BIOMETRIC EVOLUTION OF SPACE

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1 INTRODUCTION

This paper describes how reciprocally creative relationship can be forged between music and physical space using digital technology. It allows observers to witness an evolution of spatial form to suit the unspoken taste in music of a listener. The paper describes a process that can reverse-engineer an implied acoustic space from sonic stimuli. The aim of the experiment was to allow psychophysiological responses to sound and space to act as a fitness criterion in an evolutionary process that is developing an acoustically sensitive volume.

A series of pieces of anechoically recorded classical music was played to listeners who developed a 'space' for each piece. The space was formed from the optimisation of an early reflection sequence and overall reverberation time of a virtual acoustic space The spatial coordinates of the early reflectors were then sent to a 3D modelling environment where the virtual space could be seen as a fully fleshed-out piece of architecture. 23 listeners were tested and over 92 halls, or spatial volumes, were created. these went on to show a trend towards drier and more articulate spaces as a popular environment for listening. The tests also showed an ability for the system to allow unconscious personal preference to come to the fore and develop a personally tailored space.

2 BACKGROUND

2.1 Precedents

Previous examples of developing evolutionary optimized, parametric acoustic environments[1, 2, 3] have been successful in developing an environment that will adapt itself to established acoustic criteria. Such efforts have all used ISO 3382 standards as a benchmark to optimise an acoustic space. However, using such standards as a fitness criterion forces the algorithm to adapt itself to an existing benchmark that matches industry assumptions and is unlikely to develop anything original in the process. The work developed by Sato et al. (2004), for example, showed that it was possible to develop by evolutionary processes a hall that matches the Musikvereinssaal using ISO 3382 metrics. Echenagucia et al. (2014) optimised shoebox and fan-shaped halls, but that was where the optimisation stopped. Variation, by exceeding or falling short of the standards, was deemed unsuccessful and ignored. Such thinking will not allow for critical assessment of the metrics in the context of an evolving listening public. An approach must be considered that allows a reassessment of what the listening public prefers in terms of a listening environment, one that takes in differing tastes in listening habits outside of the constraints of the ISO 3382 standards.

2.2 Emotional response as a fitness criterion

Key to this study is developing a way to decouple acoustics from the standard metrics and link them to a much more fluid and personal preference - an unconscious link between sound and space. Established methodologies on biometric sensing[3] have shown how psychophysiological responses to sound and space can be measured. Utilising such methodologies to generate a response allows us to see how the body is responding to music and an environment, and then allow computational processes to develop and finesse according to the response. Such a process generates an immediate objective response to a given situation, using measurable data that can drive computational processes, optimising any given situation. The process described here demonstrates how a parametric environment can be developed and generated purely from the body's response to the musical environment, and not driven by established acoustic metrics. This process will show what the unconscious body is feeling during a musical event, and how it can feed an optimisation process. The outcomes of such a process are significant; the system could reinforce existing acoustic conventions or could demonstrate a divergence from the current paradigms that are yet unexplored and unarticulated.

2.3 Process

Understanding causal links between sound, space and the body carries many contextual issues that cannot be overcome in a simple test, the enjoyment of music in a concert hall is not only dependent on music and spatial volumes, but also on the mood of the listener, the company of the listener, and a range of other factors and underlying issues that can lead to a heightened sense of emotion.[4] To counter such issues, this work builds on the findings of two significant pieces of research. Firstly, research into lateral reflections and emotional response, where it was established that focused spatial features of a room (predominantly the strength of early lateral reflections) could heighten the emotional response of a listener[5]. Secondly, the reverse-engineering of auditoria from the sound out, where a hall could be developed by spatialising an impulse response.[6] These works suggest a test procedure that can be undertaken in isolation, independent of the normal context of a concert hall experience and show a positive or negative valence towards differing acoustic environments. Undertaking the test in laboratory conditions allows an objective reading of the body's psychophysiological reaction to external stimuli in a straightforward way that is decoupled from overriding external conditions, such as prevailing moods and company.

This was a project undertaken at the Bartlett School of Architecture in UCL, London UK, and is an architectural design exercise using ideas from acoustics and evolutionary systems. The work described here is an exercise in research through design, a research exercise that borrows from the field of scientific enquiry; a 'design' exercise that acts as an exploration in new areas of interest for future development.

