Audio Cartography: Visual Encoding of Acoustic Parameters

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Abstract

Our sonic environment is the matter of subject in multiple domains which developed individual means of its description. As a result, it lacks an established visual language through which knowledge can be connected and insights shared. We provide a visual communication framework for the systematic and coherent documentation of sound in large-scale environments. This consists of visual encodings and mappings of acoustic parameters into distinct graphic variables that present plausible solutions for the visualization of sound. These candidate encodings are assembled into an application-independent, multifunctional, and extensible design guide. We apply the guidelines and show example maps that acts as a basis for the exploration of audio cartography.

1- Background and Objectives

Human, cultural, and environmental sciences are concerned with the effects of sound in urban environments. They examine medical and social problems of acoustic immission caused by increasing transportation and industrial production. For example, the World Health Organization (WHO) documents several direct relationships between constant noise nuisance and medical or psychological damage, such as hearing impairment or high blood pressure (WHO 2009). In the political arena, the European Union (EU) released the directive 2002/49/EC (END) to attend to the expanding

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noise exposure. Since 2002, European agglomerations are legally obliged to conduct noise mappings and to publish the results on maps (EU 2002).

In physics, improvements in computing and simulation algorithms enable the advanced geometric modeling of micro- and macro-scale sound propagation, such as in streets or large urban areas (Kang 2007). Psycho-acoustics analyzes the subjective perception of sound and emphasizes the influence of urban parameters, such as the contentment with the residential area or the importance of the sound source (Lercher 1998). With an anthropogenic and sociological background, an international research network works on soundscape analysis where linkages between environmental sound and society are explored (soundscape-cost.org 2011). Concurrently, the International Organization of Standardization (ISO) develops standards for the perceptual assessment of soundscape quality and discusses definitions and methods (ISO 2010). Also, planning disciplines developed a conspicuous awareness of auditory aspects of urban and architectural designs (Arteaga and Kusitzky 2008). Some of these research results attracted public interest to the extent of triggering several national and international initiatives, such as local action groups or the International Noise Awareness Day (Deutsche Gesellschaft für Akustik e.V. n.d.).

Each of these domains deals with different facets of the sonic environment. Whilst each focuses on spatial characteristics of sound, they develop individual means of its description. These might be considered different languages for visually describing properties of sound. Their incompatibility means that, when it comes to an exchange of perspectives, interdisciplinary discourse is difficult. Appropriate tools for supporting this activity do not exist.

The objective of this study is to provide fundamental building blocks for communication, documentation, and presentation to involve all stakeholders concerned with the sonic environment. This includes systematic visual encodings and mappings of acoustic parameters into distinct graphic variables as plausible solutions for the visualization of sound. Consequently, the codifications lead to the compilation of guidelines according to specific tasks. They are assembled into an extensible visual design guide as the basis for audio cartography as a visual communication framework for the systematic and coherent description of the sonic environment.

2- The Visualization of Sound

The human process of external cognition uses graphical representations to describe and exchange mental concepts (Scaife and Rogers 1996). The creation of visual metaphors for information depicting structures of the real world aims to reveal patterns, amplify cognition, and generate insights whereby insight enables discovery, decision-making, and explanation (Card et al. 1999, Ware 2004). These principles specify the missing components in connecting the diversified knowledge of the sonic environment. The display of sound in varying contexts would enable the visual utilization of acoustic information and provide a solid common level of communication. Based on extensive research of multidisciplinary perspectives on the sonic environment and their visual communication techniques, the visualization of sound has to meet the following challenges.

2.1 Envisioning Sound

Envisioning sound involves the fundamental problem of designing visual presentations of information that has no clear relation or association to familiar physical geometries (Bugajska 2003). Sound is an audible and invisible entity, and human perception is not familiar with its visual interpretation. Depictions of acoustic data range from musical notations and synaesthetic images as subjective visual perceptions of music to aesthetic visual installations of acoustic signals in the field of artistic visualization (Woolman 2000, Baron-Cohen and Harrison 1997, Nicolai et al. 2008). Although these concepts mainly relate to musical compositions, they can be assigned to the visualization of sound in large-scale environments. The universality and uniformity of music notations underline the requirement to develop a general and consistent visual encoding of acoustic information. Synaesthetic perception, even when it is rare, suggests the capability to transfer an auditory stimulus to a visual metaphor. Artistic transformations of sound highlight the possibility to visualize abstract acoustic data in an appealing and aesthetic way.

