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Urban Sound Mapping for Wayfinding – A theoretical Approach and an empirical Study

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Abstract. Conventional navigation systems use visually perceptible landmarks to navigate their users from a starting point to a destination. However, sometimes visual information is not enough for route guidance. Visually-impaired or elderly people may not be able to navigate using the visual sense. Furthermore, there may exist no outstanding (i.e., salient) visual landmarks that could be used to navigate. In such a case auditory information may be a helpful guide. We performed two online studies and a focus-group interview to identify possible sound classes in an urban environment. Based on our results, we gathered sounds in Augsburg and classified them according to their source. The findings support our notion that auditory information can be useful for spatial orientation and guidance in addition to or even replacing visual information.

Keywords. Navigation systems, auditory landmarks, GIS data collection

1 Introduction

"Auditory perceptible landmarks complement their visual counterparts and also stand to be beneficial for certain groups like the visually impaired and the elderly" (Baus et al., 2007, p.302). Although Baus et al. (2007) stated this already 16 years ago, mobile pedestrian navigation systems continue to solely use visually perceptible landmarks to guide their users. Other modalities than vision – e.g., the auditory sense – are valuable for landmark-based wayfinding, but still neglected in current navigation systems.

This observation has implications for mobile pedestrian navigation systems and for basic cognitive research on wayfinding. There is currently a very strong bias towards the visual modality (e.g., Hamburger (2020)), while other modalities are less well investigated. This is not to say that vision is obsolete, it remains the most prominent and most valuable modality for us to gather information from and about the environment. It is rather to say that humans possess more perceptual and cognitive capabilities than just vision and that these capabilities contribute to the wayfinding experience. These skills need to be investigated and if they prove to be of importance, they need to be implemented/integrated into state-of-the-art navigation systems. An example for a route description in a mobile navigation system using sound could be: "Go straight on. At the next crossing you hear trains. You have reached the station." Visually-impaired could get a description solely based on sound, while normal-sighted could get a combination of text and sound (Baus et al., 2007). This is helpful when persons are simultaneously involved in other demanding tasks (full hands, supervising children) and have only limited attentional capacity to spare for a navigation system requesting attention for the depiction of a visual landmark (Holland et al., 2002). Therefore, we here address the auditory sensory modality in psychological surveys and mapping with GIS (geo-information systems).

For the psychological part, we base our online studies with sighted participants on a study by Koutsoklenis and Papadopoulos (2011) in which they gathered information about the usefulness and the frequency of use of auditory information in visually-impaired and sightless people in everyday life.

To map auditory information of our spatial environment we make use of GI (GeoInformation) methods (Bill, 2016). We propose a taxonomy and a corresponding conceptual model to represent data about urban sounds for pedestrian wayfinding in a GISystem (GIS). We collect sounds using this taxonomy and represent them on a map.

Our studies address three major questions:

1. Is it possible to use auditory instead of visual information for wayfinding and is it possible to integrate such information into pedestrian navigation systems?
2. Since information processing in everyday life is multimodal in nature, can we combine the informa-

tion from different sensory modalities for successful wayfinding?

3. How can we combine different research fields (here Psychology and GIScience) in order to provide better information for human spatial orientation and to better integrate information into navigation systems (based on human perception and cognition)?

2 Related Work

Here, we review general information about sounds in human wayfinding (Section 2.1). We give insights into ongoing work in smartphone-based urban soundscape mapping (Section 2.2) and conceptual and ontological frameworks as bases for sound mapping (Section 2.3).

2.1 About Sounds

Investigating the meaning of auditory information for humans is mainly found in the field of ergonomics. For instance, Boer and Withington (2004) investigated the potential use of acoustic beacons in tunnels in case of an emergency. However, this is already a form of applied science, while we do not know much about the underlying perceptual and cognitive processes (of sighted people) concerning auditory-based spatial orientation. Research on auditory information in the field of spatial orientation is rather focused on visually-impaired people. For this population it is obvious that they can't make use of visual information and that it is important for them to have other (sensory) information at hand. Thus, we first need to make sure that we do not confuse 'information for spatial orientation' with 'visual information'. We know that it is possible to generate spatial representations not just from visual information but also from acoustic information (e.g., Loomis et al. (1998); Marston et al. (2007)). One example making this obvious to most of us, is the auditory signal often provided at traffic lights and crosswalks for visually-impaired people. These signals not only help them to safely cross a street but also help them to structure their spatial environment. Sighted people perceive this information as well and very often they are aware of them but they hardly integrate them into their spatial representations (i.e, cognitive maps). Based on these circumstances the question arises why sighted people do not (or just rarely) make use of such information? However, before we can answer this question, we need to find information that can serve as information for successful orientation and we have to figure out whether this information can be mapped (from perceivable for most/all people to being present on a regular basis so that it is useful; e.g., for the latter case the horn of a car or truck occurring just once would be useless).

