inter.noise
21-24 AUGUST
SCOTTISH EVENT CAMPUS
GLASGOW
2022

Can acoustic design accommodate aural diversity?

William J. Davies[1]
Acoustics Research Centre, University of Salford
Newton Building, The Crescent, Salford M5 4WT, UK

ABSTRACT

Up to now, the acoustic design of almost everything has assumed a typical listener with "normal" hearing. This includes the physical environment (homes, workplaces, public space), products that make sound (transport, appliances, loudspeakers), and systems for broadcast and reproduction (TV, radio, games). But at least one in five people in the world has atypical hearing. They are either narrowly medicalised (e.g., hearing aids) or mostly ignored (e.g., noise sensitivity). As the global population ages this proportion will increase. Aural diversity is a way of reconceptualising human experience of sound that emphasises the broad and semi-continuous distribution of differences that exist in detecting, processing and responding to sound. This paper explores whether acoustic design could adapt to incorporate the concept of aural diversity and what might be gained in doing so. The literature is reviewed to see how several different kinds of aural divergence are currently characterised and to identify some other auditory differences that are under-researched. A conceptual framework is proposed in which a single "normal" hearing model could be replaced with a hearing distribution or a multi-dimensional space of aural experience.

1. INTRODUCTION

The concept of normal hearing is everywhere in acoustics, even if it is often implicit. Students of acoustics are taught about the normal hearing threshold and the functioning of the otologically normal ear. They may be taught about the underlying psychophysical relationships that underpin the decibel and the A-weighting curve, but soon the units are used as if they correctly represent the response of all humans. Hearing is thus partitioned into normal and impaired. Acoustic design usually has targets based on user acceptability – noise level, reverberation time, and so on – but these are almost always tacitly based on normal hearing (unless we are designing a hearing aid). Variance in human response to sound, whether community noise annoyance or perception of audio artefacts, is often treated as an annoying but inevitable statistical noise. It can be dealt with by recruiting enough participants and finding the average response. For many purposes, this is perfectly adequate. However, growing societal awareness of the need to better accommodate the widest range of human ability, partly driven by the disability rights movement, is driving a re-think. A large and growing proportion of the population has atypical "non-normal" hearing. Some of these people do not necessarily see themselves as impaired, but rather disabled by acoustic environments which do not cater to them. Inspired by the neurodiversity movement, Drever coined the concept of aural diversity as a way to represent the multi-dimensional, complex picture of hearing differences [1]. Aural diversity is seen as being in opposition to the binary partition of all humans into normal and impaired hearing. Aural diversity encompasses all kinds of individual differences in human

[1] w.davies@salford.ac.uk

response to sound, including hearing differences (and impairments), auditory processing differences (and disorders) and sound response differences.

Aural diversity presents an interesting challenge to acoustic design: Can design move away from assuming a single normal hearing type and move towards accessible design that work for an aurally diverse population? This paper aims to make a start on this large question by first reviewing the existing acoustics literature to see how aural diversity and individual and group differences have been represented so far. It then makes a proposal for a new aural-space framework that could both represent and quantify aural diversity while (eventually) providing useful data on how to design for it.

2. LITERATURE REVIEW

2.1. Aural diversity

Finding previous acoustics research on aural diversity *per se* is difficult. The concept as defined by Drever [1] is as recent as 2017. Searching specifically for "aural diversity" produces a small number of papers since then. On the other hand, one might suspect that in the huge psychoacoustic and physiological acoustics literatures, the concept of a distribution of hearing types (rather than a division of normal and impaired) might have been invented before, perhaps multiple times. Accordingly, a structured search of the literature since 2012 was made using the databases and search strings shown in Table 1.

Table 1: Databases and fields searched, search query and number of results.