2.2 Mapping Sound

Over millennia, maps have been powerful instruments to communicate geographic spaces that are too large or too complex to be seen directly (MacEachren 1995, Dodge et al. 2008). Existing communication techniques indicate that mapping sound is an appropriate instrument for an integrative and interdisciplinary documentation of the sonic environment. One of the main tasks of the END is the publication of noise maps to communicate immediate problems of noise exposure to the general public (EU 2002). Concepts developed in multimedia cartography add audio visual features to noise maps to facilitate their understanding (Scharlach 2002). Cartographic visualizations within soundscape research highlight acoustic spatial identities or auditory effects of the sonic environment by using simple black-and-white points, lines, areas, or graphic semiologies (Southworth 1969, Servigné et al. 1999). Cutting-edge simulation approaches implement sound propagation based on punctual or spatially extended sound sources. This allows for the graphic representation of sound in relation with other topographical objects, such as buildings (Michel 2008). Graphical intersections with other topographical objects are important to provide orientation in the setting, give insight into the spatial dimension, or reveal interactions of the acoustic parameters. Consequently, the visualization of sound demands an integrated map design that suits the perspicuous presentation of both acoustic and topographical objects.

3- Approach

The heterogeneity of disciplines dealing with characteristics of the sonic environment opens up a huge range of involved stakeholders, such as domain experts, scientists, planners, decision-makers, people concerned with noise, and the general public. Therefore, we need a cross-disciplinary communication framework that is suitable for multiple applications according to specific questions or target audiences. This includes a medium- and application-independent concept to guarantee its general qualification and usage. Furthermore, the design has to operate on a broad range of media formats, such as paper or computer-based and mobile devices.

Our approach is to develop a simple graphical language that connects the above mentioned knowledge levels. This consists of an appropriate set of graphical constructs that describes this highly complex topic. Within our methodology, we abstract data and vocabularies utilized by potential target groups and derive discrete acoustic parameters to standardize the description of the sonic environment. Subsequently, we visually encode the parameters by systematically assigning graphic variables. Hence, we obtain an exemplary set of encoding guidelines that is assembled into an application-independent, multifunctional, and extensible design guide. In the end, we apply our encoding and generate sample maps within two case scenarios.

4- Abstraction

Abstractions help to derive generic descriptions of sound and simplify the complex structure and dynamic behavior of it. We consider a cross-disciplinary selection of acoustic information that is measured, computed, or described and throughout used in science and practice. They are based on formally structured requirements elicitation with experts, specifications by legislature, and field studies (Kornfeld 2008). Each parameter describes a particular aspect of an acoustic situation. Although they rely on a specific background, the compilation and combination of them prepare for an integrated view on the relevance of environmental sound. The list is intended to be continued:

- *Geometric shape of sound*: The natural shape of sound is a wave traveling through air. Due to large scales, this is abstracted to a simple geometric shape of sound.
- *Sound source*: The END defines major sound sources primarily responsible for high noise levels (EU 2002). Descriptions in soundscape research also relate to properties of particular sources (Schafer 1977). Setting up categories and subcategories depends on the certain use case.
- *Dominant soundmark*: Sound sources that silhouette against the audible environment are expressed as soundmarks. Dominant soundmarks completely mask other sounds (Schafer 1977).
- *Sound energy*: Geometric sound propagation calculates emitted sound energy of a source. It serves as a useful linear measure to detect sound intensity which summates all immitted sound energy at a particular location.

- *Sound pressure level*: Sound pressure level on a logarithmic scale in Decibel (dB) serves as a common noise indicator. For example, the END calculates A-weighted long-term average sound pressure levels (EU 2002).
- *Frequency spectrum*: A sound source emits waves of different frequencies measured in Hertz (Hz). With frequency on a logarithmic scale the distribution of sound energy over frequency is defined as frequency spectrum.
- *Spatial reach*: Soundscape surveys often map the spatial reach or extent of an auditory perceived sound (Schafer 1977).
- *Noise limit value*: There are regional, national, and international noise limit values that are both recommendations and stipulations by law. For example, the WHO observes sleep disturbances at noise levels above 40 dB (WHO 2009).
- *Rhythm*: Sound is a four-dimensional phenomenon and undergoes spatio-temporal changes. Soundscape research considers this characteristic by describing sound sources in terms of their rhythm (Schafer 1977).