2.2 Smartphone-based urban Soundscape Mapping

Southworth (1969) introduced the term "soundscape", describing the acoustic environment. The term was further popularised by Schafer (1969), leading to a growing research field in a number of disciplines ranging from social sciences to urban planning and noise control engineering (Kang and Aletta, 2018). The perception of sounds in an urban environment is affected by various sound sources including traffic noise, human-generated sounds, and natural sounds (Hong and Jeon, 2014). To identify the most important ones numerous studies have been carried out. Zhang et al. (2018) present a study of soundscapes in public squares and discover the effect of four dimensions: relaxation, communication, spatiality, and dynamics. Hong and Jeon (2014) investigate soundscape mapping in urban contexts using GIS techniques. They generate maps in various urban settings such as commercial, business, recreational, and residential areas. They show that soundscape perceptions and spatial variation in urban soundscapes are closely related to their corresponding urban contexts by evaluating questionnaire surveys and acoustic measurements.

Over time, four major data collection methods for soundscapes emerged: soundwalks, interviews, listening tests, and focus groups (Engel et al., 2018). Traditional soundwalks guided by experimenters are typical to collect perceptual data regarding sound (Adams et al., 2008; Brambilla et al., 2017). Binaural recordings and questionnaires are commonly used to describe the acoustics of the environment at different places within an urban area (Brambilla et al., 2017).

Today, mobile devices with several apps in combination with the internet can support data collection. Soundscape mapping can often benefit from crowdsourcing and participatory sound monitoring (Brambilla and Pedrielli, 2020). This data collection method is used for respondents participating in soundwalks guided by an investigator but also for persons autonomously selecting the place and time of the soundscape, and then submitting the data via the internet (Brambilla and Pedrielli, 2020).

2.3 Conceptual and ontological Frameworks for Sounds

Developing conceptual frameworks to address the need for data and applications is found to be important in GIScience (e.g., Dunkel et al. (2019); Koylu (2019); Wei and Yao (2022)). New representational models are required to structure data in various types and forms (Yao et al., 2019). The conceptual frameworks for the description of sounds range from simple sound classifications, to more complex cases such as taxonomies, to highly complex ontologies (Giordano et al., 2022). Taxonomies are arranged in nested, cumulative hierarchies, extending to certain depths (Giordano et al., 2022). An ontology is a specification of a representational vocabulary for a shared domain of discourse and defines classes, relations, functions, and other objects (Gruber, 1993).

Several ontologies have been proposed to represent geospatial data (e.g., Fonseca et al. (2000); Couclelis (2019); Daneshfar et al. (2022)) also in the field of navigation and wayfinding (Letalle et al., 2020; Sarjakoski et al., 2013; Timpf, 2002; Wang and Issa, 2020). Ontologies and taxonomies for the characterisation of everyday sounds have been developed in several research fields, including auditory cognition, soundscape research, and artificial hearing (Giordano et al., 2022). Gaver (1993) introduced a theoretical framework in the early 1990's that has been very influential for subsequent auditory cognitive research on real-world sound perception (Giordano et al., 2022). He proposed a classification of everyday sounds and identified three fundamental sources (vibrating solids, liquids, and aerodynamics). Since then, several researchers proposed sound ontologies, e.g., for real-world computational auditory scenes analysis (Nakatani and Okuno, 1998), for labelling datasets for audio events (Gemmeke et al., 2017), or for neural networks to classify sound (Jimenez et al., 2018).

While taxonomies and ontologies for wayfinding and navigation and those for sound coexist, there does not exist a common framework covering both. Some related work goes in this direction, such as, e.g., the work of Salamon et al. (2014) who suggested a taxonomy of urban sounds and a new dataset, called UrbanSound. They do not apply the dataset to navigation and wayfinding – a gap that we want to close with our study.

While investigating related work about ontologies and taxonomies about sounds, it became clear that the terms are used in a number of ways differing greatly in terms of their methodology and complexity (Giordano et al., 2022). In our opinion, what constitutes an ontology, is the availability of relations between classes. Since we do not have relations, we refer to a taxonomy of sounds with classes, sub-classes, and properties.

3 Identification of Sound Classes

As basis for the mapping of the sounds and the development of a taxonomy, we need to identify possible sound classes in an urban environment. To this end we performed two online studies (Section 3.1) and a focus-group interview (Section 3.2).

3.1 Online Studies

In the study of Koutsoklenis and Papadopoulos (2011) visually-impaired people were asked to name and judge (subjectively) valuable information for spatial orientation in the acoustic modality.