3 METHODS

Participants: Over the pilot tests and full experiments, 53 healthy student volunteers were recruited from University College London by advertisement. The breakdown was 20 male and 33 female participants, and the mean age was 28. All test participants were informed of the procedures of the tests by written statement and invited to take part by advertisement. All participants gave their written informed consent and were paid for their participation.

Ambisonic Sound Lab / Equipment: All listening tests were undertaken in the UCL sound lab, a first-order ambisonic lab with 12 individually addressable Genelec speakers in a cube layout. The room was box-shaped, with dimensions of 3.49 m (width), 3.35 m (length), 3.16 m (height) A comfortable armchair on which the listener was seated was positioned centrally. The reverberation time (T30,500Hz–2kHz) measured in the test conditions with the interrupted noise method (6 microphone-source combinations, 2 source positions, 3 decays in each position) was 0.13s. The stimulus was presented by Cycling '74's Max/MSP software running on a MacBook Pro 2020. Sound was delivered via USB to an RME Fireface USB interface, then spilt across 12 channels.

GSR Dermal Response to Stimuli: Skin conductance was used as a measure of emotional response to be in line with previous tests undertaken in GSR & music and sound. Sensors were placed on the medial phalanges of the non-dominant hand, just as in the other tests. The equipment used was Grove Seeed's GSR sensor running into an Arduino microcomputer, with the serial data running into Max/MSP. Running the data into Max/MSP allowed for live analysis and to output triggers if the system detected a significant change in the data. The Max patch developed for dermal response analysis would send a trigger (pulse) to the evolutionary programming code if the GSR stream had varied +/- 5 ms in the past 3 seconds. The system could be calibrated to deal with listeners with livelier skin responses, or flat responses. Max was only using the raw data from the Arduino which had been passed through the Grove Code and took out a little noise. The final stream was recorded in a text file and then imported into Matlab's Ledalab for final analysis. This would further triangulate the results and ensure that emotional responses had occurred when the system believed it had.

The listeners were seated in a comfortable chair with the test equipment on their fingers, positioned as discreetly as possible. The non-dominant hand was resting on an adjacent table for comfort, and the participants were asked to find a comfortable position and avoid as much unnecessary movement as possible. During the tests, the observers sat outside of the sound lab to monitor the stimulus presentation and record the physiological data. The experiments lasted for 30 to 40 minutes in total.

The GSR data from each participant was recorded at a sampling rate of every 10th of a second. This generated a text file of raw skin response data in Ms (microsiemens), alongside which was a time code and onset marker. This text file was then reformatted to a csv format that could be imported into Matlab's Ledalab, a specialist application for analysing GSR data. Within Ledalab, the raw data was imported with the time code and manually smoothed with a Gauss Window of 8. The extraction of the continuous phasic and tonic activity was undertaken via continuous decomposition analysis. This separated the data into phasic and tonic activity. This later GRS analysis played no part in the evolution of the halls but was used to verify and triangulate the responses of the participants and the readings from Max/MSP.

Evolutionary Programming: the major optimisation process undertaken in the tests was interactive evolutionary programming (EP)[7]. As in most interactive evolutionary processes the most significant issue that arises in the tests is that of the search space. Having a larger number of variables in the initial phase (genotype sequence) gives more opportunities for diversity in the results, and a greater number of usable solutions. But this increase in variables requires more time to go through the options available and test each one according to a success criterion. A typical computational optimisation search, such as a genetic algorithm, will undertake thousands of generations before it reaches any degree of cover in a large search space. This is because all the variables are known and the system can run through the options until an optimum is reached, either user-defined or time-based. In an interactive situation, this is impossible; a user will reach saturation after a limited number of options, and further testing will be meaningless. Thus, the search space must be limited to a reasonable limit where a meaningful result can be achieved from limited variables. In the tests, the search space was limited as much as possible to reduce the search space and limit user fatigue. In a 'search' where epochs are limited to tens rather than thousands, it is also advantageous to generate a meaningful result as quickly as possible. The existent architectural and acoustic searches did not use user interaction and benefited from expanded search fields of thousands of generations. As this was an interactive system with limited input, it was decided to tighten up the mutation coefficient every epoch, so that the tests would start off with a wide search field, and for every emotional response recorded, the mutation would get smaller, so that the range of options offered to the participant would reduce. Over 20 generations, this would result in an exponentially reduced search space, and allows trends to be seen over the results of the listeners. Common to both tests was a limit of 20 responses which would reduce the mutation from 50% variability to 1%.