5- Visual Encoding

With the technique of visual encoding, we systematically assign graphic variables to the previously defined acoustic parameters informed by cartography and information design. We employ plausible codifications according to established practice based on perceptual and cognitive principles (MacEachren 1995, Bertin 1974, Cleveland and McGill 1984, Mackinlay 1986). The objective of the encoding is to provide a unique and discernible graphic counterpart for each parameter which matches its physical characteristics and variability. In the case of correct encoding, the graphic variables allow recognition, permit estimation, and exhibit association with the underlying phenomena. It must be possible to utilize and read the graphic variable alone as well as in combination with other dependent variables. The aim is thus a systematic and modular usage of the variables for reoccurring visualization needs within various domains.

5.1 Geometric Shape of Sound

The encoding of the geometric shape of sound employs basic graphic elements, i.e., points, lines, and areas and matches the type of its spatial dimensionality (Fig. 1). We achieve further variations by applying the variable shape to the graphics (Bertin 1974, Wright 1944). Punctual presentations are useful to present locally discrete phenomena, e.g., sound particles. The usage of line segments is suitable to delimit areal phenomena, such as contour lines of noise pollution or when sound is modeled as rays. Additionally, spatially extended sources, such as streets are assumed as line segments. Areal presentations indicate the geometric shape of sound as a spatial continuous phenomenon and are commonly used in noise mapping (MacEachren 1995).

Figure 1: Basic graphic elements varied in shape

5.2 Sound Source

The parameter sound source is presented by the graphic variable color hue as it is useable for nominal parameters (Bertin 1974). By this means, we match the perceptual variation in the referent with the perceptual variation in the phenomenon and allow for qualitative description or comparison of sound sources. With a two-level hierarchy of sound sources we require both an encoding of source categories with equidistant color hues and an encoding of source subcategories with color hues that cluster around the associated category's color hue. We use the CIELuv color model where distances between colors are proportional to perceptual discrimination (Wood et al. 2010, Wijffelaars et al. 2008). Additionally, all color hues consist of 100 % saturation to allow a further encoding of this variable. Based on a qualitative analysis of audio recordings, we come up with an exemplary categorization of sources (Fig. 2). We transfer auditory stimuli into visual metaphors by associating a source with a color hue and display traffic with blue, economy with yellow, human activity with red, and nature with green. Blue symbolizes exhaust gases of vehicles that usually come along with the emission of sound. The color yellow indicates artificial or chemical production and serves as a visual equivalent for sources connected to economy. Red associates people and matches sound caused by human activities. In general, green is a symbol for nature and adequately presents environmental sound sources.

Figure 2: Color hues envision (sub)categories of sources

5.3 Dominant Soundmark

We present nominal point symbols as possible candidate encodings for the visualization of dominant soundmarks that can be pictorial, associative, or geometric (Robinson et al. 1984). We provide a set of associative point symbols for dominant soundmarks as they are nominally described discrete phenomena (Fig. 3). The auditory perception of dominant soundmarks and the interpretation of their corresponding symbols are highly subjective and context-sensitive so that our candidate solutions serve as sketches.

Figure 3: Associative nominal point symbols present dominant soundmarks

5.4 Sound Energy

We apply the graphic variable saturation to present linear sound energy (Morrison 1974). This is achieved by connecting the variable with color hue to simultaneously present sound energy and the corresponding source (Fig. 4). Our visual encoding considers attenuation of emitted sound energy due to absorption and varies the saturation of the color. Perceptual variation in color hue and saturation is non-linear, but using the perceptual CIELuv color model we are able to vary saturation in a perceptually-linear manner (Wijffelaars et al. 2008).

