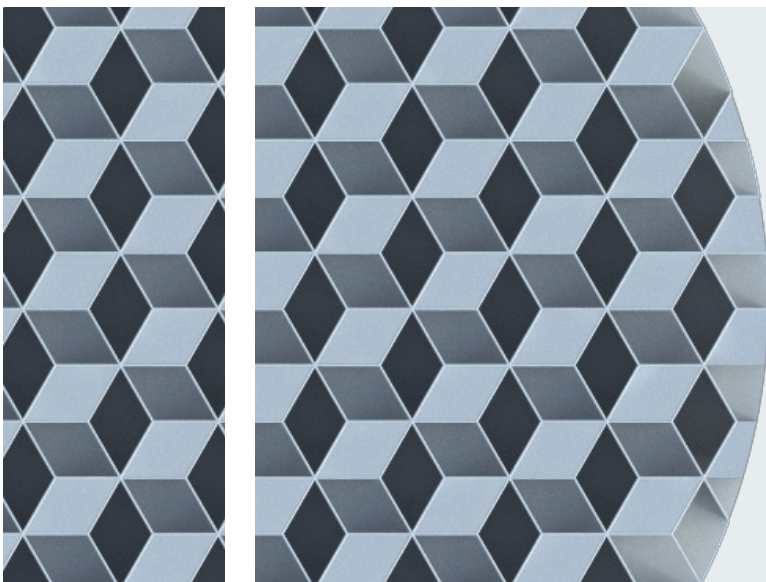
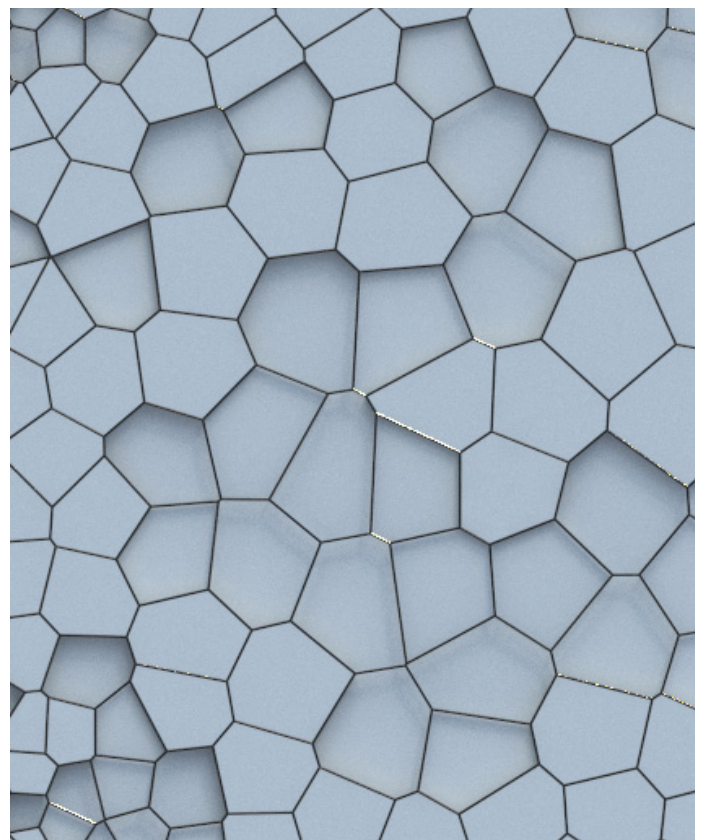
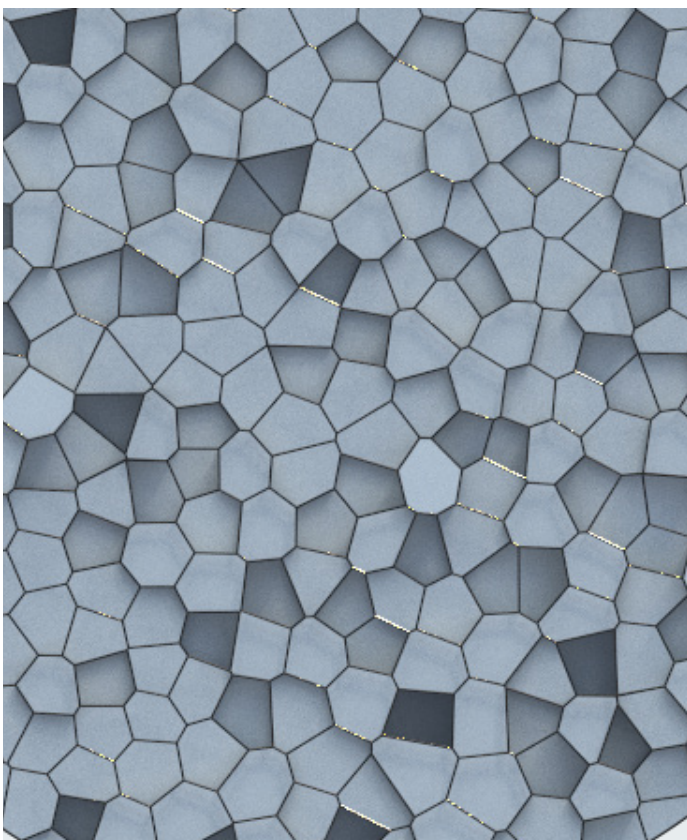
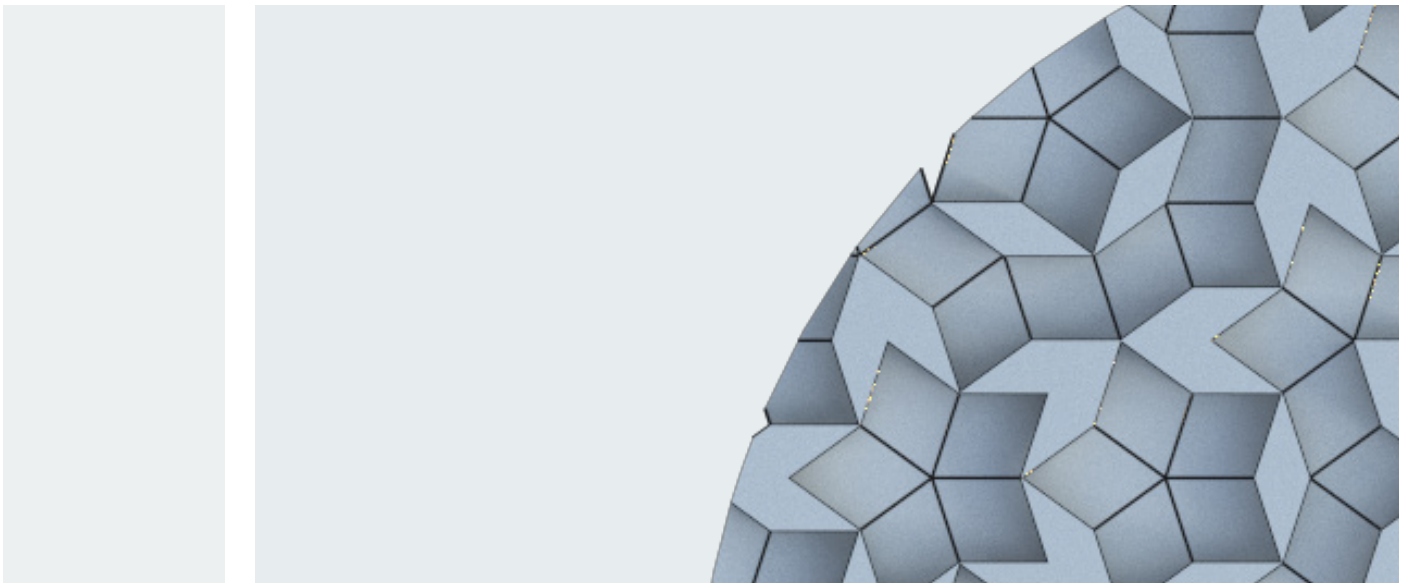




BRICKS AS SPATIAL SOUND MODULATORS

Towards tuning the geometry



[www.archdaily.com/202358/vitra-telefonplan-rosan-bosch/]

Acknowledgments

I have always been a team-player and given that the current thesis had to be an individual research project, various challenges and concerns arose. The fact that I managed to accomplish this task strengthened my self-confidence but at the same time proved my initial hypothesis: nothing can come to a successful end, unless it's a product of discussion, critical thinking and debate among different individuals.

Thus, the first deeply "Thank you!" goes to my tutors Dr. Michela Turrin and Dr. ir. Martin Tenpierik that provided me with meaningful insight into my results and allowed for a deeper understanding in order to draw valuable conclusions. Their thoughtful suggestions, critical questions and precious feedback guided the decision-making process and structured my methodology.

Next, I want to express my gratitude to Adam Foxwell from ARUP for the key-discussion we had at the initial part of my research that helped me re-structure my focus and enabled for a more holistic approach than I had originally envisioned.

My friends, both in Greece and the BT Boys & Girls for sharing our "ansia", having fun and long discussions about current concerns and future plans.

Last but never least, my Family (all included)! Without their support in all levels I would have never been introduced in a research centred design that opened a new perspective for my personal awareness as a sustainable designer.

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The current research is part of a transdisciplinary discussion on the long-lasting impact of the acoustic environment on cognitive performance, preliteracy and auditory perception for pre-school children, aiming to underly the increasing necessity to perfectly tune every-day facilities such as schools and work spaces, rather than only performance auditoriums. The main focus is placed on improving speech intelligibility, which is the task of recognizing the message from the din, by evaluating the speech-in-noise perception. The research is based on a promising hypothesis that hybrid devices should allow for low-frequency absorption and high-frequency diffusion which correspond to certain properties of vowels and consonants respectively. Given the transition to the modern aesthetics of the flat wall, compared to the inherent complexity of surface ornamentation in the past, there is a growing demand to provide acoustic solutions that allow for a higher level of complexity towards an improved acoustic environment. The effect of periodicity on a uniform scattered distribution is investigated by examining different geometrical patterns, aiming to convert traditional materials into sound controlling devices. Customized and mass-produced versions are developed, arguing whether a lower level of complexity can meet the same goals if certain low-level rules with high level of self-organization are applied, introducing the idea of simplicity and architectural smartness by preserving the economy of means for the end users. Last but not least, since speech transmission is related to spatial context and surface properties, both the macro-scale and micro-scale are examined.

The study envisions an open-source toolbox for designers for generating design alternatives providing a deeper understanding on how periodicity affects the acoustics of a given space. Since periodic surfaces reduce the complexity of the reflected sound field, designers are encouraged to focus on aperiodic patterns aiming for a non-repetitive sequence via the geometry articulation. Further it suggests the manipulation of certain parameters, such as period, depth-to-width ratio and well width, towards an integrated workflow to achieve an optimized acoustic design. These alternatives can then be used as input for a software similar to Pachyderm Acoustics plug-in for Grasshopper, in order to get a glimpse which of those showcase a high scattering performance within the relevant frequency range. This should for no reason substitute the necessity for a thorough acoustical study as a next step but would however, involve designers more actively in the initial process of form-finding, while gaining awareness of the impact of their design choices on the acoustic environment.

List of acoustic principles [Burry & Burry, 2012]

image shift: source localization, the sound source appears to be coming from the wrong place

timbre: the quality of sound that distinguishes it from other sounds of the same pitch and loudness (frequency dependency of parameters)

colorations: audible change in timbre, usually caused by early reflections

echo: high amplitude reflection perceived as a separate sound source

wavelength: pitch

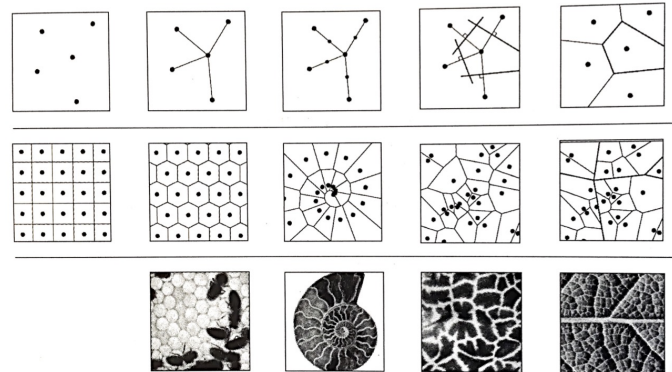
amplitude: loudness

frequency: height of tone

timing: phase

tone: harmonics

List of geometric principles [Burry & Burry, 2012]



Acoustic optimization: a qualitative process, despite the contribution of measurement and quantitative analysis

Algorithm: a specific set of instruction for carrying out a procedure that transforms input to output and usually has an end command

Aperiodic tiling: two-dimensional tile shapes that in combination tile the plane completely and cannot be mapped onto themselves by translation (Roger Penrose, Robert Berger, Donald Knuth, Raphael Robinson, Robert Ammann)

Danzer packing: three-dimensional aperiodic tiling in response to quasicrystals, experiencing long-range orientational order, but no translational symmetry, when subjected to appropriate matching rules

Finite-element analysis: uses the forces coming from each tiny cubic block that is impacted by the forces transferred from its immediate neighbours

Fractals: spatial patterns irregular or fragmented following the self-similarity concept, in that the same shapes and patterns are found at successively smaller scales, either by growing recursively or subdividing the starting shape

Sequence: an ordered list of objects, which may be infinite, in that the same term may appear multiple times in the ordering

Voronoi (Dirichlet tessellation): space is subdivided into adjacent cells, in that each point relates to a cell consisting of all the points closer to that location than to any other.



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[<http://www.ogassian.com/>]

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This research report is part of the thesis project "Acoustical blocks for improved speech intelligibility. Towards tuning the geometry" within the Master of Architecture, Urbanism and Building Sciences, track Building Technology at the Technical University of Delft. The research will be conducted in four stages, namely a literature review, a case study to evaluate the room properties for different absorption and diffusion coefficients per frequency band, a computational iterative procedure for producing surface design alternatives and a Finite Volume Method Acoustics simulation of the most promising designs. This report investigates the mechanisms for both the room properties that influence speech-in-noise perception and the surface properties of micro-geometries that affect the acoustic response of space.

The sound of space is one of the most complex engineering problems. In acoustic design, each decision affects the way in which signals are produced by people and has an impact on sound by transforming the signal. Acoustic performance is influenced by speech transmission which is strongly related to the interference of the building environment, the spatial context and the surface properties (Reinhardt et al., 2016). Speech-in-noise perception relies on the talker's visual and auditory experience and depends on cognitive systems such as attention and memory, linguistic and pragmatic performance considering both information and context, and sensory processes involving encoding of the speech stream (Thompson et al., 2016).

Having said that, one of the biggest challenges for acoustic design is to account for speech intelligibility in everyday facilities such as schools or offices. In those spaces the treatment involves both absorbers and diffusers for creating a sound environment. A balance can be reached with absorbers being used to adjust the level and reduce the reverberation time, and diffusers being used to control early reflections, avoid sound focusing as well as flutter echoes, while preserving sound energy. Though surface absorption is investigated for more than 100 years, only in recent decades research was focused on the role of scattering (diffusively reflective) surfaces. Moreover, most common absorber technologies are susceptible to dust contamination since they involve fibrous materials and to damages caused by the children's activities. Consequently, a hard hybrid surface of diffusion and fibreless absorption is proposed instead in order to offer a combination of improved acoustical performance with a more robust treatment. (Cox & D'Antonio, 2016).

Nowadays the problematic of school noise control has been shifted from classrooms and universities rooms towards preschools and innovative learning environments (ILE) due to their open-plan arrangement. Since the auditory mapping incidents that are most crucial occur before children have obtained adult-like speech recognition, successful auditory processing during the learning process for that age group has long-lasting impact on cognitive performance and auditory perception as well as for development of communication skills. Moreover, the struggle for speech recognition under unfavourable listening conditions has been linked to a rise of learning problems (White-Schwoch, Davies, et al., 2015). During early childhood (3-5-year-old) children start developing a diverse lexicon while trying to understand the soundscape by creating exact representations of speech signals. Since language is not yet crystallized, critical listening in noisy environments is challenging, due to the convergence of auditory and cognitive aspects that are responsible for speech identification and the heterogenous development of central auditory processing (White-Schwoch, Davies, et al., 2015). Distractors, specifically those consisting of speech, can interfere with their ability for comprehension and learning of a language (Newman, Morini, Ahsan, & Kidd, 2015). Absorbing the teacher's input despite the noise is a complicated task that involves simultaneous synthesis of attention, memory, sensory perception and linguistic cognition, all of which remain under

development in pre-schoolers (Thompson, Woodruff Carr, White-Schwoch, Otto-Meyer, & Kraus, 2017).

The aim is to identify possible aspects that lead young children to an inferior listening performance and create tailored interventions for enhancing auditory processing, after investigating the biological and cognitive mechanisms for improved speech-in-noise perception. A noise control environment can be achieved by modulating reverberation and blending the direct and early reflected sound signal accounting for enhanced clarity and speech intelligibility. A complementary list of acoustic requirements affecting the specific age-group are important to be addressed. The current report contributes to the problematic of the acoustic properties of different surface geometries that aim to alter the coloration of sound, while being applicable to the principles of digital fabrication.



2.1 Problem Statement

More and more schools are turned into innovative learning environments (ILEs), posing great challenges for ensuring a sound acoustic quality. The ILEs open-plan arrangement often leads to high noise levels, that increase stress and reduce concentration, whereby there is a tendency for people to raise their voices, known as the Lombard Effect (Tiesler, Machner, & Brokmann, 2015). The biggest problem is found to be speech-in-noise perception, mostly caused by the children's voices and activities and less by walking sounds. Since this skill improves with development, preschool children as well as those facing learning difficulties are recognized as the critical group for this design thesis (Daniels, Freemantle, & Patel, 2014). Early interventions are important in order to avoid rise of learning and preliteracy problems. To understand how speech transmits information its fundamental properties need to be analysed. Speech power comes from low frequency vowels (125-500Hz), whereas speech intelligibility is given by high frequency consonants (2000-6000HZ) (D'Antonio, 2013). Considering the way brain processes speech in such an early age it is important to note that children listen to a broadband or to all frequencies simultaneously. High frequency phonemes are stored into the left hemisphere, which already shows adult-like development in speech-in-noise perception, whereas low frequencies syllables are stored to the right still immature hemisphere (Thompson et al., 2016). Several studies proved that the response quality for these high frequency acoustically dynamic speech cues is degraded by noise (White-Schwoch, Davies, et al., 2015). These high frequency consonants need thus to be strengthened by introducing diffuse reflection, complementary to an absorption treatment for the lower frequencies. The acoustical treatment for improved speech intelligibility that is currently implemented in schools is mostly focused on absorption techniques given by porous materials. Additionally, most materials used start absorbing well from 250 to 500 Hz onwards excluding the 125 Hz octave band frequencies, which are of equal importance. Nowadays, there is a growing need for robust acoustic surfaces in the school environment, which the current porous absorbers fail to fulfil. This combined with the need for a balanced ratio of absorption and diffusion to account for improved speech-to-noise perception justifies the emergence of hybrid surfaces (Cox & D'Antonio, 2016). The flexibility important for an open-plan environment combined with the need for both visual openness and acoustical privacy requires the development of light-transmitting and acoustically closed enclosures dedicated for communication and play based learning activities (Vugts, Oorschot-Slaat, Brokmann, & Campbell, 2017).

2.2 Research Questions

Research Question

How can different periodicity patterns applied on fibreless surfaces provide a toolbox for designers that aim for a balanced ratio of speech intelligibility and speech privacy in an ILE school by allowing low-frequency absorption and high-frequency diffusion?

Sub questions

- 1| Which properties of room acoustics are affected when modifying fractal partitions in an open-plan environment?
- 2| What are the proportions of absorption and diffusion that serve to control loudness associated with background noise, while improving the hub's signal-to-noise ratio and the surrounding privacy in a typical absorptive scenario?
- 3| Which geometric properties are associated with low frequency sound absorption and which with high frequency diffusion?
- 4| Which factors influence high frequency scattering for different surface patterns considering both mass-produced and customized options?
- 5| What system could allow for a sustainable assembly and disassembly process while adapting to the ever-changing needs of a preschool population?

2.3 Research Objectives

The aim of this thesis is the evaluation of different hybrid surface topologies that combine low frequency absorption and high frequency diffusion for improved speech intelligibility and privacy in open-plan preschool environments. Geometrical properties already associated with absorption and diffusion will be analysed and principles based on aperiodicity will be further investigated in relation to their acoustical properties. The most common diffusers are based on the design of Schroeder and fall in the category of Quadratic Residue Diffuser (QRD). However, these devices do not completely disperse sound to all directions while being blamed for audible coloration in close distances. Though during the last decade refined proposals for Schroeder's Diffusers using optimization algorithms, proved that following proper design principles and applying all the current knowledge results in high quality sound, current state-of-the-art prefers custom design and hybrid acoustical surfaces. This is achieved through the use of numerical optimization to allow the surface shape to meet both acoustic and visual requirements (Cox & D'Antonio, 2016). However, customization is not always a preferable option since it involves a raised cost for both clients and end users. Instead, mass production embracing the design freedom of the digital fabrication can be considered. In that sense, further investigation of geometrical principles that carry acoustical properties can provide a toolbox for designers to manage different shapes in regard to acoustic design and budget requirements in particular projects. The aim of this thesis is not to come up with a final optimized design, but to test radically different typologies and sequences, while subdividing the open-plan school space in clearly defined activity zones. The block module system ensures the required flexibility of an innovative learning environment while at the same time accounts for a sustainable assembly and disassembly process. The proposed materials will be carefully chosen depending on their sustainability properties while considering their effect on the indoor air-quality with the ambition to turn a variety of conventional materials into sound controlling devices through geometry (Barrett, Zhang, Davies, & Barrett, 2015).

2.4 Methodology

The initial departure point of this thesis is regarded as research for design, including activities of observation, literature review and analysis from gathering and interpreting scientific knowledge to learning specific information about acoustical principles, identifying the factors that support speech-in-noise perception and exploring the critical groups for which the design will be made. Furthermore, the geometrical properties that are associated with devices that are already tested for low frequency absorption and high frequency dispersion are identified and illustrated with examples of already existing case studies. Middle-level knowledge can thus be gained from examples concerning the background and the current research on hybrid surfaces, forming an annotated portfolio that leads to their classification. At this stage the acoustic properties should be clearly defined. Open-plan schools should aim for (Vugts et al., 2017):

Intelligibility $STI > 0.6$ (hub)
 Privacy $STI < 0.2$ (between domains)
 Mid frequency reverberation time $T_{mf} < 0.6s$
 Spatial Decay $D_{2,S} > 7 \text{ dB/dd}$
 Signal to Noise ratio $SNR > 15 \text{ dB}$

The second part discusses the impact of different absorption and diffusion surface properties for T_{30} , STI and U_{50} measures. Since no previous literature study is available concerning the percentages of absorption and diffusion per frequency band that could improve speech intelligibility without compromising speech privacy, an elaborative acoustic study of a typical classroom with an absorptive ceiling is conducted prior evaluating surface treatment alternatives. Inevitably this led to the generation of knowledge, answering questions that have not been part of the initial problem. What is important is that the insights during this process were fed back into the literature review strengthening the theory, while reflecting, measuring, discussing and analysing the results.

The third part involves research through design focused on gaining digital insight of the complexity between geometry and acoustical properties, framing and reframing it, while developing design alternatives that address it. The aim was to recognize typologies of geometries that were promising for improving speech intelligibility and ensuring speech privacy by developing design artefacts that play a central role in the knowledge-generating process. The focus was placed mostly on changing parameters for high frequency diffusion since this the most questionable due to the effect of periodicity. At this stage "premature optimization" was avoided.

The fourth part involved generating and testing the various surface patterns through a stream of parametric modelling and a series of simulations in order to derive statistical data on their acoustic properties and deduce design options. An agreement was reached for a series of design alternatives associated with the equivalent coefficients, while investigating the effect of periodicity. The principles and theoretical notions were further illustrated with result data and diagrams. Last but not least, a combined design proposal was achieved, followed by evaluation of the research procedure.

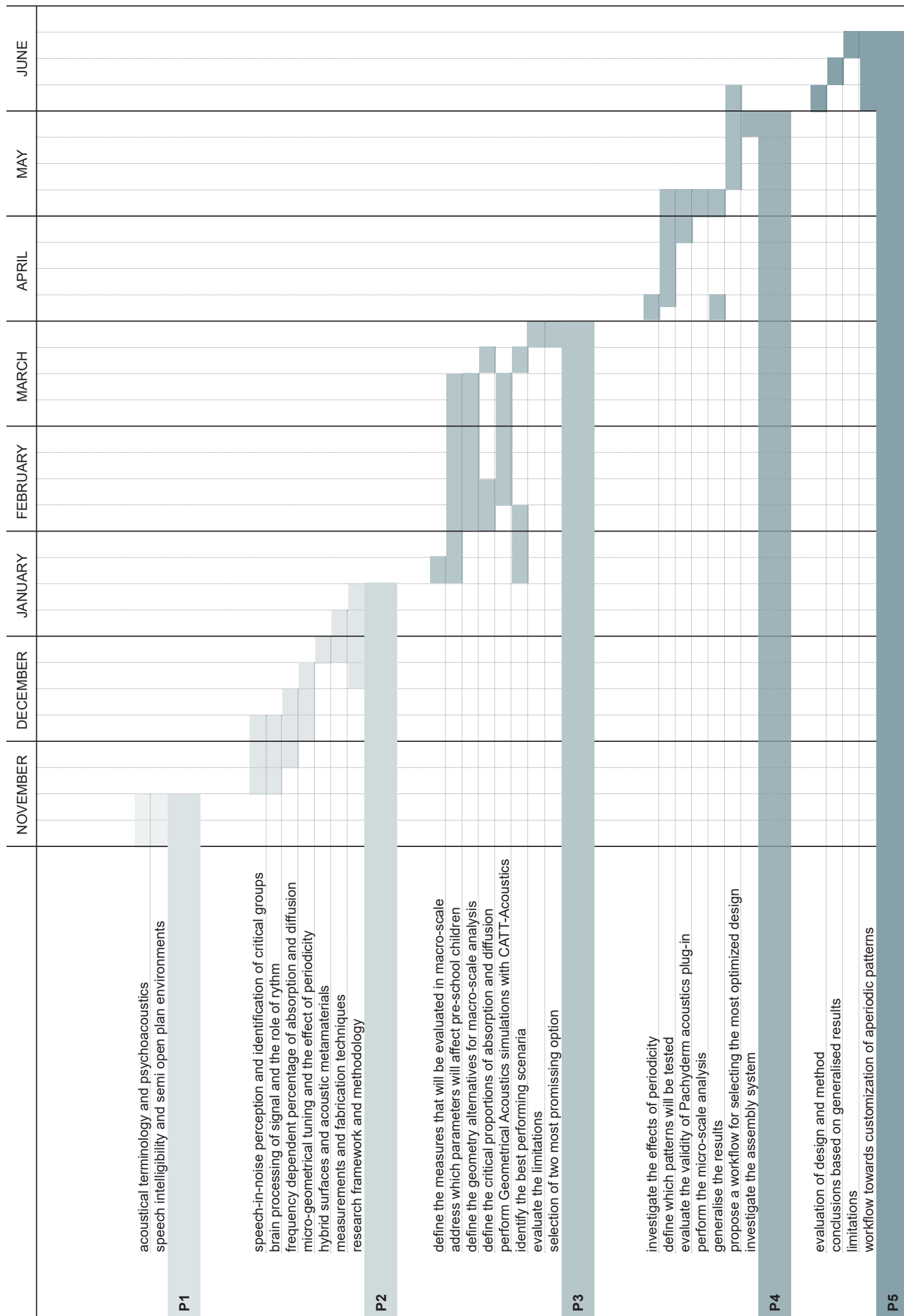
Mostly, this thesis is a "design-inclusive research", where actions not only aim at achieving a local improvement in a single product or situation but also serve to discover, exemplify, clarify and promote new workflows, while arguing upon recent findings on periodicity, scattering and acoustic performance.

2.5 Relevance

In classical architecture, typologies such as columns, statuary, coffered ceilings or relief ornamentation, provided complexity that served structural, aesthetic and acoustic purposes. The evolvement of architecture guided by the International Style lead to simpler rectangular forms, which altered the acoustics. Today's challenge lies in developing forms that serve contemporary architecture acoustically and visually (Cox & D'Antonio, 2016). Designing and realizing design alternatives that meet acoustic criteria can be nowadays possible due to the confluence of a computational workflow with digital fabrication techniques. One of the drivers for contemporary acoustic materials is visual aesthetics and the need to provide options for both customization and mass-production. A series of hybrid acoustic block modules with a carefully designed assembly system, is thought to provide designers with the tools to customize their design based on different requirements.

The idea for this toolbox investigates acoustical properties strongly related to geometrical parameters rather than material, thereby allowing any material to be used in order to serve any custom design. Recognizing the standards that dictating acoustic alterations can enable their implementation into a design scheme following a computational workflow. Such a toolbox related with criteria that affect acoustic performance can create different options for designers. The idea lies in using this design tool to investigate mathematical principles that affect acoustic performance in order to achieve optimized geometric forms (Peters & Olesen, 2010).

The literature review was based on different sources and made use of various databases providing a synthesis from a wealth of publications concerning the topic. Different fields were investigated to cover the whole spectrum for speech-in-noise perception, involving psychoacoustics, the neurological processing of signal in noise, the effect of musical practice and the surface properties associated with acoustical properties. Though, most of the literature was selected to be up-to-date ranging from 2012 to 2018, the basis of the acoustic principles was formed by the book "Acoustics: architecture, engineering, the environment" published in 1998 in order to get a good level of understanding of the acoustical terminology that remain unchanged throughout the years. Most of the acoustical properties were based on the third revised version of "Acoustic Absorbers and Diffusers" published in 2016 as it forms a solid argumentation combining a variety of current research and testing while eliminating the outdated principles. Both a theoretical approach and case studies of acoustic treatment form the basis for supporting the arguments given during this research. Knowledge on measuring acoustical indicators for absorbers and diffusers is given by a series of scientific papers. Geometrical principles that are present in architectural applications are discussed through a series of examples found in the book "The new Mathematics of Architecture". Sustainability factors associated with the assembly system of the proposed block module are further considered.



Location: open-plan preschools

PROBLEM STATEMENT ▼

speech-in-noise perception
transdisciplinary approach

RESEARCH QUESTION ▼

How can different periodicity patterns applied on fibreless surfaces provide a toolbox for designers that aim for a balanced ratio of speech intelligibility and speech privacy in an ILE school by allowing low-frequency absorption and high-frequency diffusion?

RESEARCH OBJECTIVE ▼

convert traditional materials into sound controlling devices

▼ hybrid

absorption + diffusion

▼ periodicity

low-level rules

high-level of self-organization

WORKFLOW ▼

▼ macro-scale (where)

optimum proportions of absorption and diffusion

▼ micro-scale (how)

non-repetitive sequence for uniform dispersion

PARAMETERS ▼

▼ pattern

depth-to-length ratio

well width

period

▼ elements

finite set

EVALUATION ▼

▼ selected pattern

increase complexity of the reflected sound field

▼ properties

overall simplicity (preserve the economy of the means for the end user)



3.1 Acoustics and Psychoacoustics

Human hearing can be separated to physiological and perceptual aspects, with physiological reflecting the auditory process that is associated with acoustical incidents, while perceptual refers to the analysis of acoustic events related to the brain. The measurement of human perceptual response to sound is less predictable, and has a non-linear relationship to physical measurements. The change in the physical dimension does not correspond to the same proportional change in the perceptual dimension. For these reasons, a distinction is made between acoustics and psychoacoustics (Charles, 1998).

In order to understand the importance of direct and early reflected sound the following should be considered. When the sound's path from the source that reaches the listener is straight, both ears receive the same signal because the head is symmetrical and hence the sound travels an identical path. In the case that reflections come from the side, the signal that is perceived by each ear differs, meaning that the sound is significantly altered due to its late arrival. The brain senses that it is in a room because of the differences between the ear signals, and a feeling of being enveloped by different sounds. In that sense a diffuser's task involves the promotion of early arriving lateral reflections for spatial impression and clarity. (Cox & D'Antonio, 2016)

Previous conducted studies considering impact sound's perception, point out strong correlations between the pitch of the sounds produced reflecting upon the perceived size of objects and between the dispersion of spectral elements influencing the perceived shape of objects, whereas material perception is mostly related to the damping of spectral elements, in that the sound decay, namely the decrease of the sound energy, is given as a function of time. Though damping is associated with material identification, is not the ultimate factor for distinguishing among different materials. For material perception, effects of frequency play an important role as well, in that higher pitches are given for example to rubber and glass rather than steel or wood (Ystad, Kronland-Martinet, & Jensen, 2009). To that, psychoacoustics should not be neglected since certain materials in a space affect a person's perception of sound as previously described. The example of Iowa's new Voxman School of Music describes an attempt to disguise the "inferior" acoustic perception expected from a metal ceiling reflector that was successfully designed to reach the acoustic goals in order to overcome the effect of psychoacoustics (Figure 1).

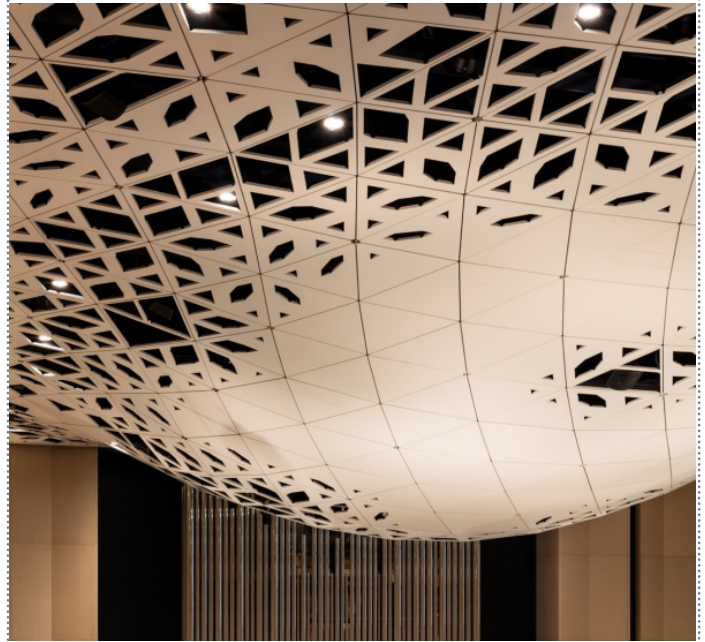


Figure 1: University of Iowa's new Voxman School of Music, LMN Architects (Photo by Tim Griffith). Since the chosen material was metal and hence quite thin, the architects called for folded up edges to give it a thicker and robust appearance. What was important was that the reflector didn't read like an industrial element.

3.2 Semi-Open Plan Preschool Environment

Currently, a shift towards innovative learning environments has been made, moving from teaching to learning, based on the four Cs approach (Communication, Collaboration, Creativity and Critical Thinking) (Figure 2). This shift though, raises concerns due to high levels of noise in such spaces leading to stress and concentration problems. This dense and interactive environment that runs at a high occupancy rate has an acoustic dynamic with children being encouraged to participate in group discussions. The factors that are thought to affect acoustic performance aim at constraining the direct spread of sound over distance eliminating its disturbing paths among different activity spaces. A balance between speech privacy and speech intelligibility is sought, while ensuring a good level of physical openness and transparency. Those spaces need to be acoustically quite closed without compromising the value of them being educationally open. Last but not least, measures to control sound levels and indoor ambient noise are important (Vugts et al., 2017). The effects of human spatial impression are to be investigated, since the perception of sound propagation in an open-plan and less private space leads to people raising their voices to compensate for sound being lost (Rahm, Ramsgaard Thomsen, & Nguyen, 2018).

Preschools usually welcome these ILE, where according to research, children's activities and voices are the primary source of noise. Room acoustics, total number of children, pedagogic methods applied, ventilation systems, all influence the level and sound characteristics. Since social interaction promotes knowledge at this age, asking for a quiet classroom is not a suitable solution. Typical values of sound pressure levels (SPL) in preschools are in the range of 75-80 dB, with children being exposed to higher SPL than personnel, namely 85 dB. Important to note is that there is a correlation between high SPL and frequency spectrum, in that high rates were reached in sound frequencies of 1000-4000 Hz, namely the typical spectrum of children's voices. Four categories of uncomfortable sound were deducted from the data related to sound typology and the source identification: threatening sounds -screaming, crying, anger-, high frequency sounds -squeaking, creaking, scratching-, background sounds -fan, radiators, ventilators- and communication sounds (Waye, 2009). Especially children with special educational needs, including delayed language performance, attention deficits, various hearing impairments, other auditory processing disorders and ESL, which are increasingly integrated into mainstream schools could be benefited from decreased background noise levels (Mealings, Demuth, Buchholz, & Dillon, 2015). Moreover, the behaviour and attitude of all students and teachers is improved when traditional classrooms are acoustically optimised for such students (Vugts et al., 2017).

The sound environment in an open plan preschool is challenging and the division into smaller parts is essential to provide flexible learning spaces aiming for an activity-based design. To that, the routes of children and their activity schedule need to be mapped for learning versus playing activities to be distinguished by dividing the space in clear zones. It is clearly beneficial to have acoustic barriers to substantially decrease the transmission of intrusive noise (Mealings et al., 2015). An overview of design requirements is given in the report 'Clever Classrooms' (Figure 3).

3.3 Speech-in-Noise Perception

There is a longitudinal relationship between cognitive and biological development and speech perception in the presence of noise. Since preschool children have an under-developed nervous system, factors that subside with development, such as reduced intrinsic attention and relative heightened internal noise lead to decreased speech-in-noise performance in comparison to older children and adults. This delayed development, which is also associated with children that face learning difficulties is the critical reason behind them performing worse than their classmates (Thompson et al., 2017). Effective learning at a school environment with numerous distractions can be enabled if children clearly perceive speech in noise. The critical listening ability requires the assessment of word-in-noise perception, neural responses to speech and cognitive skills that are related to short-term memory (STM), attention and intelligence, which is found to be enhanced by improving word-in-noise perception (Thompson et al., 2017). The words in noise task has a small cognitive and linguistic load and can be associated with detecting the signal (Thompson et al., 2016). This is further associated with processing of the fundamental frequency (F0), which is proved to be essential acoustic cue for separating the target signal from competing inputs allowing for speaker localization and analysis of the auditory scene. At age 4-5 both variables are strongly related, in that improvements and declines of the first leads to enhancements and diminishments of the second one respectively (Thompson et al., 2017).

