From Deterministic to Probabilistic Soundscapes: A critical tour around the soundscape circumplex

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I. INTRODUCTION

Methods for collecting data on how people experience acoustic environments have been at the forefront of the debate in soundscape studies for the past 20 years. While the soundscape research field as we understand it today dates back to the late 1960s with the pioneering work of authors like M. Southworth and R.M. Schafer, the theme of data collection methods for soundscape assessment emerged more prominently only recently (Kang *et al.*, 2016). There is a general consensus in the research community that standardized tools to gather individual responses on the perception of urban acoustic environments are indeed desirable, to provide comparable datasets and soundscape characterizations across different locations and times and samples of people. This was actually one of the main drivers for the establishment of a Working Group at the International Organization for Standardization (ISO) back in 2008, which was named "Perceptual assessment of soundscape quality" (ISO/TC 43/SC 1/WG 54) that has so far published three documents within the ISO 12913 series on soundscape. Part 1 provides a general framework and definitions (ISO, 2014), while Part 2 and Part 3 offer guidance on how data should be collected and analyzed, accordingly (ISO, 2018, 2019). Different methods are proposed for data collection in Part 2 (ISO, 2018), but in the context of this study we focus on Method A, because it is the only one underpinned by a theoretical relationship among the items of the questionnaire that compose it, the circumplex model of soundscape (Axelsson *et al.*, 2010). This is in turn based on the Swedish Soundscape Quality Protocol (SSQP), originally developed at Stockholm University (Axelsson *et al.*, 2012).

The circumplex model of soundscape, as originally defined by (Axelsson *et al.*, 2010), is commonly understood to be a two-dimensional space (its main orthogonal components being annoying-pleasant and uneventful-eventful) where all regions of the space are equally likely to accommodate a given soundscape assessment (Aletta *et al.*, 2016). For instance, in theory, an extremely vibrant soundscape (e.g., with a score of 1) should be as likely to occur as an extremely annoying one, as well as one neutral on all dimensions (e.g., with a score of 0). However, a recent work by Lionello et al. (Lionello *et al.*, 2021) incidentally highlighted a possible issue with the process for representing soundscape assessments with the current ISO protocols. More specifically, when considering big numbers, soundscape assessments seem to have a bivariate normal distribution around the origin of the circumplex model. This would imply that not the whole space of the model is equally accessible to any given soundscape. Studies in the field show that data collection campaigns rarely return extreme values for soundscape dimensions (Mancini *et al.*, 2021) and so far the general interpretation has been that some soundscapes (e.g., extremely monotonous) may simply be difficult to find and detect with people in urban contexts (Sun *et al.*, 2019). However, in this work we question whether there are some issues related to the data collection instruments and data analysis methods per se.

A. Objectives

Several consequences of the current ISO standard implementation of the soundscape circumplex model are identified and discussed, in particular that of the coordinate transformation process given in Equations A.1 and A.2 of ISO 12913 Part 3 (ISO, 2019). These consequences arise, not out of any particular real-world implementation or data collection, but instead are strictly the result of the model framework and mathematical transformations laid out in the standard. We believe that the results presented here have not been fully discussed previously and may contradict much of the general understanding of the circumplex model within the field.

Once the existing consequences of the standard are identified and discussed, we then present two proposed treatments of the circumplex framework which may bring the model more closely in line with the current understanding within the field.

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II. THE CURRENT ISO STANDARD

The core of the questionnaire-based soundscape assessment in ISO 12913 Part 2 (ISO, 2018) are the 8 perceptual attributes (PA) originally derived in Axelsson *et al.* (2010): pleasant, vibrant (or exciting), eventful, chaotic, annoying, monotonous, uneventful, and calm. In the questionnaire procedure, these PAs are assessed independently of each other, however they are conceptually considered to form a two-dimensional circumplex with *Pleasantness* and *Eventfulness* on the x- and y-axis, respectively. In Axelsson *et al.* (2010), a third primary dimension, *Familiarity* is also found, however this only accounted for 8% of the variance and is typically disregarded as part of the standard circumplex.