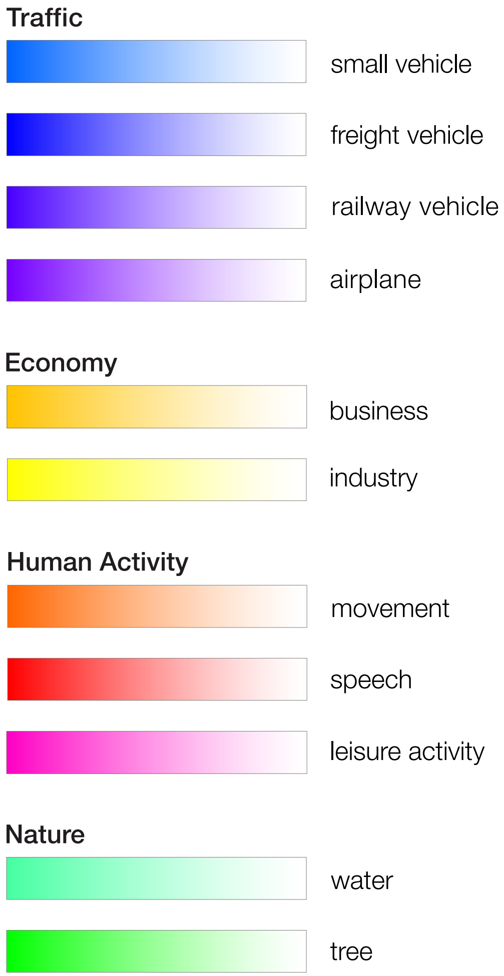

Figure 4: Color hues are perceptually-linear varied in saturation

5.5 Sound Pressure Level

Although END noise mapping is standardized, the color schemes used for the presentation of sound pressure level differ extremely and particularly lack in an appealing design (Working Group on the Assessment of Exposure to Noise 2008). Frequently, public authorities apply contrasting or unintuitive colors recommended by ISO standards that contradict established cartographic practice (Brewer 1994). We suggest an encoding that adopts functional requirements but results in an effective sequential color scheme (Fig. 5). We insert perceptual steps of saturation to match the logarithmic nature of sound pressure level. The candidate color schemes are approved and validated by user or usability studies (Harrower and Brewer 2003). A sequential color scheme indicates order and qualifies for the presentation of numerical or ordinal parameters. As sound pressure level is a logarithmized and normalized derivation from sound intensity, the visual encodings differ concerning their variation of color saturation. We employ sequential schemes consisting of single hues to assure the compatibility with the visual encoding of sound sources.

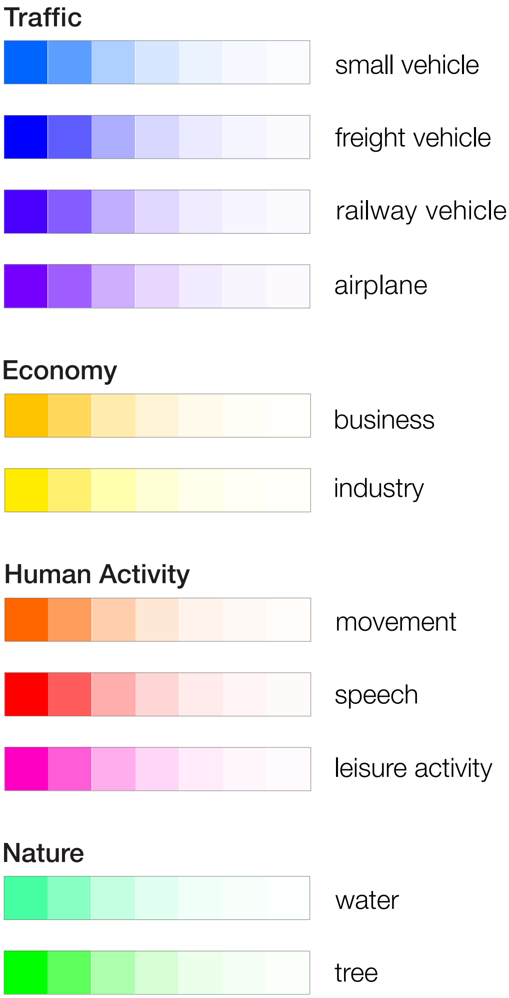

Figure 5: Sequential color schemes with perceptual steps of saturation based on single hues

5.6 Frequency Spectrum

We encode the parameter frequency spectrum with the graphic variable texture. Our encoding covers an irregular point texture, and we vary the density of the texture as the ratio of texture units to the background according to the spectrum width (Fig. 6). Thus, a narrow frequency spectrum generates a low ratio of texture units whereas a broad spectrum produces a high ratio of texture units (Caivano 1990).

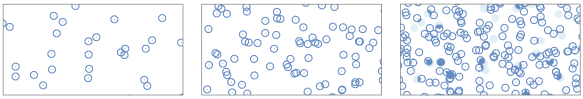

Figure 6: Irregular point textures display width of narrow, medium, and broad frequency spectrum

5.7 Spatial Reach

Spatial reach implies the auditory perception of a sound and is usually specified by geographic coordinates. As the parameter relies on subjective perception, we consider uncertainties in the underlying information and need a modifiable visualization concerning its clarity. Therefore, we encode spatial reach with the variables size and crispness (Bertin 1974, MacEachren 1992). A possible realization adopts color hue from a specific sound source to qualitatively determine the source and to geographically describe its spatial reach or extent (Fig. 7). The color hue is varied in crispness to selectively filter edges or fills of an object.