However, the linguistic content of unwanted speech influences the degree of interference, having effects at multiple levels. During "energetic masking" (IE) neural representations found in the auditory periphery obscure the target speech, whereas "informational masking" (IM) involves higher levels of processing of target and competing sounds. Linguistically-based IM occurs due to speech sounds that are independent from sentence processing, but arise from competing activated lexical representations or from confusing the source. Considering that as language develops from infancy throughout childhood so does masking, children at the age of preschool run a greater risk than adults of being exposed to IM, especially coming from non-speech sounds caused by stimulus uncertainty. Though they have not yet fully developed the ability to analyse the linguistic signal of a masker, their language development by the age of 4 allows for an improved performance in the presence of an unintelligible time-reversed speech masker, indicating a mature linguistic interference by that age (Newman et al., 2015). Findings prove that brain processing involved in cognitive functions for speech-in-noise noise perception is associated with an exponential development during early childhood, in that already 4-5 year old children show adult-like spatial release from masking, meaning that the auditory perceptual networks are already developed to some extent (Thompson et al., 2017). This performance however, is reached under energetic masking conditions, whereas under informational masking conditions the adult-like performance is not reached until the age of 10, placing constraints on both speech perception and neurophysiological processing (White-Schwoch, Davies, et al., 2015).



Figure 2: Dovey and Fisher's learning space typologies [Soccio & Cleveland, 2015]



Naturalness:

light, temperature and air quality



Individualization:

ownership and flexibility



Stimulation:

complexity and color



Secondary factors:

Sound, Links to Nature and Connection

Figure 3: Design Principles [Barrett, Zhang, Davies, & Barrett, 2015]

3.4 Consonant and Vowels

One of the most computationally challenging task for the brain, is recognizing the message from the din, since noise and speech are transmitted as a single stream. This ability includes factors such as cognitive skills that involve memory and attention, as well as precise identification of sound sources (Kraus & White-Schwoch, 2017). Performance in a noisy environment relies upon accurate speech perception and comprehension, which depend on signal extraction and noise suppression (Thompson et al., 2016). In challenging listening scenarios consonants rather than the vowels are more susceptible to masking. Consonants consist of acoustic cues with low intensity and short duration with a changing spectral content, whereas vowels are of higher amplitude, last longer and show an almost stable spectral content (White-Schwoch, Davies, et al., 2015).

Speech signals that are processed by the brain distribute information in hierarchical time scales covering a whole spectrum from short lasting phonemes to long lasting ones like syllables or prosody. This is translated into a hemispheric lateralization in order to track acoustic cues, whereby the left hemisphere is dedicated for resting state, short, fast, high frequency (25ms; 40Hz) periods and the right for long, slow, low frequency (200ms; 5Hz). Such a temporal asymmetry is present already from the age of 3-5 years and influences the level of speech-in-noise performance. It was found that since during early childhood the right hemisphere is still immature, the low frequency components were symmetrically distributed. As a consequence, a better perception of words in noise is associated with enhanced leftward high frequency asymmetry, whereas for children with reversed or lower levels of asymmetry the perception of speech-in-noise is challenging (Thompson et al., 2016).

The indicator known as frequency following responses (FFRs) is a metric that has been recognized for its subcortical and cortical contribution as a representative of different levels of auditory processing (Thompson et al., 2017). It is a neural measure that is important for speech-in-noise perception and is associated with the synchronous firing activity of midbrain nuclei. Reduced auditory performance in listening environments dominated by reverberation with increased background noise is associated with slight asynchronies, whereas increased perception is linked with enhanced subcortical neural synchrony (White-Schwoch, Davies, et al., 2015).

Stable neural coding of speech timing is proved to be essential for language development and understanding during early childhood (Woodruff Carr, Tierney, White-Schwoch, & Kraus, 2016). In order to prove the argument that the response quality is degraded by noise a group of pre-school children was tested for perceiving a consonant-vowel syllable in both a quiet and noisy background. Though each child was associated with a specific response preserved in both situations, a decrease in performance was more intense in relation to the consonant transition rather than the vowel. Meaning that in the presence of noise the acoustically dynamic speech cues rather than the static ones are more susceptible to masking. Though this poor performance in noise is especially problematic for coding consonants, mainly stop consonants such as /d/, other cues such as the harmonic-based ones, which contribute to consonant's perception, are hardly accessible at that time as well (White-Schwoch, Davies, et al., 2015).

The language and reading skills of 3-6-year-old children are strongly related to neural coding of consonants that are degraded in noise, which can be used as indicators of their literacy capabilities, in that individual differences such as poor phase locking or low attention may lead to faulty processing, failing to build robust phonemic representations. The phonological processing is an essential skill for reading development especially for the early stages of reading acquisition. A struggle for literacy development could be

overcome through access to interventions. If struggling pre-readers identified with problems with auditory temporal processing, were provided with the necessary early interventions reading difficulties could be avoided (White-Schwoch, Woodruff Carr, et al., 2015).

3.5 Music for Speech-in-Noise Perception

Brain systems involve a highly interactive and self-reinforcing network of music, language and listening which combined with rhythmic theories of attention manage the auditory streams by guiding the attention to one stream, while weakening the others. Neurophysiological processing can be stabilized by providing early music training, which could further improve the language performance by assigning sound-to-meaning connections. Auditory-temporal awareness can be achieved by identifying which acoustic cues found in sounds disclose message in language (Kraus & White-Schwoch, 2017).

With respect to the FFR, research has proven that music training can lead to enhanced sound processing with strong brain responses to speech. While training music, the organization of sound processing enhances the neural processing of speech, proving that auditory brain processes have a high level of plasticity. Acoustic response indicates the efficiency of processing sound cues such as harmonics, pitch and timing in correlation of the hearing brain being fine-tuned, whereas innate factors are health indicators that reflect the infrastructure of sensory processing mechanisms. Fine-tuning as a principle of auditory learning can increase specific features of sound that are relevant for both music and language processing. Key cues, such as pitch, can be processed stronger by a musician rather than by a non-musician in both music and language. Music training could change listening strategies as well, considering that non-musicians identify sounds in noise mostly depending on pitch- cues, whereas musicians count on harmonic-bearing cues. Speech-in-noise perception is strongly related to harmonics for musicians due to acoustic aspects, since they have enhanced neural encoding. Harmonics by bringing their "timbral" characteristics in speech they aid to phoneme's recognition (e.g., identify between /b/ or /p/). Another advantage of music training during early development is that it can speed up the development of intrinsic sound processing (Kraus & White-Schwoch, 2017). When noise is present, harmonics are considerably degraded but since they reinforce the periodicity of a target speaker's fundamental frequency they remain important in order to extract relevant information from the auditory stream. The harmonic frequencies of speech adjust the effect of periodicity to strengthen the fundamental frequency, whereby enhancing speaker identification and localization. Eliminating F₀ by removing low frequency information can still achieve a pitch perception, whereas a loss in high-frequency encoding could lead to worse perception. (Thompson et al., 2017).

Beat synchronization is thought to play a central role for assessing developmental auditory neural function in early childhood, since it is related to the individual's degree of neural fidelity of processing dynamic stimuli such as speech. Findings suggested that language learning is associated with internal sound representations, that could be stabilized by a procedural encoding of low frequency (100 to 400Hz) spectrotemporal acoustic cues. During such a stable listening and learning practice cognitive systems such as working memory and attention will be involved boosting phonological development, while subsequently facilitating reading acquisition. A rhythm-based music training program could aid to a refinement of temporal processing and to further strengthen literacy and language performance (Woodruff Carr et al., 2016). Auditory function, especially the conveyance of phonemic cues in speech, is highly important in reading development. Since musicians driven by auditory working memory reach high levels of speech-in-noise perception, music training could support both learning and reading conditions. Three factors of auditory-neurophysiological processing that are related to literacy are: timing of the auditory system, differences of neural firing as well as processing of specific acoustic cues such as consonants (White-Schwoch, Woodruff Carr, et al., 2015).

3.6 Speech Intelligibility

Room geometry, signal-to-noise ratio, background noise level as well as reverberation time are the factors affecting speech intelligibility. Reverberation time criteria can be expressed as a function of frequency and room volume. Room volume is directly proportional to reverberation time aspects, whereas the surface area and the percentage of sound absorption are inversely proportional. Complementary to criteria associated with reverberation time, the audio signal's imaging and echoes need to be taken care of. Early sound reflections though beneficial, can affect timbre and localization phenomena if coming from nearby adjacent surfaces, resulting in listeners localizing the talker to another location than where he or she is actually standing, whereas later reverberation is known to mask speech. Therefore, all reflections can be considered a form of noise correlated to the signal (Charles, 1998).

In a classroom, the signal consists of the direct sound and the fused early reflections, while the noise consists of external intrusion, HVAC, occupant noise, and reverberation. Establishing acceptable reverberation times that vary with respect to frequency has proven to be successful, whereas a surplus of reverberation ends up blurring the sounds thereby diminishing speech intelligibility. In order to achieve lower reverberation values, options such as increasing sound-absorbing material, narrowing down the volume of the room or improving the surface area ratio, should be considered. However, it is important to note that speech intelligibility is directly related to the signal-to-noise ratio (SNR). Therefore, accounting for short reverberation times by increasing the quantity of absorption material can reduce sound levels, while leading to lower SNR values and consequently degrading speech intelligibility. However, including diffusers that preserve early reflections in the classroom's treatment can eliminate the negative impact of excessive absorption and lower speech levels. The idea is to passively increase the signal and reduce the reverberation time to achieve an SNR in excess of 15 dB and provide sufficient reverberation control (Cox & D'Antonio, 2016). At this stage, a preliminary attempt was made to match certain design requirements associated with preschool environments with acoustic principles (Figure 4).

air quality children are vulnerable to pollutants	-->	fiberless treatment robust and avoiding dust contamination
physical openness behavior can be managed more passively	-->	transparent partition educationally open / acoustically quite closed
flexibility many well-defined zones for play-based learning	-->	sound traps sound insulate the separate learning zones
visual complexity enough to stimulate the attention, but presenting a degree of order	-->	a-periodic surface: diversity or atypicality leads to geometrical complexity

Figure 4: Design qualities matched with acoustic requirements

4 ABSORPTION AND DIFFUSION



[<http://www.bldgblog.com>]

The decision between absorption or diffusion (**Figure 5**) lies on whether a reduction of reverberation time and/or sound level is desirable. Usually, a balance is preferred to achieve a lively listening environment. Absorption is needed to remove first-order strong reflections, while adjusting reverberation time and level. At the same time, in order to avoid deadening the acoustics while accounting for flutter echoes, focusing of sound, and sound coloration, scattering needs to be introduced (Reinhardt et al., 2016). Diffusers are complementary used to support intelligibility, in that they delay and temporally diffuse early reflections, since they can affect the perceived sound, changing the timbre and causing image shift, while preserving sound energy and control early reflections (Cox & D'Antonio, 2016). In order to passively improve the hub's signal-to-noise ratio, while controlling loudness associated with background noise, both ceiling and wall surfaces need to be treated.

The influence for the central hypothesis for the current research was based on a proposal for acoustic environments that replicate nature by bringing the outside in without echoes. Observing the acoustic environment of forests, where high levels of speech intelligibility were given, it is argued that this was due to the effect of high reverberation levels in the higher frequency spectrum, as opposed to the lower frequencies, especially at 125 Hz, where almost no reverberance was noticable. Such properties are unusual for classrooms but their relevance lies upon further investigation.

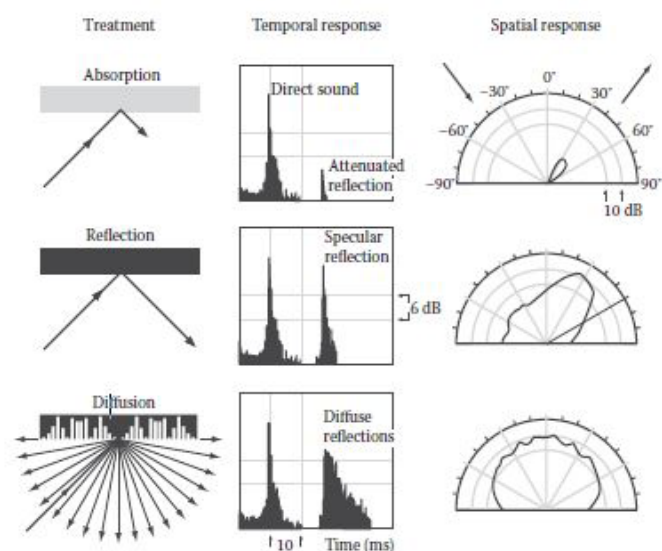


Figure 5: The temporal and spatial characteristics of absorbing, specularly reflecting, and diffusing surfaces [Cox & D'Antonio, 2016]

4.1 Low-Frequency Absorption

The first treatment that is thought to contribute to low frequency absorption is associated with porous materials. However, this type of absorption is ineffective if it is too shallow compared to wavelength, and consequently, the graph indicates that high absorption is usually achieved from 500 Hz and above, whereas little absorption is achieved for bass frequencies. Thus, the common technique to provide low-frequency modal control, is to add considerable depth to the device (Cox & D'Antonio, 2016). This indicates that porous absorbers are a preferable option in a wide range from mid- to high frequencies (Padhye & Nayak, 2016).

When savings in the occupied space are required targeting narrow low frequency bands, resonant absorbers are a better alternative that require less depth. Such absorbers are the so-called resonating diaphragm or a volume of air. They reach their highest performance if placed in high-pressure corner location or at the room's reflection points. In case of space being a constrain, resonant absorbers or hybrid typologies that constitute partly absorbing diffusers, are usually preferred for low frequency treatment. Important to note is that achieving low frequency absorption, requires good workmanship. (Cox & D'Antonio, 2016). Several types of resonators were designed and tested during the last decades with the two most popular being membrane or panel absorbers and Helmholtz absorbers.

A membrane/panel absorber is a mass-spring system. The mass is the membrane or panel made out of various materials that vibrate, whereas the spring is associated with the air trapped in the cavity (Padhye & Nayak, 2016). The design frequency of such systems is related to the membrane mass, stiffness, and cavity depth. In multipurpose spaces, low frequency absorbers in form of inflatable membrane absorbers, which can be switched on and off can provide flexibility in terms of acoustics (Adelman-Larsen, Thompson, & Gade, 2007).

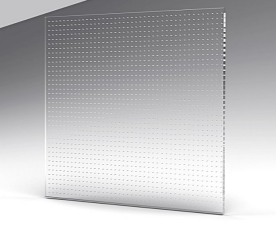
Another way of exploiting resonance is to place a perforated sheet in front of the porous absorbent to form a Helmholtz absorber. In that case the mass is given by air being plugged through a perforated sheet via the openings and the spring is associated with air confined in the cavity (Padhye & Nayak, 2016). These types of Helmholtz absorbers show an attenuated specular reflection within their absorption bandwidth, whereas at other frequencies they act as a solid flat panel by reflecting efficiently all of the incident sound. Variables such as the percentage of spacing, panel thickness, cavity depth, all can be used to design systems that absorb over a desired frequency range. The design parameters of these absorbers are unlimited due to computer numerical control(CNC) fabrication (Cox & D'Antonio, 2016). The variables to achieve low-frequency resonance include a large cavity, a long neck with a small cross-sectional area (Padhye & Nayak, 2016).

Towards minimizing the weight, microperforated (MPP) devices can provide absorption by inherent damping through high viscous losses based on the movement of air through the holes that are only a bit larger than the boundary layer. Thinner material (0.1-0.2 mm) and smaller holes that are closer together are factors that account for good speech intelligibility. They are also less susceptible to getting clogged up even in very dusty environments, probably due to the vibrating plug of air within the pores, allowing their use where fibre contamination is a problem. Materials such as acrylic or PETG with laser-catted or 3d-printed micro slits can provide transparency and could further be suspended in front of glazing or integrated into the window mullions. Combining light transmission and acoustic function into one material can provide savings on materials and cost. Towards speech intelligibility and mid- to low frequency absorption such devices could be curved, tilted or shaped to provide redirection or diffusion at high frequencies (Cox & D'Antonio, 2016).

The last option worth considering are tube resonators, known as quarter-wavelength resonators, since the maximum

absorption takes place when a quarter, or odd multiple of a quarter, of the acoustic wavelength are equal to the resonator length. A sound wave entering the tube will travel to the closed end and will be reflected back to the entrance where it arrives opposite in phase to the oncoming wave. This interference between the two waves results in attenuation.

absorption ▼	material ▼	system ▼
porous		
plate		
membran		
helmholtz		
mf		
tube resonator		

Table 4.1: Absorption						
TUBE RESONATORS	MICROPERFORATED	HELMHOLTZ	PLATE MEMBRAN	POROUS	TYPOLOGY	EXAMPLES
					REFERENCE	
[Thesis by Foteini Setaki]	http://s-plasticon.gr/	http://www.majuprojekt.nl/	[Cox & D'Antonio, 2016]	http://flexac.com/	SYSTEM	
thermoviscous losses	viscous boundary layer losses	mass-spring	mass-spring	mass-spring	REQUIRE / PROVIDE	
minimized depth	minimizing the weight, transparency	unlimited design options(cnc fabrication)	minimized depth	considerable depth	VARIABLES	
length, radius + porosity, closed or open ends	plate spacing, % of perforation, material thickness	% of open area, panel thickness, cavity	placement of the foam	depth	FREQUENCY	
	<63 [Hz]	<63 [Hz]	63-500 [Hz]	< 500[Hz]		

4.2 High-Frequency Diffusion

Sound reflections given a room boundary vary upon texture, material and shape and are constituted from both specular and diffuse parts. Specular reflections mostly arising from flat, smooth and hard surfaces and follow Lambert's law of reflection, in that the angle of incidence and reflection are equal (Charles, 1998). Common wall treatments are associated with flat panels that lead to distortion of the sound due to the effect of comb filtering or echoes. In order to realise a perfectly diffusive space, where acoustic parameters, such as reverberation, are constant and independent from the position of the receiver, diffusers can be applied in order to evenly spread the acoustic energy in both space and time (Rahm et al., 2018). If the physical surface includes variations such as relaxed topologies or rough textures, curvature and changes in contrast of the material's surface properties, scattering can be achieved (Figure 6). Even in small scale if there is a phase interference between reflections across the surface, the sound field that derives from complex reflections leads to sound being scattered (Cox & D'Antonio, 2016).

The Schroeder diffuser is the most common used typology that causes a complex reflected wave front to arise by combining both spatial and temporal dispersion. Sound propagates in and out of the wells of different depths causing the wave fronts to be reflected with various delay times. This resulting interference forms a complex pattern. The simplest phase grating diffuser based on Schroeder's design is a quadratic residue diffusor (QRD) whose different depths are determined by a quadratic residue sequence based on the prime 7, which are separated by thin dividers. For this residue, the energy reflected into each diffraction lobe direction is the same. These diffraction lobes are generated due to the periodicity of the surface. QRD needs periodicity to form even energy grating lobes, yet these lobes cause uneven scattering, since periodicity can cause audible coloration. To guarantee periodicity a design with around five periods but with not too narrow grating lobes is preferred. A large period width can account for a great amount of grating lobes, which corresponds to a lot of wells per period. (Cox & D'Antonio, 2016).

Though these devices are widely used, their performance in regard to specific requirements is questioned. Tests have proven the narrow bandwidth of a Schroeder diffuser, in that the well width poses a restriction at high frequencies, whereas the maximum depth at low frequencies works in a similar way. Consequently, practical well widths are at least 2.5 cm and usually around 5cm. To avoid specular reflections at high frequencies due to wide width of the well, modulation schemes can be used. Furthermore, there is a concern that Schroeder's design doesn't account for listeners in the near field but is focused on the far field. This could be dealt with by modulating the well depths by the locus of a parabolic mirror. Changing phases of the waves reradiated from the wells causes far field beam to be focused into the near field. Last but not least, those types of diffusers are interconnected with absorption. Usually the energy flow or strong coupling between the wells can be responsible for high absorption. 2D Schroeder diffusers absorb more sound than 1D devices and this is mainly due to higher levels of energy flowing from wells found in resonance to those out of it and since the wells account for greater bulk of the absorption by quarter-wave resonant. By sloping the bottom of the diffuser wells of a Schroeder diffuser, the absorption could be reduced. The slope broadens the resonances of the wells and so decreases the energy flow within and between well resonances. Workmanship is critical for diffusers as well, since even high standard construction can have absorption coefficients higher than expected. Ensuring that any joints within the structure are well sealed either with varnish or with paint can reduce excessive absorption. (Cox & D'Antonio, 2016).

Apart from the Schroeder diffuser several geometrical

shapes were utilized in order to contribute to diffusion. A single cylinder sometimes appears as the ideal diffuser since it is an efficient disperser of sound in one plane and consequently a single sphere can disperse in all directions. However, a single cylinder is rarely used, in that an array of several cylinders is preferred. In that case the performance depends on the combination of the response of a single cylinder and the effects of periodicity. More even scattering avoiding the cylinders being arranged periodically can be given by a modulation technique or by ensuring that the repeat distance is as large as possible for the mid-frequency performance. The high-frequency performance when the number of grating lobes is very large seems difficult if not impossible to control. Semicylinders or ellipses are good at spatial dispersion in the far field, however they are not ideal diffusers, because they lack temporal dispersion, in that the reflected wavefront in front of the ellipse is still very ordered and not spread out in time. Perceptual tests need to be conducted in that case since dispersion graphs indicate that they are almost perfect diffusers but they do not sound as such due to comb filtering (Cox & D'Antonio, 2016).

Sonic crystals are examples of diffusers that use periodic arrangements of spheres and cylinders, which, when placed in the path of sound waves, result in frequencies that are not readily transmitted. These are known as band gaps. Sonic crystals also produce acoustic iridescence, where different frequencies of sound are scattered into different directions. However, in order to form a good diffuser a random or pseudorandom arrangement of scattering elements in a multi-layered or 3D array is needed (Cox & D'Antonio, 2016).

Triangles, wedges and pyramids show a wide range of scattering performance. Depending on the geometry they vary from a good diffuser to a surface that generates specular reflections. Variables consider the angle (α) of the triangle. Usually triangles are used in an array and the reflection is determined by the steepness of the side slopes. In that case additional lobes arise due to periodicity. Modulation arranging a large number of different depth triangles in a pseudorandom number sequence, so that their frequency bands of higher specular reflection energy are different, can again help reduce periodicity lobes (Cox & D'Antonio, 2016).

Concave surfaces such as domes can lead to focusing generating strong reflected energy in certain places with energy being uneven distributed across the room, producing echoes and coloration of timbre. These effects vary depending on the positions of the sources and receivers and the radius of the arc. In order to cause dispersion, though of lower performance compared with other techniques it is important that the focus of the curved surface is well above the listeners. To that the width of the focal point as well as the peak pressure are functions of wavelength (Cox & D'Antonio, 2016).

Fractal surfaces seem to have good acoustic properties due to self-similarity or self-affinity; if magnifying a surface, a similar looking surface appears, in that the rough surfaces at different magnifications can lead to scattering of different frequency ranges. This is another approach to modulation to reduce periodicity effects that also improves the low-frequency response that lead to good scattering and a broadband performance. Various fractal diffusers based on the Schroeder typology were thought to increase the spectrum of sound being diffused by merging the properties of self-similarity found in fractals with the uniform scattering performance of Schroeder diffusers (Cox & D'Antonio, 2016).

For diffusion there is a wide selection of materials since any smooth, reflective, non-diaphragmatic material is suitable. Wood, light transmitting plastics, thermoformed plastics, glass-reinforced gypsum and expanded polystyrene are possible material resources but any material selection needs to account for sustainability issues.

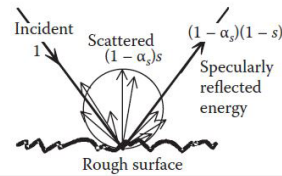


Figure 6: Definitions used for scattering coefficients. [Cox & D'Antonio, 2016]

Table 4.2: Diffusion

TYPOLGY	EXAMPLES	REFERENCE	SYSTEM	PROPERTIES	FLAWS
SCHROEDER		[Cox & D'Antonio, 2016]	spatial/temporal dispersion	uniform scattering performance	narrow bandwidth, near field performance, absorption
CYLINDERS		[Cox & D'Antonio, 2016]	spatial dispersion	ordered reflected wavefront	lack temporal dispersion
SONIC CRYSTALS		[Cox & D'Antonio, 2016]	periodic arrangement	multi-layered or 3D array	performance is not easily predictable
TRIANGLES ETC.		[Cox & D'Antonio, 2016]	pseudorandom arrangement	dependend on the steepness of side slopes	geometry dependent: vary from diffusion to specular reflection
CONCAVE		[Cox & D'Antonio, 2016]	focus above the listeners	energy uneven distributed	focusing, echoes and coloration of timbre
FRACTALS		[Cox & D'Antonio, 2016]	self-similarity, self-affinity	broadband performance, improved low-frequency response	

4.3 Hybrid Surfaces

Absorption and diffusion can be combined into a single treatment by alternating absorbing and reflecting properties. To assess the quality of a number sequence for a hybrid surface, one should account for its autocorrelation properties, which are associated with its scattering performance (Cox & D'Antonio, 2016).

The hybrid diffuser based on the Schroeder typology can provide mid-frequency absorption via resonance, as it is mounted over porous absorbent with a cavity behind. Diffusion is achieved above 3 kHz, whereas below a resonant mechanism via rectangular holes provides absorption. These holes are responsible for the peaks in absorption around 500-600 Hz. The frequency of the absorption can be varied by varying the hole size, open area, cavity depth. Another variation of this typology is given by the concrete masonry units with the addition of diffusive topology, the resonator slots provide low-frequency absorption, high frequency-absorption is achieved due to porosity and the quadratic residue topology ensures sound diffusion. Various strategies attempted to reduce the thickness of hybrid panels. Since the lengths of each well were different, well folding techniques were proposed. However, at high frequencies sound does not bend easily and the modified depth can be reduced to about half the standard Schroeder diffuser. Other approaches involved perforated sheets being placed at the front, introducing the added-mass effect that reduced the resonance frequency of the well, further affecting the depth (Jiménez, Cox, Romero-García, & Groby, 2017).

The Binary Amplitude Diffuser (BAD) is another hybrid surface that provides mid frequency absorption and high frequency diffusion. The composition consists of a porous absorber covered by a complex perforated rigid mask. A change in depth by adding vibrating mass enables the absorption of lower frequencies. For high-frequency dispersion various hole patterns can be used, in that a 2D pseudorandom binary sequence ensures a good result. An optimal binary sequence whose power spectrum is flat can be applied on the arrangement in order to achieve maximum diffusion. Alternative to the traditional periodic method, the perforated holes could be further used to form an image, by mapping the grey scale of a picture to the hole size and density (Cox & D'Antonio, 2016).

Acoustic applications based on ongoing research managed to form a novel class of materials, known as metamaterials, with properties uncommon or non-existent in nature aiming to modify and manipulate acoustic signals for specific purposes, while controlling the acoustic wave propagation in unprecedented ways (Figure 7). The idea is to achieve extraordinary acoustical characteristics with a carefully chosen arrangement of ordinary dynamic microstructural elements. The most common elements are small resonant ones -often called inclusions- such as Helmholtz resonators, resonant scatterers, and elastic membranes. Though the size of the individual elements may be small, their number and arrangement lead to a large net effect. Unlike traditional composites, acoustic metamaterials exceed known bounds on conventional material properties, in that precise control of microstructures produce materials with extraordinary combinations of properties. To understand how metamaterials might create scattering the focus is placed on sound diffusers affecting room acoustics. Usually they rely on subwavelength structure both in the individual elements geometry and in the in-between spacing- and self-interaction. Their properties are not derived from periodic microstructure, but effects of periodicity are often exploited towards simpler mathematical analysis. The research for acoustic metamaterials is more and more promising due to the confluence of additive manufacturing and advanced computation towards manipulating acoustic waves (Haberman & Guild, 2016).

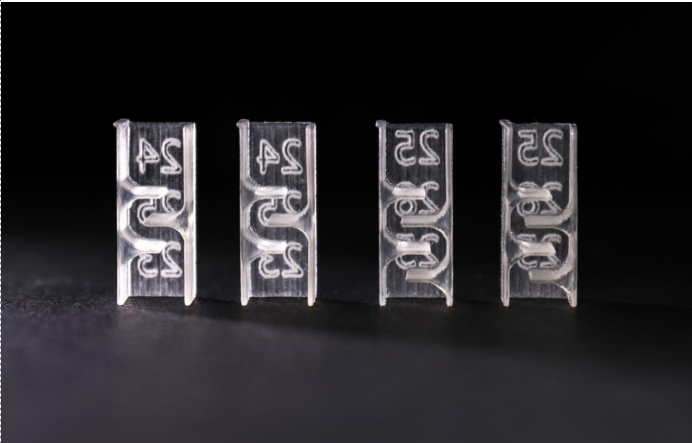
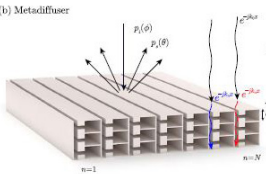
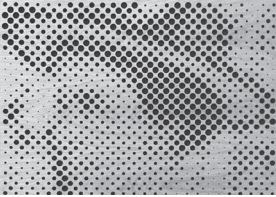


Figure 7: Acoustic meta-materials [Memoli et al., 2017]

Table 4.3: Hybrid

TYPE	EXAMPLES	SYSTEM	PROPERTIES
METAMATERIALS	 (b) Metadiffuser	[Jiménez, Cox, Romero-García, & Groby, 2017] resonant scatters	subwavelength structure both in the individual elements geometry and in the in-between spacing- and self-interaction
BAD		[Cox & D'Antonio, 2016] flat power spectrum	2D pseudorandom binary sequence: high-frequency diffusion adding mass: mid-frequency absorption
SCHROEDER		[Cox & D'Antonio, 2016] absorption via resonance	resonator slots: low-frequency absorption porosity: high-frequency diffusion absorption quadratic residue topology: diffusion

5 MACRO SCALE



Based on the properties of acoustic metamaterials the idea is to investigate which geometries could aid open plan preschool acoustic design to separate signal from competing inputs and avoid intelligible speech masking, namely prohibiting low frequency vowels from masking high frequency consonants. A promising assumption is that reflecting high frequency consonants while absorbing low frequency vowels is thought to improve speech intelligibility. Since no previous literature study is available concerning the percentages of absorption and diffusion per frequency band that could improve speech intelligibility without compromising speech privacy, an elaborate acoustic study of a typical classroom with an absorptive ceiling is conducted prior evaluating surface treatment alternatives. This step involves testing three variations of a certain geometrical topology with different coefficient combinations. The comparisons aim to improve the STI measure, account for speech privacy of the surrounding and achieve optimum reverberation time. The design aims to provide both social interaction by enabling play-based motor learning and withdrawal spaces for the individual when needed.

Though the amount of time for sound to decay by 60 dB(A) has no direct relation to geometrical shape, the fact that it is related to the surface area means that if this is not kept constant fluctuations could arise. Therefore, space filling curves and consequently space filling surfaces were thought to provide a valuable design tool due to their property of increasing their surface area despite being constrained at enclosing a certain volume (Figure 8). This property would be handy in case modulation of the RT was needed.

Motor activity

Since children spent less time outdoors, play facilities should be designed indoors. It is essential for children to be given enough space for undisturbed and free motion. The idea is to create the settings that can promote motor activity through unstructured active play. The play equipment needs to be easily manipulated and moved allowing children to recreate their play environment. Therefore, the assembly system needs to account for rotating and/or transformable partitions.

Withdrawal space

In a noisy environment preschool children undergo a transitional face from the infant coping behavior that is mostly focused on crying and seeking physical comfort to avoidance of sources of stress, in that withdrawal is sought and a need to be left alone is expressed, while at the same time they run the risk of adapting to noise due to maladaptive coping behavior (Minna et al., 2017). Moreover, though preschool is an environment for social interactions, the needs of the individual do not always comply with the preschool social demands and children should be encouraged to create and maintain a withdrawal space within the collective open school environment if they desire, allowing for freedom of the individual in regulating his/her own space (Lisa, 2017). For such small rooms the face-to-face conversation is dominated by the direct sound. Therefore, increasing speech intelligibility beyond a certain point doesn't make any difference, whereas increasing speech privacy should be considered instead (Çağdaş, Özkar, Gül, & Gürer, 2017).



Figure 8: space-filling surface [https://wewanttolearn.wordpress.com]

5.1 Acoustic Requirements

Outdoors there is a lack of parallel hard surfaces that reflect sounds, which makes the acoustic environment more preferable over indoors. Such an arrangement raises sound levels and deteriorates speech intelligibility and should therefore be avoided. In order to determine the geometric system, factors that are thought to affect the sound behaviour, such as the degree of the surface curvature and non-parallel properties, were taken into consideration. For the indoor environment it is important for the room-reflections to support high frequency consonants but not low frequency vowels. Low frequency absorption could prevent amplifying vowel sounds of active children while prohibiting them from raising their voice to be heard due to the Lombard effect. In addition to that lower frequencies, especially those at 125 Hz should have the shortest reverberation time possible, in order to approximate as much as possible, the reverberation graph of a forest, which is argued to achieve high intelligibility properties (Figure 9) (Minna et al., 2017).

Acoustic design aiming at classrooms is successful when achieving a clear, relaxed and accurate speech communication. To ensure an acceptable level of loudness for speech intelligibility a high signal-to-noise ratio is required, followed by low background noise levels to avoid any signal interference (Brady, 2015). Since noise in an open plan environment is related to meaning rather than sound pressure level, performance and health are highly influenced by the distracting effect of both intelligible speech and lack of speech privacy. Intelligible speech being associated with long-term negative effects such as stress needs to be managed, whereas privacy being a psychological factor is favoured due to the coexistence of activities that emit diverse noise. The aim would be to allow for extended reflections retaining the sound energy inside each activity zone until sound energy decayed and released into the open interior (Çağdaş et al., 2017). The proposed configurations should allow for an increased speech-in-noise ratio within the cluster designed to host conversations, while ensuring a high speech privacy level decreasing the sound transmission to the immediate surroundings (Turrin, Peters, O'Brien, Stouffs, & Dogan, 2017).

The design of passive and physical sound traps can reduce the disturbing sound paths by sound insulating the separate learning zones (Vugts et al., 2017). The parameters that influence speech attenuation of the sound path between sound source and receiver depend on the height of the sound barrier and the sound absorption coefficient. Sound propagation through the open ceiling requires the transmission paths that allow sound radiation into open-plan interior to be mapped while quantifying their contribution to speech privacy in order to achieve a high rate of spatial decay of sound from one area to another. Acoustic transmission paths affect the properties of the room and their removal could change the speech-to-noise ratio, improving speech intelligibility. Their effect is larger if considering high background noise levels (close to the sound pressure level of speech), which would subsequently mean low SNR. Reflections coming from the ceiling and sometimes the ground, as well as sound waves being diffracted over the wall surfaces seem to be the most dominant paths influencing the sound field outside the enclosure. In respect to frequencies, low frequency sound diffraction plays the most important role, whereas this effect decays at higher frequencies (Yu, Wang, Qiu, Shaid, & Wang, 2016). Subsequently, factors such as the ceiling's absorption and the cluster's height play an important role. Depending on the position of the receiver speech privacy can be enhanced via placement of absorption materials on ground and ceiling. At a close distance from the wall sound scattering can improve speech privacy, meaning that the placement of the cluster away from the wall, which is the chosen option, is proposed when speech intelligibility is favored. Further improvement of STI can be achieved if

$STI < 0.30$ 'bad' $U_{50} < -8.5$	$0.30 < STI < 0.45$ 'poor' $-8.5 < U_{50} < -3.5$	$0.45 < STI < 0.60$ 'fair' $-3.5 < U_{50} < 1$	$0.60 < STI < 0.75$ 'good' $1.5 < U_{50} < 6.5$	$STI > 0.75$ 'excellent' $6.5 < U_{50} < 11.5$
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Figure 10: U_{50} classification

considering the path of sound associated with diffraction by increasing the height of the cluster's surface, namely to 1.8m.

Measures

Speech intelligibility does not rely only on RT but can be expressed by different parameters, some are based on the signal-in-noise ratio, whereas others rely on the comparison of early-to-late sound energy C50 and D50. However, those measures lack in estimating the combined effect of room acoustics and background noise. The present study considers speech transmission index STI [-] and useful-to-detrimental sound ratios U50[-] to be complete predictors of speech intelligibility including both room acoustics and signal-to-noise ratio. Though both measures are highly correlated and assess the same room specifications, both were evaluated since the latter is argued to provide a more valid form of in situ assessment and understanding of room acoustics conditions for real speech communication in active classrooms. Since for U50 there is no standard procedure for combining information at different frequencies, the values per octave band (from 125 to 4000 Hz) are proposed to be averaged after they are frequency-weighted following the same procedure that serves to calculate the STI measure (Young-Ji, 2017). The first phase of the study includes the analysis of factors such as reverberation time (T30), Speech Transmission Index (STI) and early-arriving speech energy (U50), while accounting for frequencies relevant within the speech spectrum.

Reverberation Time (T30)

The amount of time for sound to decay by 60 dB(A) has no direct relation to geometrical shape (Rahm et al., 2018). Though for a long time, this was the most important parameter to evaluate sound's performance, it didn't account for the initial part of the decay curve, that affects speech intelligibility. RT is a compromise between speech power and clearness and shouldn't vary greatly within the frequency spectrum. In spaces with high background noise levels shorter reverberation times favor speech privacy, whereas with lower background noise levels longer reverberation times are needed. Either too short or too long reverberation time will decrease speech intelligibility (Young-Ji, 2017). Hence, it is important to prevent "overdamping" (RT<0.4s), which is associated with too low reverberation times (Nijs & Rychtáriková, 2011).