A. Coordinate transformation

To facilitate the analysis of the PA responses, the Likert scale responses are coded from 1 (Strongly disagree) to 5 (Strongly agree) as ordinal variables. In order to reduce the 8 PA values into a pair of coordinates which can be plotted on the Pleasant-Eventful axes, Part 3 of ISO 12913(ISO, 2019) provides a trigonometric transformation, based on the 45° relationship between the diagonal axes and the pleasant and eventful axes. This transformation projects the coded values from the individual PAs down onto the primary Pleasantness and Eventfulness dimensions, then adds them together to form a single coordinate pair. In theory, this coordinate pair then encapsulates information from all 8 PA dimensions onto a more easily understandable and analyzable 2 dimensions.

The ISO coordinates are thus calculated by:

$$\begin{aligned} ISOPleasant = &[(pleasant - annoying) \\ &+ \cos 45^\circ * (calm - chaotic) \\ &+ \cos 45^\circ * (vibrant - monotonous)] \\ &* 1/(4 + \sqrt{32}) \end{aligned} \tag{1}$$

$$\begin{aligned} ISOEventful = &[(eventful - uneventful) \\ &+ \cos 45^\circ * (chaotic - calm) \\ &+ \cos 45^\circ * (vibrant - monotonous)] \\ &* 1/(4 + \sqrt{32}) \end{aligned} \tag{2}$$

where the PAs are arranged around the circumplex as shown in Figure 1. The $\cos 45^\circ$ term operates to project the diagonal terms down onto the x and y axes, and the $1/(4+\sqrt{32})$ scales the resulting coordinates to the range (-1, 1). The result of this transformation is demonstrated in Figure 1.

III. ASSUMPTIONS AND IMPLICATIONS OF THE ISO

A. Application & Simulations

In order to investigate the shape of the circumplex coordinate space generated by this transformation, a dataset of 3 million randomly simulated PA responses was generated. For each of the 8 PAs, an integer value from 1 to 5 is randomly generated from a uniform distribution, meaning each of the five responses is equally likely. These simulated data are specifically not intended to include any information about correlations between the various PAs when actually answered by respondents (see (Lionello *et al.*, 2021) for more on this discussion), instead the PA responses are completely uncorrelated as they each have their own random distribution. Therefore, the simulated dataset represents a theoretical uniform coverage of the 8 dimensional PA space.

We then apply the ISO transformations given in Equations 1 and 2, resulting in 3 million coordinate pairs with a range of (-1, 1) in the x and y axes. A heatmap of the resulting two-dimensional circumplex space is shown in Figure 2, along with histograms of the individual dimension distributions. These distributions then represent the theoretical available circumplex space generated by the ISO transformation on uniform survey responses.

Two important observations can be made about the shape of the resulting two-dimensional distribution. The first is that the shape of the available space is a circle. It should be noted that, despite what the term 'circumplex' may indicate, the perceptual dimensions are not necessarily intended to circumscribe a circle. The second is that, in each dimension, the responses are normally distributed, centered around zero. These points will be discussed in detail below.

B. Circular space discussion

Visualisations of the circumplex model in soundscape tend to present it as circumscribing a circle (see Fig XX in (Axelsson *et al.*, 2010) and Fig XX in (**?**)), and this shape is further emphasised by the initial figure in **?**'s original formulation of the concept. However, it should be emphatically noted that all of these presentations are in fact artefacts of the analysis methods which generated them, not some sort of revealed pattern in the component attributes which make up the circumplex. In **?**, this first figure is generated by asking respondents to place each of the 27 attributes around a circle, according to their perceived spatial relationships - the circle shape was preimposed on the study. In both Axelsson *et al.* (2010) and **?**, the figures are generated via Principle Components Analysis (PCA) which, again, presents these results superimposed on a circle. It is perhaps a weakness of these two, otherwise strong and impactful, papers, that they did not recognise this consequence and challenge the circular arrangement.