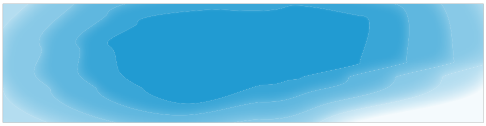

Figure 7: Variations of size and crispness mark the spatial reach of a perceived sound

5.8 Noise Limit Value

The parameter noise limit value requires a conspicuous encoding to underline the relevance of the underlying information. Blur immediately directs visual attention to relevant areas (Kosara 2001). Thus, we consider blur as a possible encoding technique to generate sharp areas exceeding critical noise levels while blurring the irrelevant areas. As blurring relies on context to create focus, the visualization requires the embedding of the parameter into a spatial setting (Fig. 8).

Figure 8: Sharp display of areas exceeding critical noise limits while unconcerned areas are blurred

5.9 Rhythm

Concerning the visual encoding of spatio-temporal rhythm, we compose a geometric point symbol as the parameter refers to spatially discrete sound sources. We draft an abstracted clock as a familiar metaphor and divide its surface into adequate or requested time units, such as one hour or one day. Then, we chart temporal variations of sound energy on the clock by saturating the source's hue according to the emitted energy at a specific time (Fig. 9). This encoding allows for the static visualization of spatio-temporal rhythm of stationary sound sources and enables their presentation on maps as point symbols with showing other topographical objects simultaneously.

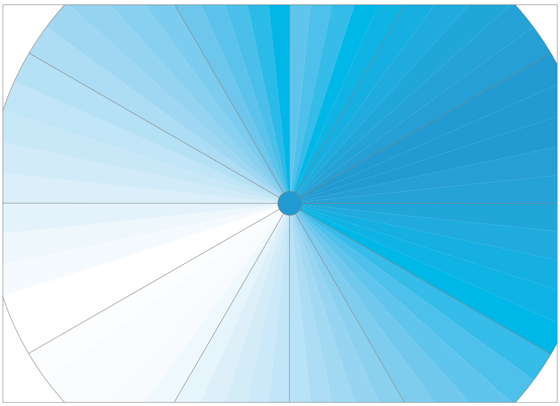

Figure 9: Geometric point symbols reveal temporal variations of sound energy

According to our encodings, we build a high-level design guide for the visualization of sound (Fig. 10). Due to different cultural and social contexts, this implementation allows for design related modifications of the variables. In particular, the choice of color has to be balanced according to specific framework requirements, such as cultural sensation of aesthetics, potential color blindness, or education and socialization background of users. Therefore, alternative arrangements are practicable when they stick to the systematic encoding of the parameters.

Figure 10: Design guide for audio cartography

6- Mapping Examples

Conform to our encoding guidelines we map acoustic parameters and generate two cartographic examples.

6.1 Noise Mapping

The map shown in Fig. 11 relies on noise mapping data from the END and presents A-weighted sound pressure levels in an investigation area in Hamburg, Germany. Accessing previous abstractions, we derive geometric shape of sound, sound source, and logarithmic sound pressure level as significant acoustic parameters. In this case, an areal presentation of sound corresponds with an areal calculation of the sound distribution. The END dictates the separate presentation of each source so our map features traffic emissions with blue. As computations merge traffic noise, the exhibition of subcategories is not needed. Public authorities cover sound pressure levels from 45 dB(A) to >75 dB(A). Thus, we create a sequential color scheme consisting of seven classes. Furthermore, the color-coding of sound sources prepares for the simultaneous presentation of multiple sound sources which is barely explored within noise mapping (Fig. 11 shows an exemplary implementation).