Speech Transmission Index (STI)

STI is a physical quality measuring the transmission properties of speech accounting for both intelligibility and speech privacy (Yu et al., 2016). Impulse responses when measured and after including the background noise level can give STI (Vugts et al., 2017). Any improvement needs to meet at least the minimum value of Just Noticeable Difference (JND) in order to be noticed by human perception and be of certain value, namely 0.1 (Turrin et al., 2017). More STI contributes to speech intelligibility, whereas less STI indicates speech privacy. An STI of 0.2 or below can ensure privacy, whereas occupants in positions with an STI>0.6 -this threshold needs to be further investigated based on qualitative criteria- are considered to be distracted. The classifications of the STI measures (Figure 10) are given for "normal" speakers and listeners. Though children cannot be considered as such, in the absence of values for this specific age-group the normal criteria are implemented. Last but not least, some concerns determining STI as a single parameter value are expressed. Considering the hypothesis that certain frequencies should be absorbed, whereas others should be scattered, current weight factors need to be further evaluated.

Early-Arriving Speech Energy (U50)

The early-arriving speech energy is considered as the useful sound, whereas the detrimental sound is given by the sum of the later-arriving speech energy with the ambient noise energy (Young-Ji, 2017).

Table 5.1 : Target values as given from literature				
Measures		Parameters		Comments
noise levels				
1	play area	$L_{A,eq}$ [dB(A)]	>60	currently up to 80dB(A)
2	high task concentration		45-55	
reverberation time				
1	open workspace	T_{30} [s]	0.4-0.6	though low, SPL can remain high
2	play room		0.4	
Speech intelligibility				
1	speech intelligibility	STI	0.6-1	for privacy reflections needed to retain the sound energy inside
2	speech privacy		0.2<	
Early-Arriving Speech Energy				
1	inside activity zone	U_{50}	?	certain criteria need to be reviseted (weight factors)
2	outside activity zone		?	

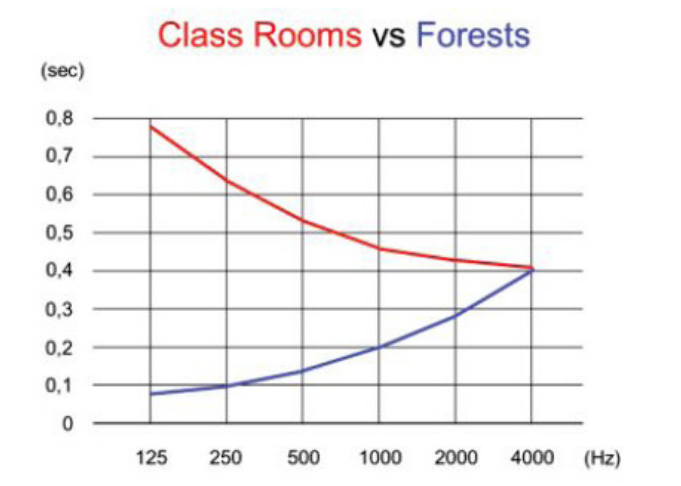


Figure 9: Common RT in Classrooms (red) and Forests (blue) (Minna et al., 2017)

5.2 GA Modelling

Since the decision was made to involve a "Geometrical Acoustics" (GA) software in the methodology aiming to define promising proportions of absorption and diffusion coefficients, limitations of the software need to be discussed. Considering that the process they follow is energy-based rather than solving the wave equation, they only offer approximations of sound propagation related to geometric and surface properties of the space. Meaning, the relation of the object and its detail size to the wavelength is not given with accuracy. In order for the GA modelling to be accurate the surface size needs to be considerably large compared to the wavelengths of sound that are evaluated. Therefore, simplicity was sought and any detailed small surfaces were avoided since they would only be valid in high frequencies. Scattering coefficients were assigned to convey the acoustic effect of the fine detailing that was lacking.

GA is implemented as a tool for "virtual" measurement, when the alternative of acoustic measurements using physical scale models is not an option. Since this was the case the first step was to establish design aims, which were later translated in numerical criteria. The selection of appropriate surface coefficients for the partitions was frequency dependent and was critical for determining the different scenarios and for ensuring the success of GA prediction. This would later also influence the size of the surface microgeometries and the detailing related to the wavelength. 100% absorption or diffusion was avoided since it was considered an implausible extreme. Auto-edge scattering was enabled for the partitions to achieve a more realistic behaviour for low-frequency scattering that excludes unrealistic specular reflections for these frequencies (Rees, 2016).

Scattering is an inherent stochastic process that leads to small run-to-run variation in the simulations. This being said, one should not forget that GA is an approximation and realistic measures of scattering are only obtained by solving the wave equation. Since a certain degree of uncertainty is inherent in GA modelling, results are further affected by the selection of source and receiver positions or the input data associated with the selection of acoustic surface properties. These were thought to be minimized by following a guide for selecting appropriate sources and receiver's distances, namely 3m. For comparison reasons four positions of omni-directional sources and receivers were chosen, two for each activity zone (play-area and classroom) as shown in Table 5.3. The model was further checked and debugged for verification reasons.

Acoustic Simulation

The evaluation of the design alternatives was aided by digital simulation tools given the complex performance of the sound wave and the human perception towards the sound. Different alternatives for the geometry of the open-plan space were modelled in Rhinoceros and validated with CATT-Acoustics software in order to provide accurate acoustic information of the room from impulse responses in different frequency bands, whereby acoustic parameters were acquired. Since many of the room acoustic parameters rely on frequency, band pass filters are applied, in that frequencies of 125 Hz, 250 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz were chosen in order to provide a detail analysis of the impulse responses in the octave band relevant for speech. The simulations performed with 16 000 number of rays, subdividing the audience surface into a grid of 0.5 m, for calculating the room's impulse response.

First, the source types and positions were defined, considering properties of directivity in order to accurately simulate a natural sound source. This was followed by the receiver type and position. As explained by Jeroen Vugts in his speech "Good Acoustics in an open plan school? How to create an optimum learning environment" teachers need to give instructions on short distance and therefore as mentioned before a maximum

distance of 3m between source and receivers was evaluated. In total four positions of sources and receivers were set for teacher to student and student to teacher for the two activity zones; playroom and classroom. Teachers were thought to speak at a raised voice, whereas students at a normal voice (Table 5.2).

For the partitions alternatives that differ from each other in absorption and in surface scattering were discussed. The height of the partitions was divided. Considering the average height of a 3-5-year-old the lower partition was set to 1m and aimed for high speech intelligibility among preschoolers, whereas the upper partition height was set to 0.8m to prohibit the teacher's direct speech being transmitted to the immediate surroundings, while accounting for transparency to obtain visual control.

Since the simulation method provides a wide range of acoustic measures, the analysis of the data for selecting the appropriate parameters in order to retrieve meaningful results is important. The aim is to ensure a successful environment for communications, while offering an acceptable level of speech privacy and a reduced distraction distance.

Background Noise

Various studies indicate that children are being exposed to high LA,eq levels especially during playtime indoors ranging from 75.7 dB to 84.0 dB. It is confirmed that children are exposed even to higher values than personnel. Measurements in preschool playrooms showed that even though the reverberation time can be low, sound pressure levels can still remain high meaning that no clear correlation between the two can be drawn. However, depending on the country's regulations the reverberation time for playrooms is set at around 0.4s for sound class A (Jansson, 2017). Further results showcase the influence of the number of children on the noise level, namely increasing their number from 7 to 14 increases the sound pressure level from 64dBA to 85dB (Jansson, 2017). In the current set-up the aim was to avoid too big groups of children, meaning that the number of children being active in the playroom was constrained to 7. Additionally, the group size per classroom was constrained to 15 children accounting for 2.5-3.75m² per child.

Acoustic quality in classrooms is strongly related to background noise levels and signal-to-noise ratios indicating that there is a growing demand to set design criteria in occupied classrooms and for active classrooms acoustic measurements. The dominant noise during school activities is produced by the children. Considering that their voices are active in the high frequencies (1KHz-4kHz) questions arise whether appropriate measures should be taken in order to reduce the background noise at those frequencies, without compromising the requirement for low frequency absorption and high frequency diffusion. First, sound power levels are considered (Table 5.4) rather than sound pressure levels since they are independent from the overall room absorption. In order to estimate the background noise for alternative / scenario, equation (1) was used after estimating the mean absorption coefficient (a) per frequency and the total geometrical area S (Nijs & Rychtáriková, 2011).

$$L_{p,noise} = L_{W,noise} + 10 \log (4/Sa) \quad (1)$$

The noise level L_p considers the sound power level L_W emitted by the source, whereas the mean absorption coefficient a and the total geometrical area S give the absorbing properties of the room.

Table 5.2: SPL normal speaker (omni-directional source)

		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
1	normal voice	46.9	57.2	59.8	53.5	48.8	43.8	38.6
2	raised voice	51	61.5	65.6	62.3	56.8	51.3	42.6

Table 5.3: SPL for overall noise level cases

Sound pressure levels (dB)		
a	general working (per 15 students)+ Speech at raised level (per person)	
b	general working (per 15 students)	
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	
d	Speech at normal level (per 6 persons)	

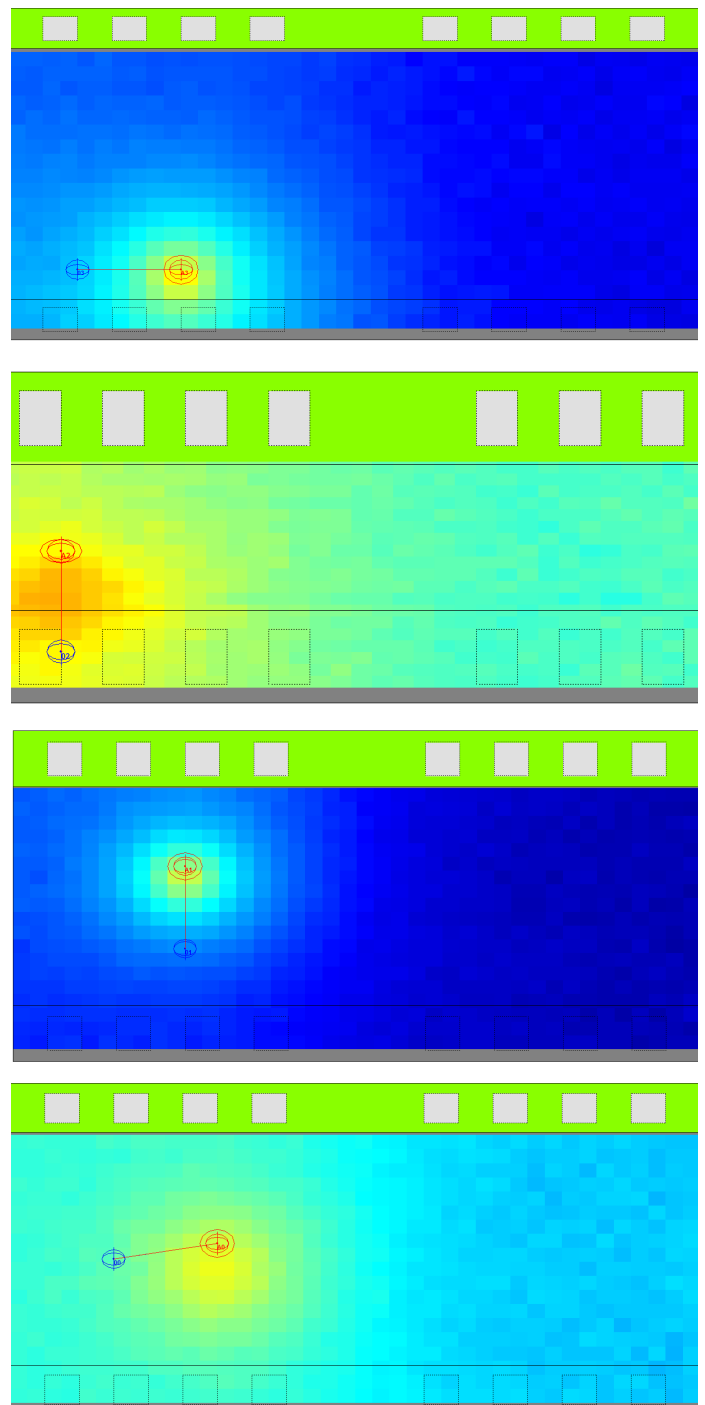
Table 5.4: SWL for overall noise level

Sound power levels (dB)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	out: student to student	64	71	75	73	65	58	51
b	out: teacher to student	62	62	62	62	57	52	47
c	in: student to student	64	74	79	74	67	60	54
d	in: teacher to student	62	72	76	70	63	57	52

5.3 Evaluating different Alternatives

Since the size of the facility indicates the quality of space, a small-scale facility of 60-75 children is proposed. Volume is ca 1800 m³ with a 'shoe box' geometry of 55x10x3.30m. The open plan layout needs to be arranged in clear spatially defined activity zones (Stankovic et al., 2015).

Though the room model consisted of large flat reflecting surfaces compared to the wavelength a small degree of scattering was still necessary. In the scenario of the empty room where most of the absorption is concentrated in one plane, namely the ceiling, Sabine calculations would be inaccurate and therefore low scattering coefficients around 10% were assigned for the room's large and flat surfaces. Moreover, standard absorption coefficients were assigned to walls/ceiling/floor and windows (Table 5.6). Since intelligibility is investigated the position and orientation of the room surfaces close to sound sources and receivers need to be accurately modeled since they will highly influence early reflections.



Serpiensky Curve

Recording the progressive iterations of a space filling curve allow us to generate what is essentially a space-filling surface. This is able to fill a three-dimensional space of any shape and size, while being a single surface. It has the unique property of keep increasing in surface area while being constrained by a certain area, which is important in relation to RT relation with surface area. The acoustic semi-enclosure, avoids being parallel to reflective walls and offers children diverse potentials for playing, while being protected from noise sources and visual distractions (Figure 11).

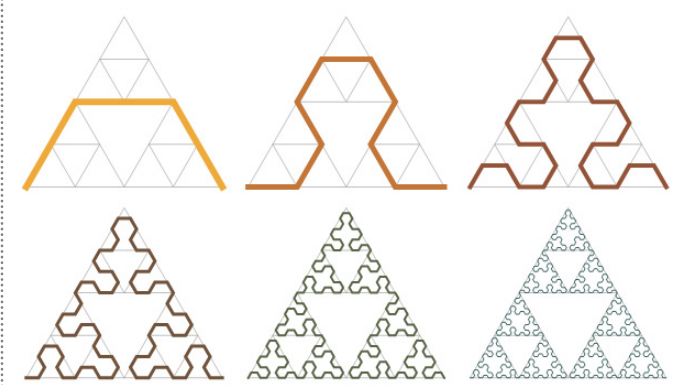


Figure 11: Serpiensky space-filling curve [https://commons.wikimedia.org]

Table 5.5: SPL for overall noise level - existing 0.0 (562m²)								
Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.6	49	56	59	53	47	40	33
b	47.6	47	47	46	42	39	34	29
c	61.6	49	59	63	54	49	42	36
d	58.5	47	57	60	50	45	39	34

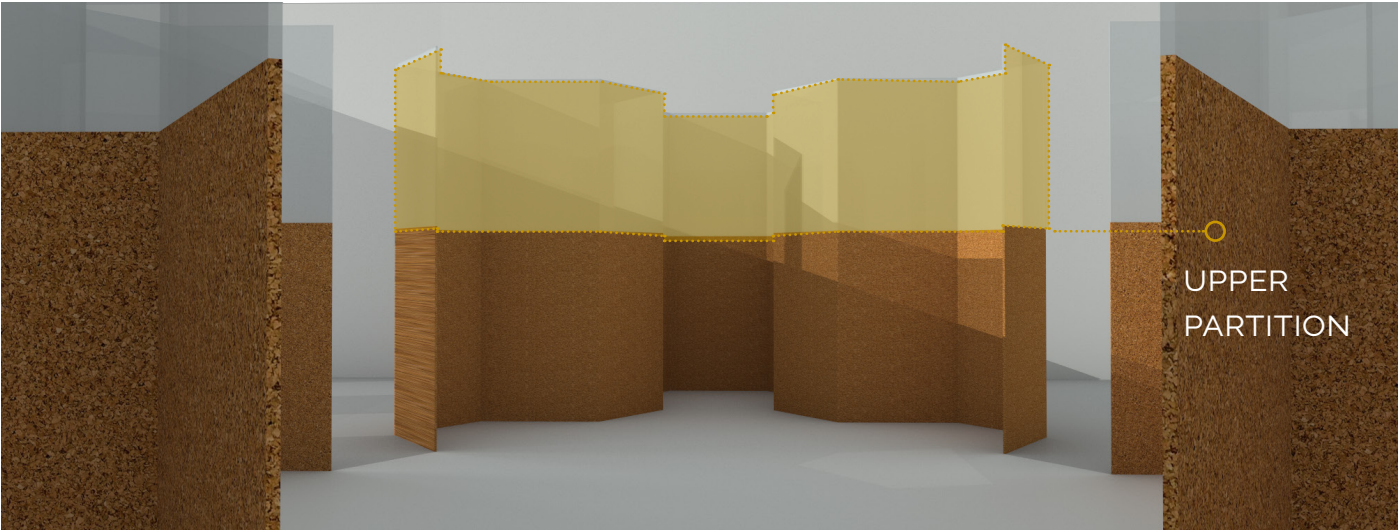
Table 5.6: absorption coefficients (a) per frequency band								
room properties		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
1	Double glazing, 2-3 mm glass, 10 mm gap	10	7	5	3	2	2	2
2	Brick wall, stuccoed with a rough finish	3	3	3	4	5	7	7
3	Perforated 27 mm gypsum board (16%), d = 4,5 mm, 300 mm from ceiling	45	55	60	90	86	75	75
4	Soft carpet, 10 mm, on concrete	9	8	21	26	27	37	37

Database by Ingolf Bork in the project of the "round robin"

1st Stage | Upper partition

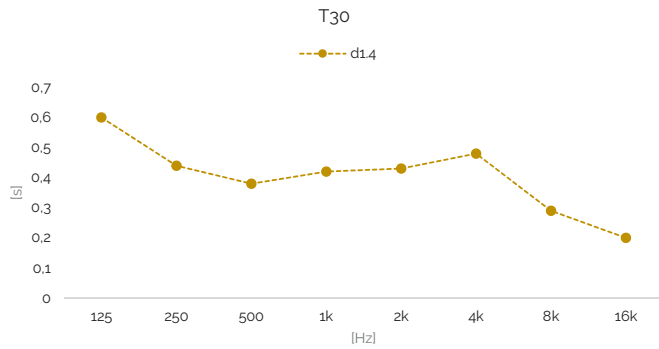
The first stage of the simulations involved testing three options for the upper partition (0.8m), which had the task of prohibiting the teacher's direct speech from being transmitted to the immediate surroundings and should account for transparency to obtain visual control.

The options of high frequency absorption (1.4), low frequency absorption (2.4) and low frequency absorption with introduced scattering (3.4) were investigated. At this stage the lower partition coefficients were kept constant and set to the balanced alternative (4) based on theory previously discussed, which aimed at 90% absorption of low frequencies and 50% diffusion of high frequencies. For comparison reasons scenario (d) with a source having a raised voice inside the playroom was used -same for the rest of the simulations-, since it was found that placing the speaker close to hybrid surfaces as the rest of the scenaria, should be avoided since early reflections can in those cases affect timbre and localization phenomena. Further the target was placed on improving the playroom's acoustics, where social interactions occur.

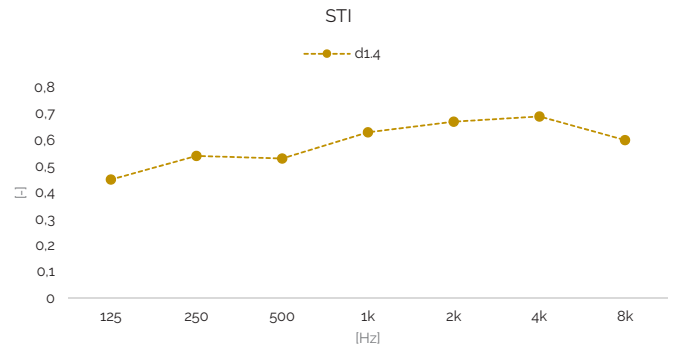


ABSORPTION COEFFICIENTS (A)							
upper partition (0.8m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
1	6	28	70	68	74	53	53
2	10	45	85	30	10	5	5
3	50	90	90	25	25	25	25
lower partition (1m)							
4	50	90	90	25	25	25	25

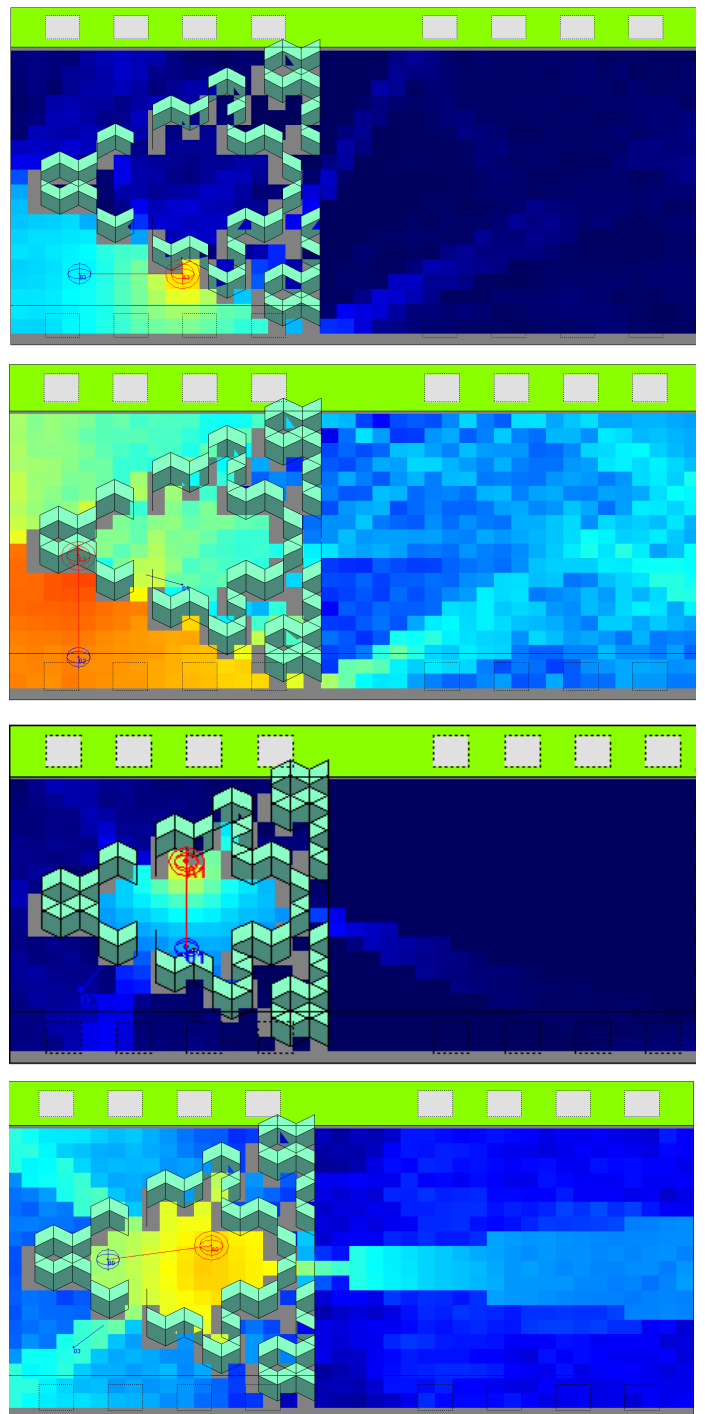
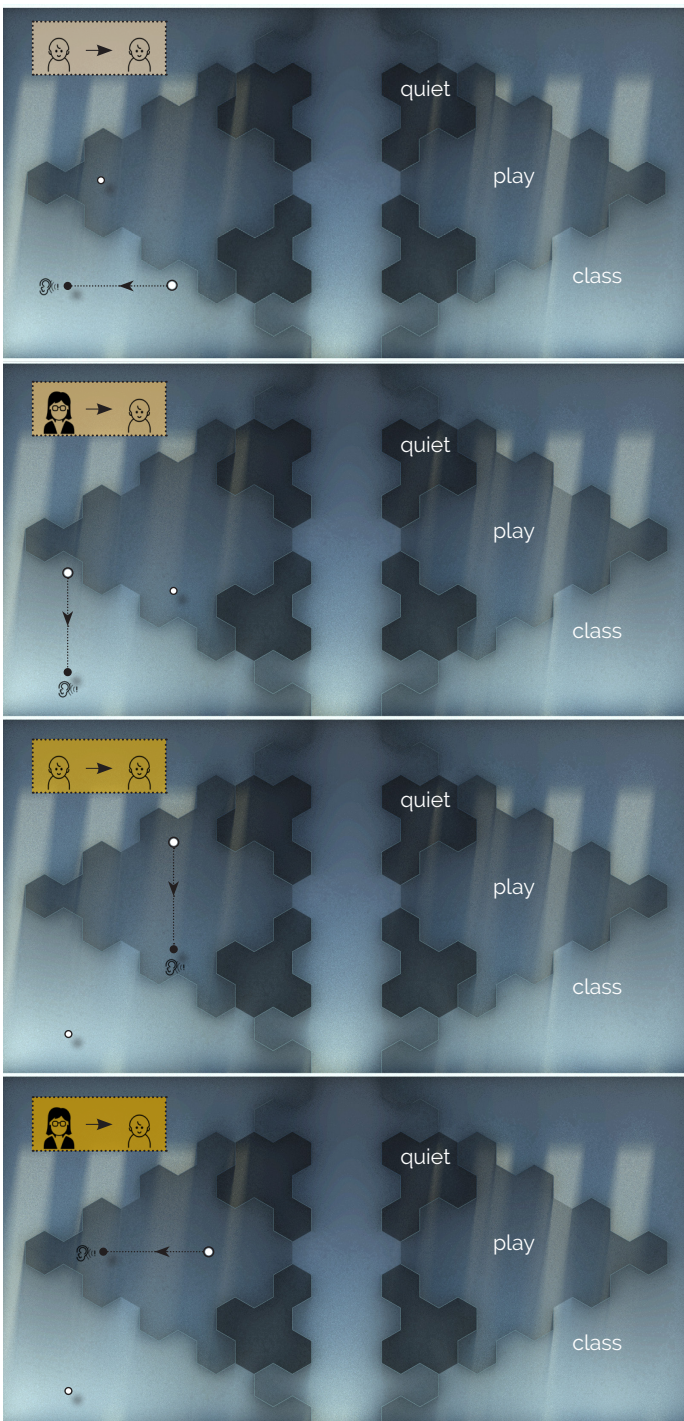
SCATTERING COEFFICIENTS (S)							
upper partition (0.8m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
1	10	10	10	10	10	10	10
2	10	10	10	10	10	10	10
3	25	25	25	50	50	50	50
lower partition (1m)							
4	25	25	25	50	50	50	50

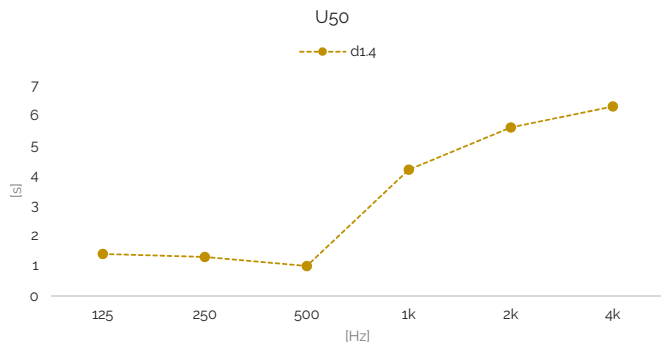


Since the reverberation time in playrooms needs to be around 0.4s the current graph is on average within those limits, though at low frequency the value increases.



The STI measure is acceptable for most of the frequencies, though lower ones seem to give an inferior performance





The U50 measure gives a relatively low performance for low frequencies with a valley at 500Hz. After this, the values are steadily improved.

Table 5.7: Results - 1st_1.4 (659m²)

Sound pressure levels dB(A)		STI		
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.44	0.01	-1.9
b	general working (per 15 students)	0.88	0.52	15.7
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.34	0.07	-6
d	Speech at normal level (per 6 persons)	0.62	0.49	4.6

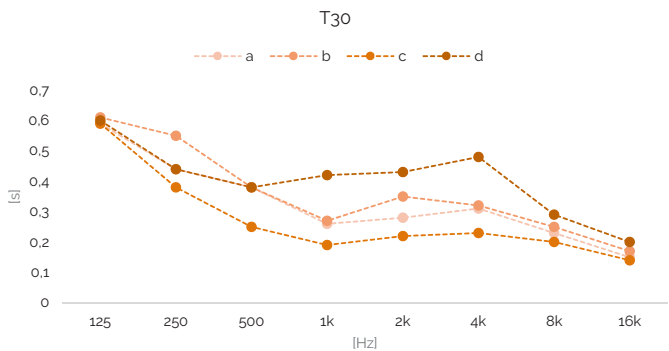


Table 5.8: SPL for overall noise level - 1st_1.4 (659m²)

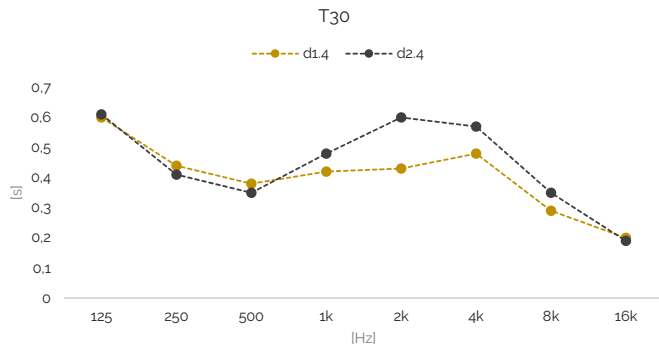
Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.3	48	54	57	55	47	40	33
b	47.5	46	45	44	44	39	34	29
c	60.8	48	57	61	56	49	42	36
d	57.5	46	55	58	52	45	39	33

Table 5.9: absorption coefficients (a) per frequency band

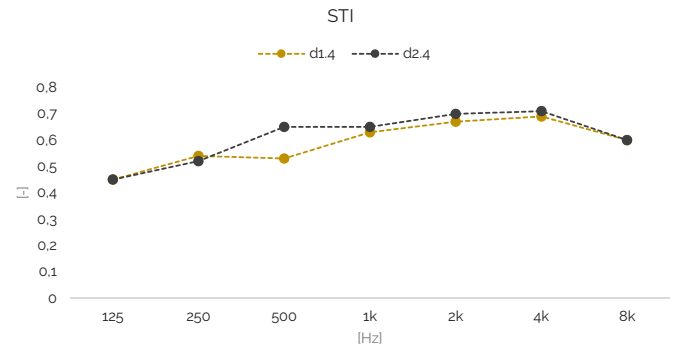
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
1	micro-perforated foil "Microsorber"	6	28	70	68	74	53	53
scenario for down partition (1m)								
		125	250	500	1k	2k	4k	8k
4	balanced	50	90	90	25	25	25	25

Table 5.10: scattering coefficients (s) per frequency band

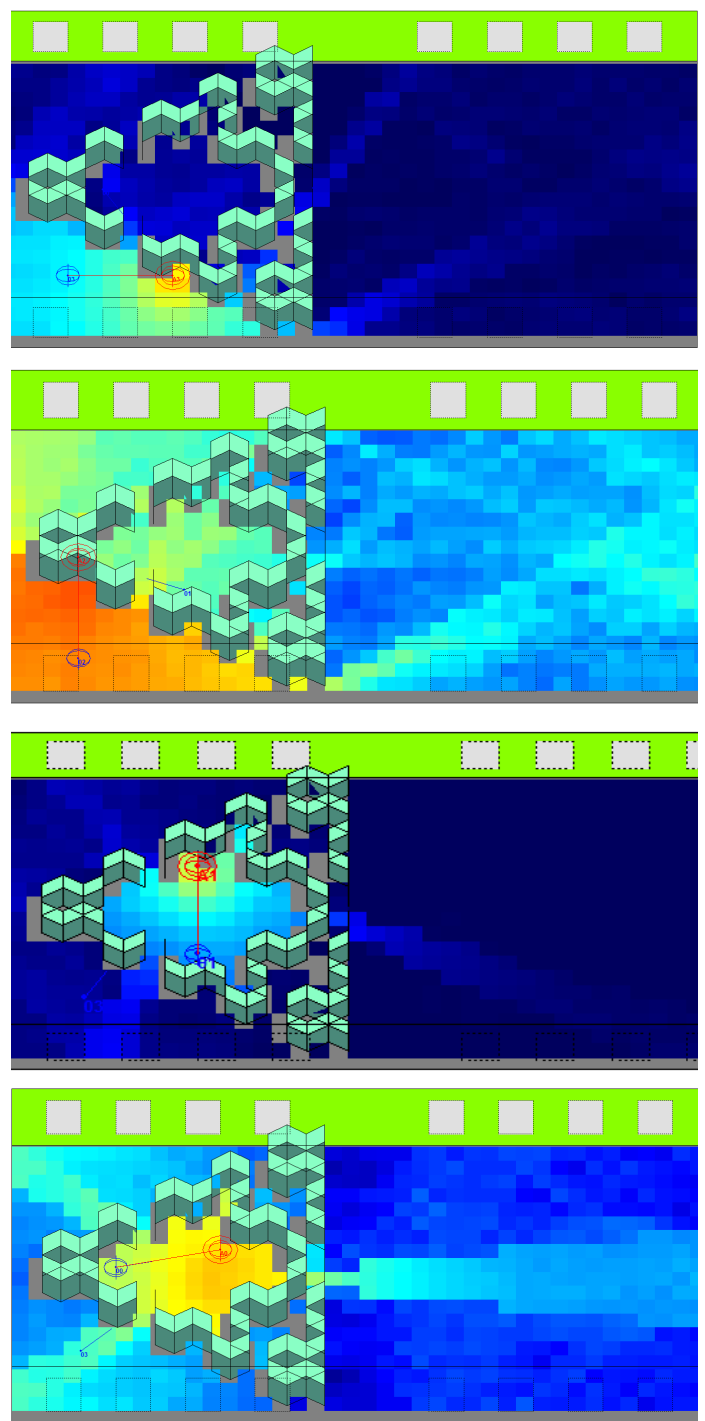
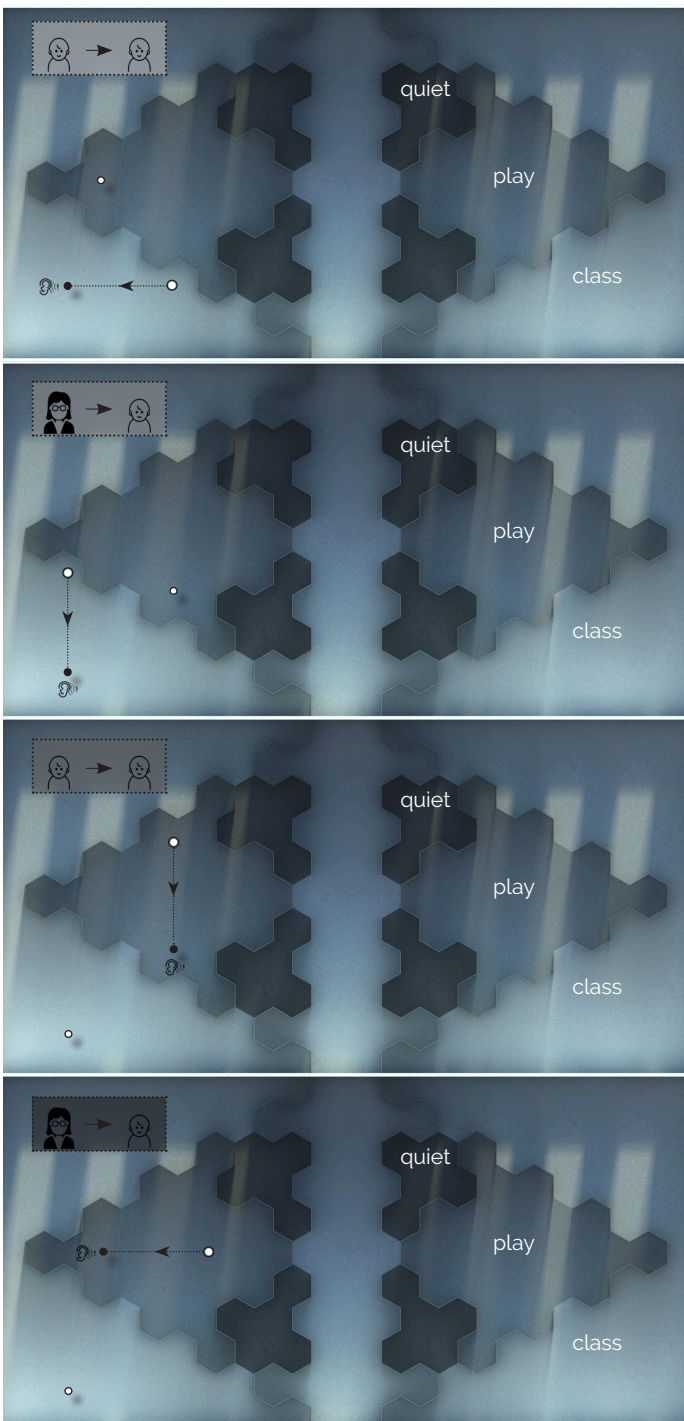
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
1	micro-perforated foil "Microsorber"	10	10	10	10	10	10	10
scenario for down partition (1m)								
		125	250	500	1k	2k	4k	8k
4	balanced	25	25	25	50	50	50	50

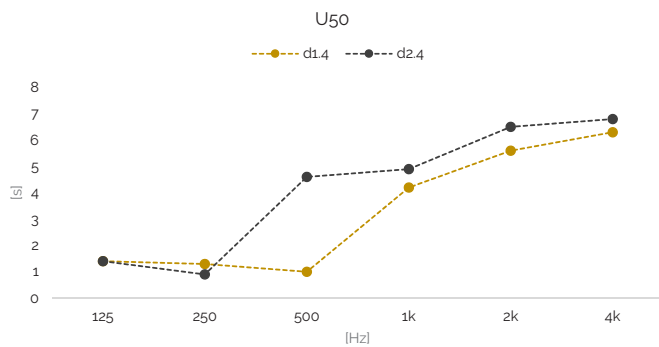


The reverberation time where childrens' voices are active (1kHz-4kHz) is increased -though within the maximum limit of 0.6s- due to decreased absorption at those frequencies.