Database	Fields	Search query	Results
Web of Science (full)	title keywords abstract	(TS=((“aural*” OR “hear*” OR “listen*”) NEAR/5 (“diversity” OR “diverse” OR "differ*") AND (“acoustic*” OR “audio*” OR “noise”))) NOT TS=("heart" OR "differential diagnosis") AND PY=(2012-2022)	3645
Scopus	title keywords abstract	TITLE-ABS-KEY(("aural*" OR "hear*" OR "listen*") W/5 ("diversity" OR "diverse" OR "differ*") AND ("acoustic*" OR "audio*" OR "noise") AND NOT ("heart" or "differential diagnosis")) AND PUBYEAR > 2011	3936
Google Scholar	Title	allintitle: (aural OR hear OR listen) (diversity OR diverse OR differ)	41

Automated removal of duplicates in Endnote reduced this dataset to 5404 papers. The dataset was then sharply reduced by a combination of manual screening and further searching for specific terms (e.g., “fish” or “bird” to remove papers dealing with non-human hearing). Many additional duplicates were found during this process. Common reasons for removing papers during screening included:

- Topic is difference in some other acoustic aspect then hearing (e.g., source, environment)
- Hearing difference noted is essentially binary (normal/impaired)
- Topic is difference or diversity within a single specific impairment (e.g., range of hearing thresholds in clinical presentations of tinnitus)
- Target is non-human species
- Topic is another kind of diversity in humans (e.g., political views)

After screening 82 records remained. Some themes emerge from this reduced dataset. Several papers discuss the distribution of various aspects of speech perception in human populations [2] [3] [4] with a general consensus that individual differences in basic neural processes such as executive function and working memory can help to explain the observed performance differences [5]. A second theme is the wide range of outcomes experienced by hearing aid users, even when they have similar pure-tone hearing thresholds. One set of papers in this theme discuss this problem in terms of adapting and improving techniques for fitting hearing aids to individual users [6] [7]. The second set of papers within this theme seek to develop new measurements of above-threshold hearing tasks which can help to predict the diverse outcomes for people with hearing impairments [8] [9]. A third theme concerns the distribution of a specific audiological measurement in a population, most typically pure-tone hearing threshold [10]. The fourth and final theme in the dataset are papers which postdate Drever and which use the term aural diversity in approximately the sense coined by him. These typically argue for an inclusive design approach for soundscapes, though hearing differences are typically still conceptualised as impairments or disease and the normal hearing paradigm still seems central [11].

During the screening process it was found that the specific term "aural diversity" has been used a small number of times in acoustics prior to Drever, but only to refer to different concepts than diversity of hearing. The earliest use found was by Lewers, who in 2004 used aural diversity to refer to a diverse range of acoustic environments which one might experience in moving through a well-designed building [12].

It was observed from the structured literature review above that searching for papers specifically on aural diversity (or similar topics) does not produce a complete picture of how the diversity of hearing and listening is represented in the acoustics literature. This is because (reasonably enough) the great majority of papers on atypical hearing are concerned solely with a specific aspect of a specific hearing condition and do not try to discuss the full range of hearing differences in humans. It is therefore helpful for this paper to briefly review the main hearing differences to build up a picture of what aural diversity might look like. This is divided into the categories of hearing (detection and peripheral processing), auditory (neural) processing and response.

2.2. Diversity in hearing

The detailed mechanisms by which acoustic waves arriving at the ear are transduced into nerve signals encoding low-level percepts including pitch, loudness and spatial location are well understood [13]. Equally well characterised are many types of hearing impairments arising from dysfunction of parts of the ear; these include the most common, such as noise-induced hearing loss and presbycusis [14] and less common such as Meniere's disease [15]. One important research gap in many conditions is an explanation for individual differences often observed clinically, in symptoms, outcomes, clinical measures, severity and changes over time.

Significant individual differences have also been found in the most basic percepts such as pitch, although these are not usually identified as dysfunctions. As well as differences in accuracy in relative pitch judgement, evidence exists for two different mechanisms for perceiving musical pitch: holistic and spectral [16] [17].

