known for its elaborate vocal mimicry
10	Great grey owl	*Strix nebulosa* (or *S. lapponica*)	North America and North Eurasia	Combine excellent hearing and sound localization abilities with near-silent flight.
11	Goldcrest	*Regulus regulus*	Europe, Eurasia to Japan	The smallest European bird, with an incredibly high-pitched call that can be almost inaudible
12	Club-winged manakin	*Machaeropterus deliciosus*	Colombia and Ecuador	Produces musical sounds with its wings
13	Laughing kookaburra	*Dacelo novaeguineae*	Eastern Australia	Its call resembles a laugh widely used as a stock sound effect for jungle-like situations
14	Amazon River dolphin	*Inia geoffrensis*	South America	A river dolphin that has a melon, an organ that is used for biosonar

FIG. 11. (Color online) The Drawn Acoustics World (French version, entitled *Les grands domaines de l'acoustique*).

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FIG. 12. (Color online) The Drawn Acoustics World (English version), with empty head title, empty center, and empty elliptical band.

FIG. 13. (Color online) The Drawn Acoustics World (text-free version).

popularization of acoustics for the general public, (4) the demonstration of acoustics' importance for various decision-makers (see R. B. Lindsay's recommendations[16]). As for the versions presented since 1968, the wheel can stand on its own, but if complemented by a speaker who knows facts and anecdotes about acoustics, it becomes a pretext for a journey into the science of acoustics. Also, the wheel presentation in Sec. II A goes from the center to the outer of the wheel, whereas a description starting from the outer four main fields to the center can be as relevant. The right way of describing acoustics using the wheel should be left to the speaker, according to a given public.

Finding different, while relevant, variations to this original proposition is not necessarily easy. Nevertheless, three lines of work are suggested hereafter.

On the one hand, Kallistratova's idea[24] of a wheel focusing on a given acoustics area could guide further work. Indeed, each specialized sector of acoustics, why not each of the 14 Acoustical Society of America's Administrative Committees, could be represented this way (Acoustical Oceanography, Animal Bioacoustics, Architectural Acoustics, Biomedical Acoustics, Computational Acoustics, Engineering Acoustics, Musical Acoustics, Noise Physical Acoustics, Psychological and Physiological Acoustics, Signal Processing in Acoustics, Speech Communication, Structural Acoustics and Vibration, Underwater Acoustics).

On the other hand, it might be appropriate to create wheel-like representations covering vast fields of knowledge, following the example of the wheel of acoustics: wheels of mechanics, physics, chemistry, life sciences, earth, and atmospheric sciences, etc., possibly mentioning or pointing the contributions of acoustics to these vast fields of knowledge.

The last line of work is to trigger more arts–science collaborations, which have recently become increasingly popular.[39] Scientists seek creative ways to connect with the public. Artists look to new materials or tools with which to work. When scientists and artists collaborate and share their respective knowledge and materials, interdisciplinarity often leads to innovative approaches, new understandings, and perspectives. As underlined, the results of such collaborations can be used to communicate science in a more accessible and engaging way and, in the present case, contribute to an improved and interdisciplinary understanding of acoustics.

SUPPLEMENTARY MATERIAL

See the supplementary material for high-resolution files corresponding to the three versions of the Drawn World of Acoustics from Figs. 11–13.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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