INTRODUCTION

Solutions for conceiving a first-person visual impression of the experience of architectural designs are widely available. The ambition exists amongst designers to construct narratives that present the sequence of experiences in a building (Bermudez, 1995). The auditory experience makes up for a large part of the narrative and emotional quality of the architectural experience (Blesser and Salter, 2006). Solutions for the evaluation of the architectural acoustics are available. Examples of such tools are CATT-Acoustic [1], Autodesk Ecotect [2], EASE [3] and Odeon [4]. However, these are dedicated to provide static impressions, leaving out the active role of the beholder in engaging architecture. Furthermore, these solutions are geared towards theatre and auditorium development, or geared towards other settings in which the demands on functional acoustics are explicitly stated. Yet, the auditory experience of our everyday architectural environment demands attention from an aesthetic perspective as well. Therefore we propose a tool that allows designers to easily conceive, evaluate and design the full auditory experience of a building, based on a digital three-dimensional model. A guiding principle has been the dynamic nature of the configuration of sound sources and listeners. Hence, a system is created that enables sound sources as well as listeners to be defined as moving entities. Furthermore, the ability exists for listeners, in their own movements and interactions, to generate sounds as well. In the system, proposed in this paper, ray-tracing is used to simulate the spatial acoustics. The paper discusses the considerations regarding several implementation choices and regarding adoption of the tool in the architectural design process.

Keywords. Auditory perception; Architectural design; Acoustics; Simulation; Auralisation.

THE AURAL EXPERIENCE OF ARCHITECTURE

Firstly, the gamut of auditory phenomena that are of importance for the experience of architecture needs to be defined. When a building is experienced, the progression of aural experiences can provide ten-
sion and harmony, similar to how regular instrumental music can evoke emotions.

The architect designs a building to house several functions, each of which comes with a distinct vocabulary of sounds. The materialisation of spaces and their shapes determine how these vocabularies are articulated. By connecting different spaces and by creating a routing the architect dictates the progression of phrases as they are perceived when moving through the building.

Furthermore, by navigating in space, the visitor functions as a personal mixing device, mixing the configuration of sound sources around into a personal experience. But, simultaneously, the visitor becomes an active element in the musical composition as a building provokes sounds from its beholders, such as footsteps, slamming of doors and conversational mutter. In presently available solutions these latter aspects are often neglected.

**E.A.R: EVALUATION OF ACOUSTICS USING RAY-TRACING**

To incorporate the aforementioned aspects of the auditory experience of architecture in a design tool, a system had to be designed that, on the one hand, evaluates the acoustics of a space, based on its shape and materialisation. On the other hand, a system that does not neglect the active role of the beholder: firstly, the freedom to move and thus to shape the perception of the configuration of sound sources. Secondly, the freedom to create sounds oneself. In the system, proposed in this paper, ray-tracing is used to simulate the spatial acoustics.

**Rationale behind ray-tracing**

Ray-tracing is a method to simulate the propagation of emitted energy from a source. The technique is well-studied to synthesise visual images from a three-dimensional scene, but can also be used to determine the acoustical behaviour of a room (Vorländer, 2008).

The use of ray-tracing for auditory evaluation is, from a purely physical stance, not entirely correct. To treat sonic energy as individual rays leaves some phenomena, such as diffraction, not to be reproduced. In the visual domain, due to the small wavelength, these phenomena are not apparent in everyday scenarios, but in the auditory domain, especially for lower frequencies, phenomena like diffraction can be quite prominent.

Nevertheless, we have opted for a ray-tracing solution for several reasons. Most importantly, in the design tool we propose we are not interested in a scientifically correct solution, but rather aim to offer a perspective from an artistic viewpoint. Furthermore, ray-tracing is easy to implement. It is able to reach a solution in a limited time. It is able to reproduce some of the most prominent auditory spatial phenomena. And lastly, most of the future end-users of the software are already familiar with ray-tracing, for example by producing visual renderings.

Furthermore, with some trickery, ray-tracing as an algorithm can be enabled to incorporate phenomena like diffraction just as well. For example, diffraction could be modelled by automatically appending fins along the bisector plane of edges, around which diffraction would likely occur. These fins would then bend the direction of rays that pass through them (Vorländer, 2008). However, at the time of writing, these additional measures are currently not implemented in the ray-tracing solution as it is presented.

**Implementation details**

The overall process of the ray-tracing solution is divided into three steps. Firstly, impulse responses are calculated using ray-tracing for every source-receiver pair that is defined. The impulse responses represent the decay of sonic energy over time at the location of the listener. Because air-absorption and material properties differ per wavelength, the impulse responses are calculated independently for several frequency ranges. The next step is the convolution process, in which the sound that is being emitted is processed to incorporate the acoustical response of the room. To match original input signal to the frequency ranges, for which an impulse response has been generated, a band pass filter is
used to filter out the relevant frequencies from the original input signal. The final step consists of adding all convoluted sounds into a single final result, as it would be perceived by the listener.

Contrary to existing solutions, a guiding principle has been the dynamic nature of the configuration of sound sources and listeners. Therefore, both sound sources and receivers have to be able to be defined as moving entities. This is accomplished by breaking down the movement of both into several key-frames. For every key-frame an impulse response is generated. As the sound from the source progresses, while moving from one key-frame to the other, the impulse response, which is used to convolute the emitted waveform, is interpolated between the two consecutive impulse responses.

The ray-tracing solution is a stand-alone application written in C++ to benefit from the increase in performance by compiler optimization and multi-threading and the availability of libraries for the Fast Fourier Transforms for the convolution process. The Graphical User Interface of the application has been created as an add-on for the open source three-dimensional modelling application Blender [5]. The add-on has been written in Blender’s native scripting language Python. The extensible plug-in architecture of Blender allows for a tight integration with the architectural modelling workflow to ease the iterative design process of alternating modelling and auralisation. Furthermore, by extending Blender, a large potential user-base is obtained that is willing to help improve experimental software initiatives, such as the one presented in this paper.