Significant differences in loudness perception, in contrast to pitch, usually are found to be significantly disabling. Increased loudness perception is usually described as hyperacusis, although there may be more than one type: in their review, Tyler et al. split the condition into loudness hyperacusis, annoyance hyperacusis, fear hyperacusis and pain hyperacusis, noting that "people with hyperacusis can experience these reactions singly or in combination" [18]. Hyperacusis may be common, although prevalence in the general population is still uncertain, at 0.2–17.2% [19].

2.3. Diversity in auditory processing

The general principles by which the signals arriving at the ear are parsed into a useful representation of our acoustic environment have been extensively studied [20], including models [21], the role of attention [22] [23], and the balance between prediction and hearing [24] [25].

Auditory processing disorder is a broad diagnosis which captures many individuals who experience some difficulty with auditory processing [26]. The definition, diagnosis and even research of APD continues to be a topic of debate [27] though the most common presentation is a person with a normal pure-tone audiogram who nonetheless has significant difficulty in processing speech, especially in the presence of noise or reverberation [28]. The category of APD includes difficulty or difference in several functions which are usually represented in auditory models as distinct processes, including source or stream parsing [29], attention selection [30] and higher-order processing such as speech prosody [31]. Thus it may be that in the future APD is decomposed into several different disorders, although one factor mitigating against this, is the prevalence of people with difficulties in more than one aspect of APD.

Autistic people are one special group who often seem to experience several different forms of atypical auditory processing. While hyperacusis and noise sensitivity are common, so are difficulties with speech-in-noise and attention differences [32]. There are also reports of autistic advantages including much better pitch detection [33], greater auditory capacity [34] and joy in soundscape decomposition abilities [35]. An interesting aspect of diversity within diversity is that many reports emphasise the heterogeneity of autistic people, so that significant individual differences in audition are to be expected within a group of autistic people.

2.3. Diversity in response

Response to sound here includes value judgements such as preference, emotional responses such as annoyance and cognitive responses as found in some soundscape research. Annoyance is probably the most common outcome measure of all in acoustics research. One of the biggest problems in noise annoyance, especially in field experiments, is the variance found when trying to correlate subjective ratings of annoyance to objective measurements of noise exposure. The scatter in response is sufficient that large-scale meta-analyses of many environmental noise trials were needed to develop our current gold-standard metrics of environmental noise [36]. Looked at through the lens of aural diversity, though, the scatter seen in dose-response relationships could also be a true reflection of stable individual and/or group differences in response. Some progress has been made in exploring variance of annoyance following the introduction of the concept of noise sensitivity [37]. This is now understood as a stable personality trait which modulates noise annoyance response [38].

Soundscape researchers typically find significant variance in human response to a given acoustic environment, including on the standardized response scales of pleasantness and eventfulness [39]. The most common theoretical model has a large box labelled ‘context’ which modulates human response, and context includes many factors, including “the interrelationships between person and activity and place, in space and time” [40]. It is not unusual for soundscape studies with large enough cohorts to find that participants partition into sub-groups according to individual differences in response [41] [42].

Research in perception of concert hall acoustics has found ample evidence of the importance of individual differences in preferences, from the seminal early work of Schroder et al. [43], through the seat-selection schemes of Ando [44], to a more recent finding of two clusters of listeners: one preferring an intimate, detailed sound, and the other a louder, more reverberant acoustic [45].

3. AURAL-SPACE

It is currently difficult for acoustic design to take account of aural diversity. On the one hand, almost all design is currently based on an assumed normal hearing user. Designers may want to move beyond this hearing model to allow a broader range of users to access their building, soundscape or product. But then they face either too much information or not enough. Too much information, in the sense that the hearing research literature contains enormous quantities of data on a wide range of conditions. Too little, information, in the sense that the connections between physiological and psychophysical data and everyday aural experience is often not obvious, because some possible group and individual differences have yet to be studied, and also because there is a lack of an overall organizing framework.