The STI measure is improved for 500Hz, meaning that shifting the absorption design frequency of the upper partition to lower values, from 2kHz to 500Hz is effective.





There is a considerable improvement for the value of 500Hz frequency, moving the valley towards lower frequencies.

Table 5.11: Results - 1st_2.4 (659m²)

Sound pressure levels dB(A)				
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.45	0.03	-1.8
b	general working (per 15 students)	0.88	0.55	15.5
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.34	0.07	-5.7
d	Speech at normal level (per 6 persons)	0.65	0.52	6.0

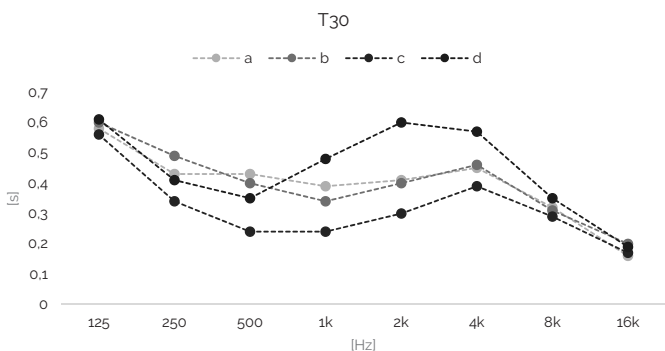


Table 5.12: SPL for overall noise level - 1st_2.4(659m²)

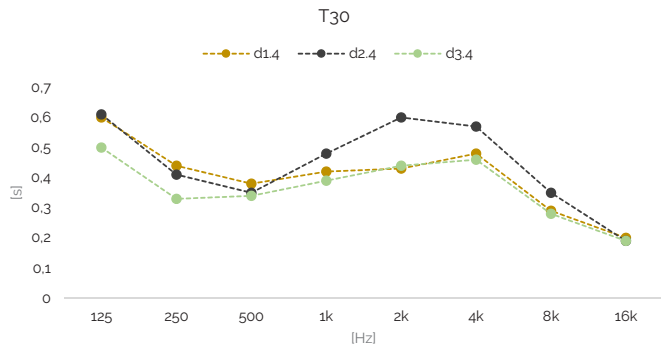
Sound pressure level dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.3	48	54	57	55	47	40	33
b	47.5	46	45	44	44	39	34	29
c	60.8	48	57	61	56	49	42	39
d	55.8	46	55	54	52	45	39	34

Table 5.13: absorption coefficients (a) per frequency band

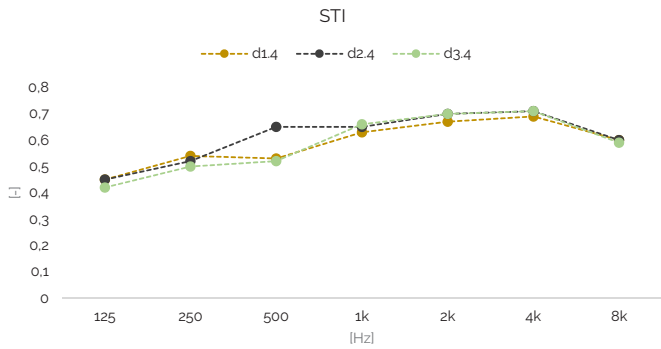
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	45	85	30	10	5	5
scenario for down partition (1m)								
4	balanced	50	90	90	25	25	25	25

Table 5.14: scattering coefficients (s) per frequency band

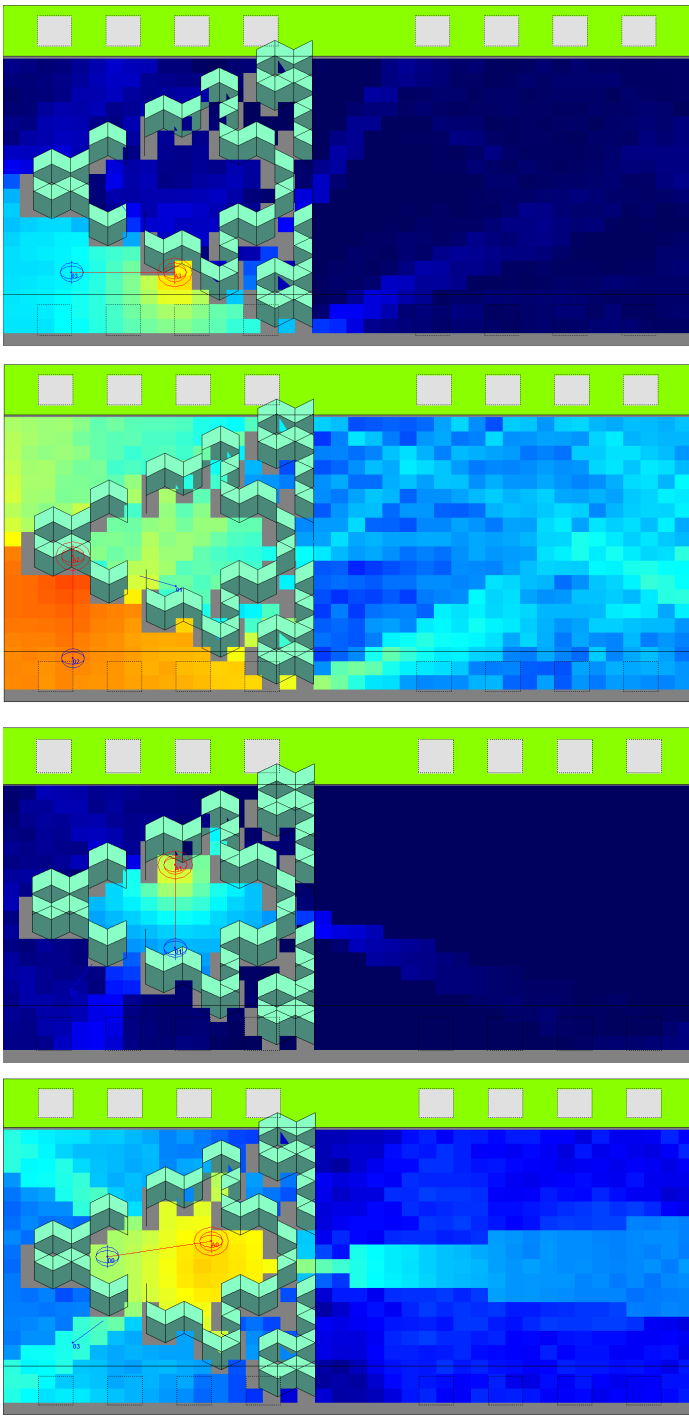
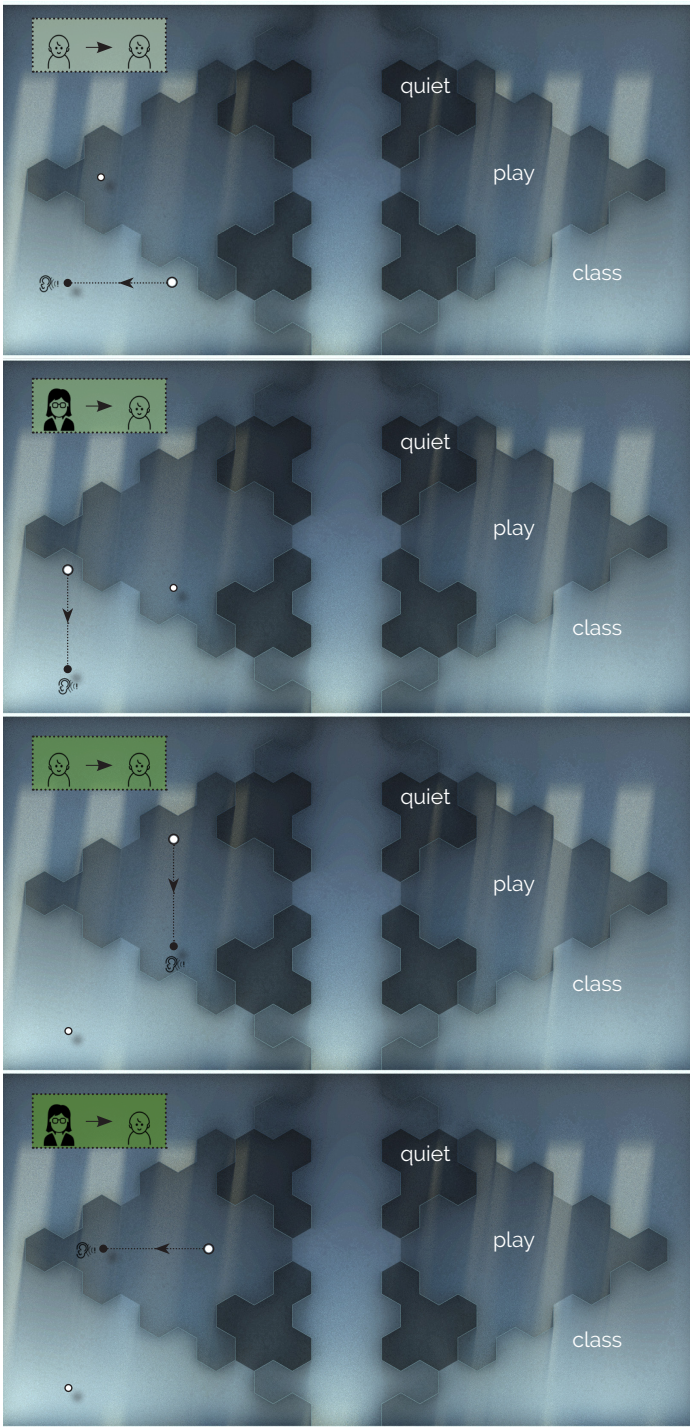
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	10	10	10	10	10	10
scenario for down partition (1m)								
4	balanced	25	25	25	50	50	50	50

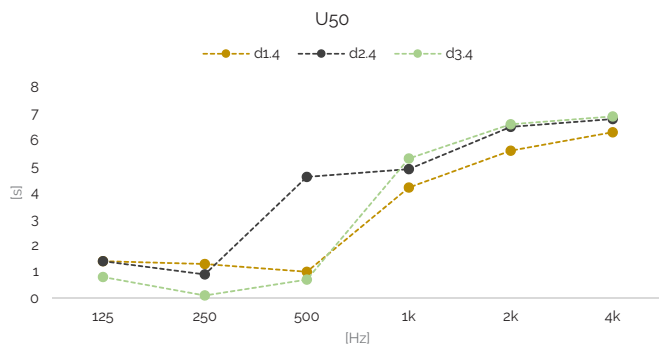


There is a considerable drop for low frequency reverberation time, since the absorption is increased. Nevertheless, overdamping is of concern due to values lower than 0.4s.



The STI measure has a similar performance to version 1.4, questioning the effect of scattering scattering alongside with shifting the absorption design frequency to lower values.





The measure shows a bad performance for values up to 500 Hz, with a valley at 250 Hz.

Table 5.15: Results - 1s_ 3.4 (659m²)

Sound pressure levels dB(A)				
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.45	0.02	-1.7
b	general working (per 15 students)	0.88	0.55	15.7
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.36	0.08	-5.6
d	Speech at normal level (per 6 persons)	0.63	0.49	5.1

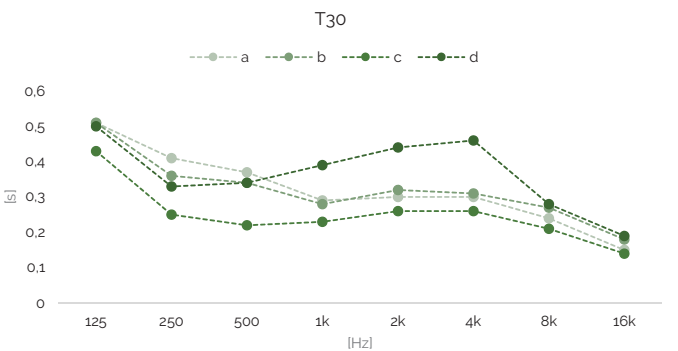


Table 5.16: SPL for overall noise level - 1st_ 3.4 (659m²)

Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.3	48	54	57	55	47	40	33
b	47.5	46	45	44	44	39	34	29
c	60.8	48	57	61	56	49	42	36
d	57.5	46	55	58	52	45	39	34

Table 5.17: absorption coefficients (a) per frequency band

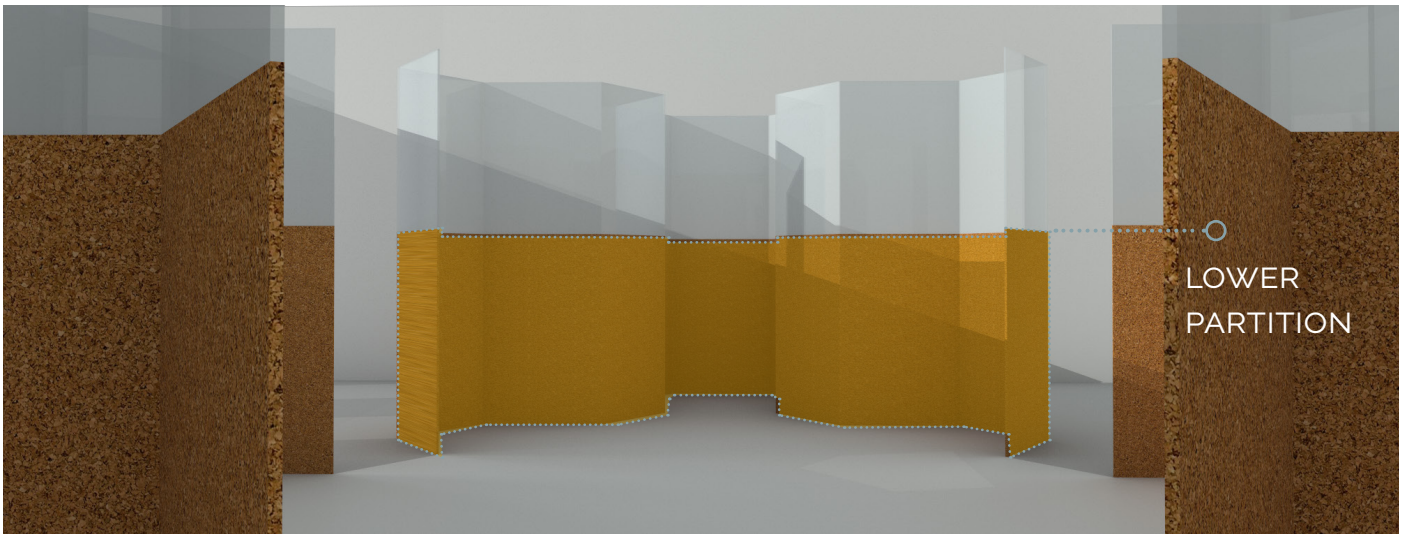
scenaria for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
3	balanced	50	90	90	25	25	25	25
scenaria for down partition (1m)								
4	balanced	50	90	90	25	25	25	25

Table 5.18: scattering coefficients (s) per frequency band

scenaria for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
3	balanced	25	25	25	50	50	50	50
scenaria for down partition (1m)								
4	balanced	25	25	25	50	50	50	50

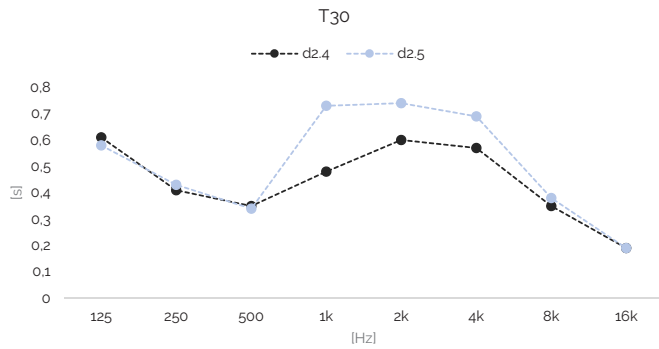
2nd Stage | Lower partition

What followed was keeping constant the upper partition, while varying the percentages for the lower one (1m), aiming for high speech intelligibility among preschoolers + extended reflections for privacy. The selected version from the 1st Stage was the version 2.4, which showed an increased performance for STI around 500Hz. At the second stage more options for the down partitions were investigated. Option 2.5 accounts for 10% scattering in order to test whether the values of T30 for low frequencies are influenced. Option 2.6 accounts for 90% diffusion of high frequencies in order to investigate whether such a choice could have an added value for speech privacy, since adding reflections in appropriate places of the semi-enclosure is proposed aiming for repetitive reflections on the inside. To ensure an acceptable level of loudness for speech intelligibility a high signal-to-noise ratio is required, followed by low background noise levels to avoid any signal interference. Option 2.7 aims to further reduce the background noise at the frequencies where children's voices are mostly active (1kHz-4kHz) by raising the percentage of absorption from 50 to 90 for this range.

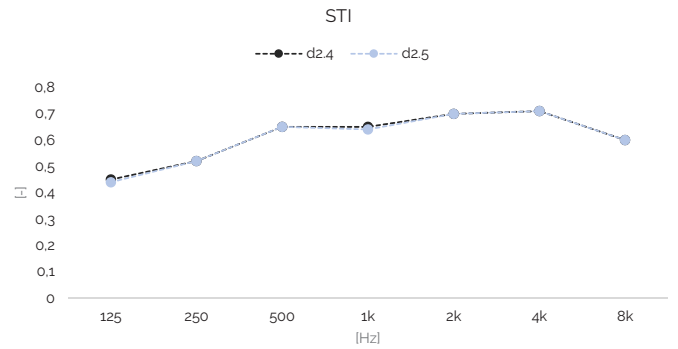


ABSORPTION COEFFICIENTS (A)							
lower partition (1m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
4	50	90	90	25	25	25	25
5	50	90	90	25	25	25	25
6	50	90	90	25	25	25	25
7	50	90	90	90	90	90	25
upper partition (0.8m)							
2	10	45	85	30	10	5	5

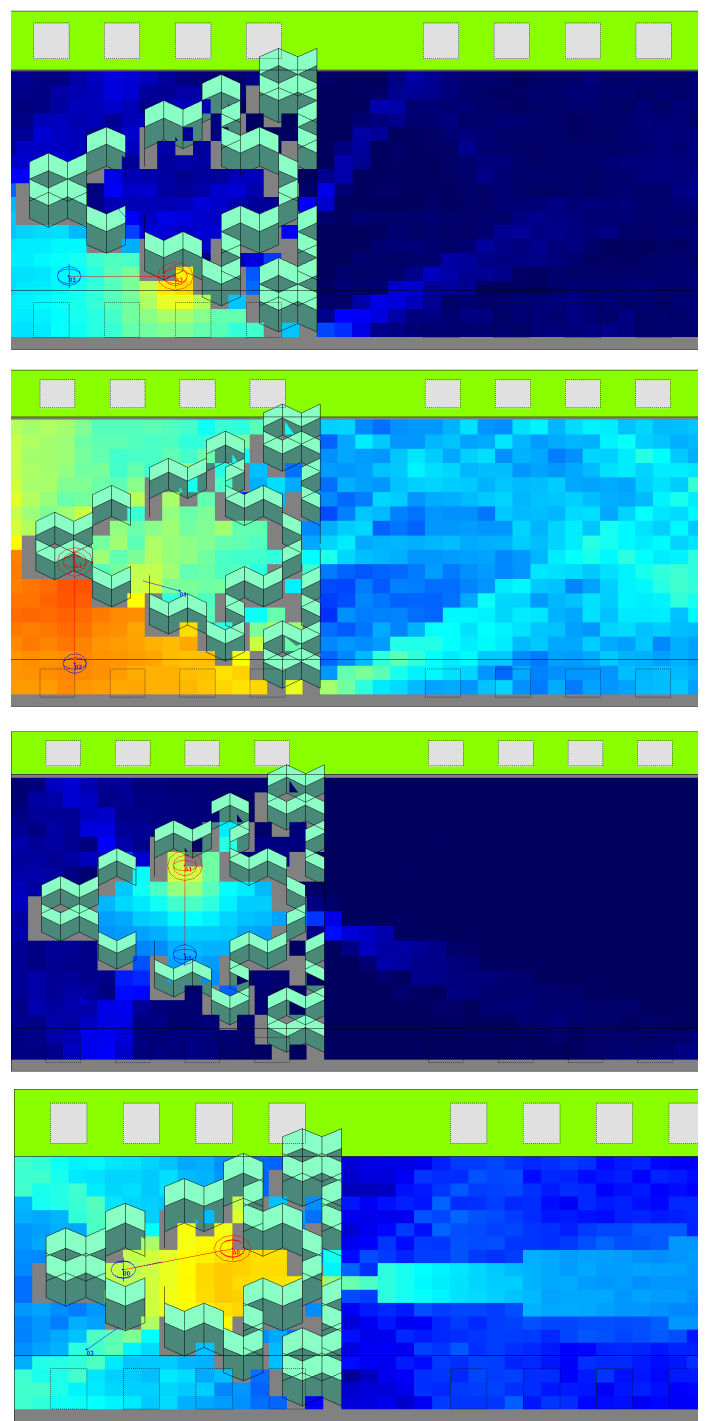
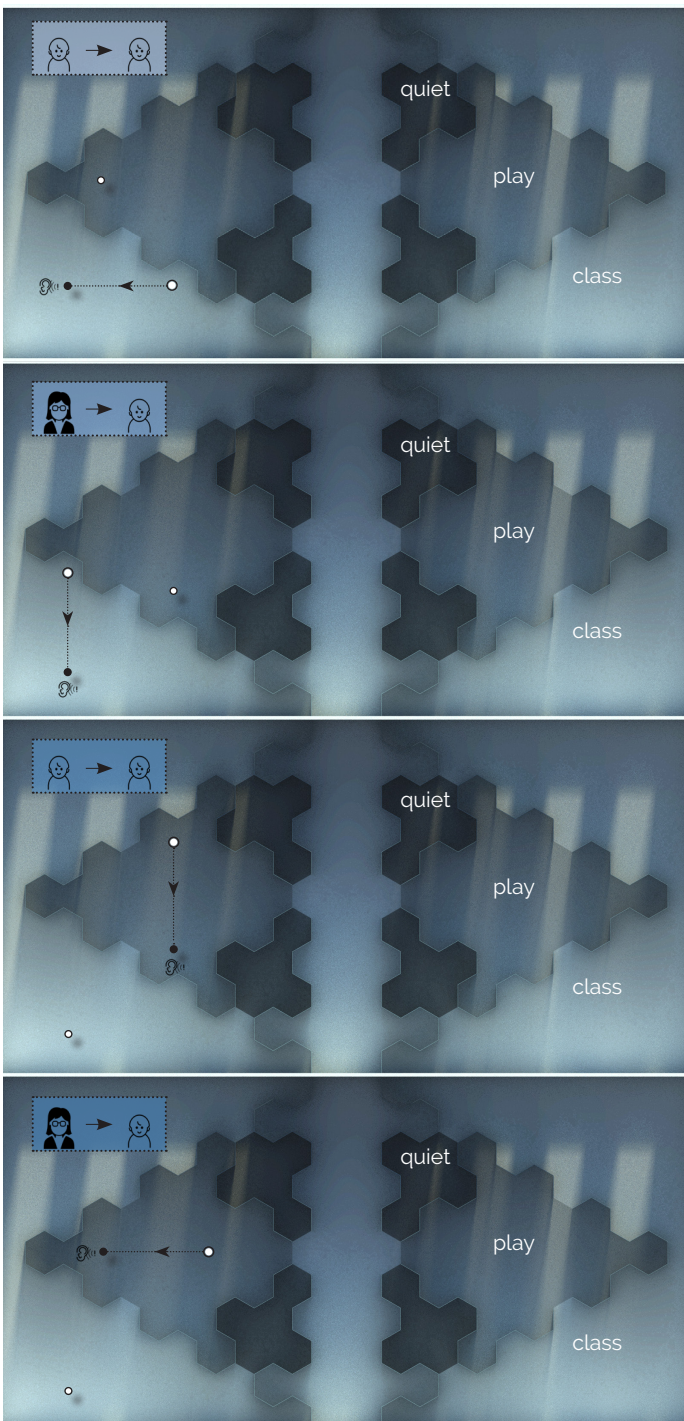
SCATTERING COEFFICIENTS (S)							
lower partition (1m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
4	25	25	25	50	50	50	50
5	25	25	25	10	10	10	10
6	25	25	25	90	90	90	50
7	25	25	25	50	50	50	50
upper partition (0.8m)							
2	10	10	10	10	10	10	10

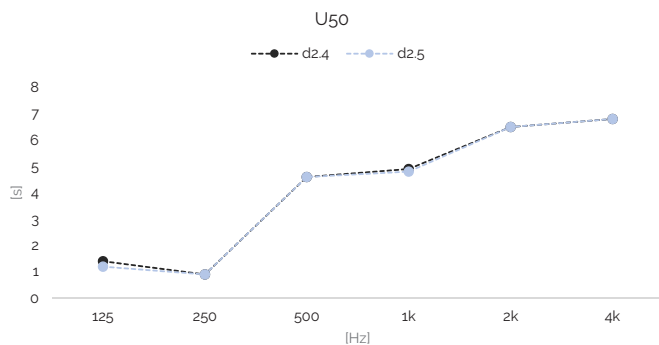


There is a considerable increase of mid-high frequency reverberation time, above the maximum limit of 0.6s, when there is less scattering for high frequencies.



The STI measure has a similar performance to the version 2.4. This justifies that though reverberation time shows an inferior performance, this is not visible in the intelligibility measure.





The performance of U50 is similar.

Table 5.19: Results - 1st_2.5 (659m²)

Sound pressure levels dB(A)				
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.46	0.03	-1.3
	general working (per 15 students)	0.88	0.56	15.6
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.36	0.09	-4.9
	Speech at normal level (per 6 persons)	0.65	0.52	5.9

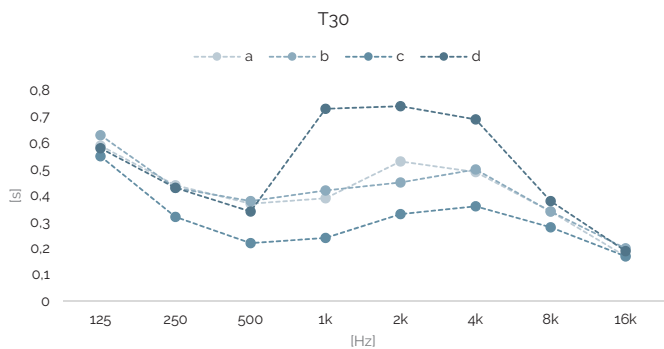


Table 5.20: SPL for overall noise level - 1st_2.5 (659m²)

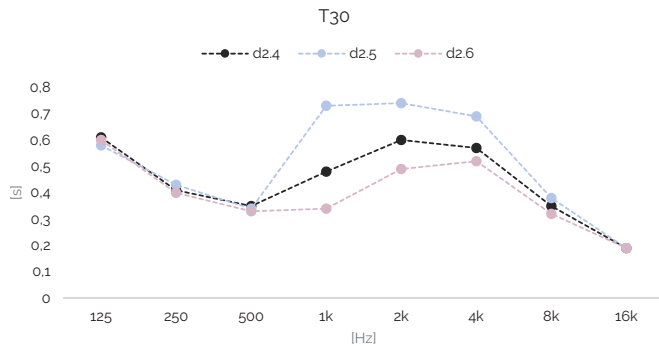
Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.3	48	54	57	55	47	40	33
b	47.5	46	45	44	44	39	34	29
c	60.8	48	57	61	56	49	42	39
d	55.8	46	55	54	52	45	39	34

Table 5.21: absorption coefficients (a) per frequency band

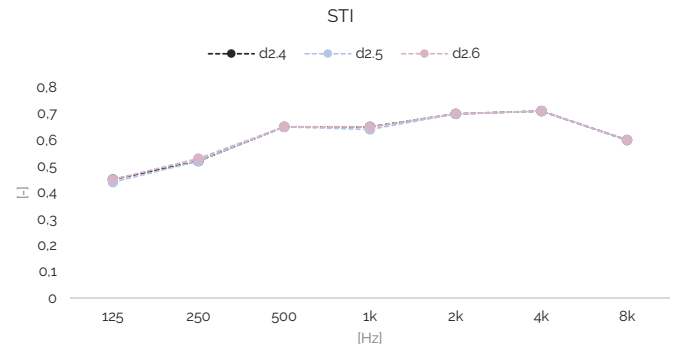
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	45	85	30	10	5	5
scenario for down partition (1m)								
5	uniform scattering	50	90	90	25	25	25	25

Table 5.22: scattering coefficients (s) per frequency band

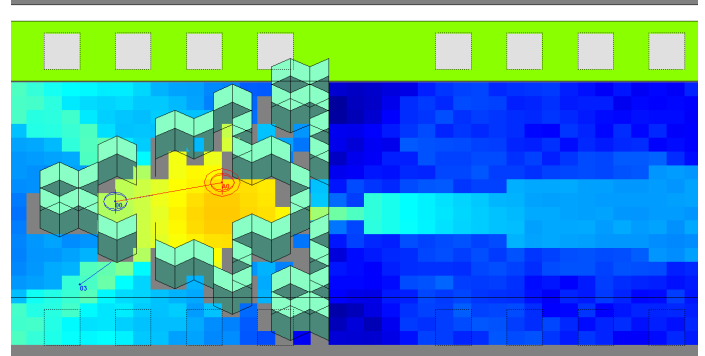
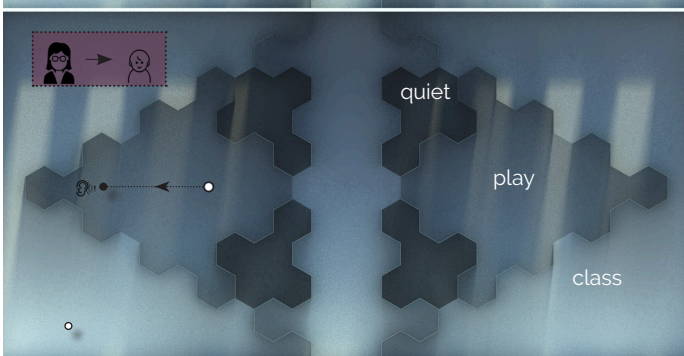
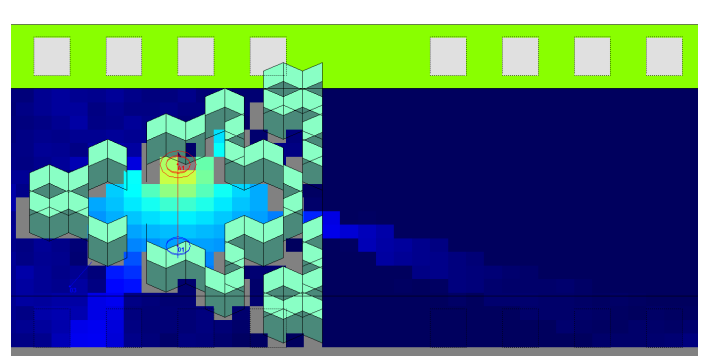
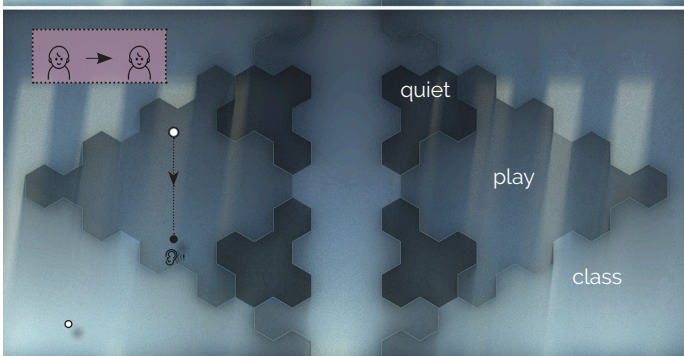
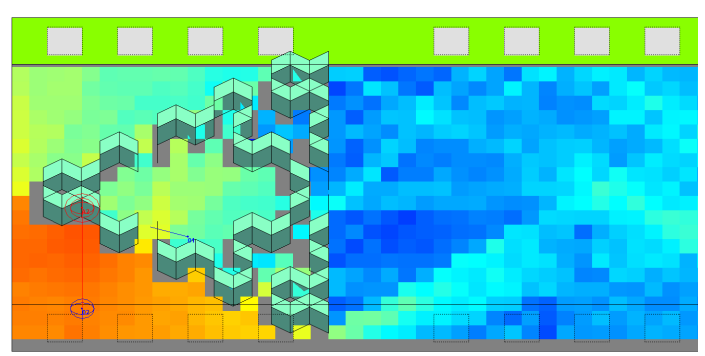
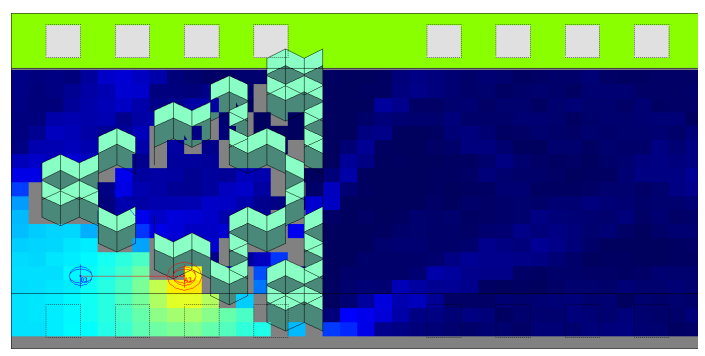
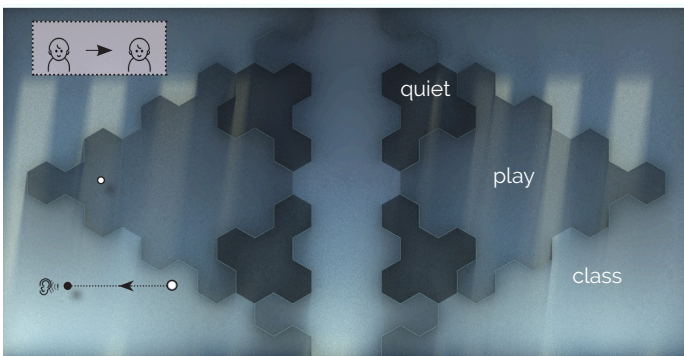
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	10	10	10	10	10	10
scenario for down partition (1m)								
5	uniform scattering	25	25	25	10	10	10	10

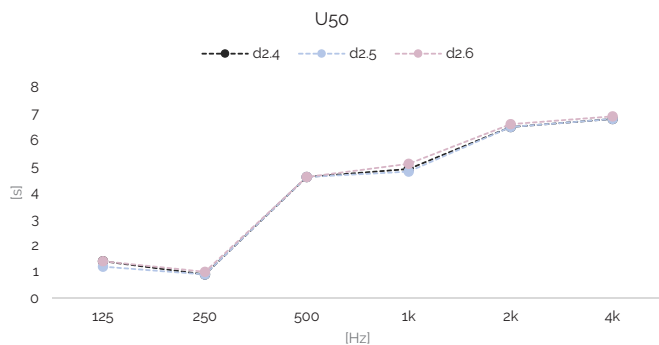


There is a considerable drop of mid-high frequency reverberation time, when more scattering is introduced for higher frequencies, leading towards a smoother curve.



Again the STI measure remains constant, highlighting the importance of taking several measures into consideration for evaluating a certain acoustic performance.





The performance of U50 is similar.