**STORYBOARD**

Apart from the acoustics of the enveloping surroundings, another important factor to the aural experience of architecture is that listeners, in their own movements and interactions, generate sounds as well. To incorporate this notion in the auralisation process, the collection of auditory events alongside the path of a listener can be automatically mapped onto a storyboard. This includes the visitor’s own sounds from exploring the building, such as footsteps. To ease the designer in conceiving this storyboard, a library of materials is supplied. Aside from how the materials interact with the rays being traced – such as the amount of reflectivity, transmittance,
absorption and specularity – the library also defines how the material sounds when walked upon. To apply spatial acoustics to the generated storyboard, the storyboard itself is treated as a sound source and is fed back into E.A.R.

**SIMULATION RESULTS**

E.A.R is primarily intended to give an artistic impression of the spatial acoustics and auditory experience of a configuration of sound sources, listeners and geometry. Therefore striving for scientific accuracy was not one of the main goals. Nevertheless it is important to have an understanding of how E.A.R performs in relation to the existing body of literature.

One of the most studied subjects in the field of architectural acoustics is the reverberation time of a room. It has a tremendous impact on the quality, appearance and intelligibility of a concert hall and hence has been the subject of thorough examination. Several formulas have been conceived, based on empirical or theoretical study, that have proven to predict the reverberation time of a room rather well within some well-known constraints. These constraints are best explained as the necessity for the modelled room to qualify as being normal, by which one would mean that all dimension components have the same order of magnitude and that the room has a uniform distribution of material properties. Given these preconditions, the formulas of Sabine (1) and Norris-Eyring (2) predict the RT sixty rather well. The RT sixty is defined as the time needed for the reverberation of a sound to decay by 60 decibels below the level of the direct sound itself. The formulas operate on the volume V and surface area S of the enclosing volume, the weighted average absorption a of the surface and the attenuation coefficient for air absorption m.

\[
RT_{60} = \frac{0.161V}{(S-a+4mV)} \quad (1)
\]

\[
RT_{60} = \frac{0.161V}{(-S\ln(1-a) + 4mV)} \quad (2)
\]

The RT sixty is also a property that is easily derived from an impulse response as rendered by E.A.R. Hence it allows for a comparison between the outcome of E.A.R and the values that the formulas predict. The graph in Figure 6 shows that the reverberation times, as to be deduced from the rendered impulse responses, do not deviate a lot from the predictions by Norris-Eyring. The room in question was a 10 by 6 by 4 meter shoebox room, but in other configura-
congress centre, because the aural implications of it are of both an aesthetic and a functional nature: people generally visit the same congress centre only a limited times, leaving room for visitors to be surprised by the auditory experience. Yet, at the same time, a congress centre imposes strict functional constraints on the acoustics. Both the functional and the aesthetic component of the design can be validated by the tool.

The design is organized as a narrative sequence of auditory experiences that resembles a musical progression. By situating the design next to a highway the positive and negative connotations of traffic noise are investigated. An elevation of the design can be found in Figure 7, but thoroughly explaining the details of the design falls outside the scope of this paper.

The use of the auralisation tool in the design process helped to conceive and unravel the building as a sequence of interesting aural experiences. At the same time, however, during the design process the difficulty to effectively communicate the rendered aural impressions manifested itself. A credible reproduction of the rendered impressions requires a sufficiently accurate sound system, one that is not always available, even when giving presentations. Furthermore, a lot of the communication around

Figure 5
Chart of reverberation times as predicted and simulated.

Figure 6
Elevation of the design prototype.
building process is geared towards conveying scale models or graphical artefacts, either digitally or in print.

**CONCLUSION**
The use of ray-tracing in the auditory domain proved to be a relatively easy way to provide an auralisation solution for artistic use. The case study design project illustrates the use of such a tool in the architectural design process, but also shows that effectively communicating a convincing impression of the auditory experience of the design yet proves to be difficult.

The entire ecosystem of tools that has been developed for this project has been open sourced. This way the system can be extended by others, to eventually make the evaluation of auditory experiences from three-dimensional models just as common as the creation of visual renderings. We hope for a widespread use of the tool in architectural design, but see room for use of the tool in other disciplines as well, most notably film making and special effects. The source code of the open source design tool is available on-line [6].

**FURTHER RESEARCH**
Further research can be undertaken to validate the accuracy of the ray-tracing algorithm. This can be accomplished either by supplying additional algorithms for integrating acoustics, based on Finite Elements Analysis or Differential Analysis, that solves the wave equation to simulate sound propagation or by comparing computer generated results with real-life measurements.

Within the context of the ray-tracer further research can be undertaken on the subject of Just Noticeable Differences. Research on this topic can provide guidelines to the acceptable spacing between two consecutive impulse responses along the path of the beholder, as the consecutive impulse responses are interpolated to suggest the perception of the movement.

A third research area is the use of GPGPU (General-Purpose Graphics Processing Unit) computing.

With its unmatched performance, in terms of parallel floating point operations, the algorithm could be evaluated in near real-time, opening up whole new ways of interactive aural design.

Regarding the design process, additional research can be undertaken to find ways to efficiently embed the use of auralisation into the architectural design process. Communicating aural impressions seems not to be a part of the universe of discourse of the architect. Additional research can be undertaken to represent aural impressions using visual feedback to ease the communication process and remove the dependency on accurate tools to reproduce the rendered aural impressions.

**REFERENCES**