Other research areas have made significant progress when an organizing framework in the form of a multi-dimensional space was imposed. A good example is face-space, developed by Valentine to organize and theorise visual perception of the human face [46] [47]. The dimensions of face-space are unspecified but can represent any aspect on which human faces can be discriminated, including simple physical measurements like jaw width, to more abstract perceptual traits like assertiveness. Face-space has been successfully used as a framework to explain several phenomena in how faces are perceived, including why some faces are more memorable than others, and how people adapt to different faces over time. Inspired by face-space, other authors have proposed other perceptual spaces, including mind-space, which seeks to explain how humans represent the thinking of others (theory of mind) by proposing that our perception of the minds of others may be represented in a multi-dimensional space [48].

Aural-space is here proposed as a multi-dimensional space to represent the full distribution of human aural experience. In keeping with Drever's concept of aural diversity, aural-space is conceived as representing human aural *experience* of the world, not any particular set of audiometric, behavioural, acoustic or neural measurements. Like face-space and mind-space, aural-space will therefore be a high-dimensional construct. A point in aural-space represents the aural experience of an individual. Two individuals with similar aural experience (hearing, processing, responding) will be represented by points close together in aural-space. Vectors in aural space represent various divergences, a common auraltype is a cluster of points in aural-space, and the aural diversity of a population could be characterised along one or more dimensions of its aural-space. If aural-space is a valid construct, then it is likely that, like face-space, it could be represented by a low-dimensional projection for some specific purpose, such as setting the optimal reverberation time of a specific type of room. An example 3D projection of aural-space is shown in Fig. 1. The true dimensions of aural-space would have to be determined by experiment (as they have been for face-space [47]).

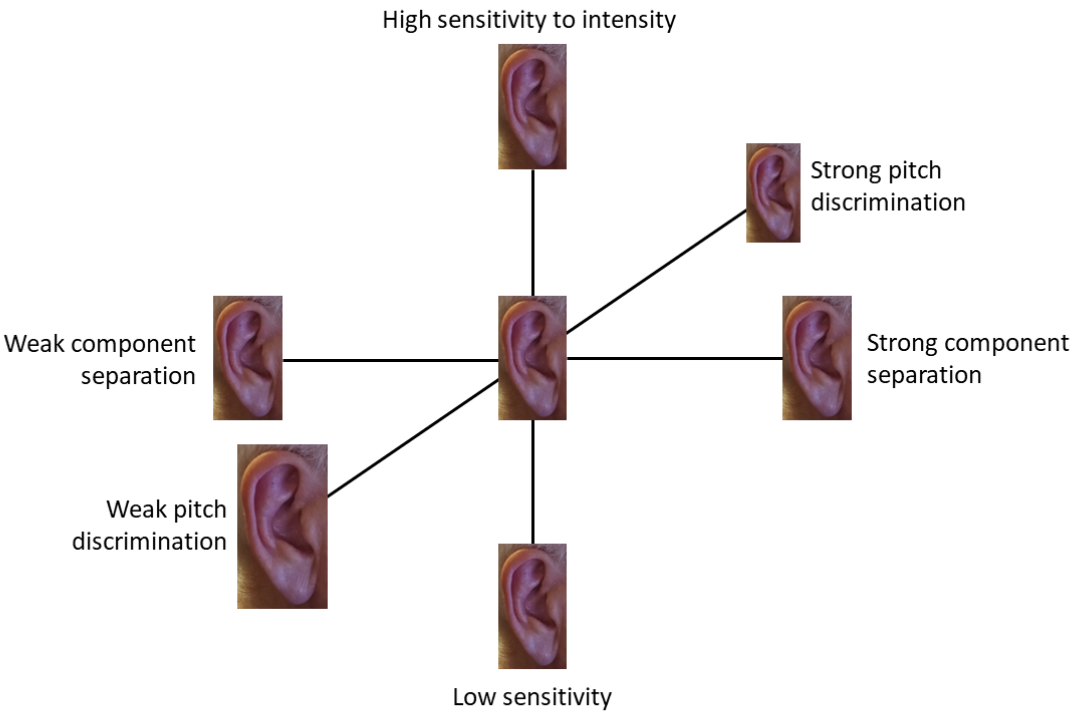

Figure 1: Aural-space is a multi-dimensional space representing the full range of individual differences in aural experience. In this example projection, the dimensions represent differences in parsing components of an acoustic scene (e.g., speech and noise), sensitivity to intensity, and ability to discriminate pitch. The actual dimensions of aural-space are yet to be determined empirically.