Table 5.23: Results - 1st_2.6 (659m²)

Sound pressure levels dB(A)				
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.45	0.04	-1.9
b	general working (per 15 students)	0.88	0.55	15.8
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.32	0.07	-6.2
d	Speech at normal level (per 6 persons)	0.65	0.52	6.1

T30

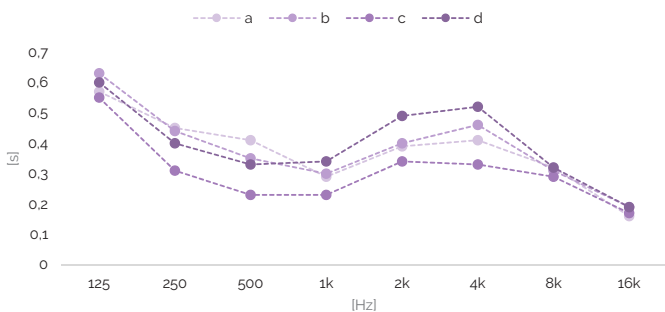


Table 5.24: SPL for overall noise level - 1st_2.6 (659m²)

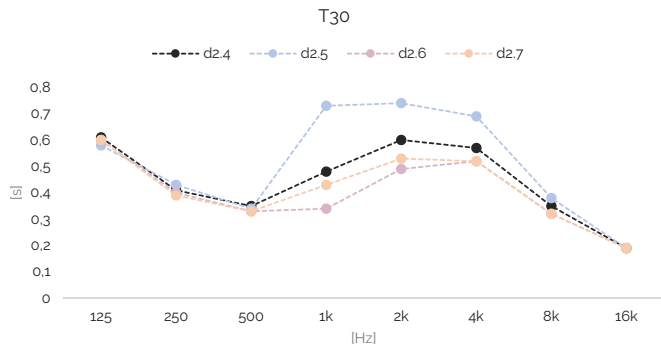
Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.3	48	54	57	55	47	40	33
b	47.5	46	45	44	44	39	34	29
c	60.8	48	57	61	56	49	42	39
d	55.8	46	55	54	52	45	39	34

Table 5.25: absorption coefficients (a) per frequency band

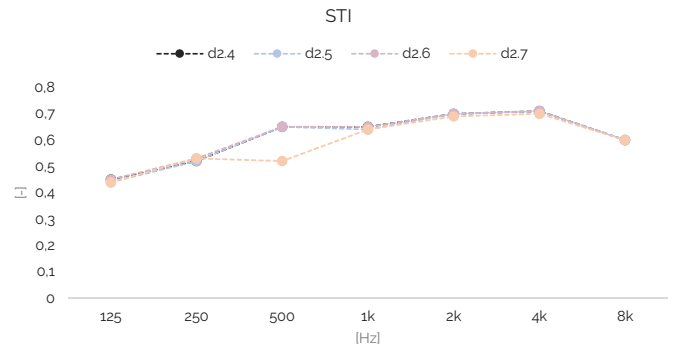
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	45	85	30	10	5	5
scenario for down partition (1m)								
6	broadband scattering	50	90	90	25	25	25	25

Table 5.26: scattering coefficients (s) per frequency band

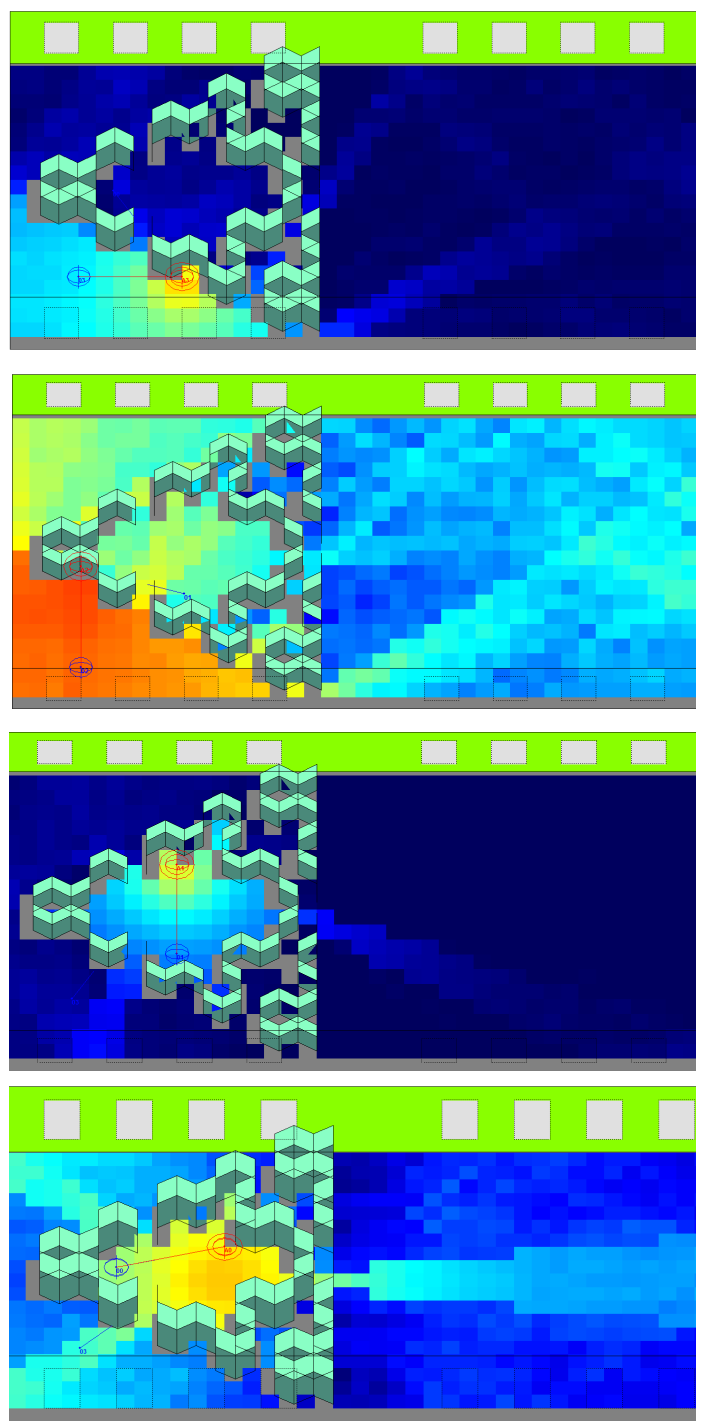
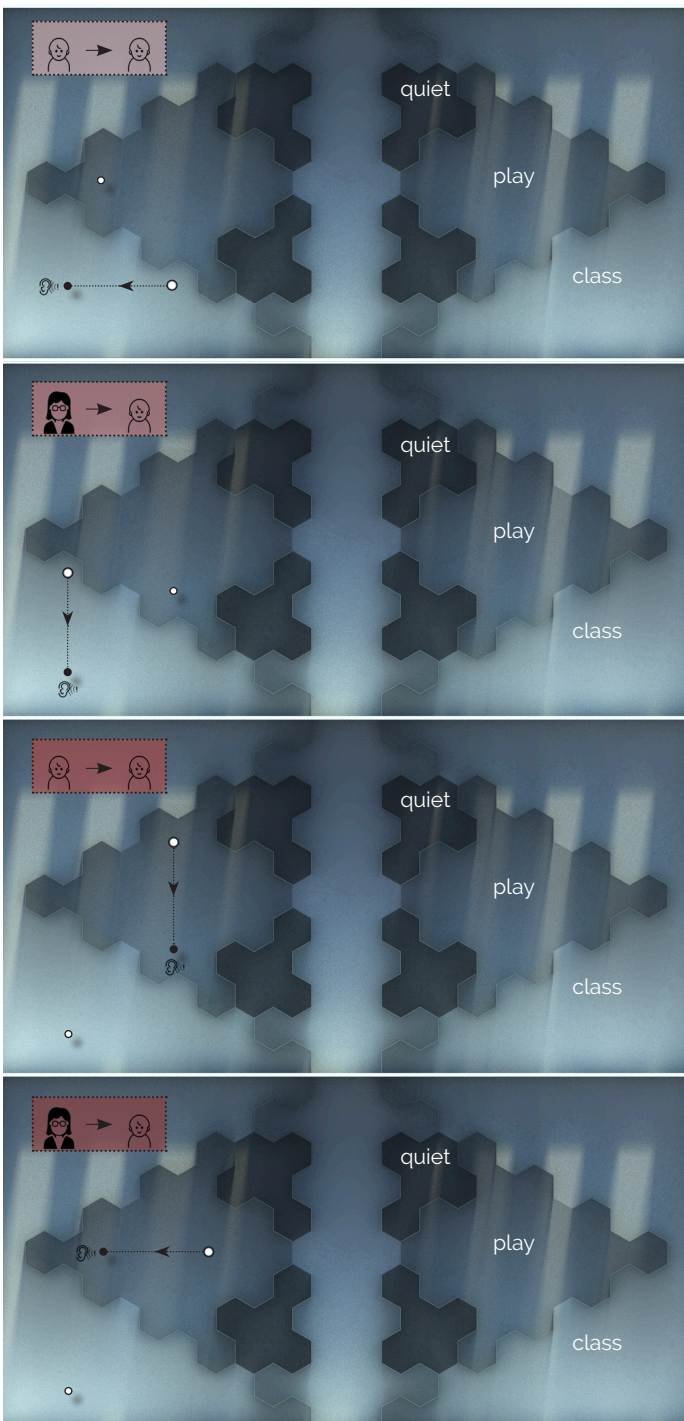
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	10	10	10	10	10	10
scenario for down partition (1m)								
6	broadband scattering	25	25	25	90	90	90	50

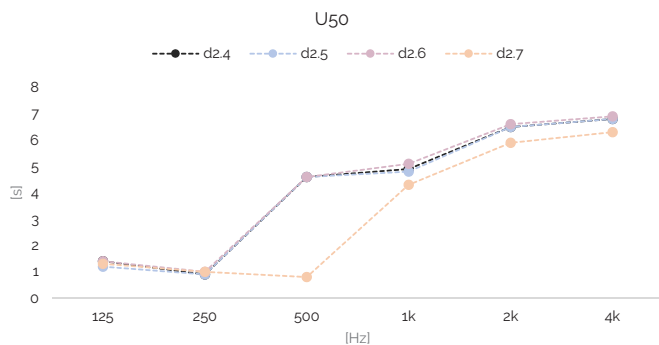


There is a smoother graph, when increasing absorption at those frequencies.



The STI measure drops at 500 Hz, though the influenced frequency range starts from 1kHz, indicating that increased percentage of absorption can lead to lower STI levels.





The increase of the absorption performance decreases the values of U50 with the valley visible again at 500Hz.

Table 5.27: Results - 1st_2.7 (659m²)

Sound pressure levels dB(A)		STI		
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.44	0.02	-2.2
b	general working (per 15 students)	0.91	0.55	16.9
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.31	0.07	-7.1
d	Speech at normal level (per 6 persons)	0.62	0.52	4.7

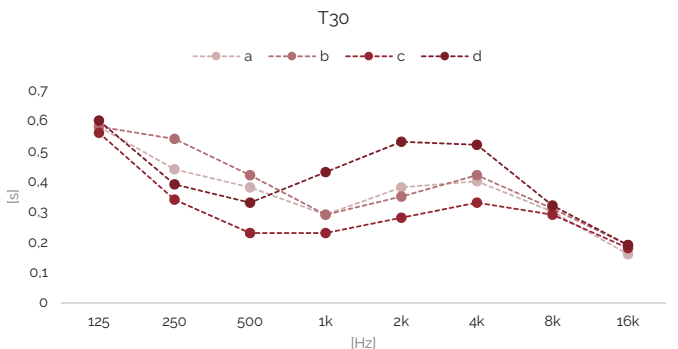


Table 5.28: SPL for overall noise level - 1st_2.7 (659m²)

Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	57.7	48	54	57	54	46	39	33
b	46.9	46	45	44	43	38	33	29
c	60.4	48	57	61	55	48	41	36
d	57.1	46	55	58	51	44	38	34

Table 5.29: absorption coefficients (a) per frequency band

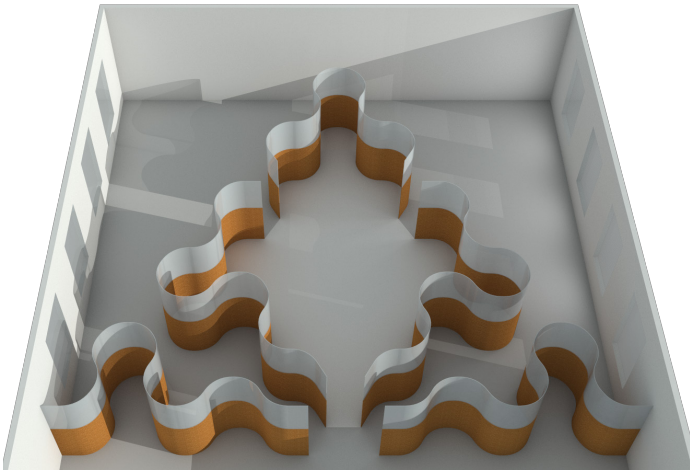
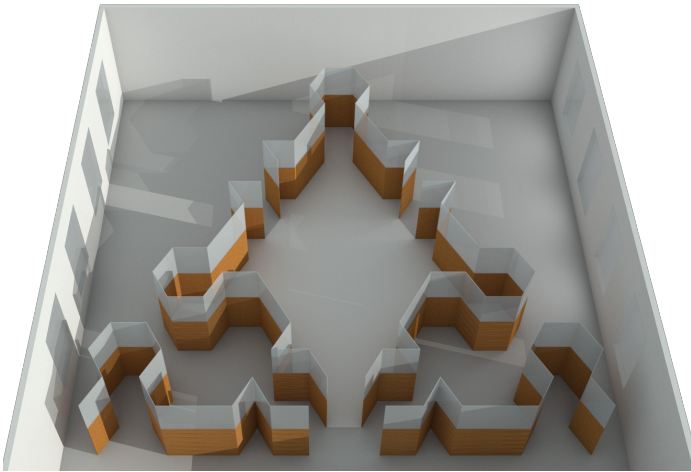
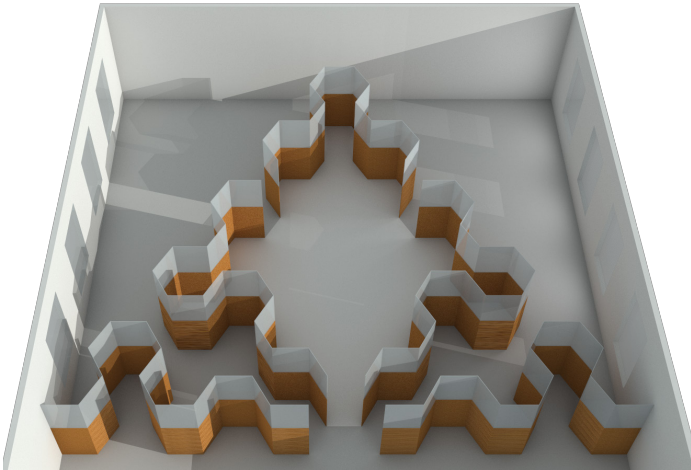
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	45	85	30	10	5	5
7	broadband absorption	50	90	90	90	90	90	25

Table 5.30: scattering coefficients (s) per frequency band

scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	10	10	10	10	10	10
7	broadband absorption	25	25	25	50	50	50	50

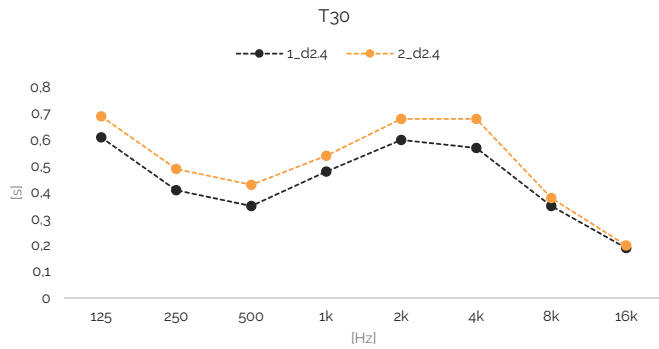
3rd Stage | Macro-geometry

Since research and design go hand in hand, three modified variations of the basic spatial configuration were tested that aimed to fulfil both acoustic and design parameters. The acoustic criteria were tested upon design criteria for social interaction by enabling play-based motor learning as well as withdrawal spaces for the individual when needed. The aim was to prove in what extend does the modification of the global shape affect speech intelligibility and/or privacy regardless of acoustic materials. The volume of the cluster was kept constant throughout the alterations given that this has a high influence in defining the sound in space, whereas the number and length of sides, the curvature type and magnitude were set as the geometrical parameters (Turrin et al., 2017). Since the three alternatives were compared for their geometrical properties and didn't aim at accounting for the material's impact, all surfaces were assigned with the same coefficients shown in Table . The chosen version for the comparison was 2.4 (balanced). Though version 2.6(broadband scattering) had an overall improved performance, the balanced version was thought to be more appropriate for comparison reasons, in order for the focus to be placed on the geometrical configuration.

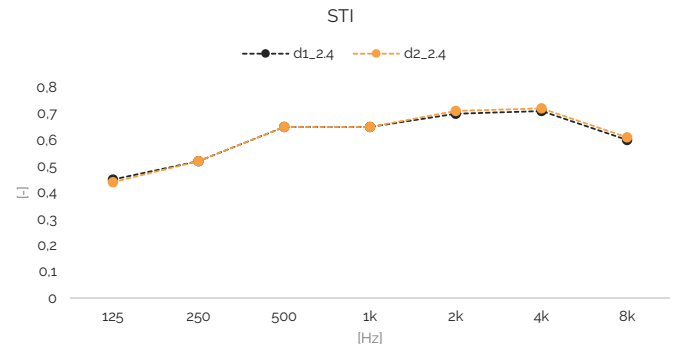


ABSORPTION COEFFICIENTS (A)							
upper partition (0.8m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
2	10	45	85	30	10	5	5
lower partition (1m)							
	4	50	90	90	25	25	25

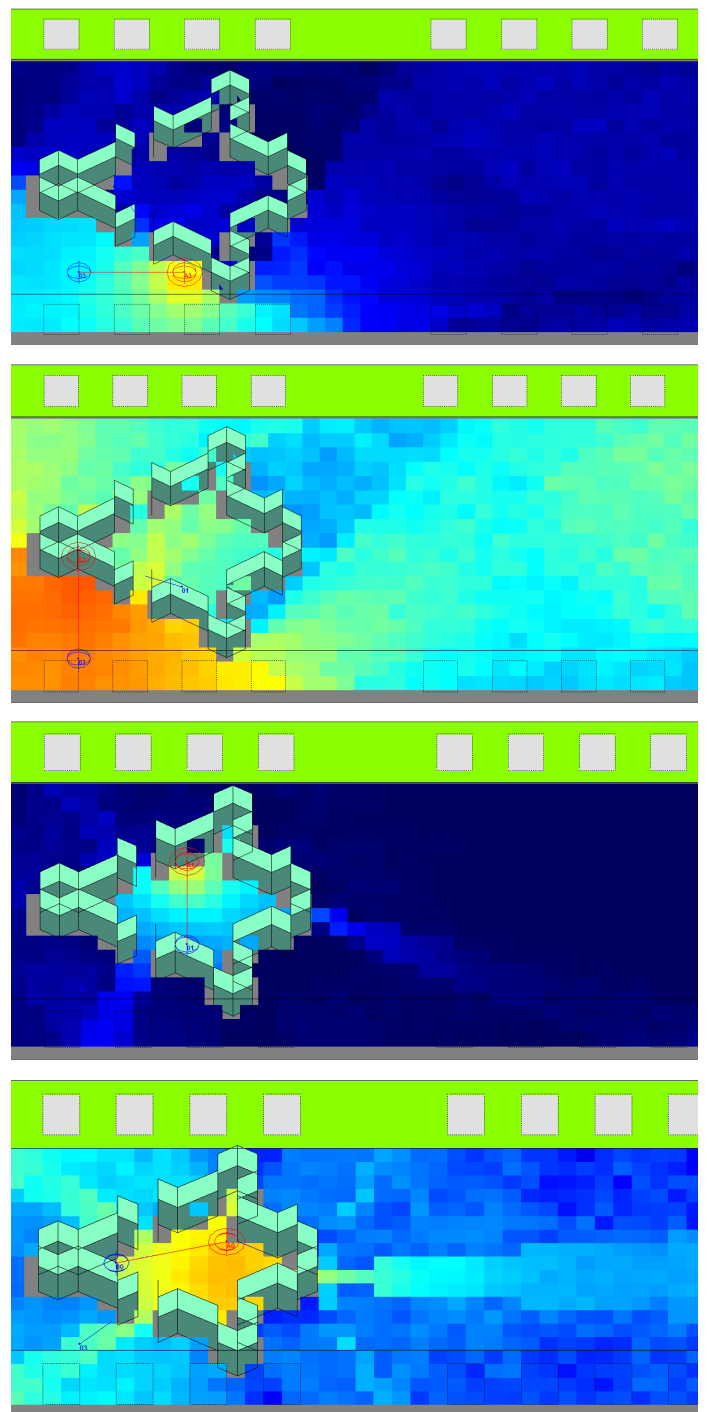
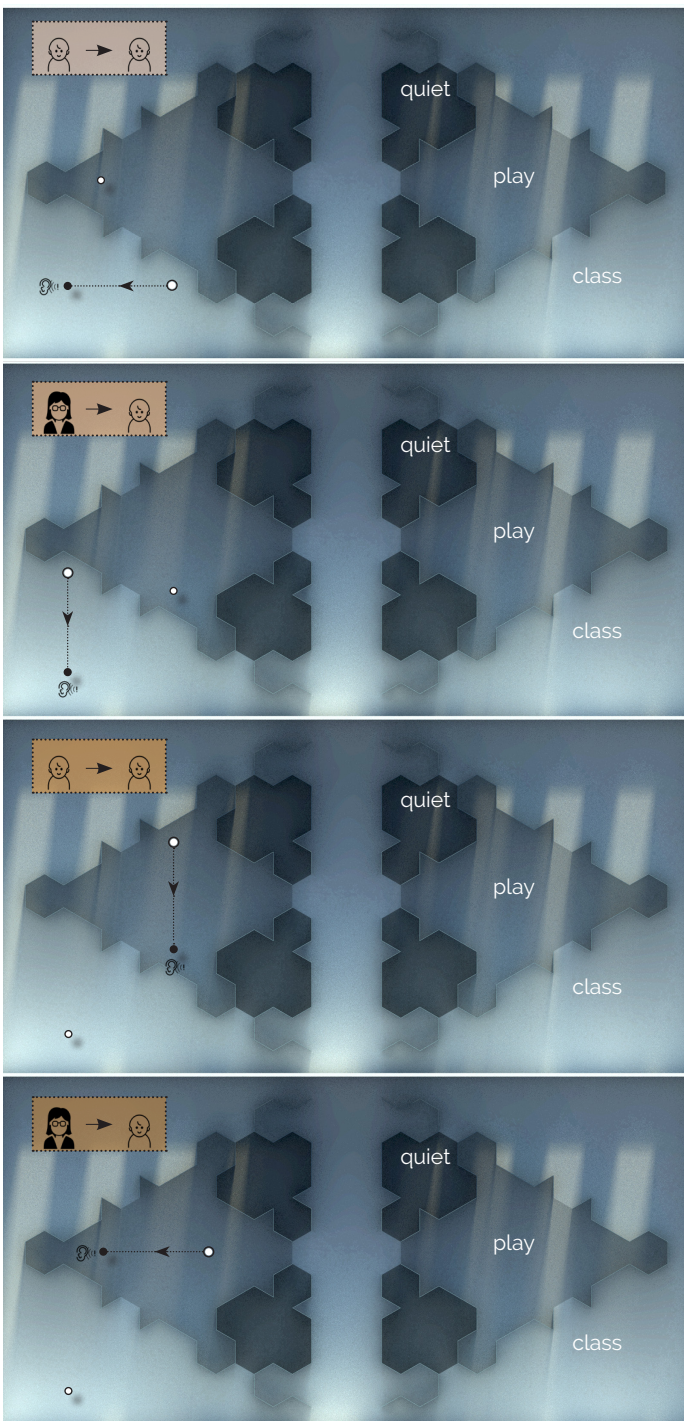
SCATTERING COEFFICIENTS (S)							
upper partition (0.8m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
2	10	10	10	10	10	10	10
lower partition (1m)							
	4	25	25	25	50	50	50

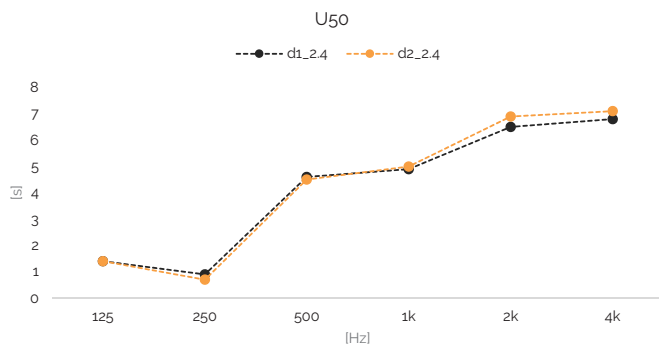


A uniform increase of the reverberation time is noticeable. From theory RT is not related to geometry changes, but could be to changed distance between the source and the walls.



The STI measure of both cases is similar.





The performance of U50 is relatively similar, what is expected since the geometry has only been modified via rotation.

Table 5.31: Results - 2nd_2.4 (659m²)

Sound pressure levels dB(A)		STI		
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.45	0.07	-1.7
b	general working (per 15 students)	0.88	0.54	15.4
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.33	0.08	-5.8
d	Speech at normal level (per 6 persons)	0.66	0.52	6.1

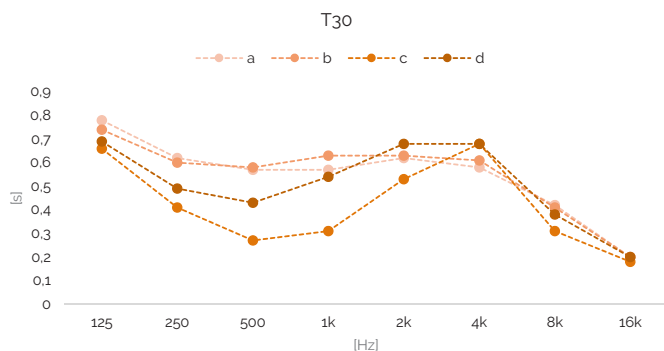


Table 5.32: SPL for overall noise level - 2nd_2.4 (659m²)

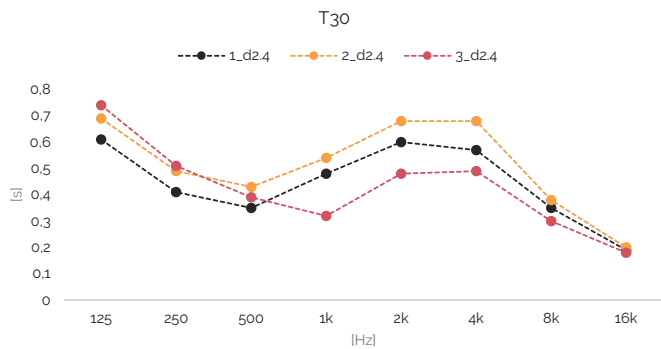
Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.3	48	54	57	55	47	40	33
b	47.5	46	45	44	44	39	34	29
c	60.8	48	57	61	56	49	42	39
d	55.8	46	55	54	52	45	39	34

Table 5.33: absorption coefficients (a) per frequency band

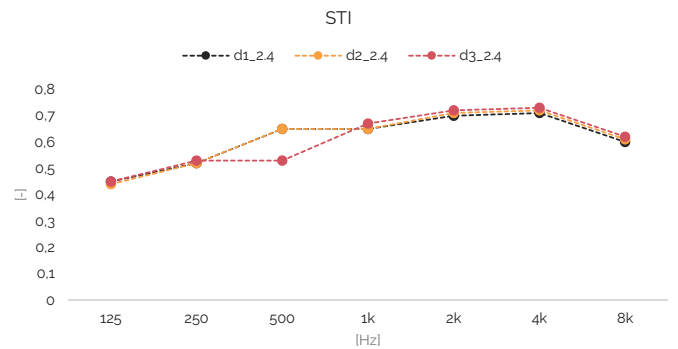
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	45	85	30	10	5	5
scenario for down partition (1m)								
4	balanced	50	90	90	25	25	25	25

Table 5.34: scattering coefficients (s) per frequency band

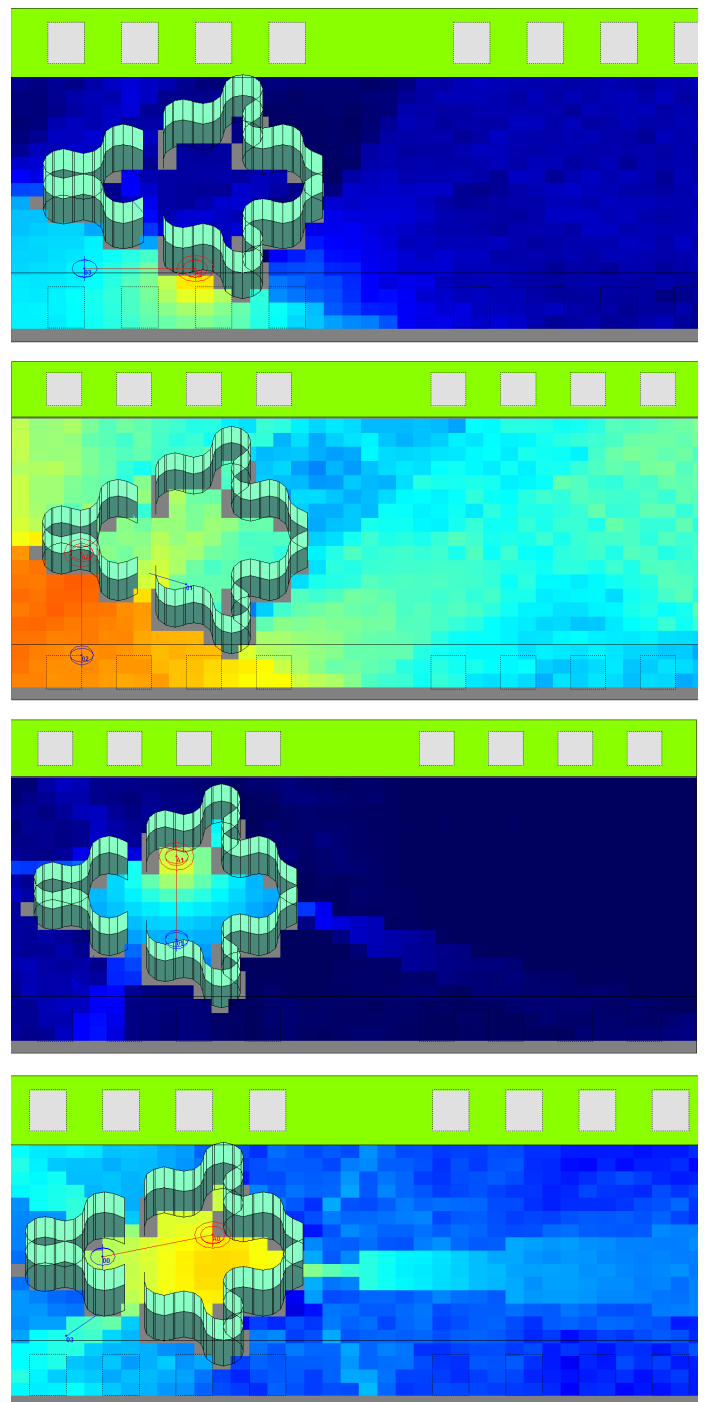
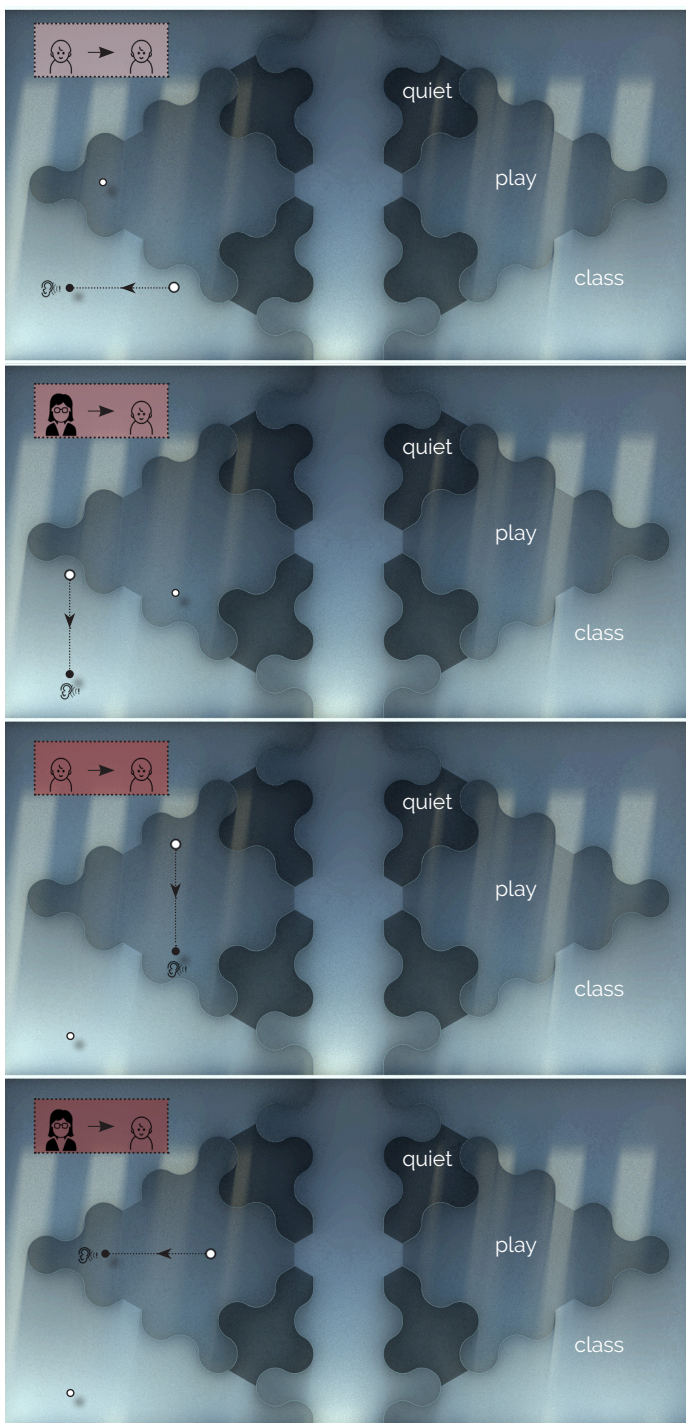
scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro-perforated glass sheets, 5 mm cavity	10	10	10	10	10	10	10
scenario for down partition (1m)								
4	balanced	25	25	25	50	50	50	50

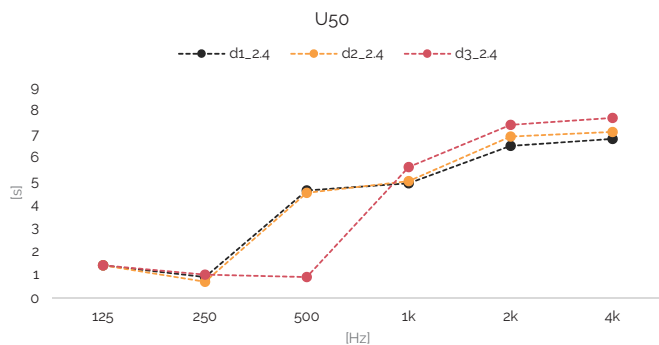


The reverberation time graph changed, though the surface area decreased only by a small percentage due to smoothed corners. This could be again due to the position of the source.



The STI that was affected was again visible for the 500Hz frequency. The drop of the STI curve always at this specific frequency needs to be further investigated.





The U50 measure gives a considerable drop for 500 Hz. It does however slightly improve for higher frequencies.

Table 5.35: Results - 3rd_ 2.4 (650m²)

Sound pressure levels dB(A)		STI		
		STI	STIout	U50
a	general working (per 15 students)+ Speech at raised level (per person)	0.45	0.04	-1.8
b	general working (per 15 students)	0.87	0.51	15.3
c	Speech at normal level (per 5 persons) + Speech at raised level (per person)	0.36	0.10	-5.5
d	Speech at normal level (per 6 persons)	0.65	0.48	5.8

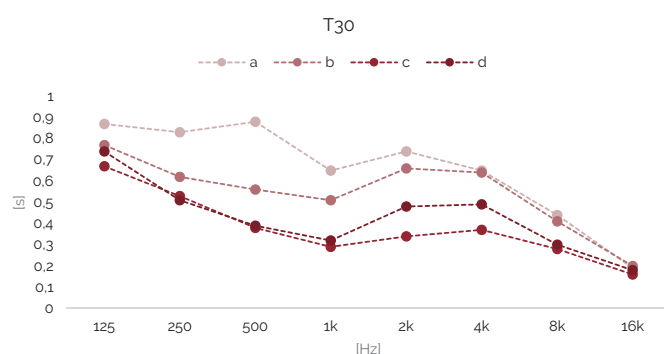


Table 5.36: SPL for overall noise level - 3rd_ 2.4 (650m²)

Sound pressure levels dB(A)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
a	58.3	48	54	57	55	47	40	33
b	47.5	46	45	44	44	39	34	29
c	60.8	48	57	61	56	49	42	36
d	57.5	46	55	58	52	45	39	34

Table 5.37: absorption coefficients (a) per frequency band

scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro- perforated glass sheets, 5 mm cavity	10	45	85	30	10	5	5
scenario for down partition (1m)								
4	balanced	50	90	90	25	25	25	25

Table 5.38: scattering coefficients (s) per frequency band

scenario for upper partition (0.8m)		Octave band centre frequency (Hz)						
		125	250	500	1k	2k	4k	8k
2	micro- perforated glass sheets, 5 mm cavity	10	10	10	10	10	10	10
scenario for down partition (1m)								
4	balanced	25	25	25	50	50	50	50



Discussion

The method to achieve high speech intelligibility without compromising speech privacy is a matter of optimization. The aim is to minimize ambient noise levels for acceptable speech-to-noise ratios and thus SNR component, rather than reverberation time, is of primary importance (Young-Ji, 2017).

- In the empty room scenario deviations from the Sabine theory can be observed, due to the rooms uneven absorption distribution (mostly concentrated on the ceiling)

- Modulations being inherent in speech lead to fluctuations in background noise, which influences the STI. Therefore, it is suggested that CATT- acoustics simulations should be made with lower overall background noise level than measured, namely around 55dBA (Vugts et al., 2017): This was confirmed, since exceeding this limit reduced the STI measure for a normal voice.

- The averaged values of the STI measure for intelligibility and speech privacy varied between 0,05 among the different alternatives., This is lower than 0,1 which is the limit of JND, indicating that there is no impact of the chosen surface properties and modified geometrical versions on simulated values of speech transmission index measure, This however was questionable and thus the complete frequency range plot was provided. The comparison indicated several drops and peaks around 500Hz related to different surface treatments.

- In the 1st stage, the selected alternative was version 2.4(microperforated glass sheets) for the upper partition, whereby the STI and U50 graph was improved.

- Alternative 3.4 had very low reverberation time, which is associated with larger reductions of speech levels, decreased SNR and consequently, considerable reduction of U50 (SNR component is more critical for obtaining close to optimum conditions for speech).

- In the 2nd stage, very low values for scattering (10%) in high frequencies given by alternative 2.5 increased the reverberation time more than 0.6s, which is the limit for speech intelligibility, whereas very high values(90%) decreased the reverberation time graph.