If we turn back to Russell's original work on the circumplex model of affect, we can see some indications that a circle does not, in fact, describe the spatial relationship of the perceptual attributes. Fig. XX of (**?**), which did not pre-impose the circular arrangement in its analysis, instead most closely resembles a square with rounded corners. Continuing from this conception, when Russell presents a graphical method of assessing the two

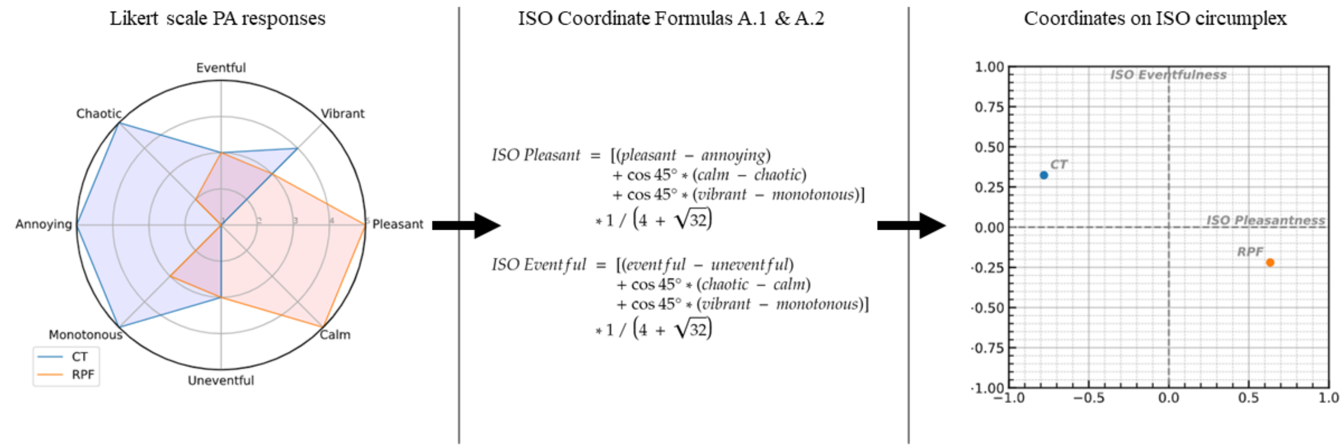

FIG. 1. Placeholder radar plot and projection. Need to remove the middle set of equations, since they are being included in the text