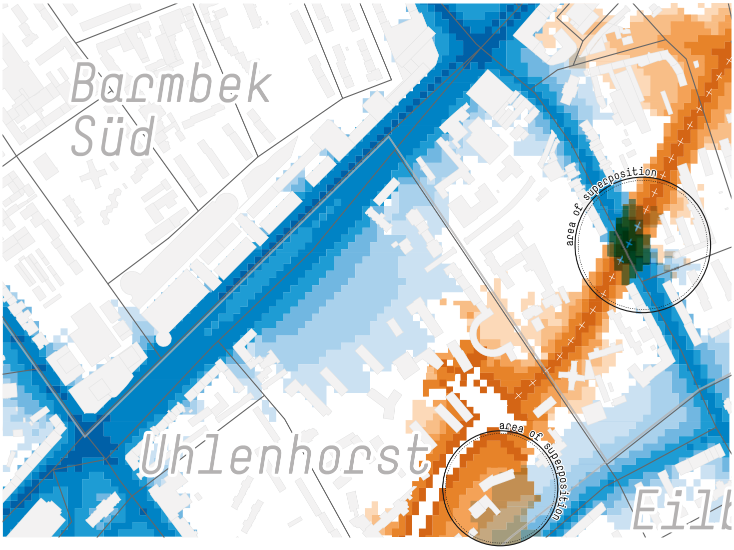

Figure 11: Map features sound pressure levels of sources

6.2 Simulation of Sound Propagation

Fig. 12 traces back to a research project dedicated to the simulation of sound propagation in cities. The algorithm is based on ray tracing methods and models the emission of sources within a small section of the above mentioned area. This application focuses on a simulation of the spatial distribution of rays and presets default emission input values, such as number of rays and power of the source. We derive geometric shape of sound, sound source, and linear sound energy as relevant acoustic parameters. We utilize line segments to describe the distribution of sound. Instead, we use dashed lines to illustrate the scattering at building façades. As this application implements source placeholders, we apply the color hue of traffic emitters to map the sources. We consider a perceptually-linear variation of saturation that emanates from absolute values, i.e., a range from 100 % to 0 % saturation. It is possible to adjust the variation range when concrete input and output data are valuable. We decrease transparencies of the color-coded rays to match the resulting energy value of the reflected sound due to absorption. Transparency allows for graphical superpositioning of emitted sound energies to detect sound intensities at specific receiver locations. Beyond that, the change of opacity of the color hue meets the absorption coefficient of the reflecting material.

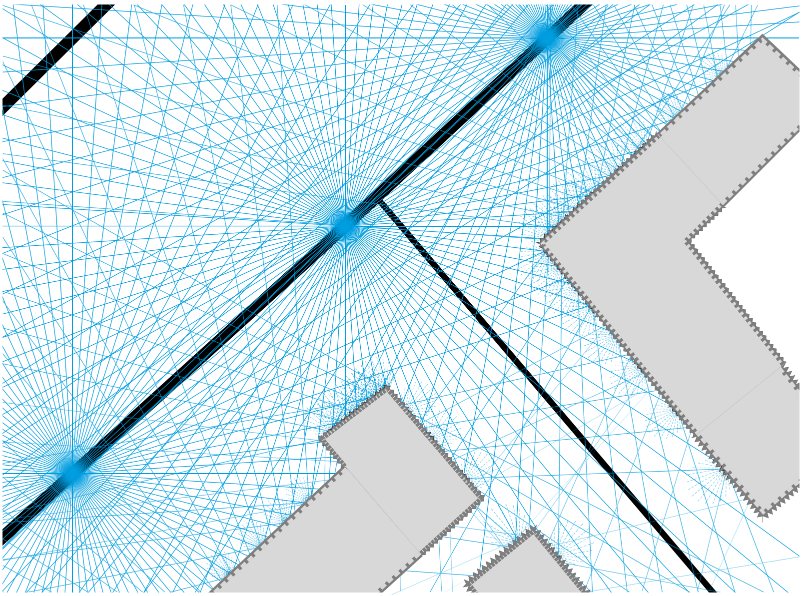

Figure 12: Map depicts distribution of rays and varies color hue according to their sound energy

Together, we yield exemplary cartographic presentations that describe aspects of the sonic environment. Further hypothetical examples of visualization are conceivable, such as spatial reach or soundmarks within soundscape research or the depiction of noise limit values in combination with demographic and socio-economic data.

7- Conclusion

This contribution addresses the shortage of appropriate tools supporting an interdisciplinary discourse about the sonic environment by providing a visual communication framework for its systematic description. We created fundamental building blocks for the spatial visualization of sound and offer guidelines for an audio cartography.

The guidelines meet essential design challenges as they provide the means to envision and map sound in large-scale environments. We are able to transfer auditory stimuli systematically to visual metaphors by accomplishing a consistent visual encoding of acoustic parameters. A multifunctional and –disciplinary usage of the design is expected by facilitating a modular usage while fostering the continuation or modification of the guidelines. In subsequent work, we apply our encodings and mapped them onto cartographic presentations. We show that our suggestions support an integrated map design and graphical intersection with other topographical objects.

We aim at an automation of our guidelines based on certain use cases. This approach assembles the compilation of design patterns and libraries which would enrich the functionality of audio cartography. It would be of great value to get empirical feedback via crowdsourcing as a possible means of validation.

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