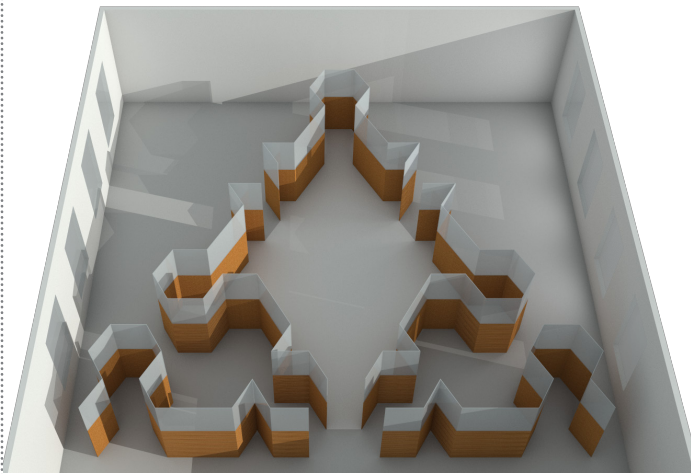
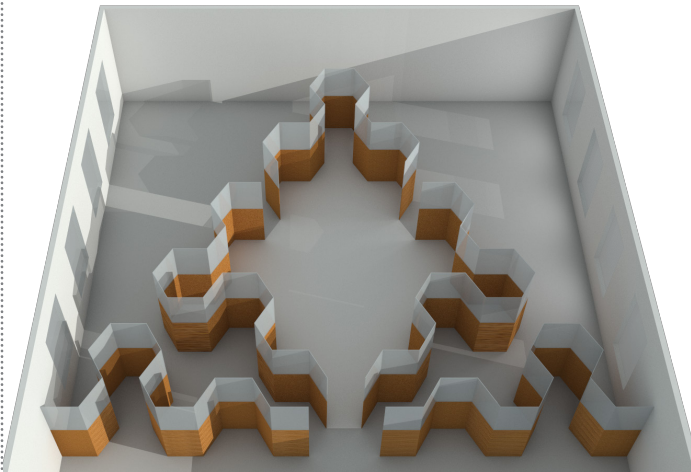
- Alternative 2.6 (broadband scattering) was selected that is in agreement with the research hypothesis and further prevents the reverberation time graph from greatly vary within the frequency spectrum. For that it was also taken into account that in a perfectly diffusive space, acoustic parameters, such as reverberation, are constant and independent from the position of the receiver. This property was never totally achieved but the aforementioned alternative gave similar graphs for different receivers' positions.

- The average sound absorption at low frequencies was in all cases larger or equal to mid or high frequencies, this is due to the air absorption of sound being much higher for high frequencies. The "forest" reverberation time graph was never achieved.

- The modified versions of room geometry 2_2.4 and 3_2.4 gave high reverberation times, which is questionable since the room volume remained constant. Especially for alternative 2_2.4, the surface area remained constant as well, since the overall shape was modified based on certain elements' rotation. An explanation for that could be that by changing the surface geometry, while keeping the sources' locations constant the distance between them and the wall altered.

Future Research

- The results are applicable only in case of an absorptive room, the impact of surface scattering and absorption on those measures under different room properties need to be further investigated.
- The room acoustic parameters that are actually of value in preschools needs to be further investigated.
- Speech intelligibility and privacy are related to more than the acoustic properties. It extends to the number of children per group, amount of personnel, positioning of the source etc.
- A qualitative investigation is still needed for accurate results, since two positions in a room may give equivalent measures, but still sound different subjectively.
- A more detailed study of the room should allow for identifying problematic locations for acoustic performance. Diffusers need to be evaluated at receiver positions where aberrations such as focusing may occur.
- A revised method for estimating the STI and U50 measure depending on new weighted factors is proposed. Current weighted factors do not account for increased speech intelligibility for the high frequencies where consonants are active.



ABSORPTION COEFFICIENTS (A)							
upper partition (0.8m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
2	10	45	85	30	10	5	5
lower partition (1m)							
4	50	90	90	25	25	25	25
SCATTERING COEFFICIENTS (S)							
upper partition (0.8m)	Octave band centre frequency (Hz)						
	125	250	500	1k	2k	4k	8k
2	10	10	10	10	10	10	10
lower partition (1m)							
4 6	25	25	25	50-90	50-90	50-90	50

Both the macro-geometry of a space, including curved, flat or intersected walls, as well as the micro-geometry of different surface patterns, influence the way in which an emitted sound is heard after being projected back into the space. In that sense, certain geometrical properties can allow design products to act as acoustic filters, concentrating and/or dispersing sound in temporal and frequency domains (Çağdaş et al., 2017). After considering the overall geometry of the space, surface articulation is next in order to tune the sound performance of the interior. In order to investigate geometry formulation, simulations that are strongly dependent on geometry, rather than material properties are required. To that end, the scattering coefficient can be useful as a comparison measure, in that smaller geometries are favoured for high frequency scattering, whereas for low frequencies larger geometries are preferred (Rahm et al., 2018). There is an assumption that in general more complex surfaces are expected to yield greater scattering. However, this research argues whether a lower level of complexity could yield similar performance.

Alongside with the arrangement of the surface geometry, the effect of periodicity is investigated in depth since scattering performance is strongly associated with this property. Scattering directivity of periodic surfaces is deeply related with incidence angle and frequency and is thought to reduce the complexity of the reflected sound field, whereas non-periodic surfaces show potential for uniform directivity, while moderating frequency related performance (Hyojin, Yuzo, & Tetsuya, 2018). The main classification aims to evaluate different types of periodic, non-periodic and aperiodic geometrical arrays, followed by a distinction among mass-produced and customized options. For this two of the most versatile typologies in Computational Geometry are investigated, namely Voronoi diagrams and plane tiling.

The first group -mass-produced- was given in terms of tiling. Tiling is defined as a countable group of closed sets that covers the plane in a non-overlapping manner (Cáceres & Márquez, 2002). In a mathematical sense this is given as the use of finite set of shapes arranged in a system that covers a surface via geometric patterning, while local rules give the constraints on the way neighbour tiles can fit together (Ostwald, 2015). A project from the department of Mathematics at the University of Cornell defines a tiling as periodic if there exist, among the symmetries of the tiling, at least two translations in non-parallel directions (Figure 12). Meaning that one can outline a region of the tiling and tile the plane by translating copies of that region (without rotating or reflecting). When no translations can recreate the same region, a tiling is thought to be non-periodic. A set of prototiles that can never tile the plane periodically is said to be aperiodic. The most famous aperiodic prototiles were invented by Roger Penrose in 1974. For this research project the "twin parallelograms" set (Figure 13) is selected. Penrose tiling is an aperiodic tessellation of the plane by two prototiles without gaps or overlaps. The pair of rhombuses has equal sides but their angles differ. The thick rhomb has angles of 72° and 108° and the thin rhomb 36° and 144° (Hyojin et al., 2018). An interesting property is that the ratio of the two is the golden mean. Further properties involve self-similarity found mostly in fractals and last but not least, a fivefold rotational symmetry due to quasiperiodic structure. Though Penrose tiling seems a chaotic sequence, it does represent a very regular local structure by having greater organisational depth (Cáceres & Márquez, 2002). The aforementioned aperiodic sequences are juxtaposed to a rhombus periodic tiling set, namely the Rhombille tiling.

The second typology, known as the "Voronoi diagram" achieves tessellation of a plane, while allowing for customization of a design. Dealing with proximity to a countable set of sites P , the Voronoi region $V(p)$ in the Euclidean plane consists of all the points at least as close to p as to any other site. The set of those Voronoi regions constitutes a plane tessellation denoted by $Vor(P)$ and goes by "Voronoi diagram"

generated by P. Following the rules for periodicity a Voronoi diagram of a non-periodic site set is a non-periodic tiling of the plane (Cáceres & Márquez, 2002). Considering periodicity properties in the Euclidean space, a special type of Voronoi sets is further investigated, which goes as periodic centroidal Voronoi tessellations (PCVTs). In this case the generators of the Voronoi tessellations coincide with the mass centroids of the respective Voronoi regions and satisfy certain properties that enforce periodicity regarding some unit cells. The most common method for computing CVTs is the Lloyd algorithm (Zhang, Du, & Emelianenko, 2012).

The different samples were examined varying certain parameters in order to conclude which geometric properties influence their performance per design frequency. Among others, parameters broadening the frequency range that the devices are effective were investigated. First, the effect of the depth range was evaluated, giving various heights relative to the tile length. This was followed by altering the shape of the profile, comparing an extruded and a tapered version. Next, the effect of reducing the well width on normal incidence scattering coefficients was considered. Last but not least, the length of the tile increased, giving a lower number of elements for covering the same surface area, while keeping the structural depth constant. The conclusions indicate parameters relative to the frequency range that are responsible for various scattering measures.

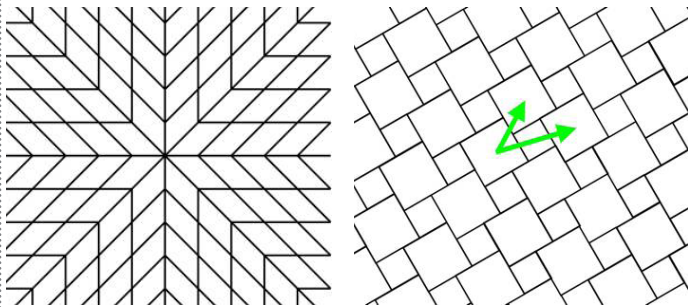


Figure 12: aperiodic pattern(left, periodic pattern(right) [http://pi.math.cornell.edu]

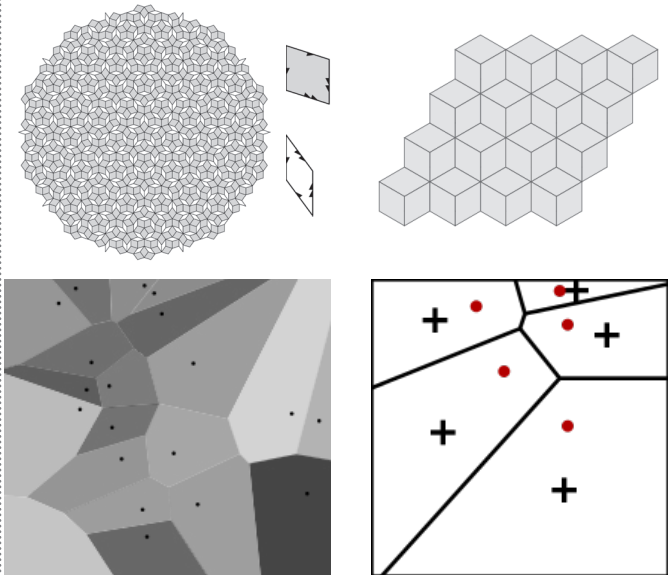


Figure 13: Aperiodic prototile set for the rhombic Penrose tiling [http://www.mdpi.com] and non-periodic Voronoi diagram (left) [https://www.revolvy.com] The Rhombille tiling http://[www.wolframalpha.com] and Lloyd's algorithm for generating the centroidal Voronoi tessellation CVT(right) [https://www.revolvy.com]

Table 6 : Periodicity				
	TILING		VORONOI	
	Periodic	Aperiodic	Periodic	Non-periodic
periodicity				
finite set of shapes	yes	yes	no	no
properties	at least 2 translations in non-parallel directions	set of tiles can tile the space, but only non-periodically	certain properties enforce periodicity	no translational symmetries
type	Rhombille	Penrose	CVT	basic
DESCRIPTION	face transitive, edge transitive, dual of the regular tessellation of the trihexagonal tiling , every edge lies on a line of symmetry of the tiling.	non-periodic, self-similarity: "inflate-and-subdivide" process: "Repetitivity" and uniform pattern frequency: 5-fold (even 10-fold) rotational symmetry	Lloyd's algorithm/relaxation: close approximation of CVT, optimal partition due to optimal distribution of generators, uniformly sized convex cells	the Voronoi diagram of a set of points is dual to its Delaunay triangulation, the closest pair of points corresponds to two adjacent cells in the Voronoi diagram.

https://www.revolvy.com

6.1 Acoustic Measures

In order to evaluate the performance of a certain design arrangement, a sort of physical or digital test sample is needed. As far as absorption is concerned, the measurements to determine the acoustic performance are conducted in association with the presence or not of the testing sample as apparent reverberation time. The change in reverberation time defines the absorption coefficient. The absorption coefficient, which typically lies between 0 (non-absorption) and 1 (complete absorption) is the ratio of the amount of absorbed energy to the incident one (Cox & D'Antonio, 2016). An impedance tube measurement could verify the absorption coefficient if a normal incidence is considered (Reinhardt et al., 2016). Though the research proposes a hybrid design aiming for both absorption and diffusion the absorption properties are chosen taking into account the results of several previously conducted studies.

Evaluating diffusion is more complicated and requests a more thorough investigation, since - as absorption- too much or too little diffusion can result in acoustic aberrations. The common method to evaluate diffusion lies upon the ISO scattering coefficient, which is usually evaluated in one-third octave bandwidths. Achieving complete scattering at the design frequency and its multiples ensures that energy is not reflected in the specular direction but does not evaluate the quality of the produced dispersion. A diffuser apart from redirection needs to achieve spatial dispersion in order to reduce echoes without moving problems to a different place. Though energy dispersion is the most dominant approach for evaluating current diffusers, the phase in the polar response or the reflected impulse response are equally important. An ideal diffuser produces a polar response that remains constant though changing the angle of incidence and the frequency within its operational bandwidth. Moreover, there is no correlation of the scattering performance and the arrangement of the wells in a diffuser. Though the shape of the polar responses for different arrangements changes, the energy reflected in the specular direction, does not.

Towards diffuser optimization the diffusion coefficient, which is frequency dependent, is of great importance, complementary to the scattering coefficient, providing an index to measure its quality. To avoid confusion due to edge diffraction at low frequencies, the normalized diffusion coefficient is introduced (Cox & D'Antonio, 2016). The ISO scattering coefficient is related to the surface property to extract energy from the direction of specular reflection, whereas the diffusion coefficient evaluates the level of uniform spatial reflections (Cox & D'Antonio, 2016).

In the present, the most common measurement set-up for estimating ISO scattering coefficients involves 1:10 physical scale models. Each sound disk must be set on a turntable in a scaled model reverberation chamber, where a random incidence measurement is conducted, by emitting a long duration MLS signal and retrieving impulse responses for various source and receiver locations that are synchronously averaged (Reinhardt et al., 2016). The approach requires the specimen's structural depth to be small compared to the overall size of the sample in order to provide trustworthy results. Since the sample must be shallow and not too absorbing, an empirically derived limit for its structural depth (h) is $h \leq d/16$, with the turntable having a diameter d . (Figure 14) The measured scattering coefficients are very sensitive to edge conditions, since the edge corrugations can cause scattering coefficients to be larger than 1 at high frequencies. For round samples, there needs to be a smooth and rigid border covering the edge corrugations. Since most diffusers are rectangular and scattering from the rectangular edges results in additional scattering and misleading results, the samples need to be recessed within a circular base plate (Cox & D'Antonio, 2016). Nevertheless, since such facilities were not available in the faculty of Architecture and the Built

Environment of TU Delft, this method was not applicable. Furthermore, considering the difficulties for measuring sound diffusion and analysing acoustic scattering and the time-consuming procedure of wave-based computer simulations, an alternative workflow had to be invented, while ensuring the validity of the acquired results.

For estimating the scattering coefficients of different digital samples, the plug-in for Rhinoceros Pachyderm Acoustic Simulations was chosen. This is an open source code that recently incorporated a wave-based analysis of Finite Volume Method for estimating the correlation scattering coefficient as an input for Geometrical Acoustics software. The method for evaluating a diffuser performance by estimating the correlation scattering coefficient from polar responses was originally suggested by Mommertz (2000). The scattering coefficient is then given by the correlation of the scattered pressure polar responses from the tested surface and a flat surface. The coefficient definition differs from the aforementioned coefficients, in that the measurement gives the dissimilarity between the test and flat surface scattering over a polar response, rather than the energy moved from the specular direction when the surface is moved. For randomly rough surfaces similar results can be obtained for both the ISO and the correlation scattering coefficient, but even in cases when the two coefficients are not identical, the correlation scattering coefficient can indicate and contradict the performance of diffusion and scattering coefficients. Hybrid surfaces are excluded from this method, because the current formulation for the correlation scattering coefficient interprets any absorption as being scattering. The formula goes as follows:

$$\delta_c = 1 - \frac{\left| \sum_{i=1}^n p_1(\theta_i) p_0^*(\theta_i) \right|^2}{\sum_{i=1}^n |p_1(\theta_i)|^2 \sum_{i=1}^n |p_0(\theta_i)|^2}, \quad (2)$$

p_1 =scattered pressure from the test surface

p_0 = scattered pressure from the flat surface

$*$ = complex conjugate

i = receiver angle of the i th measurement position

n = number of measurements in the polar response

The performance of a diffuser can be assessed by the far-field polar pressure distribution, which essentially is a Fourier transform of the reflected field along the surface. Good sound diffusion properties in that sense are connected with structures whose reflection coefficient distributions present a uniform magnitude Fourier transform (Jiménez et al., 2017). A follow-up validation of the results could involve estimating the scattering coefficient through a circular FFT power spectrum analysis along circles that trace the path of the sample as it rotates in the acoustic measurement procedure. This method is proposed in the paper "A Mathematical Model Linking Form and Material for Sound Scattering", whereby results in a limited population of six samples associated the low spatial frequency magnitude of surface modulation with scattering coefficients. This method seemed promising in order to perform an acoustic surface analysis prior to additive manufacture or the physical acoustic measurement. Such a shortcut could be advantageous considering the current computationally intensive procedures of boundary element method or finite element method for a surface acoustic evaluation (Çağdaş et al., 2017).

Though the time schedule did not allow for a perceptual study, it should be taken into consideration in the discussion of the results. Psychoacoustics refers to the scientific study of human auditory perception in order to establish a standardized relationship between physical and perceptual phenomena, i.e. sound pressure level and loudness (Charles, 1998). Given that the frequencies that exhibit maximal sensitivity are those associated with speech (approximately 200 Hz to 5 kHz), no absolute conclusions on acoustical properties for the surface samples can be drawn without considering this parameter.

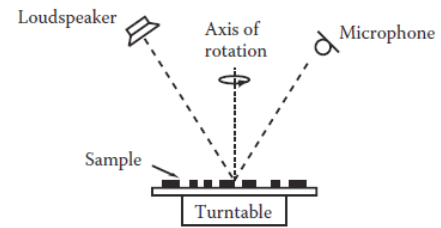


Figure 14: Model scaled reverberation chamber [Cox & D'Antonio, 2016]

[Cox

6.2 Workflow for Surface Evaluation

Since the previous chapter discussed what percentages of absorption and diffusion are more relevant given a typical preschool environment with specific acoustic properties, this chapter investigates how these percentages can be achieved, while meeting design standards. The investigation lies upon a Mass-produced and Customized solution, testing different variations of the two in order to obtain certain properties (**Figure 15**). The research at this stage mainly draws the correlation of design choices on scattering performance, while investigating the effect of periodicity of a given pattern.

Since a diffuser's design is based upon sequences, the effect of periodicity causing uneven scattering, was set as the main parameter to be further examined. Since the complexity of the reflected sound field can be reduced due to periodicity in the surface, aperiodic patterns are thought to achieve high performance scattering (Reinhardt et al., 2016). However, considering that at high frequencies the dispersion by a modulated array is often worse than for a periodic arrangement, designs need to be tested for their diffusion performance (Cox & D'Antonio, 2016). An appropriate sequence towards aperiodicity can be recognized from its good autocorrelation properties, such as a unipolar sequence with minimum side lobe energy. One possible solution that would however raise the cost since it would involve a customized design could be the use of a single, long number sequence with good aperiodic autocorrelation, giving just a single period without repetition, would give a more uniform scattering performance. Another idea could be to use two or more diffuser types and arrange them according to a pseudorandom sequence to eliminate any repetition (Cox & D'Antonio, 2016). Those strategies are summarized in **Figure 16**. In regard to these principles, the two geometric typologies -Voronoi and tiles- were chosen for their unique properties, trying to achieve a non-repetitive sequence with the geometry articulation itself.

Parametric Pattern Generation

The interdisciplinary collaboration among generative design and computational workflows can easily provide alternatives for acoustic analysis and simulation and evaluate novel surface geometries that have the potential to change the acoustic response of space. Geometric principles if integrated with scripting logic, varying surface size, angle and depth through computational design can lead to successive acoustic design alternatives that can be tested for their properties.

For tessellating the plane two different discretisation strategies were applied, based on the manipulation of two-dimensional grids, defining parametrically different surfaces. The patterns were then remapped on surfaces and three-dimensional geometries were achieved via extrusions or tapered poly-surfaces according to specific parameters. The research was structured upon the fact that the variables that guide sound diffusing patterns can be applied in terms of width and depth constraints, allowing visual freedom of the shape (Rahm et al., 2018).

Tiling, though having a low degree of freedom due to them complying with inherent rules, allowed for manipulation of their vertical dimensions, while keeping the length of each side constant. The two prototiles covered a surface of 1m² with a total number of around 300 cells, which were given two heights respectively -the thick rhombus was acting as the well of the diffuser-. Three different depths of the wells were examined for both an extruded and a tapered version, in order to investigate the effect of the vertical profile and the well depth. Next to that, two cases of various heights were compared between a swallow and a deeper device. A scaled version of the pattern by a factor of 0.8 for the tapered versions gave a different arrangement for the wells, which in this case were set to be the boundaries of the pattern. Last but not least, the effect of a larger period was evaluated, which reduced the number of

cells to half. For comparison reasons, a similar procedure was followed for the periodic Rhombille tile, which required 350 cells to cover the same surface area. Since this involved only one prototile the vertical orientation was selected to act as the well of the device.

The Voronoi seeds allowed for different iterations and random seed generation changing the relative arrangement of each element, while preserving a certain number of elements. The number of cells was set to 400 in order to preserve a similar amount to the Penrose and Rhombille tiles. Towards the definition of the wells, five groups of polygons were formed depending on the amount of their sides (4-8 sides). The 4-, 5- and 6-sided polygons were selected as the wells of the devices. As far as the centroidal Voronoi is concerned the Lloyd algorithm was used to generate 400 cells, whereby the wells were again selected based on the amount of their sides. For both cases a similar procedure with the one described above was followed.

Selecting dimensions relative to the design's frequency

The wavelength of sound (λ) equals the speed of sound divided by frequency ($\lambda = c/f$). A well depth that is given as $\frac{1}{4}$ of the wavelength λ , results in a 180° phase shift relative to a part of the surface without well. This was the procedure that determined the different heights relative to frequency ranges of 1kHz-4kHz, due to the potential for local sound cancellation and complex reflection patterns (Reinhardt et al., 2016).

	periodicity	parameters	profile	constrains
steps	• aperiodic • periodic • non-periodic	• side legh • well • period	• extruded • tapered	amount of cells
				production
depth-to-length ratio				
well				
two depths	d=20% l [m]	d=50% l [m]	d=150% l [m]	
various depths	d=20% l [m]: 3			d=200% l [m] : 3
narrow width	d=20% l [m]	d=50% l [m]	d=150% l [m]	

Figure 15: design properties tha affect scattering performance



»

COMPLEX SURFACES
-> GREATER SCATTERING



»

PERIODIC SURFACES: REDUCE THE COMPLEXITY OF THE REFLECTED SOUND FIELD

NON-PERIODIC SURFACES: POTENTIAL FOR UNIFORM DIRECTIVITY



»

LONG NUMBER SEQUENCE WITH GOOD APERIODIC AUTOCORRELATION



»

NON-REPETITIVE SEQUENCE VIA THE GEOMETRY ARTICULATION

Figure 16: design strategies for uniform scattering performance

6.3 Workflow for Acoustic simulations

The first stage of surface evaluation involved the aforementioned software Pachyderm, version *Pachyderm2.0RC20* using the Finite Volume Method, which though experimental for reliable quantitative predictions, it was still useful for comparison of alternatives related to geometrical properties (Rahm et al., 2018). The samples were placed with their centre at the origin (0,0,0) and it was advised to keep the sample entirely below the green sphere, and to not have any geometry in the model except for the sample. Next, it was required to set a 'Measurement Radius' that is wide enough in order for a sphere of that radius to fully encompass the sample. The radius of the samples was set to $r=0.5\text{m}$ with a circular perimeter, guided by the process followed in the scaled reverberation chamber measurements. The depth (d) of the samples varied with several length to depth ratios. Last but not least, the frequency range was set to 8kHz. What is important to mention is that different results were obtained when a more recent version was used.

An overview of the simulation alternatives and their parameters is given in Table 6.1. Firstly, the ratio of depth relative to the side's length varied among 20%, 50% and 150% of the average side length of the individual elements. This involved a comparison of two vertical profiles, an extruded and a tapered version, for the aforementioned depth variations. Next, two scenarios of 3 to 5 variable depths were compared for a maximum depth of 20% and 200% of the given length. What followed was narrowing the width of the well for the tapered version, constraining it within the pattern borders based on the given depth variations. Last but not least the period of the pattern was modified by increasing the size of the elements, while reducing their amount.

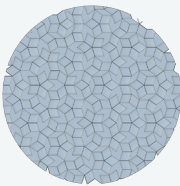
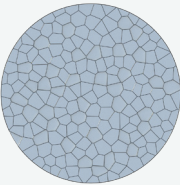
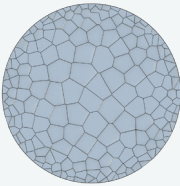
Validated case study from Literature

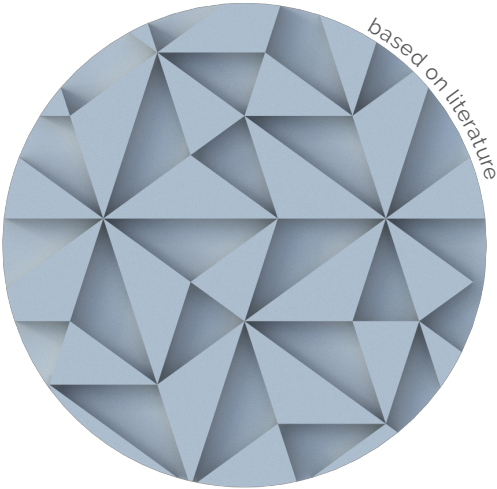
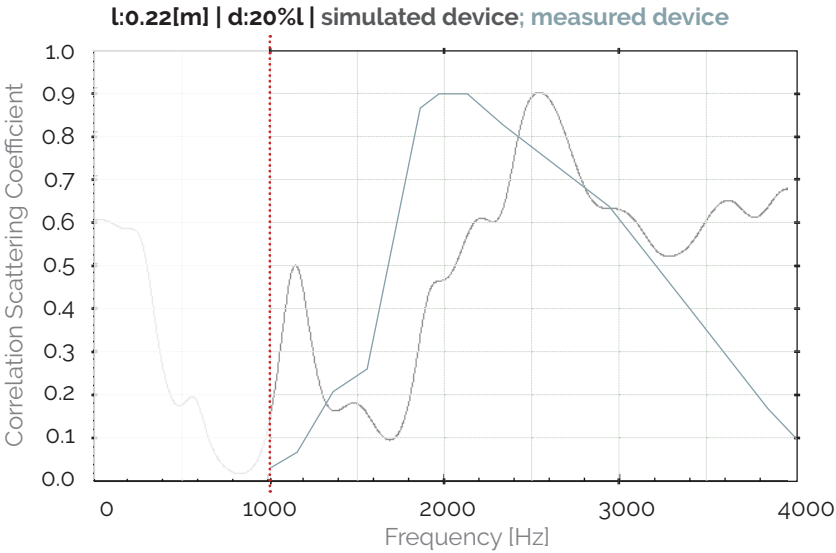
Considering a recent paper "Acoustic scattering characteristics of Penrose-tiling-type diffusers" (Hyojin, Yuze, & Tetsuya, 2018), where different Penrose typologies were examined for uniformity of scattering directivity, it was thought relevant to compare the results of a measured device with those drawn from the simulation of the same device in Pachyderm acoustics. This would ensure a certain degree of validity for the selected procedure.

The selected device was a symmetric arrangement stated as Type S with a side length of 219mm and a depth of 40mm (d:20%l). The results given by the normal-incidence scattering coefficient measurement seem on average to agree with the simulation. Mostly, two differences are observed, a shift of the peak frequency by about 500 Hz and some sort of plateau reached by the simulation between 3000 and 4000 Hz versus the measurement drop in this frequency range.

Several reasons can be responsible for those discrepancies, including inaccuracy of the measurement or the simulation procedure, considering that the last one is highly experimental, slight differences in the geometry used and finally different resolution, namely measurements with a 200 Hz interval; simulations with a very small interval. The most important reason, however, is that the measurement considers a different coefficient than the simulation, namely the ISO scattering coefficient versus the correlation scattering coefficient, which do not match under all circumstances. The results will be discussed in juxtaposition with the conclusions of the aforementioned paper, since they are part of the recent debate whether periodicity has an impact on the acoustical performance of a geometric pattern.

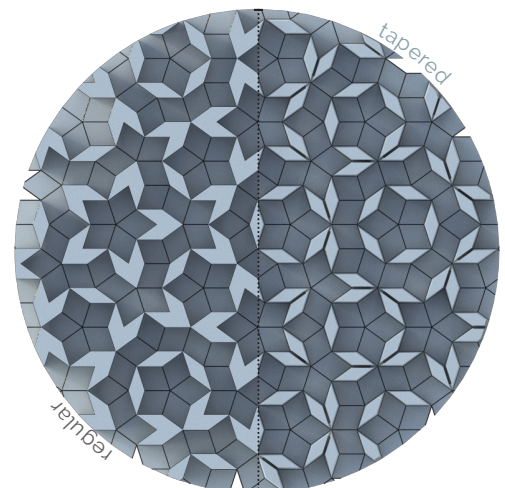
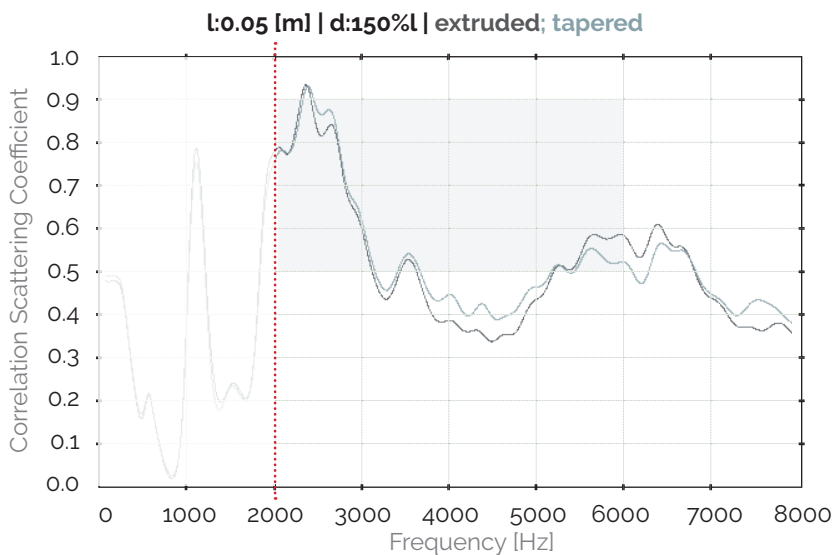
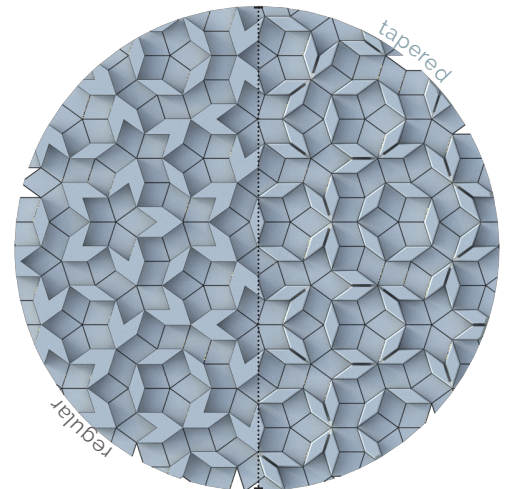
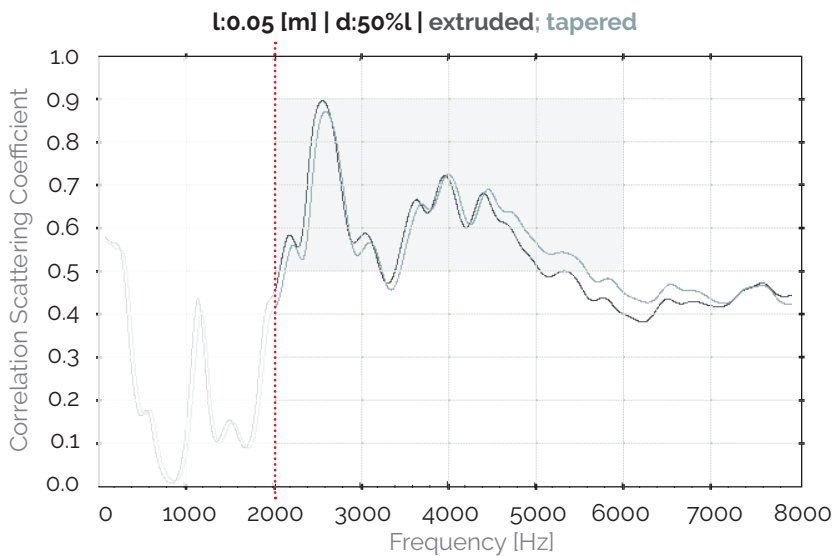
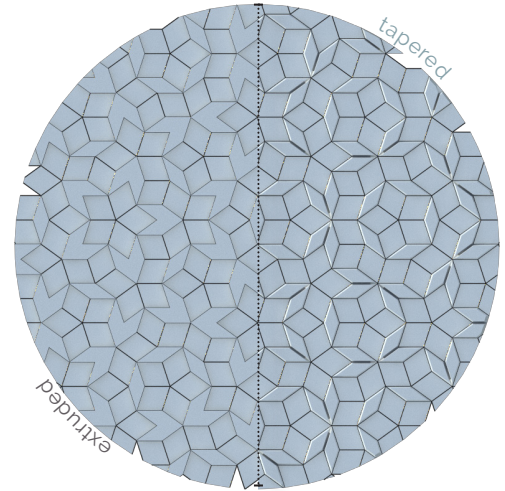
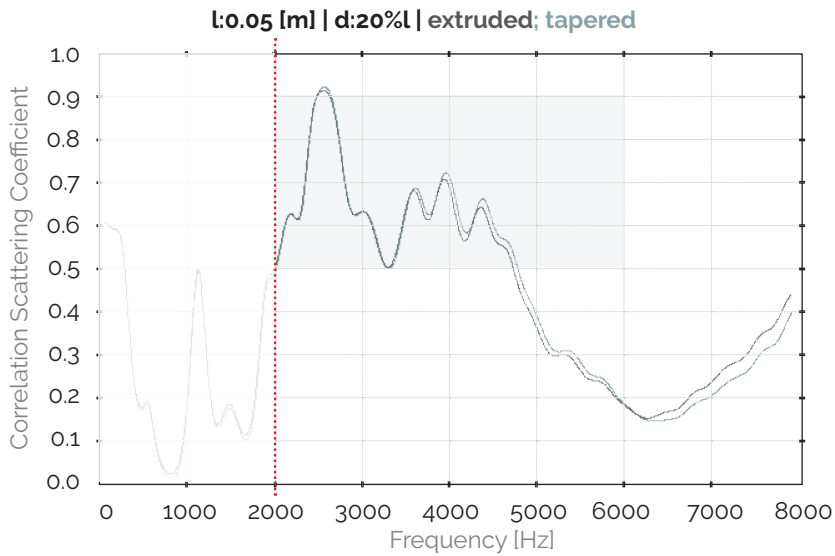
Table 6.1: Simulations

typologies				properties	well		depth				
							20% l [m]	50% l [m]	150% l[m]	200% l[m]	
TILING	PENROSE		small	legth: 0.05 [m] cells: 300	extruded	two depths	0.01	0.025	0.075		
						various depths	0.0025; 0.005; 0.01			0.025; 0.05;0.1	
			tapered		two depths	0.01	0.025	0.075			
					narrow width	0.01	0.025	0.075			
	RHOMBILLE		large	legth: 0.085 [m] cells: 150	extruded	two depths	0.01	0.025	0.075		
			small		legth: 0.05 [m] cells: 350	extruded	two depths	0.01	0.025	0.075	
							various depths	0.0025; 0.005; 0.01			0.025; 0.05;0.1
tapered	two depths	0.01	0.025	0.075							
	narrow width	0.01	0.025	0.075							
VORONOI	BASIC		small	legth: 0.03 [m] cells: 400	extruded	two depths	0.006	0.015	0.045		
						various depths	0.0015; 0.003; 0.0045; 0.006			0.015; 0.03; 0.045; 0.06	
			tapered		two depths	0.006	0.015	0.045			
					narrow width	0.006	0.015	0.045			
	large	legth: 0.05 [m] cells: 200	extruded	two depths	0.006	0.015	0.045				
	CVT			small	legth: 0.03 [m] cells: 400	extruded	two depths	0.006	0.015	0.045	
							various depths	0.0015; 0.003; 0.0045; 0.006			0.015; 0.03; 0.045; 0.06
		tapered		two depths		0.006	0.015	0.045			
				narrow width		0.006	0.015	0.045			
		large		legth: 0.05 [m] cells: 200	extruded	two depths	0.006	0.015	0.045		



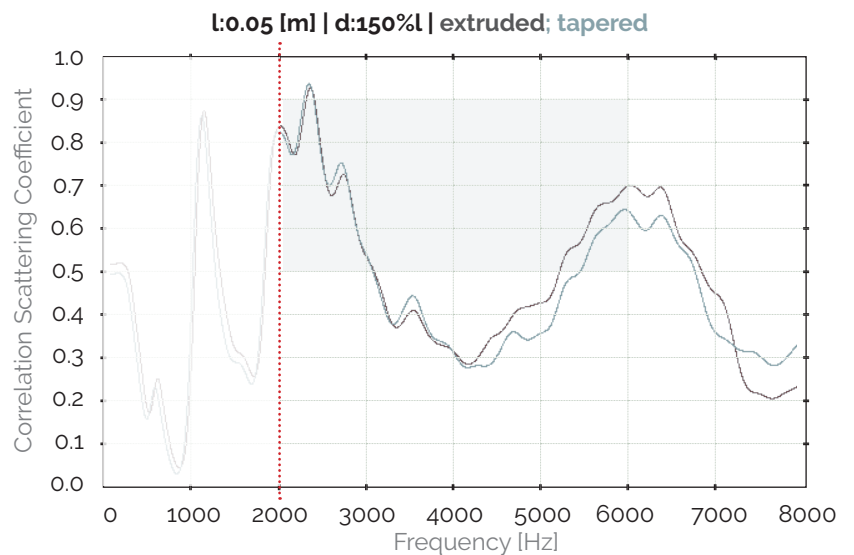
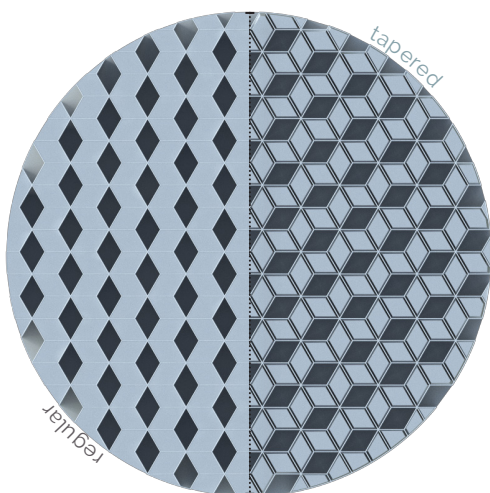
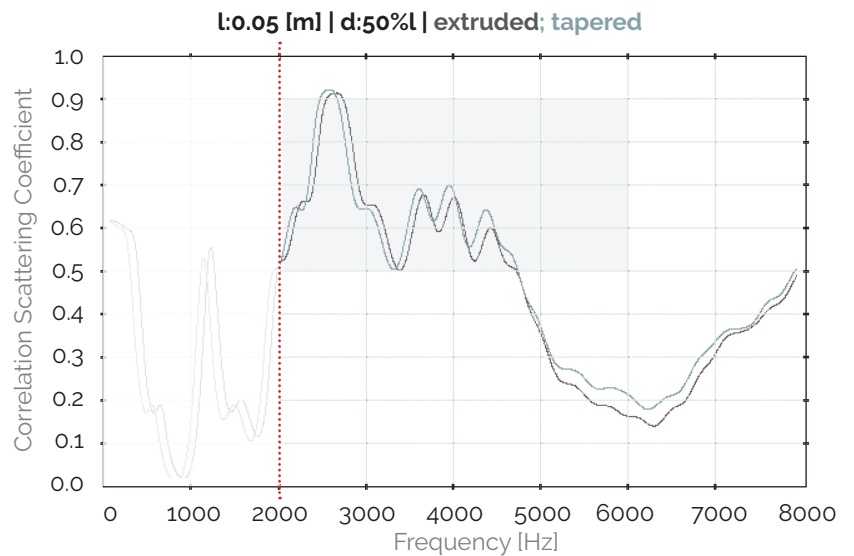
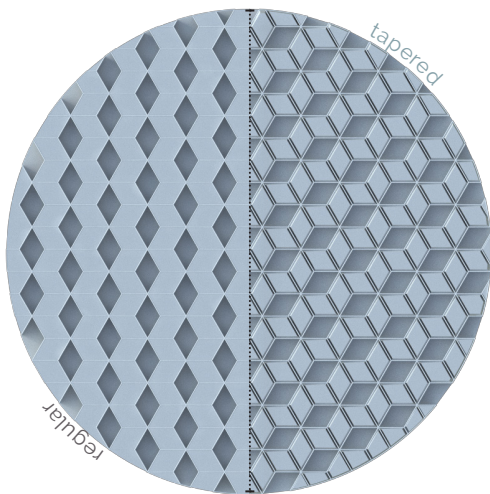
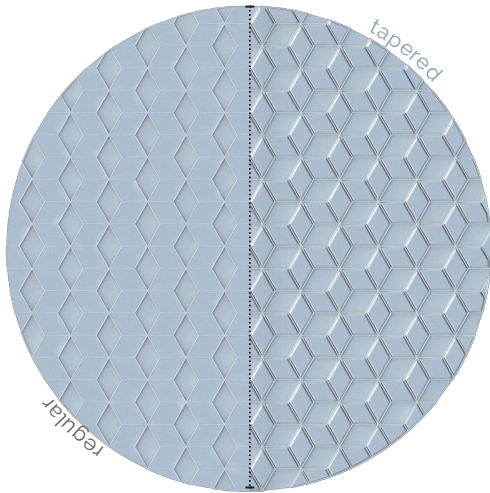
Aperiodic Penrose Tiling

Considering the variation of the depth, the case of d:50%l has a smoother curve, whereas the higher the percentage, there is an increase of magnitude in higher frequencies, meaning that the coefficients increase steadily as the depth becomes greater relative to the side length. Next to that, the effective frequency range broadens when d:150%l but a drop of magnitude for the mid frequency range is to be noticed. The tapered version seems to have on average increased magnitude than the extruded but the effect seems to be relative small.