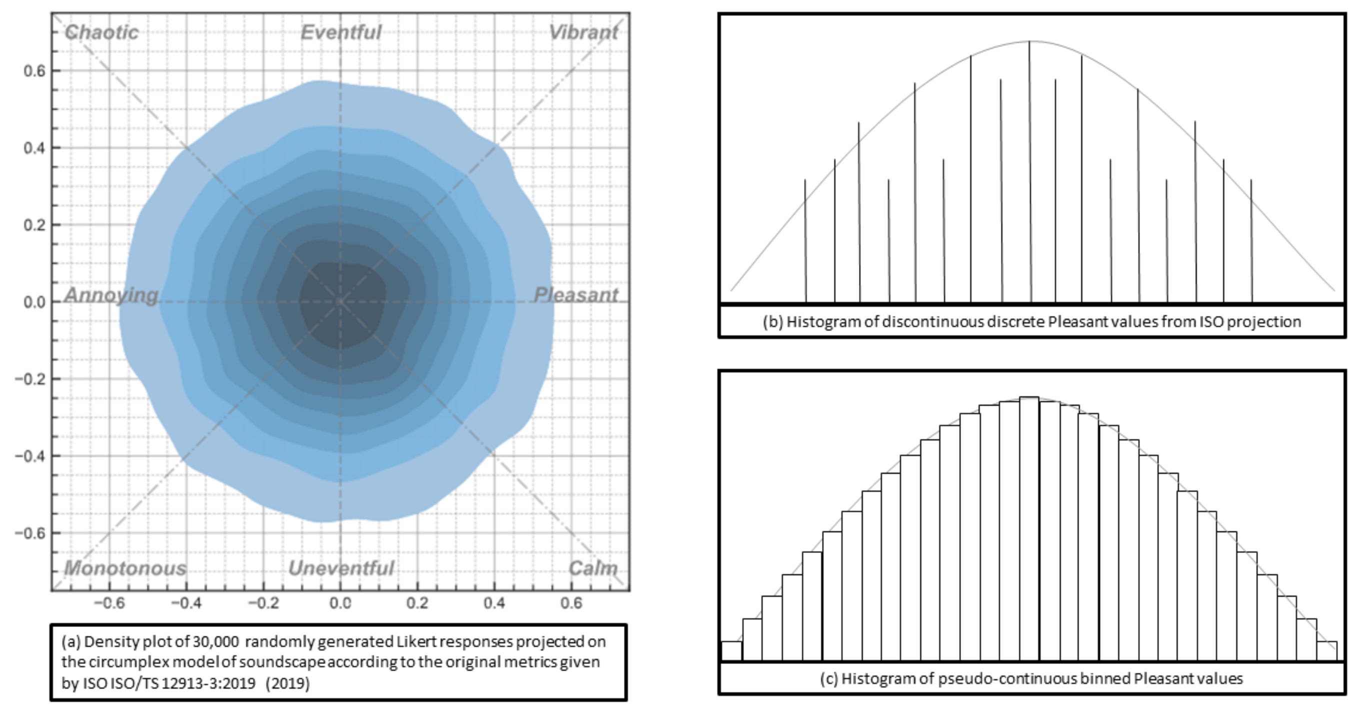

FIG. 2. Mockup placeholder simulation heatmap plot from Lionello 2020 and discrete vs binned transformation values. For new one, need to include distribution histograms along each axis.

dimensions of affect (pleasure and arousal) (**?**), they use a square grid. This is all to say that, although the term 'circumplex' and the foundational analyses which lead to a soundscape circumplex may lead us to assume it must take the form of a circle, both the framework laid down by Russell and the common treatment of the spatial relationships of the attributes actually describe a square, instead.

This treatment of the 8 PAs makes several assumptions and inferences about the relationships between the dimensions. As stated in the standard (ISO, 2019, p. 5):

> According to the two-dimensional model, vibrant soundscapes are both pleasant and eventful, chaotic soundscapes are both eventful and unpleasant, monotonous soundscapes are both unpleasant and uneventful, and fi-

nally calm soundscapes are both uneventful and pleasant.

From this, we would infer that a maximally vibrant soundscape is both maximally pleasant and maximally eventful. However, when the projection transformation is applied it imposes certain limitations on the relationships between the dimensions which do not conform with this assumption. As shown in Figure 1, when a soundscape is maximally vibrant (i.e. a diagonal vector distance of 1), the maximum pleasantness value it can have is determined by the $\cos 45^{\circ}$ term, giving a max pleasantness value of ~ 0.7071. The implication of this is that no soundscape can be both maximally pleasant and maximally eventful at the same time, meaning that these dimensions are not in fact considered as orthogonal, and that a highly vibrant soundscape cannot be considered highly pleasant or highly eventful. Similarly, if a soundscape were to begin at a maximum Eventfulness, with neutral Pleasantness, in order for the soundscape to become more pleasant, it must by definition become less eventful. This is not conceptually correct or borne out in the treatments of previous literature. These same relationships and violations hold true for the other diagonal dimensions, chaotic, calm, and monotonous.

This implication violates both the assumptions made within the formulation of the circumplex model and the way that soundscape practitioners have understood and presented the interpretations of soundscapes within the circumplex space. In cases where the PA dimensions are referred to directly (Steele *et al.*, 2016, 2019) and those which have made use of the Part 3 transformation to 2-dimensional coordinates (Lionello *et al.*, 2021; Mancini *et al.*, 2021; Manzano *et al.*, 2021), *Check Manzano2021importance* the conflation of maximal values on the diagonal axes with maximal values on the primary axes is made, as in the assumptions made by the standard. This is the first of the common understandings of the circumplex which are violated by the trigonometric transformation.

C. Normal distribution discussion

We can also see from the histograms included along the axes of Figure 2 that the projection creates a normal distribution in both dimensions. It is important here to remember that the input to the projection formulas were uniform distributions for each of the 8 PAs, and it is the projection into the two primary dimensions which results in this normal distribution. When looking at the distribution heatmap in Figure 2, it is useful to picture the gradients as representing the available space in the circumplex model.

Need to add more here? Different transition?

Probability Density Function From the simulated distributions, we can derive a normal probability density distribution (PDF) for each of the dimensions.

$$f_X(x) = \frac{x^{-(x-\mu)^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}}$$

with a mean $\mu = 0$ and standard deviation $\sigma = 0.3$.