Post Test Questionnaire: After each test, the listener was questioned on their thinking during the test to detect positive and negative valence. This was important as the GSR output can detect an 'emotional response' but cannot detect if the reaction was positive or negative; both emotions would be read as the same. Thus, a sound that elicited a negative valence in a listener would be read as a false positive and the test would have offered the listener more options based on something they felt was incorrect. The post-test questions removed this risk, and tests with a predominant negative valence were removed from the results.

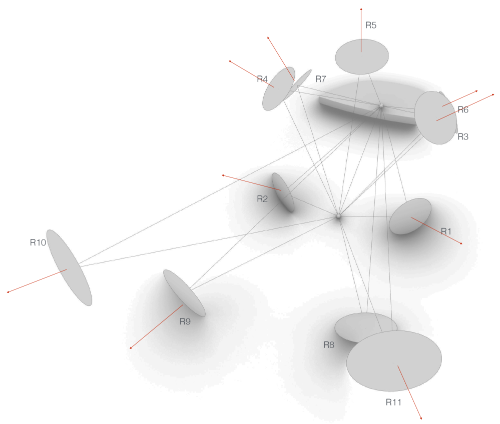
3.1 Stimuli & Outputs

Each listener listened to 4 pieces of music during the tests[8]: Mozart (1756-1791): An aria of Donna Elvira from the opera 'Don Giovanni', Beethoven: 'Symphony no. 7', I movement, bars 1-53, Bruckner: 'Symphony no. 8', II movement, bars 1-61, Mahler: 'Symphony no. 1', IV movement, bars 1-85.

The works were fully anechoic and were selected as illustrative of the 'golden age' of the Western canon, their use by other researchers, and the limited availability of fully anechoic orchestral music. The pieces were played in random order to the listeners with a 5-minute gap between each test. The was undertaken in the sound lab via an IRCAM's SPAT system in Cycling '74's Max/MSP audio software. SPAT is a modular software that allows for the generation of virtual acoustic spaces presented in ambisonic conditions.

The second part of the process was heavily modified so that the virtual architecture (defined primarily by the early reflections) could be made addressable and individually placed in the sound field. 11 key reflectors were chosen to replicate the addressable reflectors in Boning and Bassuet's work. However it should be noted that a typical acoustic response from a physical structure would consist of hundreds of reflections between 20ms and 80ms, each requiring addressable data to enable it to be positioned in a space. This would generate a significant amount of data and expand the search space to unusable proportions. 11 were used here as this was the amount used in the Boning and Bassuet research with published results. Boning and Bassuet allowed the user to consciously modulate the spatial locations of the early reflections and generate a reverse-engineered sound space to personal preference. The system described here aims to undertake the same process, but unconsciously using biometric responses, rather than making a conscious action.

The 11 reflection points were sited around the listener using the azimuth, elevation parameters as outlined in Boning and Bassuet's study. However the distance integer should be aligned to match the surface position of a real space as a starting point. In this case, a model of the Musikvereinssaal was used to define the distance location of the 11 reflectors. Each of the reflectors could be moved by the optimisation process by 5m inside its starting position, or 10m outside of its starting position, thus allowing an optimisation based on reality. *(Fig 1.)* The AED vectors (Azimuth, Elevation and Distance) were ported to Grasshopper via UDP (User Data Protocol). This data was then used to modulate the spatial parameters of a digital architectural model in Rhino, a popular modelling program for architecture. The receiver and source positions were fixed in both the max model and the architectural model. The only elements available for optimisation and spatial relocation were the reflection points.



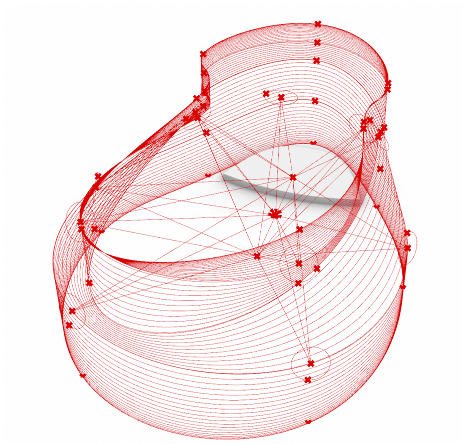


Figure 1 & 2: Reflectors in position showing axis of movement and an early skinned model showing reflector positions

The reflection points were points on a 3D mesh that could be relocated as per the AED data from Max, but the skin being modulated was always at an equal angle between source and receiver. Thus, as the virtual model in Max/MSP was modulated to reflect a listener's preferences, so was the digital 3D Model in Rhino. *(Fig 2.)* In addition to the 11 early reflection points in the chromosome chain, there were 4 variables in SPAT that were linked to an overall room response and late reflections. These were: Overall RT time and low mid and high frequency absorption as a material construct of the room.