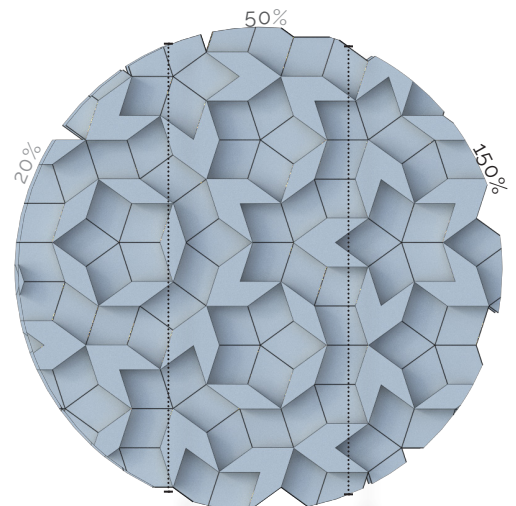
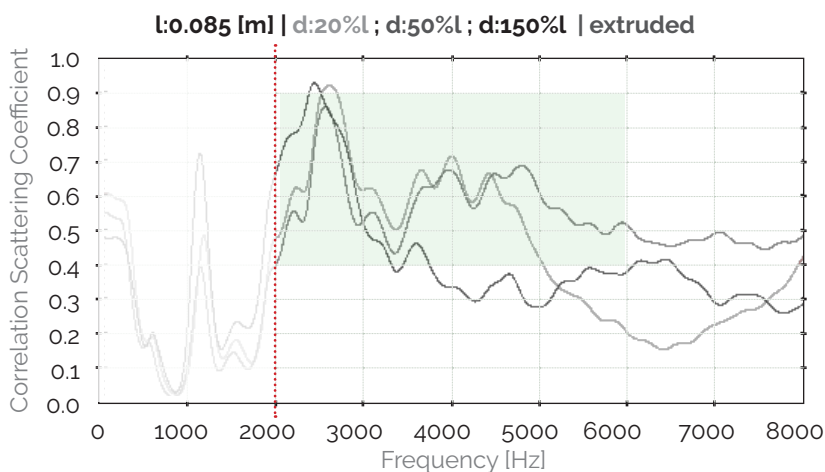
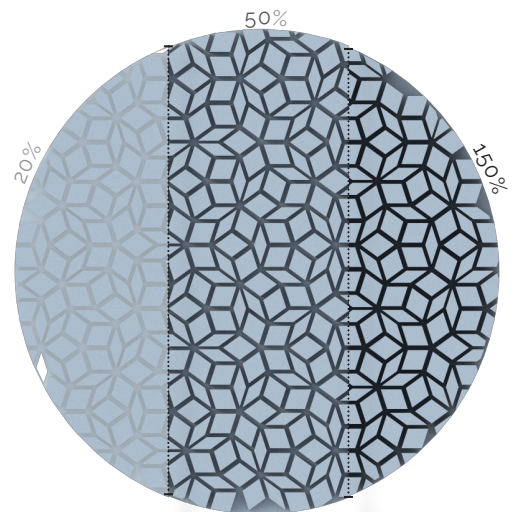
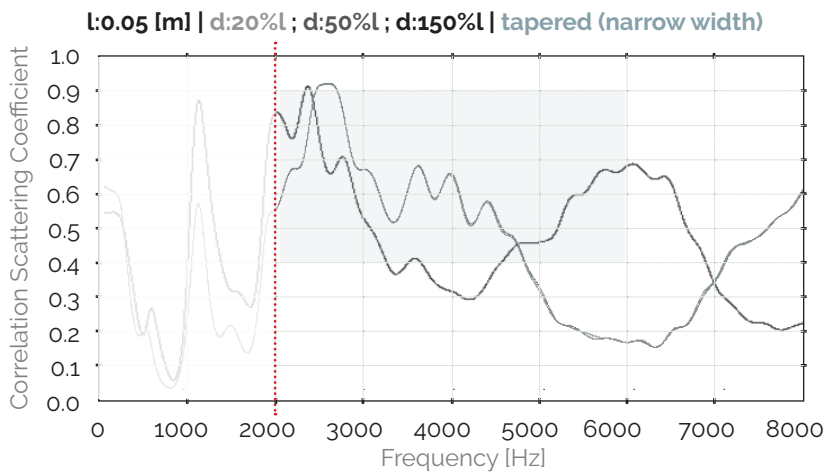
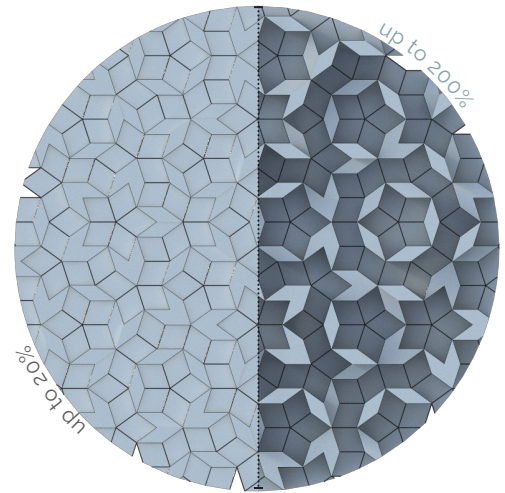
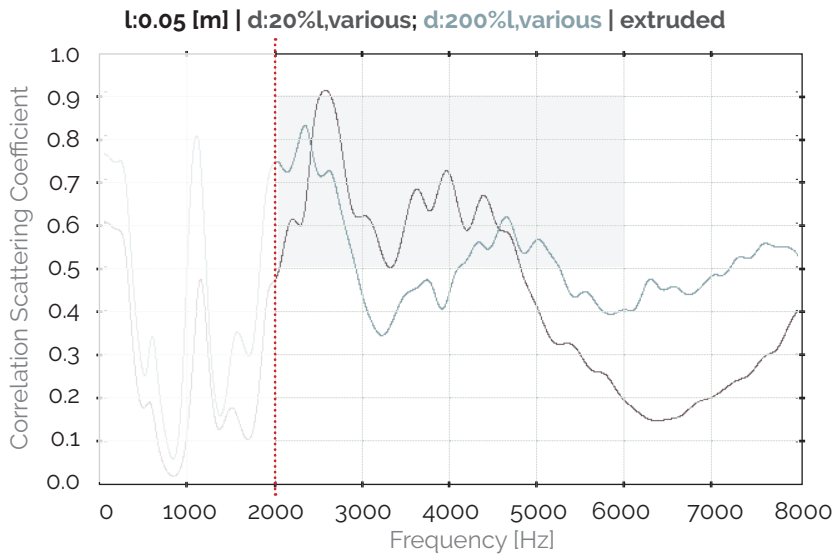
Periodic Rhombille Tiling

Comparing the periodic with the aperiodic device, the effect of periodicity is not clearly noticeable. Only in case of d:50%l the aperiodic device gives a smoother graph for higher frequencies. Nevertheless, the periodic arrangement of d:150%l gives the highest values for high frequencies. Again, the tapered version goes with relative higher values except for the d:150%l where a considerable drop is noticed for the higher frequencies.



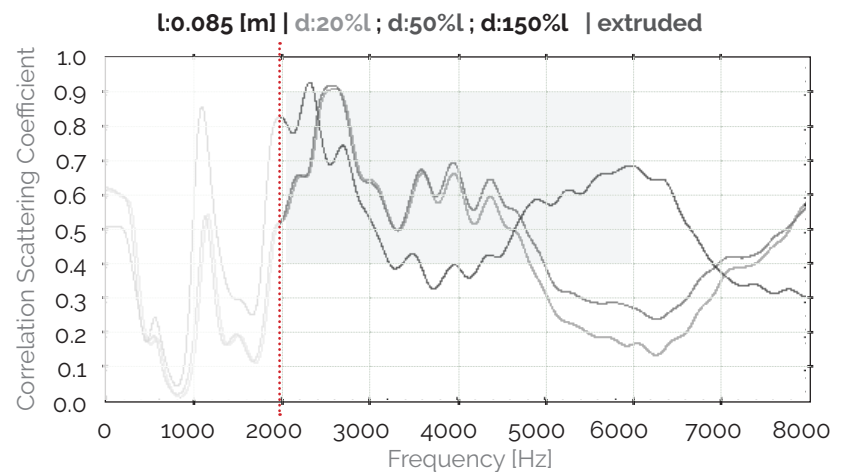
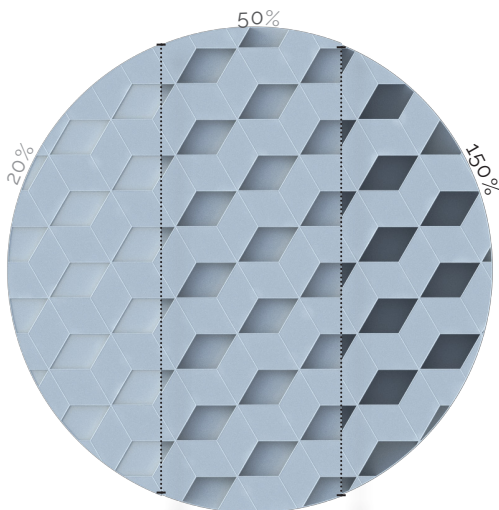
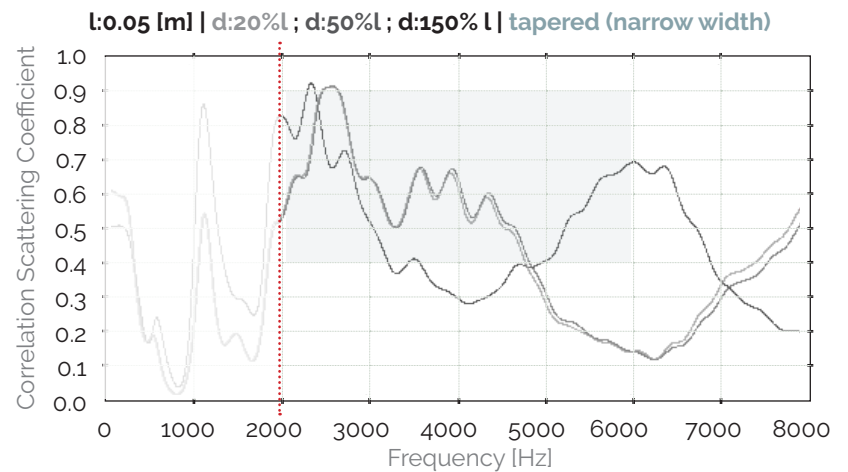
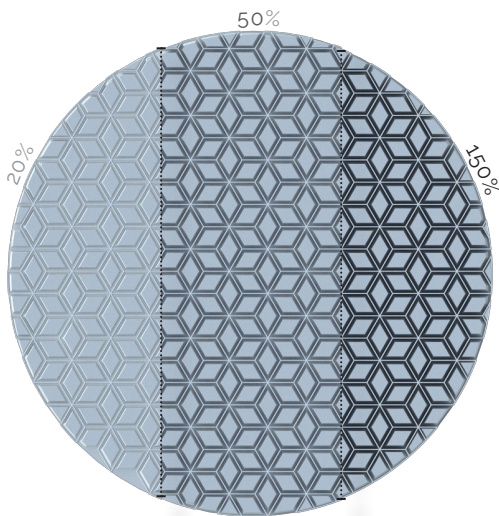
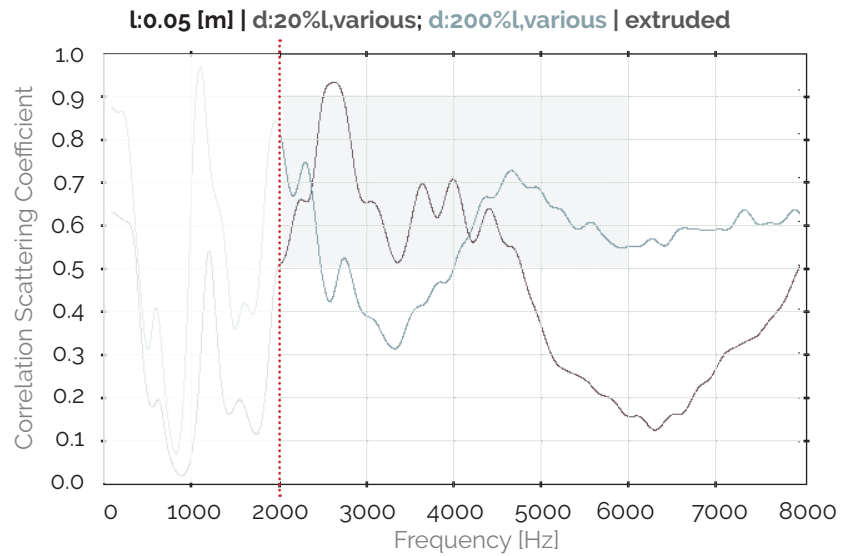
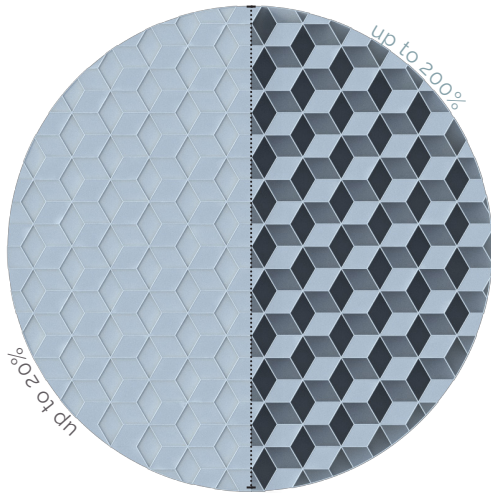
Aperiodic Penrose Tiling

When varying depths, setting the maximum to d:200%l extends the effective frequency range though a considerable drop of frequency design magnitude, whereas decreased maximum depth gives an increased design frequency. Last but not least, increasing the period for the same depth to length ratio gives similar performance for d:20%l and d:50%l but a considerable decreased magnitude with d:150%l.



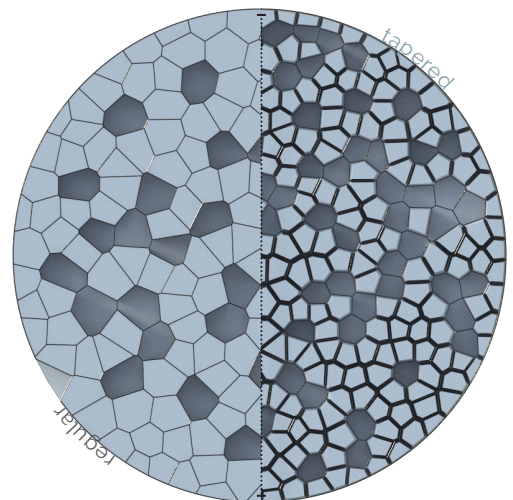
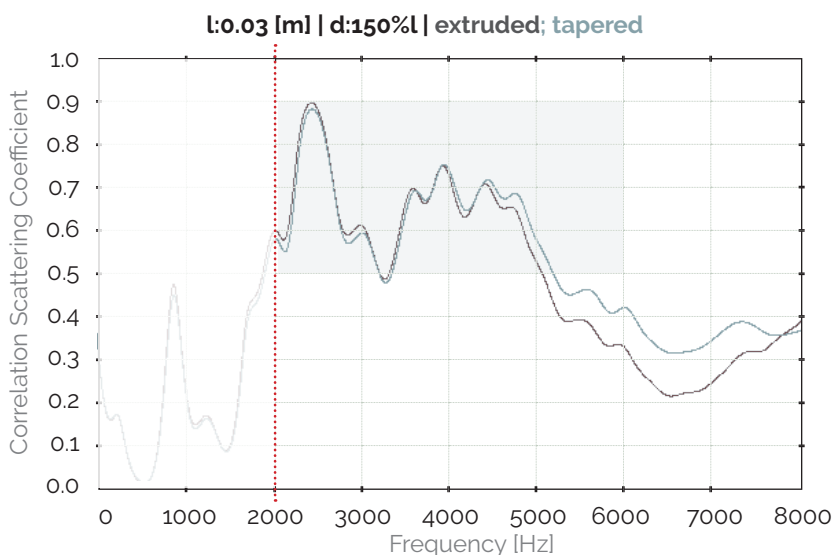
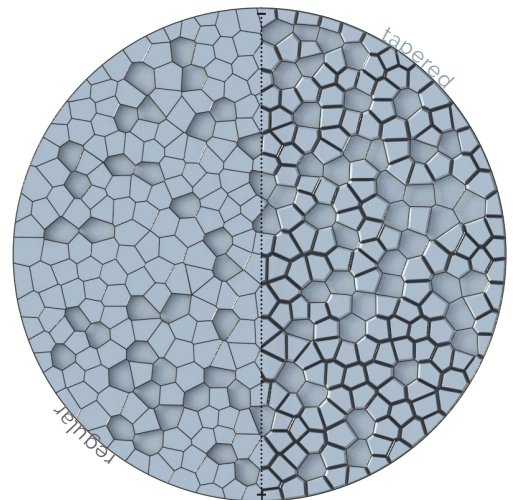
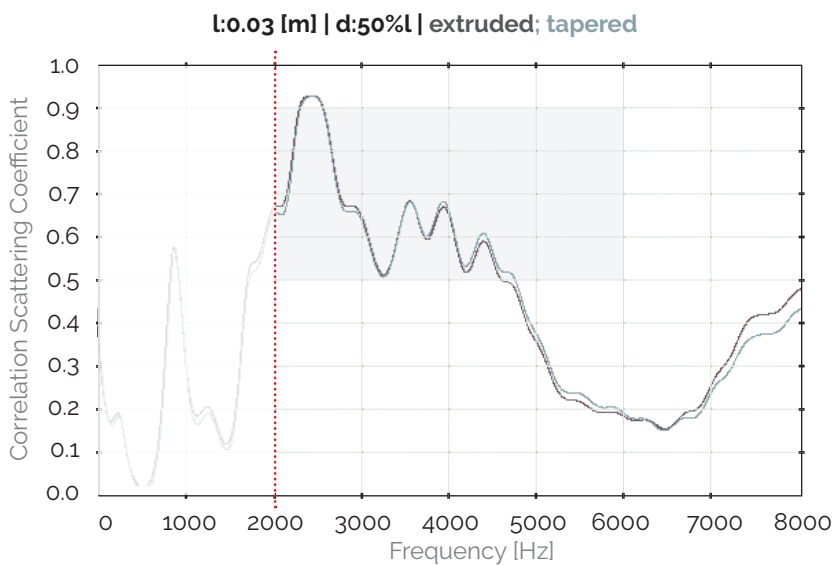
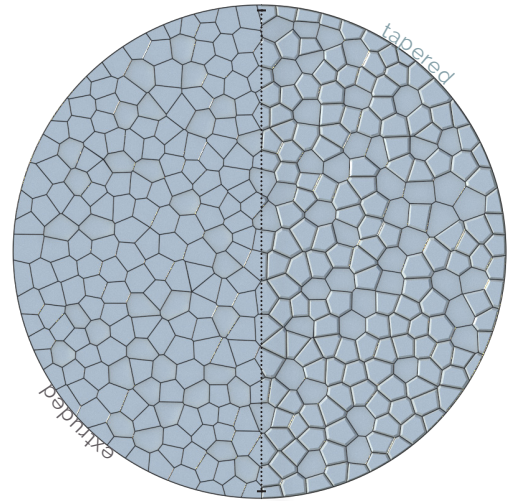
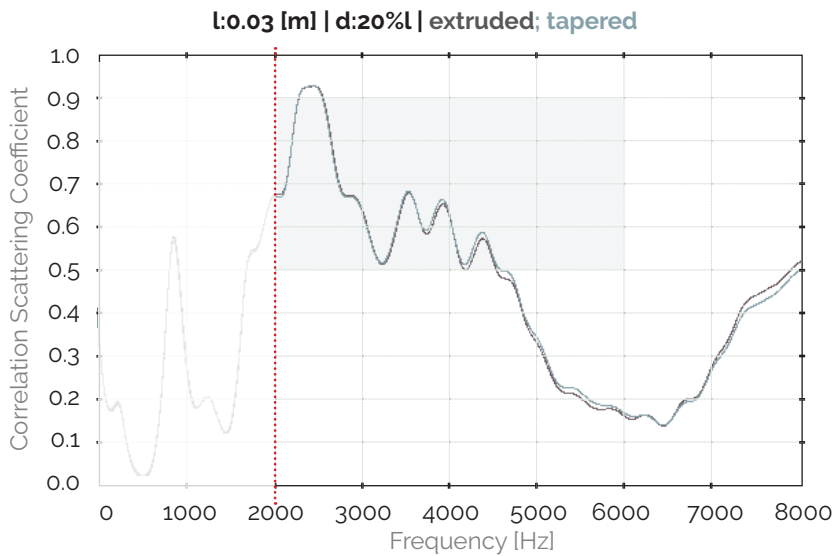
Periodic Rhombille Tiling

The case of various depths is the only one where the influence of the well depth on the frequency range is visible. Next to that, as expected, if the well depth gets bigger, the magnitude of the design frequency drops. The peaks and valleys continue to be visible, though in case of various heights and a maximum of $d:200\%$ the performance is extended to higher frequencies. The *narrow width* does not give any differences compared to the previous tapered versions.



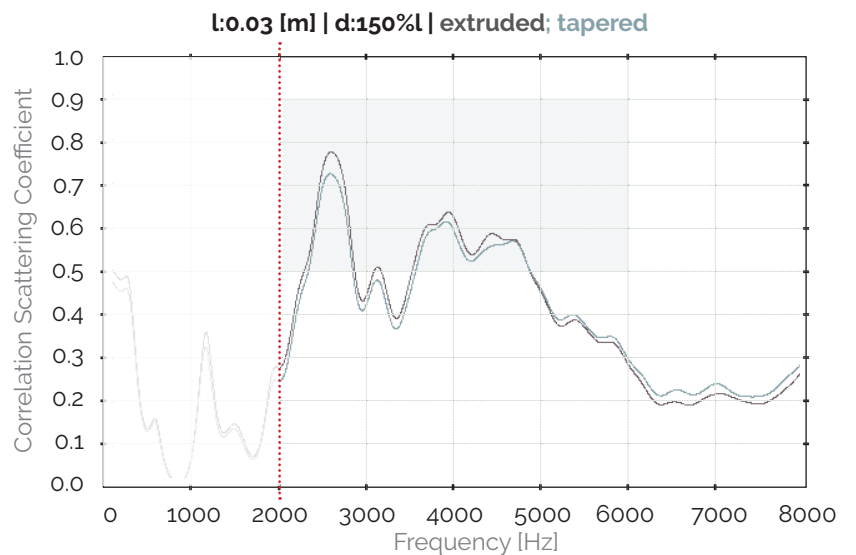
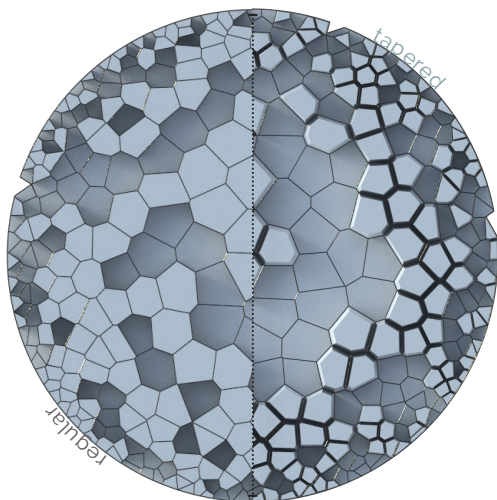
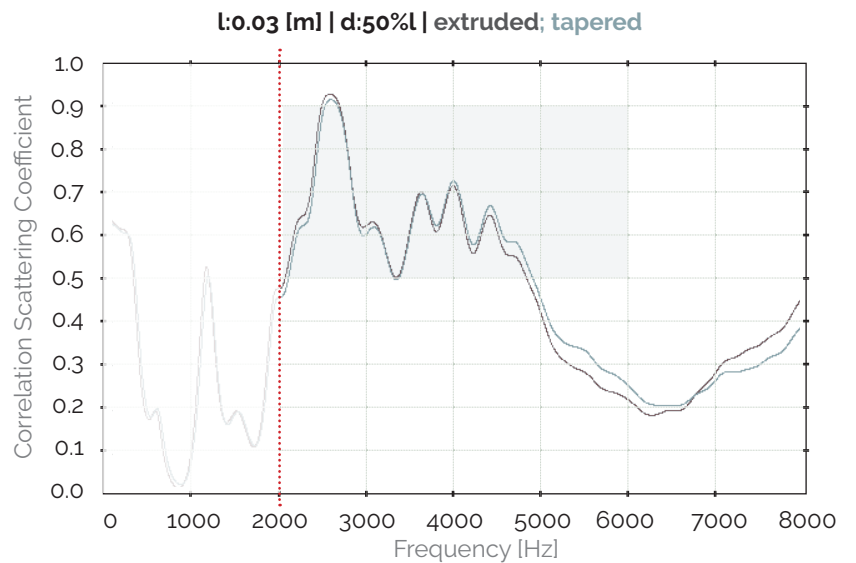
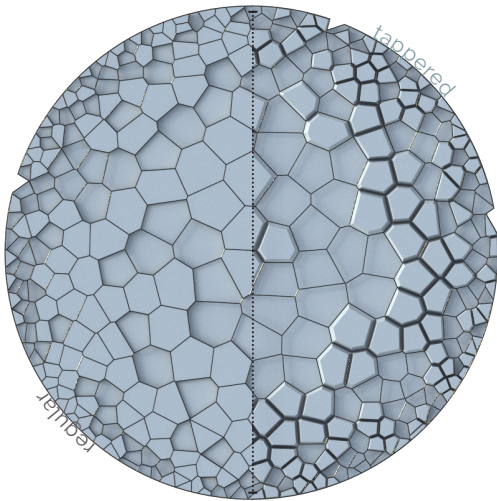
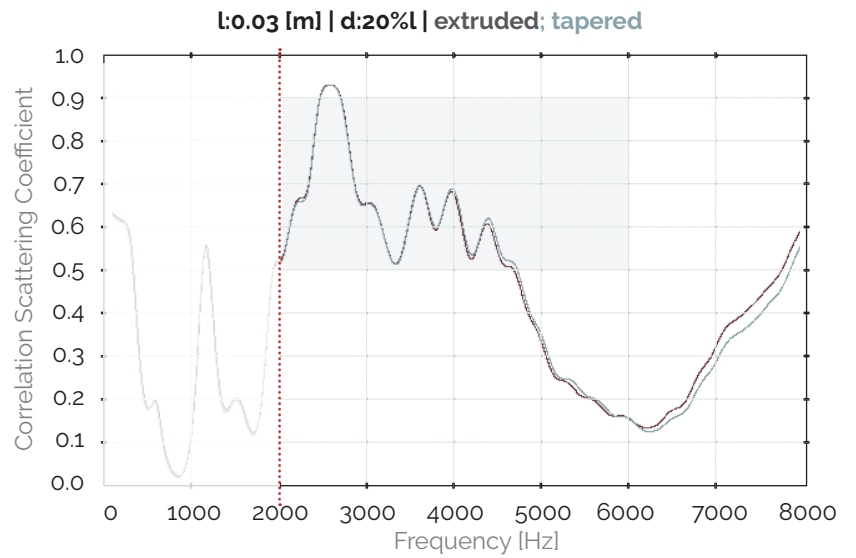
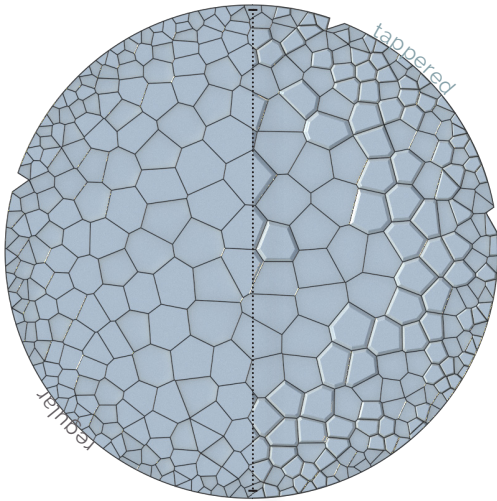
Non-periodic Voronoi

The non-periodic devices show a similar performance to the periodic devices with visible peaks and valleys. The tapered version shows a significant improvement when $d:150\%$, whereas a broader mid-frequency range is noticeable with increasing depth, rather than the drop that was noted for aperiodic devices. However high frequencies tend to have decreased magnitude. What is to be noticed is that the effective frequency range is not extended with increased depth, as in cases of aperiodic devices.



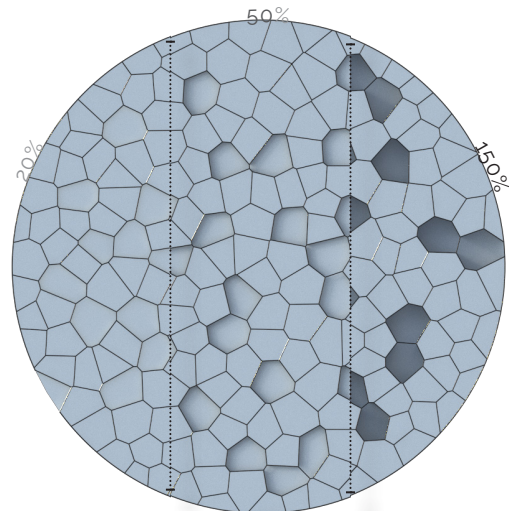
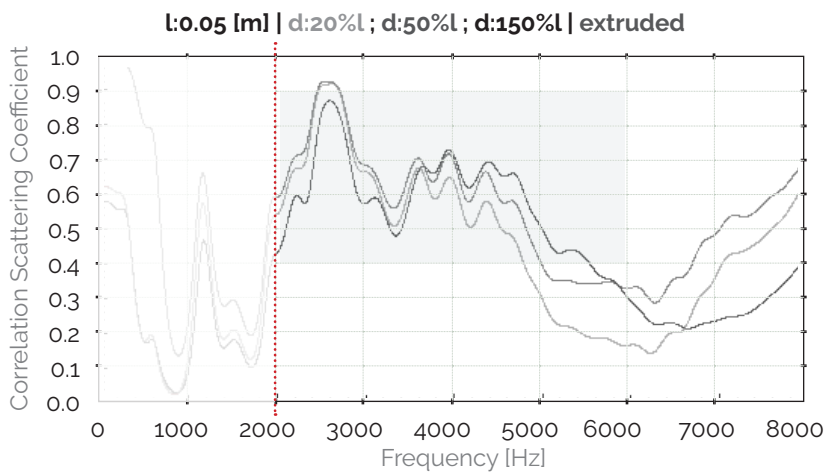
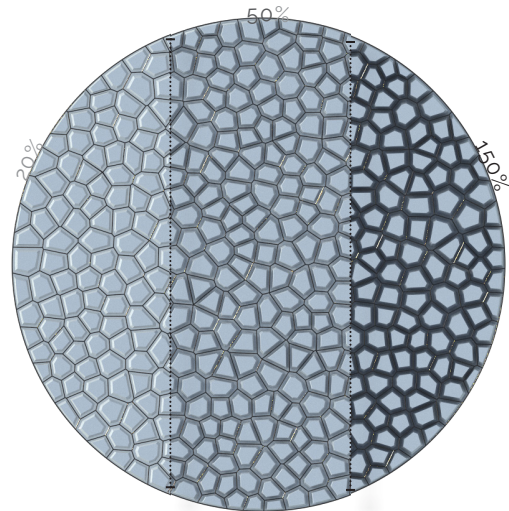
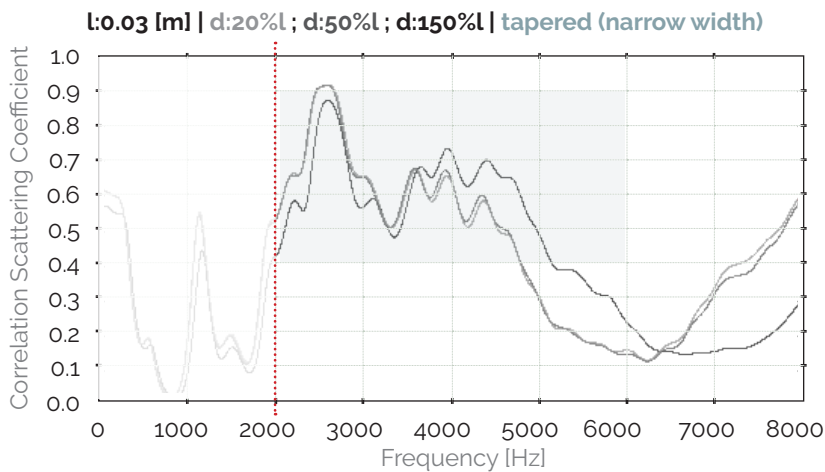
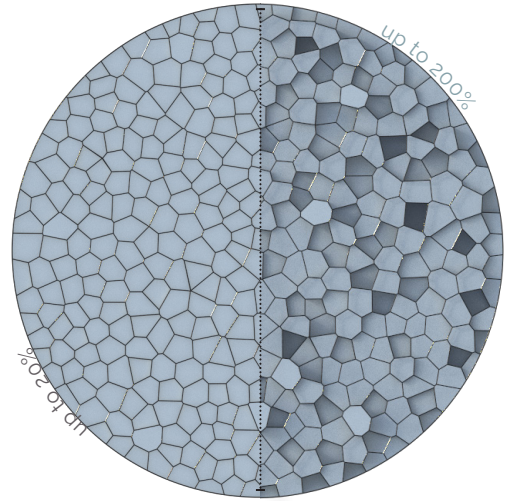
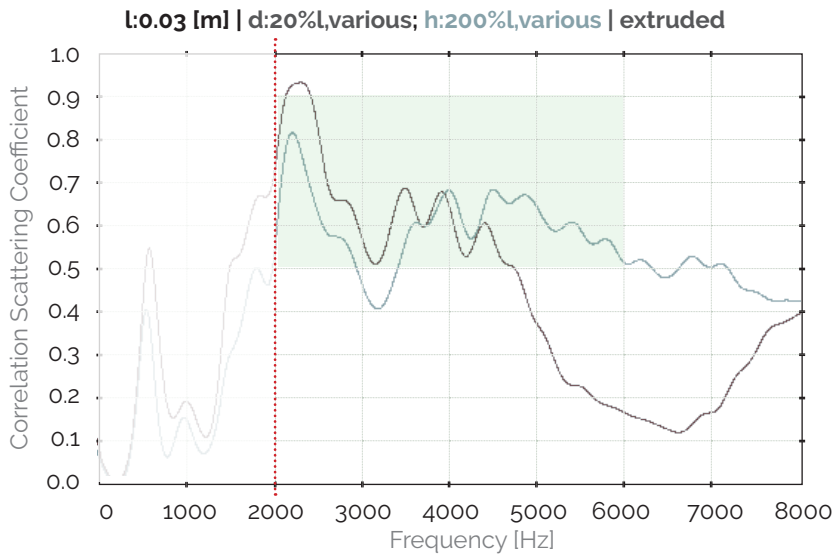
Periodic Centroidal Voronoi

The periodic devices in this case have an almost identical performance compared to the non-periodic ones. This is also because this typology is created as an approximation of a periodic device. However, what is relevant to be mentioned is a considerable drop of magnitude for d:150%l of the design frequency compared to the non-periodic performance.