Realistic max values When we start to think about real-world urban soundscape data collection, where the discussion of the soundscape of a space is not limited to a single person's perception, we need to start thinking in statistical terms. Theoretically, the limits of the projected Pleasantness are (-1, +1), however according to the PDF calculated above, the 3σ value is $\pm$0.XX. This means that only 0.3% of values fall outside the range (-0.XX, +0.XX). It may be argued that as long as +1 can theoretically be reached, this should be what is considered the maximum value for that dimension. However, in any situation which involves using multiple individual soundscape assessments in order to characterize the overall soundscape of a location, this max will effectively never be reached. According to the large-scale, multi-location data set reported in our previous study, it appears that the effective maximum values for Pleasantness and Eventfulness for the combined assessment of multiple people for a space is in reality approximately (-0.6, +0.6) (Lionello *et al.*, 2021).

As such, extreme values on each of the perceptual dimensions are less likely to occur than are coordinate values which place the soundscape in the neutral areas of the circumplex space. This means an extremely calm (or chaotic, or vibrant, or pleasant) coordinate is significantly less likely to occur than a neutral coordinate.

Non-linearity of movement around the space We can further use this as a demonstration of how we might conceive of a soundscape moving within the available space. * ease of getting to a certain area

* clustering near neutral

D. Non-continuous projected values

An implicit assumption of the transformation is that the resulting coordinates are now continuous values, which allows linear regression and correlation methods to be used. Indeed, the transformation of the 8-dimensional ordinal Likert scale data to the two-dimensional coordinates creates a higher resolution of intervals, which would appear to be pseudo-continuous. Upon further investigation, the transformation actually results in XX discrete possible values. Figure 2(b) shows a histogram of this raw output from the transformation, demonstrating that these discrete values, while following the general normal distribution discussed above, are not evenly filled - some adjacent values may be much more or less likely than their neighbors. This poses potential issues for further analysis which assumes either continuous or equally-spaced discrete values.

IV. PROPOSED SOLUTIONS

A. Probabilistic Distribution Thinking

The instruments described in the ISO 12913 Part 2 ISO (2018) were originally designed primarily for the context of individual or small group assessments. In these scenarios, the focus is on assessing the particular soundscape of the person in question. Recent advances in the soundscape approach since the development of the standards have shifted some focus from individual soundscapes to characterizing the overall soundscape of public spaces (Mitchell *et al.*, 2020). In this context, a consideration of the natural variation in people's perception and the variation over time of a soundscape must be a core feature of how the soundscape is discussed. Boiling a public space which may have between tens and tens of thousands of people moving through it in a single day down to the mean (or median, or any other single metric) soundscape assessment completely dismisses the reality of the space. Likewise, this overall soundscape of a public space cannot possibly be determined through a 10-person soundwalk, as there is no guarantee that the sample of people engaged in the soundwalk are representative of the users of the space (in fact it is very likely they would not be).

This shift is part of a move towards a more holistic approach to urban noise and to integrating the soundscape approach into urban design and regulations.

B. Proposal for CDF projections

The CDF of the simulation of the ISO projections is thus:

$$\Phi(x) = \int_{-\infty}^{x} \frac{e^{-x^2/2}}{\sqrt{2\pi}}$$

V. DISCUSSION / CONCLUSIONS

In a recent editorial paper on Soundscape Assessment, Axelsson and colleagues observe that it is important to critically discuss current theories and models in soundscape studies and to examine their effectiveness, while also looking at how to integrate different methods and perspectives for the discipline to make further advancements (Axelsson *et al.*, 2019). This work was mainly aimed at addressing the issue of meaningful comparability and representation of soundscape assessments. Part 2 of the ISO 12913 standard itself does not provide ultimate answers: the technical specifications recommend multiple methods, as consensus around a single protocol could not be reached. This diversity of methodological approaches should be interpreted as a fact that soundscape theory is still under development and, for this reason, the standardization work should probably take a step back and focus on developing a reference method for comparability among soundscape studies, rather than a single protocol for soundscape data collection. Some attempts have indeed already been made in literature for the different methods proposed in the ISO/TS 12913-2:2018 (Aletta *et al.*, 2019; Jo *et al.*, 2020).

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