Impulse response output: When the anechoic music had concluded, a click was sent through the final SPAT settings to generate an impulse response for later acoustic analysis. This was recorded in B-Format, on a 4-channel WXYZ audio .WAV file. The IR was initially included in the full recording of the music in the evolving space, so it needed to be extracted from this root file in Audacity, a sound editing software, and trimmed for later analysis. The IR was then imported into IRIS for full acoustic analysis, IRIS also outputted a full plot showing the spatial relationship between the source and receiver, as well as early reflections. This again triangulated the model data and showed that the spatial data from the impulse response matched the developed model in Rhino and Grasshopper.

3D Model Outputs: Once the model was fully evolved, it was then further analysed using acoustic analysis tool Pachyderm. This is a plugin for Rhino that will generate an impulse response in the 3D model for ISO 3382 analysis. This was used as a method to test the validity of the SPAT model as a full 3-dimensional exercise. This would smooth out any irregularities that may have developed from a purely auditory exercise and bring the work closer to an architectural scale. In Pachyderm, materials with acoustic performance had to be assigned.

This process was undertaken in Pachyderm for all of the resultant halls and robust acoustic data was developed for each.

4 RESULTS

The mutation coefficient of the optimisation algorithm allowed 20 generations before there would be no further change, so the system stopped recording emotional responses after 20. As the mutation was inversely exponential, there was much variation in the lower integers, before finally reaching a stable conclusion around the 18th generation. This meant that any participant who scored a figure of <18 emotional responses would be ruled out as having not reached a definitive point of positive valence in the process. Beethoven and Mozart proved highly popular, with 221 and 218 overall emotional responses. Mahler was less so, with 185 overall responses, and Bruckner achieved only 169, with only three participants actually stating they enjoyed the experience. This low score of 3 and low overall valence meant that Bruckner was excluded from future analysis.

To establish a cogent model to extract meaningful data from,the output of all distance integers from the AED vectors in Max/MSP was collected and added, averaged and then manually inputted back into Max/MSP, creating a new room representing a mean response for all the listeners. An impulse response click was then passed through this and then analysed in IRIS. The new room formed the basis of the analysis in Pachyderm. This process was undertaken for the Beethoven, Mahler and Mozart outputs. Analysis of various acoustic metrics on each room follows:

Room volume: Due to search space constraints, the ability to change room shape and volume was limited, yet there was ability for each room to grow to –5m / +10 outside of a starting value. Even so, there was little variation in volume between each hall. As the variables were established on the Musikvereinssaal, the room could develop to a volume either exceeding or lower than 15,000m^3. All halls settled around 10,300m^3 as an average. This is considerably less than the Musikvereinssaal, and it would be expected to generate a very dry sound which is certainly outside the typical standards used in contemporary halls. The loss in volume was mainly due to the height of reflector R05 which governed the overall height of the space, and reflectors R10 and R11 whose height was linked to R05. The Mahler piece generated the greatest volume at 10,521m^3, with the Beethoven room coming in second at 10,318m^3 and Mozart generating the smallest volume at 10,108m^3. The Mozart room is the closest in volume to a typical chamber hall, such as the Queen Elizabeth Hall on London's South Bank Centre, whose volume is 9,600m^3.

LF: Whilst the overall volume and room shape was largely kept intact through all evolutions of the work, the lateral fraction, or early lateral energy, was certainly modulated through the user experience. In all instances the LF is equal to typical halls and on the higher side of the ISO 3382 standards. This is clearly in line with Lokki and Pätynen’s assertion that higher lateral energy can generate a more pronounced psychophysiological response in a listener[5]. The mechanics of the increased LF value lie in the proximity of reflectors R01 and R02 which are directly adjacent to the R1 receiver position. The algorithm can bring these points inward and outward, or toward or away from the listener. In all cases, the reflectors were observed to be drawn in toward the listener, generating an increased lateral fraction reading. Whilst this appears positive, architecturally speaking, it creates problems in that the room limits sight-lines towards the rear of the hall.