Although the dimensions of aural-space represent differences in subjective aural experience, an obvious research target would be to find objective correlates of the subjective dimensions, as has been done in many perceptual space research before. In this case, the objective correlates might be some combination of audiological, neural and physiological measurements. If aural-space were adopted as an organizing framework it might help direct efforts to find objective metrics that better correlate with common aural divergences such as APD. Existing multi-dimensional spaces of audiological measurements are uncommon, but Sanchez-Lopez et al. recently proposed a two-dimensional space to represent a diverse group of people with sensorineural hearing loss in four distinct clusters [6].

Advantages of aural-space include:

- Representation of the most important aspects of subjective aural experience
- Representation of full range of individual differences
- Represents common experience fairly as clusters
- Retains normal hearing as a central cluster while fairly representing other auraltypes and individual divergence

Disadvantages of aural-space include:

- Current absence of data to populate and scale aural-space

How would any of this benefit acoustic design? An initial rendering of aural-space would allow acoustic designers (and everyone else) to have a clearer picture of aural diversity. But further steps would be needed. A significant gap would still remain in understanding how to best fit a particular acoustic design to a particular group or whole population. For example, what range of reverberation time would optimize a room for human conversation for a given percentage of the population or a particular set of clusters in aural-space? This and similar questions might be answered by research which sought to construct a multi-dimensional space of acoustic environments and then map it to aural-space. Multi-dimensional metric spaces exist for some types of acoustic environment, such as concert halls [49], everyday rooms [50] and (to a partial extent) outdoor urban soundscapes [51].

4. CONCLUSIONS

Human hearing (and processing and responding to sound) is very varied. The normal hearing model is very useful but because it does not represent significant individual difference, can result in acoustic design which excludes some people. Aural diversity is a concept that suggests replacing the single normal hearing model with something that acknowledges the multi-dimensional variance in hearing. A review of the existing literature showed that there is evidence of many different kinds of divergence, though many research gaps yet exist. Finally, a novel frame-work, aural-space, was proposed to represent and characterize aural diversity in such a way as to motivate future research and to eventually provide better information to acoustic designers about their users.

5. REFERENCES

1. Drever, J.L., *The Case For Auraldiversity In Acoustic Regulations And Practice: The Hand Dryer Noise Story*, in *Proceedings of the 24th International Congress on Sound and Vibration ICSV24*. 2017, The International Institute of Acoustics and Vibration: London.
2. Trevino, A. and J.B. Allen, *Individual variability of hearing-impaired consonant perception.* Seminars in Hearing, 2013. **34**(2): p. 211-214.
3. Kong, E.J. and J. Edwards, *Individual differences in categorical perception of speech: Cue weighting and executive function.* Journal of Phonetics, 2016. **59**: p. 40-57.
4. Reinhart, P.N. and P.E. Souza, *Listener factors associated with individual susceptibility to reverberation.* Journal of the American Academy of Audiology, 2018. **29**(1): p. 73-82.