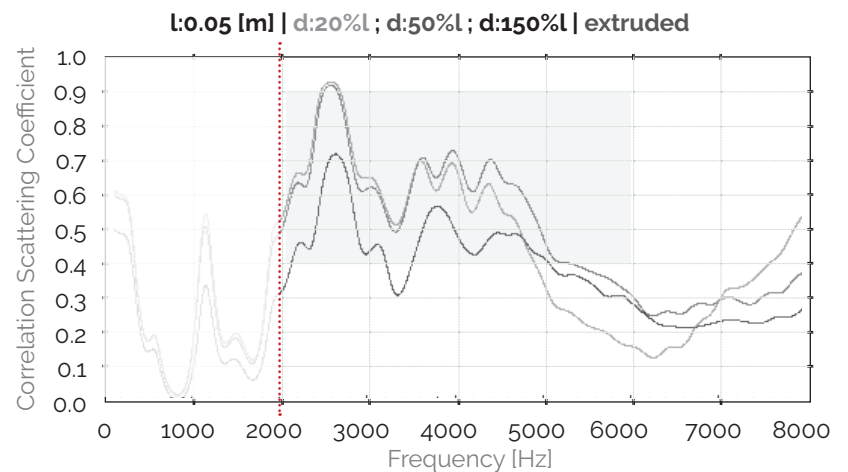
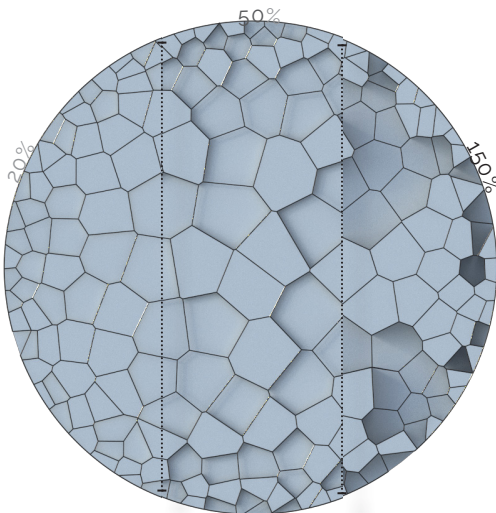
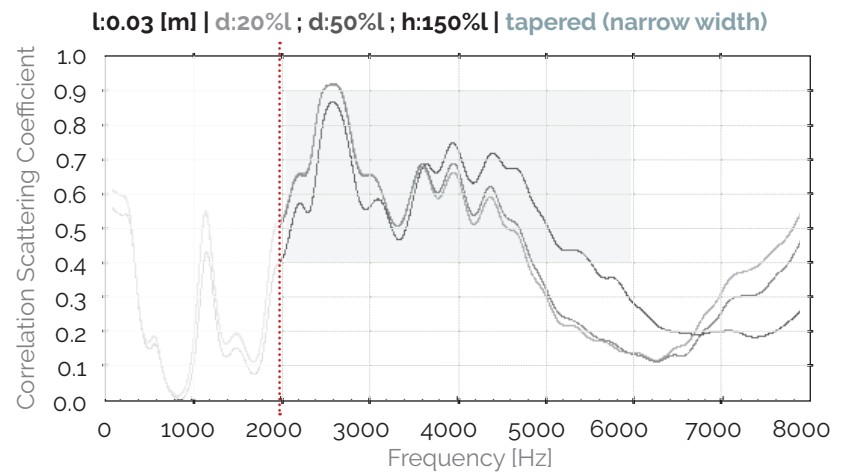
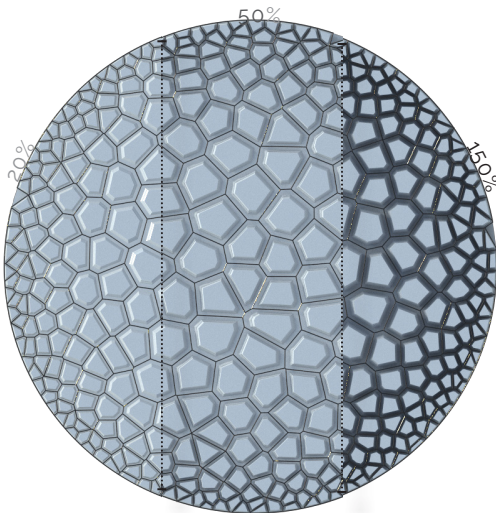
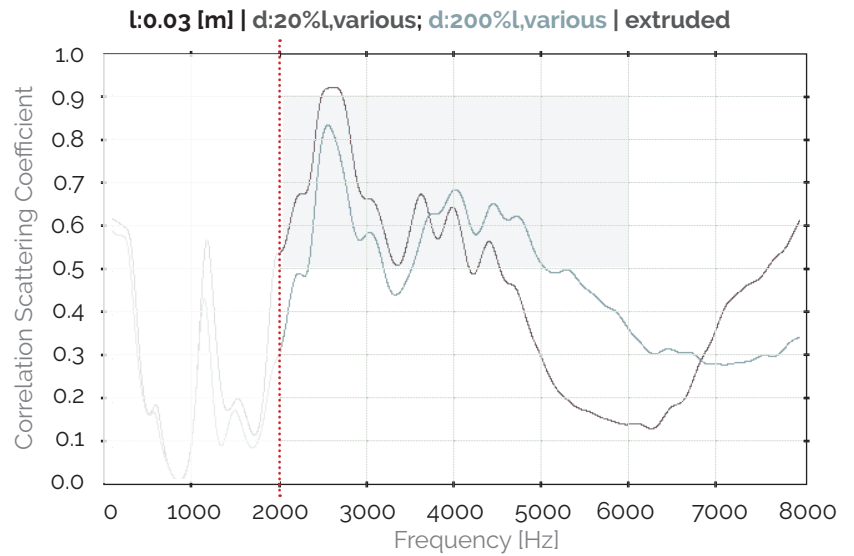
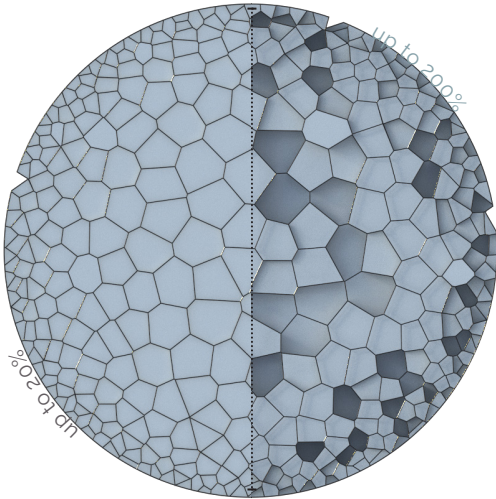
Non-periodic Voronoi

For the non-periodic devices, the most extended scattering performance is achieved with various depths and a maximum of $d:200\%l$ -again with decreased magnitude of the design frequency-. Moreover, the coefficients are roughly equal to the previous results when a narrow width tapered version or when the period is increased.



Periodic Centroidal Voronoi

Comparing the periodic with the non-periodic devices, a considerable drop is to be noticed for high frequencies when various heights are given, indicating that the device's performance cannot be extended in higher frequencies. Last but not least, similar to the previous results for d:150% a considerable drop of the design frequency is to be found also in case of increased period.



Case Study

- Though from theory of the Schroeder diffuser it would have been expected that the peak of the design frequency would change as the depth of the well changes, this was not the case for the aperiodic devices. According to the case study this performance varies depending on whether there is a random or normal incidence. Though this applies for random incidence, in case of normal incidence -simulations- the design frequency is not shifted relative to different well depths. Nevertheless, the effective design frequency range is extended.

- Another important result from the case study was the comparison between the Penrose devices with an 1D rectangular periodic surface of the same depth. Though both had similar scattering plots, the incidence-angle dependence was remarkably different between them, whereby the periodic device had decreased scattering capacity under specific incidence angles at high frequencies.

Discussion for selection (Figure 17)

- The influence of wave-related effects (interference and diffraction) needs to be considered, in that the rear of the surface was not enclosed in a box. In addition to that, geometrical errors have led to missing tiles of the circular area. The scattering performance due to this may be responsible for high values of low frequency scattering.

- Considering comparison cases of the ISO scattering coefficient and the correlation scattering coefficient their performance seems to match mostly for higher frequencies (Cox & D'Antonio, 2016). Therefore, the obtained graphs are comparable after 2kHz.

- For randomly rough surfaces the ISO and correlation coefficients will be similar, but for diffusers with distinct polar responses, this is not the case (Cox & D'Antonio, 2016). Nevertheless, with caution, fast comparison results can be obtained for geometric room acoustic modelling.

- Narrow width of wells indicated a similar scattering performance, which is questionable. Nevertheless, considering that the width was very small certain limitations of the software for evaluating microgeometries could be the underlying reason.

- The depth of the well is strongly related to its diffusion properties. In order to achieve soft reflections a depth of 10-30mm is efficient, whereas to eliminate echoes a greater depth of 50-90 mm is more appropriate (Rahm et al., 2018). Further, deeper valleys potentially increase absorption, which was not included in the results of the simulations

- However, more than 50% depth-to-length ratio was found to decrease the scattering performance within the relevant frequency spectrum.

- The vertical profile had a small impact on the magnitude of the scattering coefficient with the tapered profile achieving on average higher values. However, at high frequencies small scale specular reflection is expected for angled or curved surfaces which was visible mainly for the Voronoi designs especially when the depth increased.

- The variability of surface depths made to clear contribution to the magnitude of the correlation scattering coefficient for the relevant frequencies, thus such a variation is suggested to be avoided in order to lower the complexity.

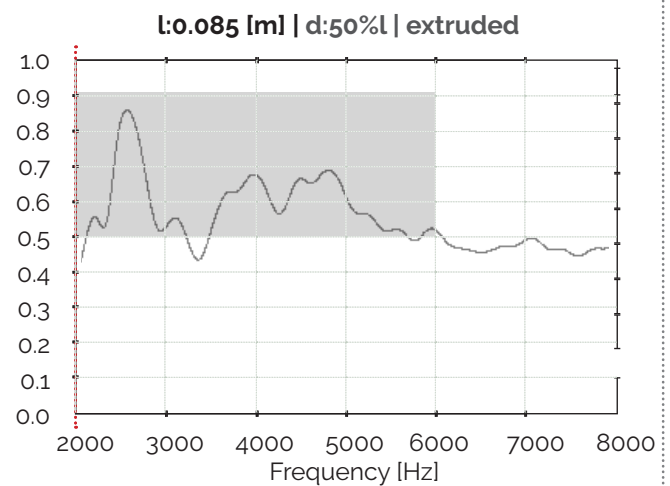
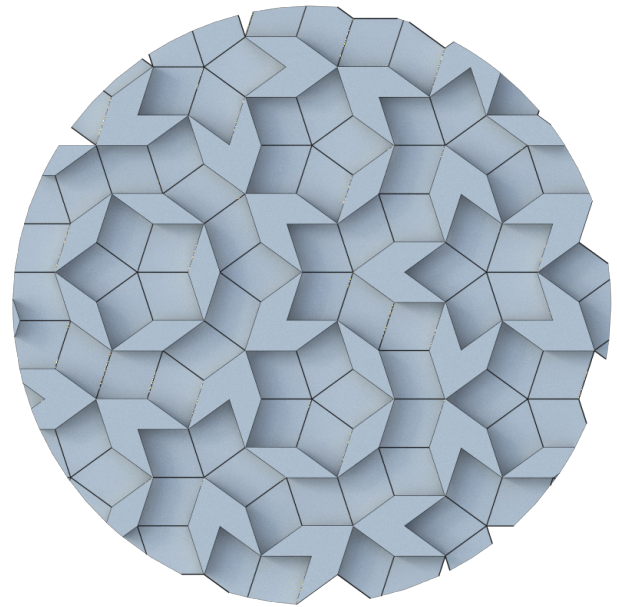
- Based on the results of the paper of Penrose diffusers, given that the simulation considers normal incidence and since periodic surfaces are deeply related with incidence angle the visible differences between periodic and aperiodic performance were limited. Nevertheless, only the 50% depth-to-length ratio aperiodic pattern managed stay within the targeted frequency range, which seems promising.

- Tiling -periodic and aperiodic- was found to perform better than Voronoi patterns, which managed to achieve the performance within the required frequency range only in case of various heights and 200% depth-to-length ratio.

[Reinhardt et al., 2016]

Future research

- Different angles of tapered geometry need to be further investigated, since an increase of magnitude was noticeable for the tapered versions.
- Investigate the uniformity of scattering directivity (directional diffusion coefficients), since higher diffusion coefficients are associated with higher uniformity of scattering directivity.
- The ISO specification suggests that a test sample with rotational symmetry shall be placed in such a way that the centre of symmetry is displaced from the centre of the turntable. Considering the Penrose tiling pattern (5-fold rotational symmetry), the right placement lies on further investigation to obtain more accurate results.
- The extend of valid results for microgeometries evaluated by the Pachyderm plug-in need to be further investigated for the validity of the results. Results obtained for d:20%l and 50%l raised concerns when placed on z=0 and therefore a z=0.05 was thought to give more valuable results in those cases.
- The unusual properties of Penrose tiling that move beyond them being simply plane-filling patterns, seem promising for estimating further acoustic properties. The influence of self-similarity of the Penrose tiles needs to be further investigated, since incorporate different periods might yield a smoother curve.
- Deeper analysis is required for typologies that though unstructured globally, show a high degree of regularity locally and can be of value for their non-repetitive sequences for uniform dispersion of sound.
- Investigate properties of space-filling rather than plane-filling geometries -Ammann's tiles, rhombohedra- that allow for three-dimensional aperiodic configurations.
- Further research is required to draw geometric relationships between parameters that describe surface form and acoustic scattering
- New ways of estimating scattering performance need to be invented. Combined workflows need to allow for designs to be evaluated without the need for measurement equipment. To that end, the FFT power spectrum analysis seems promising.



CHOOSE APERIODIC PATTERN



CONSTRAINS: MINIMIZE AMOUNT + AVOID
VARIABILITY OF ELEMENTS



INVESTIGATE DIFFERENT VERTICAL PROFILES



PARAMETERS: SIDE LENGTH + PERIOD [BIG] +
WELL [NARROW]



AVOID MORE THAN 50% DEPTH-TO-
LENGTH RATIO FOR IMPROVED SPEECH
INTELLIGIBILITY

Figure 17: Final selection of aperiodic pattern

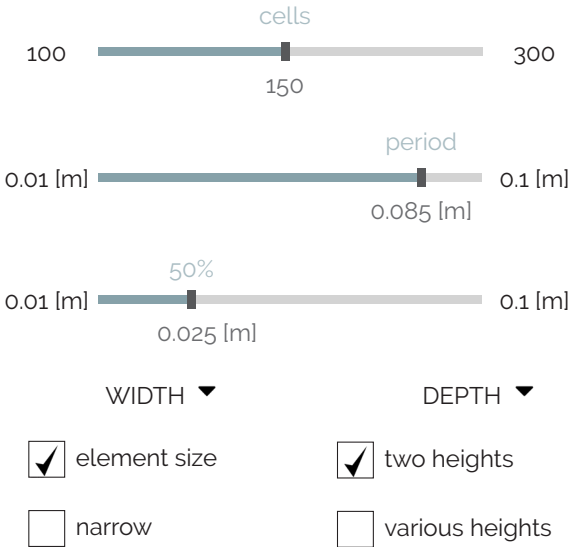
Combining the results of the previous stages, the case study scenario is developed, based on a balanced ratio between acoustical and design standards. The aim is to minimize depth, number of elements and complexity without compromising the acoustic performance.

In line with the research hypothesis, the chosen geometrical configuration targets coefficients determined within the range of alternative 2.5(balanced) and alternative 2.6(broadband scattering), whereby the basic configuration of the Serpiensky arrangement meets the requirements for constituting the macrogeometry. Due to similar results in the geometrical acoustics simulation, this is allowed to be modified by the children in the second configuration by rotating certain panels and interacting with the structure. Last but not least, for transparency reasons and since this seemed to improve the acoustical performance, the upper partitions do not include scattering and aim for transparency via a microperforated glass sheet.

For the microgeometry the selected typology (Figure 18) goes by Penrose tiling due to their unique properties and recognised potential for uniform scattering. As far as the dimensioning is concerned $l=0.085$, namely the bigger period with $d=50\%$ seem to be a good match for a preschool environment. The increased period gives similar results of scattering performance, whereby reducing to half the number of prototiles for covering an 1m^2 surface area is efficient in terms of material usage and ease of constructability.

Considering the requirement for a hybrid surface for the lower partition, absorption had to be incorporated. Attention was given to the Schroeder diffuser's flaw, which was found to have high absorption at low frequencies due to application of resonance in the well system. The techniques of introducing either resonance in the wells of the diffuser, or micro-perforation on the surface pattern had to be considered.

pattern ▼	profile ▼	parameters ▼
Penrose tiles	tapered	cells
Robinson tiles	extruded	period
Ammann tiles		well
Shield tiles		
Danzer triangles		
Wang tiles		
Robinson triangle		



absorption ▼	material ▼	system ▼
porous	cork	
plate	bamboo	
membran	desert sand	
helmholtz	bioplastics	
mf	timber	
tube resonator	mycelium	

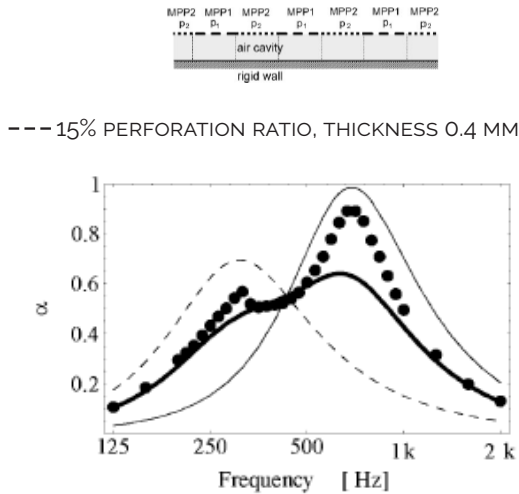


Figure 18: Procedure for selection of optimum pattern



Material considerations come next, whereby sustainability concerns and optimum weight -with high frequencies requiring less weight to reflect sound (Rahm et al., 2018)-, are factors that guide the decision. The option of cork seems promising for a pre-school environment due to its antimicrobial, non-allergenic and fire retardant properties. Being harvested from the bark of living cork oak trees, it is associated with a renewable process, since it regrows after 10 years. Last but not least, considering the safety requirements for a playroom such an option is favorable due to the inherent softness of the material.

The assembly system involves a set of two pre-manufactured 3D unit cells (**Figure 19**), termed prototile bricks, which can be assembled on-demand. The bricks become, in isolation, the building blocks of an assembly, encoding prerequisite phase delays. Starting from a limited set of unique bricks, a meta-surface is synthesized via optimizing the number of bricks and the depth of the wells, laying the foundations for realization of spatial sound modulators (SSMs). A dual function is further suggested, whereby children can interact with the design. The blocks are in two different colours, whereby the elements can rotate in order for the users to manipulate the visual appearance of the pattern as a whole and gain awareness how modifying the micro-scale affects the macro-scale.

The system is designed for disassembly in such a way that the components of the design can later be upcycled. The frame can become useful as shelves, whereas the prototiles can become elements of block play learning resources, whereby children learn and develop the essential skills of critical and creative thinking, literacy and numeracy, analytical problem solving, communication and collaboration.

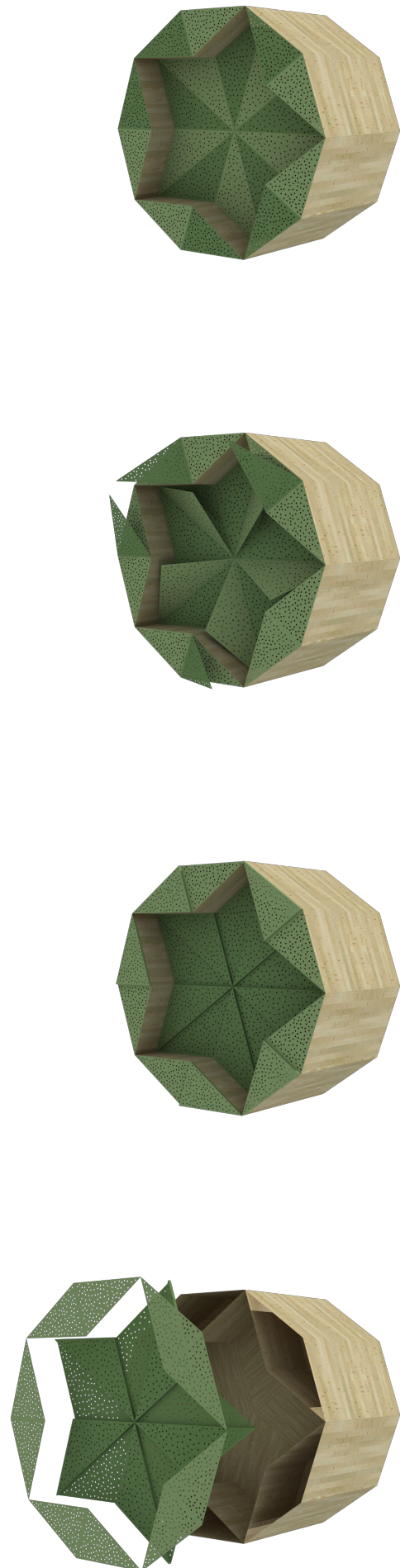
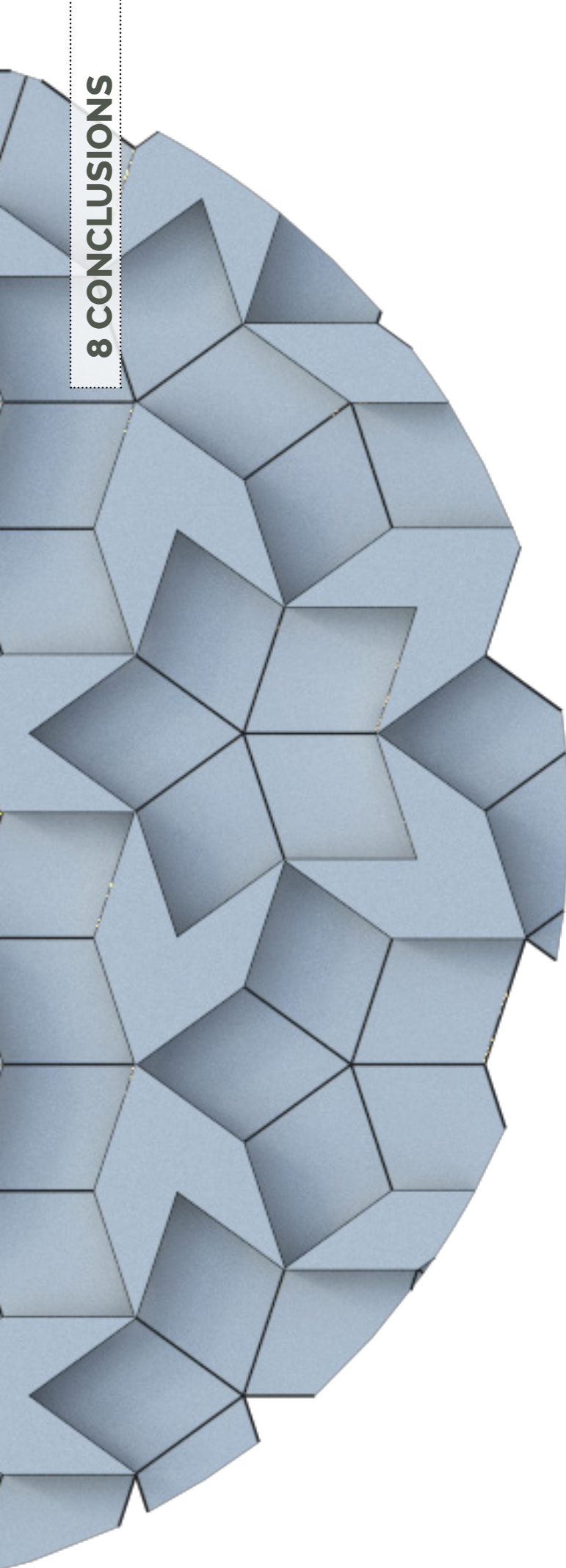


Figure 19: two prototile unit cells



Poorly designed room-acoustics have a detrimental effect on the performance and physiological condition of the individual and as such care should be given, shifting the focus from perfectly tuning performance spaces to carefully designing everyday facilities where people spend most of their time. In order for designers to be encouraged to comply to acoustic guidelines during the design process, each treatment can serve a dual function - being a toy as well as an acoustic modulator. Of course designers will and should not become acoustic consultants but they need to gain a basic understanding under which circumstances can certain geometric rules be successfully applied and further become aware how their design choices will affect the acoustics of a space both in a micro- and macro- scale.

In order to argue upon the initial hypothesis "How can different periodicity patterns applied on fibreless surfaces provide a toolbox for designers that aim for a balanced ratio of speech intelligibility and speech privacy in an ILE school by allowing low-frequency absorption and high-frequency diffusion?", the methodology needs to be deconstructed and the answer should be given in a reversed order. Several guidelines for designers can then be drawn.

The first step is to carry a macro-scale analysis in order to define what are the optimum proportions for absorption and diffusion that comply with the desirable acoustic measures for a given scenario. In terms of the current research for an absorptive situation (acoustic ceiling), 90% absorption for low-frequencies and 50-90% diffusion for high-frequencies is suggested. A first remark according to the macro-scale study is that not every surface should be treated similarly. The percentages could also vary with the given height. Therefore, it is important to identify early in the design process where critical acoustical treatment is needed in order to inform design decisions in parallel with an acoustic analysis. It is important to study how the reflections would distribute within the macro-scale in order to identify long-path echoes. The chosen diffusing pattern should then serve two functions; cause soft reflections or eliminate echoes, by respectively increasing the depth.

In order to achieve a balanced ratio of speech intelligibility and speech privacy the aforementioned percentages of absorption and diffusion play a central role, whereby the question of "where" needs to be clearly addressed. This should account for privacy allowing for extended reflections within the enclosure and prohibit sound from being transmitted in the immediate surroundings. Complementary to that, certain measures that are used to evaluate acoustic performance should be carefully revised and tailor-made for diverse user groups. By today, there are distinctive measures for different genders but more groups need to be further included. Children's voices are active in a different frequency range than adults and therefore the weighted factors for estimating STI, U50 etc that are taken into account for preschools or schools should differ. Modified weight factors are further suggested based on the hypothesis that low-frequency vowels should be absorbed in order not to mask high-frequency consonants, whereas the latter ones need to be scattered for improved speech intelligibility.

Moving from macro- to micro-scale the periodicity of the selected pattern towards uniform scattering performance should define the geometrical rules that will lead to improved speech intelligibility. In general, it was noticed that tiling - periodic and aperiodic - had a better performance than Voronoi patterns, which justifies that simplicity in terms of a finite set of elements is preferable. However, due to the fact that the Pachyderm simulation considers normal incidence and since periodic surfaces are deeply related with incidence angle, the current research did not manage to confidently state whether aperiodic, periodic or non-periodic patterns are preferable. Nevertheless, the selected design -aperiodic- was the only one that fulfilled the requirements within the relevant frequency range. This fact, followed by the conclusions drawn

during the stage of literature review, strengthens the possibility for aperiodic patterns having a superior performance. From the simulated versions various properties can be identified. Increasing the depth-to-length ratio more than 50% was found to decrease the magnitude of the scattering coefficient among all the tested periodicity patterns. Further, the variability of heights is suggested to be avoided, since it does not seem to have any direct contribution for the targeted frequency range, whereby the complexity of the final design is raised. The selection of the period should be made in close relation to the depth-to-length ratio. According to the results in case of a 50% ratio, a bigger period for all periodicity patterns improves the performance for the high frequency range. Lastly, the width of the well is suggested to be kept narrow, though this could not be successfully simulated via the software since this does not seem to provide accurate results when it comes to evaluating microgeometries.

The dimensioning of the selected pattern should then be combined with an absorption treatment in order to allow for a hybrid function of both absorption and diffusion, whereby a fibreless approach is favoured. The selection can be based on the targeted frequency range as well as on transparency and spatial requirements.

Last but not least one should consider the users, whose demands the design must meet. Preschool children were identified as the most vulnerable group for speech intelligibility, as argued from experts in psychology and neuroscience. The confluence of various disciplines apart from the ones that operate within the construction sector was thought to be of great importance. Therefore, aside from fulfilling the acoustic requirements, the aim was to further include variations of the proposed design since children have plenty of curiosity and imagination. Considering their fairly short attention spans, the proposed design aimed to boost motor activity, which was found to improve performance as well as facilitate social interaction critical for this age group. Towards that direction the current research is the first step towards defining some acoustic guidelines, while moving from an interdisciplinary to a transdisciplinary era, where various perspectives transcend each other to form a new more holistic approach.

Limitations

The macro-scale analysis was structured upon previously conducted studies, whereby the existing weighting factors and averaged measures were questioned. The measures per frequency band were preferred instead since the results had to be evaluated following common guidelines. As far as the micro-scale is concerned the research in this field is still ongoing and as such there is no proven flawless methodology available. Acknowledging however, that the aim was to evaluate the effect of periodicity which is highly dependent on the incidence angle a different software had to be chosen. The realization that the Pachyderm acoustics plug-in accounts only for normal incidence was made later in the process, thus the time constrain did not allow for an alternative approach. The current research investigated only the correlation scattering coefficient of different alternatives, which was however a better alternative than using the ISO coefficient since the measure gives an indication of performance for the given pattern compared to the flat surface, which was actually the departure point for this research.

Future developments

It is thought highly important to investigate whether any non-repetitive aperiodic sequence can indeed account for uniform dispersion of sound. An important last step would be a qualitative analysis, though preschool children are one of the most challenging user groups for conducting research.

The current research is part of the Sustainable Design Graduation studio within the master track of Building Technology. The link between the focus of the graduation lab, the master track and the problematic introduced by this project is the improvement of indoor environmental quality with respect to a sustainable assembly and disassembly system, while targeting the specific needs of a preschool population. Next to that the research had to fit within two disciplines, which in this case were Climate that formed the base of the literature review and Computational design that provided the mean to produce and evaluate different design alternatives.

Considering the inherent complexity of the chosen topic the approach followed by this research tried to handle the different scales that affected the perceived sound moving from macro-geometry to micro-geometry. After formulating the working hypothesis based on previously conducted research, the initial idea was to evaluate different surface patterns and conclude upon which frequency ranges needed to be diffused, rather than absorbed aiming for improved speech intelligibility and speech privacy. However, various questions arose in the process that raised the level of complexity. To what extend should some frequencies be absorbed or diffused? What properties of the spatial geometries influence the acoustic measures? What design properties concerning preschool environment could inform the acoustic research? Can a simple surface pattern raise a similar acoustic performance to a complex one? Can the design rules of a mass-produced finite set of tiles covering a surface with reduced manufacturing cost have a comparable performance to a customized expensive solution? Can the relevant depth for scattering be minimized if certain geometrical rules are applied, accounting for reduced material resources? These are only a few of the questions that triggered this research. Considering that every design proposal aims to improve the environmental quality of its users and since the target users of a preschool population are sensitive to various parameters, a holistically approach was favoured. As far as the evaluation procedure of different surface samples is concerned, the methodology had to be revised given the available resources. Since acoustic scattering on the contrary to absorption is a topic that is under investigation only for the past decade, software for estimating such coefficients being currently under development, are computational intensive and pose limitations. Though the tools used are highly experimental, they do provide results that are thought to be trustworthy for comparison purposes.

The societal matters that influence the current project vary. Modern architecture was once based on efficient, rational, fast industrial production to provide affordable designs for the public. The target however nowadays has been shifted from the user to the investor, in that buildings are now speculative tools for users that are unknown. To that end, evaluating results of previously conducted research that are based on the analysis of users' needs and quality standards is thought to be of great importance. Moreover, the complexity of the form is occasionally increased in order to achieve higher profit. The current project tries to avoid complex digital forms and seeks for simplicity and architectural smartness, preserving the economy of means for the end users. Though it investigates both customized and mass-produced options, it argues that the same goals can be met also with low-cost alternatives, if certain geometrical rules are applied.

The current research-based practice is part of a recent discussion involving interdisciplinary experts ranging from acoustics, audiology, psychology to neuroscience that aim to analyse the effects of the acoustic environment on early childhood. Recent results stress out the vulnerability of young listeners and require a transition from measures of acoustics and noise coming from the adult world. A series of questions arise: how can brain research reveal facts on early auditory learning? and how do children perceive noise levels at preschools? In that discussion designers should undertake

a leading role by informing their design decisions to meet acoustic standards. Understanding how a 1-5-year-old child perceives the sound environment is crucial for evaluating the design choices.

The proposed materials are carefully chosen depending on their sustainability properties while considering their effect on the indoor air-quality. To minimize environmental impact, acoustic treatments need to account for recycled materials or resources that are natural or plentiful. Final products must be recyclable, reusable and/or biodegradable. Materials need to be sourced locally and waste recycling to be included during the manufacturing process. The product's packaging and the environmental impact of transportation need to be assessed. Nowadays, sustainable and smart building design apply leading-edge technologies in order to optimize space and design of lightweight structures by exploiting less resources while improving the performance of the acoustic solutions (Jiménez et al., 2017). In this context sustainability and indoor environmental quality need to be integral in the design process. Discussions about sustainability mainly focus on sustainable materials but rarely consider the entire lifespan of building components. If the design is unable to adapt to new circumstances and developments a series of problems arise. The solution to every problem begins with the acknowledgement that there is a problem. Since usually design interventions have a long-term relationship with their environment and their inhabitants' various questions arise. Could they be used for different purposes in the distant future? How might new technologies influence the user's demands? How will research results reform the preschool environment? Every environment should adapt to changing circumstances coming from the users' preferences or technological developments. With the demolition and construction sectors being major contributors of CO₂ emissions, principles of reuse and upcycling are becoming increasingly important. Each design system could allow to readjust its interface and in case of decay replacement of its components should be an option. The possible deconstruction of the building product could also be designed before its construction and should be guided by an ecologically sustainable process. To sum up, the future legacy of the design product is thought to be a central asset of the initial design.

Design can create a positive impact on people's lives and need to move beyond good intentions. Though the project aims at a design product rather than a building the previous mentioned principles are considered. Considering the health implications of a noisy preschool environment, where children are exposed to high levels of intermittent and often high frequency sound, acoustics are often overlooked during design proposals. However, more and more studies indicate that children of that age that spend most of their day in preschools are strongly affected by noise. In order to cope with it they develop strategies such as raising their voices, losing concentration or withdrawing. Recent studies show that preschool children need greater freedom to manipulate the spatial and temporal settings achieving both time with the collective as well as time alone (Lisa, 2017). In that respect the building environment needs to adjust in order to meet new standards for design and acoustic comfort. Sustainability should be therefore considered in terms of the assembly and disassembly system. This is considered crucial for a preschool environment, since it should be transformable due to the nature of its users. It should be adaptable to change rather than comply with a preconceived norm. To that end, the confluence of design and research is thought to be crucial.

Last but not least, the scientific relevance of this work argues upon the need for a workflow that allows the confluence of an interdisciplinary collaboration towards creative ways of improving the indoor environmental quality.

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