T30: The metrics determining the late energy decay or reverberation were on the low side of the ISO 3382 standards, with only the Beethoven hall being relatively mid-range. 2.2s is a rich reverberation that will allow the notes to blend positively over time. This is typical for halls that play music of this period. An T30 value of 1.8s and below in large halls is typical, but better suited for a much more analytical approach such as rehearsal, especially around the 1.5s mark. However, for chamber performance, a much drier acoustic is required to suit the repertoire, mimicking the drier and more upholstered interiors of late 18th-century salons and chambers. As such, the Mozart room at 1.8s is appropriate, and commensurate with rooms of the time. The volume in all rooms is significantly lower than typical halls and the T30 value is low, leading to the material build-ups of the room significantly impacting the performance of the room. The results here show that the only way a volume of 10,000m^3 could achieve a T30 of 2.2s is to have very small areas of absorption and greater areas of reflective surfaces, such as exposed concrete or heavy timber.

EDT: The nature of the tests meant that early reflections (between 20ms and 80ms) were highly pronounced and defined, as there were 11 separately defined sources in the original Max/MSP patch. This generated a usable acoustic in the tests, but when analysed, it gave a pronounced EDT that was not aligned with real-world conditions. This was one of the main drivers in further analysing the 3D model in Pachyderm to smooth out such irregularities. The resultant metrics for EDT are in line with - i.e. proportional to - their relationship with the T20 and T30 metrics, and are acceptable.

C80: The C80 value, or clarity is on the high side of the ISO 3382 standards, and in one case exceeds the standard by some margin. This is not something that would be commercially viable in a newly built concert hall, as the room will need to be able to blend the notes of a performance acceptably. However, this is a convention and not a rule. The participants commented that they enjoyed the experience and that it was pleasant and showed an improvement in the acoustic, so we cannot say that they are ‘wrong’ in going against conventions. The evolved halls in this test clearly show a bias toward a drier and clearer sound.

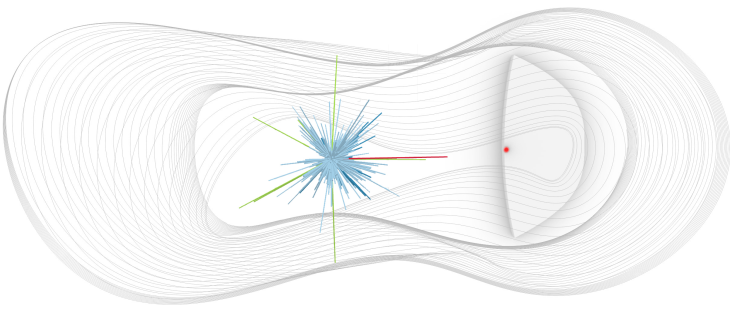


Figure 03: Beethoven Hall viewed from Top with IRIS plot showing acoustic reflection data.

4.1 Comparison with other halls

The evolved spaces compare favorably with other existing halls in use today. Whilst the system has not formed a direct replica of the Musikvereinssaal, it has generated a series of spaces that would be perfectly acceptable as commercial auditoria. The closest comparator is the Worcester Mechanics

Hall in overall volume and acoustic response. This hall itself falls below the ISO 3382 threshold yet is still a popular hall and in use in 2022. See table below for further comparison:

Standards
(center freq 500hz)
ISO 3382

ISO 3382	Rank	V	N	r_{avr}	LF	1-$iacc_e$	ITDG	T	EDT	G	G_{125} - G	C	H/W	W	Score
Criteria maximum					**0.35**			**2.2**	**2.2**	**5.4**	**3.0**	**2.0**	**1.1**	**18**	
Criteria minimum					0.10			**1.8**	**1.8**	**3.4**	**1.0**	**-2.0**	**0.8**	**32**	
Vienna Grosser Musikverinsaal	1	15000	1680	29	0,17	0,64	12	2,0	2,0	4	2	-1.0	0,9	20	100%
Berlin Konzerthaus (Shauspielhaus)	4	15000	1575	25		0,66	25	2,0	1,9	4	2	-1.0	0,9	21	100%
Tokyo Opera City, Concert Hall	6	15300	1636	30		0,66	15	2,0	1,9	4	0	-1.0	1,1	20	86%
Boston Symphony Hall	2	18750	2625	32	0,22	0,65	15	1,9	1,9	2	0	0.0	0,8	23	71%
Amsterdam Concertgebouw	5	18780	2037	29	0,18	0,55	21	2,0	1,9	3	1	-1.0	0,6	28	71%
Baltimore, Meyerhoff Symphony Hall	20	21530	2467	34				2,0	2,0	2	2	-1.0	0,6	29	71%
Hall 1: Beethoven		10318			0.14			2.2	2.1	1.5	0.9	-0.3	1.1	17.5	
Hall 2: Mahler		10521			0.35			1.8	1.8	3.0	0.0	1.0	1.3	17.5	
Hall 3: Mozart		10182			0.31			1.7	1.7	1.7	2.2	3.2	1.2	17.5	
Zurich Grosser Tonhalsaal	7	11400	1546	28		0,64	14	2,1	2,0	5	3	-1	0,7	20	57%
Lenox, MA, Seiji Ozawa Hall	13	11610	1180	28			23	1,7	1,6	4	2	0	0,7	21	57%
Brussels, Palais des Beaux-Arts	19	12520	2150	29				1,6	1,6	3	2	0	1,3	23	43%
Gothenburg Concert House	30	11900	1286	29		0,55		1,6	1,6	3	2	0	0,5	25	43%
Copenhagen Radiohuset Studio 1	43	11900	1081	28	0,16		29	1,5	1,5	3	1	1	0,5	34	14%
Worchester Mechanics Hall		10760	1343	22				1,6	1,5	4	2	1	0,5	25	57%
Bayeruth Festspielhaus		10308	1800	28				1,7	1,6	4	0	0	0,4	33	29%
Berlin Kammermusiksaal (Philharmonie)		11000	1138	29				1,8	1,8	5	1	0	0,2	49	29%

Red = Over the Criteria
Blue = Under the Criteria

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Table1: Acoustic comparisons based on ISO 3382 Standards

4.2 Discussion

This test was originally set up to develop novel approaches to acoustic space, listening habits and room shape. Limiting the search space to controlled vectors in distance -5/+10 generated little visual change in room shape. All three halls for Beethoven, Mahler and Mozart are spatially and diagrammatically very similar, and all are approximately 10,000m^3, bringing them in line with some of the world's smallest venues, the most similar being the Worcester Mechanics Hall in the United States. However, the major changes were reflected in the acoustic performance of the rooms, especially in the materiality of the space. Whilst the results did not develop any clear new directions in shape, they show a clear link between the musical preferences of the listener reflected in the acoustic conditions generated.

Other evolved approaches to music room design use multiple reviewer positions to ensure an even blend of correct metrics across the room, representing an even spread of optimum or preferable acoustic conditions in as many seats as possible. Using data-based systems such as typical genetic algorithms, this can be achieved over multiple iterations and conditions. Thus, a room optima can be achieved over a significant number of iterations. Due to issues of user fatigue, it would be impossible to develop a full room for a single user. Multiple seat positions would have to be tested and there is no guarantee that a listener would still find a redemptive quality in any music over multiple listens. If more participants were available, it would be possible to test different seat positions. It would be wise in such situations to ensure that each set of listeners was from the same demographic, or there could be significant variation in taste across the room.

As the participants were largely young and predominantly liked modern popular music with a high degree of clarity, their tastes were reflected in the output, with C80 values being higher than normal standards, way over in some cases. The participants clearly managed to generate a sense of consensus within the group that is shown by the raised clarity values over the standards. This is a definition of the success of the tests: irrespective of the test outcomes, and where the acoustic metrics sit in the context of the ISO standards and existing halls, it is possible for a group of people to develop a consensus in an approach to sound music and space.

4.3 Conclusion

This study looked at the ability of a computational system to evaluate the psychophysiological response of a listener to music and space, then optimise it according to unconscious preference. An environment was constructed that searched and evaluated emotional responses in listeners and reacted in a way that optimised listening conditions for the individual, as well as understanding what consensus existed in a clear demographic. It was observed that a group of young listeners who may have a predilection to electronic music generated a space of high clarity and focus. This may stem from the clarity of contemporary music. C80 values were observed to be on the higher end of ISO 3382 standards, and in some cases exceeded them. Future studies will include a focus on differing demographics and more participants to cover more search space.

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