5. Tamati, T.N., J.L. Gilbert, and D.B. Pisoni, *Some factors underlying individual differences in speech recognition on PRESTO: A first report.* Journal of the American Academy of Audiology, 2013. **24**(7): p. 616-634.
6. Sanchez-Lopez, R., et al., *Robust Data-Driven Auditory Profiling Towards Precision Audiology.* Trends in Hearing, 2020. **24**.
7. Wu, M., et al., *Influence of Three Auditory Profiles on Aided Speech Perception in Different Noise Scenarios.* Trends in Hearing, 2021. **25**.
8. Santurette, S., et al., *Individual Hearing Loss: Characterization, Modelling, Compensation Strategies.* Trends in hearing, 2016. **20**.
9. Bharadwaj, H.M., et al., *Individual differences reveal correlates of hidden hearing deficits.* Journal of Neuroscience, 2015. **35**(5): p. 2161-2172.
10. Kurakata, K., T. Mizunami, and K. Matsushita, *How large is the individual difference in hearing sensitivity?: Establishment of ISO 28961 on the statistical distribution of hearing thresholds of otologically normal young persons.* Acoustical Science and Technology, 2013. **34**(1): p. 42-47.
11. Botteldooren, D. *Urban sound design for all*. in *Proceedings of 2020 International Congress on Noise Control Engineering, INTER-NOISE 2020*. 2020.
12. Lewers, T., *The reverential acoustic*, in *Environmental Diversity in Architecture*, M.A. Steane and K. Steemers, Editors. 2004, Spon Press: London. p. 143-156.
13. Moore, B.C.J., *An Introduction to the Psychology of Hearing*. 5th ed. 2003: Emerald Group Publishing.
14. Cunningham, L.L. and D.L. Tucci, *Hearing loss in adults.* New England Journal of Medicine, 2017. **377**(25): p. 2465-2473.
15. Nakashima, T., et al., *Meniere's disease.* Nature reviews Disease primers, 2016. **2**(1): p. 1-18.
16. Schneider, P., et al., *Structural and functional asymmetry of lateral Heschl's gyrus reflects pitch perception preference.* Nature neuroscience, 2005. **8**(9): p. 1241-1247.
17. Benner, J., et al., *Differences in sound perception are reflected by individual auditory fingerprints in musicians*, in *The Journal of the Acoustical Society of America*. 2017.
18. Tyler, R.S., et al., *A review of hyperacusis and future directions: part I. Definitions and manifestations.* American journal of audiology, 2014. **23**(4): p. 402-419.
19. Ren, J., et al., *Prevalence of Hyperacusis in the General and Special Populations: A Scoping Review.* Frontiers in Neurology, 2021: p. 1540.
20. Bregman, A.S., *Auditory scene analysis: The perceptual organization of sound*. 1994: MIT press.
21. Szabó, B.T., S.L. Denham, and I. Winkler, *Computational models of auditory scene analysis: a review.* Frontiers in Neuroscience, 2016. **10**: p. 524.
22. Shamma, S.A., M. Elhilali, and C. Micheyl, *Temporal coherence and attention in auditory scene analysis.* Trends in neurosciences, 2011. **34**(3): p. 114-123.
23. Kaya, E.M. and M. Elhilali, *Modelling auditory attention.* Philosophical Transactions of the Royal Society B: Biological Sciences, 2017. **372**(1714): p. 20160101.
24. Bendixen, A., *Predictability effects in auditory scene analysis: a review.* Frontiers in neuroscience, 2014. **8**: p. 60.
25. Pressnitzer, D., C. Suied, and S. Shamma, *Auditory scene analysis: the sweet music of ambiguity.* Frontiers in human neuroscience, 2011. **5**: p. 158.
26. Iliadou, V.V., et al., *A European perspective on auditory processing disorder-current knowledge and future research focus.* Frontiers in Neurology, 2017. **8**: p. 622.
27. DeBonis, D.A., *It is time to rethink central auditory processing disorder protocols for school-aged children.* American journal of audiology, 2015. **24**(2): p. 124-136.
28. Flanagan, S., et al., *Speech processing to improve the perception of speech in background noise for children with auditory processing disorder and typically developing peers.* Trends in Hearing, 2018. **22**: p. 2331216518756533.

29. Lotfi, Y., et al., *Effects of an auditory lateralization training in children suspected to central auditory processing disorder.* Journal of audiology & otology, 2016. **20**(2): p. 102.
30. Moore, D.R., et al., *Evolving concepts of developmental auditory processing disorder (APD): a British Society of Audiology APD special interest group 'white paper'.* International journal of audiology, 2013. **52**(1): p. 3-13.
31. Cumming, R., A. Wilson, and U. Goswami, *Basic auditory processing and sensitivity to prosodic structure in children with specific language impairments: a new look at a perceptual hypothesis.* Frontiers in Psychology, 2015. **6**: p. 972.
32. O'Connor, K., *Auditory processing in autism spectrum disorder: a review.* Neuroscience & Biobehavioral Reviews, 2012. **36**(2): p. 836-854.
33. Bonnel, A., et al., *Enhanced pitch sensitivity in individuals with autism: a signal detection analysis.* Journal of cognitive neuroscience, 2003. **15**(2): p. 226-235.
34. Remington, A. and J. Fairnie, *A sound advantage: Increased auditory capacity in autism.* Cognition, 2017. **166**: p. 459-465.
35. Davies, W.J., *Autistic Listening*, in *Aural Diversity*, J.L. Drever and A. Hugill, Editors. 2022, Routledge: Abingdon.
36. Miedema, H.M.E. and H. Vos, *Exposure-response relationships for transportation noise.* Journal of the Acoustical Society of America, 1998. **104**(6): p. 3432-3445.
37. Schutte, M., et al., *The development of the noise sensitivity questionnaire.* Noise and Health, 2007. **9**(34): p. 15.
38. Stansfeld, S., et al. *Noise sensitivity, health and mortality–a review and new analyses*. in *Proceedings of the 12th International Congress on Noise as a Public Health Problem*. 2017.
39. ISO_12913-2, *Acoustics — Soundscape — Part 2: Data collection and reporting requirements*, in *BS ISO 12913-2:2018*. 2018: Geneva.
40. ISO_12913-1, *Acoustics — Soundscape — Part 1: Definition and conceptual framework*, in *BS ISO 12913-1:2014*. 2014: Geneva.
41. Yang, M., M. Emelin, and A. Herweg. *Factors that affect individual differences in soundscape evaluations*. in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. 2020. Institute of Noise Control Engineering.
42. Davies, W.J., N.S. Bruce, and J.E. Murphy, *Soundscape reproduction and synthesis.* Acta Acustica United with Acustica, 2014. **100**(2): p. 285-292.
43. Schroeder, M.R., D. Gottlob, and K.F. Siebrasse, *Comparative study of European concert halls: correlation of subjective preference with geometric and acoustic parameters.* J. Acoust. Soc. Am., 1974. **56**(4): p. 1195-1201.
44. Ando, Y., *A theory for individual preference of designing the sound field in a concert hall.* The Journal of the Acoustical Society of America, 1991. **90**(4): p. 2238-2238.
45. Lokki, T., et al., *Disentangling preference ratings of concert hall acoustics using subjective sensory profiles.* The Journal of the Acoustical Society of America, 2012. **132**(5): p. 3148-3161.
46. Valentine, T., *A unified account of the effects of distinctiveness, inversion, and race in face recognition.* The Quarterly Journal of Experimental Psychology Section A, 1991. **43**(2): p. 161-204.
47. Valentine, T., M.B. Lewis, and P.J. Hills, *Face-space: A unifying concept in face recognition research.* The Quarterly Journal of Experimental Psychology, 2016. **69**(10): p. 1996-2019.
48. Conway, J.R., C. Catmur, and G. Bird, *Understanding individual differences in theory of mind via representation of minds, not mental states.* Psychonomic bulletin & review, 2019: p. 1-15.
49. Ando, Y., *Concert hall acoustics*. Vol. 17. 2012: Springer Science & Business Media.
50. Traer, J. and J.H. McDermott, *Statistics of natural reverberation enable perceptual separation of sound and space.* Proceedings of the National Academy of Sciences, 2016. **113**(48): p. E7856-E7865.
51. Axelsson, Ö., M.E. Nilsson, and B. Berglund, *A principal components model of soundscape perception.* The Journal of the Acoustical Society of America, 2010. **128**(5): p. 2836-2846.