For our study, we expect that

1. sighted people provide other information than visually-impaired people but at the same time show at least some overlap for the auditory information,
2. visually-impaired people rely more on auditory information than sighted people, while
3. sighted people might have problems with the judgements, since in everyday life the use of auditory information might be rather implicit than explicit.

The participants for the studies were recruited via an email which was sent to all students via the university's data processing service centre.

3.1.1 Study 1

In an online survey conducted at Gießen University we asked participants (N=26, M=28.5, SD=10.99, 23 females and three males; a typical sample of psychology students, which also accounts for Study 2) about sounds/noises that could possibly serve as valuable (landmark) information for successful orientation. Participation was compensated with course credits if required and informed written consent was provided. From these results (Table 1) we derive possible categories for further investigation (Table 1).

Table 1. Sounds and categories of auditory information.

Sound/Noises (total number)	Category
Traffic noise (22) Trains (4)	Traffic and vehicles
Conversations and voices (17)	Human noises/sounds
(running) water (8) Wind (e.g., in trees) (6) Animal noise (12)	Nature and environment
Music (4)	Music
Dishes (rattle) (2)	-
Warning signals (2)	-

Please note that these entries just resemble what participants provided us with. At this time, it is not to be questioned how useful this information really is (for spatial orientation; e.g., a crowd). This was done to have possible landmark information at hand that could be judged on the basis of usefulness and frequency of use in everyday life (Section 3.1.2) as was done in Koutsoklenis and Papadopoulos (2011).

3.1.2 Study 2

Based on the findings of Study 1, a list of possible landmark information was created for the auditory modality (please note that all items mentioned in Study 1 were integrated into this list which was then fully addressed; see Table 1). Participants (N=39, M=25.67, SD=11.03, 30 females, eight males, and one person indicated diverse) were asked to judge the (subjective/personal) frequency of use and the usefulness of such landmark-like information for successful orientation (as was done in the original study by Koutsoklenis and Papadopoulos (2011)). The ratings were given on a seven-point Likert scale, ranging from 0 (never or not useful) to 7 (always or very useful). The mean responses are given in Table 2.

Table 2. Mean Responses.

	Frequency of use	Judged usefulness
Traffic noise	5	5
Trains	4	5
Conversations and voices	4	5
(running) water	4	4
Wind (e.g., in trees)	3	4
Chirping birds	3	3
Other animal noises	3	3
Music	4	5
Dishes (rattle)	3	4
Warning signals	3	5

As our results demonstrate,

1. there is some overlap of the ratings between our results and the results obtained by Koutsoklenis and Papadopoulos (2011) (e.g., traffic noise has been assumed to be frequently used and being useful) as well as differences for different information (for further details please compare with the original study of Koutsoklenis and Papadopoulos (2011), since this is not the immediate focus of the current work);
2. the assumption that visually-impaired people rely more on auditory information than sighted people is supported in comparison to Koutsoklenis and Papadopoulos (2011);
3. the assumption that sighted people might have problems with these judgements seems to be confirmed, since there is rather little variance for the sighted sample in the auditory modality.

3.2 Focus-group Interview

We let students walk individually through an urban outdoor environment. Beforehand, they heard a lecture defining the terms navigation and wayfinding (Montello, 2005; Golledge, 1999), introducing cognitive aspects of human wayfinding including spatial knowledge acquisition (Siegel and White, 1975), and explaining the communication of route directions (Allen, 1997). Furthermore, they learned about a definition and the characterisation of landmarks (Lynch, 1960; Sorrows and Hirtle, 1999) and were introduced to several landmark modalities (visual, olfactory, and auditory) (Hamburger and Röser, 2014). Afterwards, the students were advised to walk at least 1.5 hours in an urban outdoor environment, to hear and to collect sounds. Subsequently, we brought the students together and gathered the results in a focus-group discussion. This is a commonly used qualitative data collection approach, which emerged as technique to gather local knowledge and perspectives as a basis for research and planning (Cornwall and Jewkes, 1995). The method aims to draw from complex personal experiences, beliefs, perceptions, and attitudes of the participants of a group through a moderated interaction (O. Nyumba et al., 2018). A moderator (the corresponding author) facilitated the discussion between the students. In contrast to interviews, the moderator takes a peripheral role in the discussion (O. Nyumba et al., 2018). The students were asked to start a discussion about the sounds they heard while navigating. The discussions were documented by note-taking on a concept-board (Table 3). The sounds mentioned in the focus group varied, from noises produced by traffic, to human and animal noises, to natural sounds (such as water or wind). Please note that there is a large overlap to the findings of the first online study, indicating that the results are reliable.

Table 3. Concept board sounds.

Results focus-group interview	
Traffic (bus, train, rail, truck car, bike)	Human noises (discussions, voices, calls, child's voice)
Animals (bird twitter, barking, quacking, cats, pigeons)	Objects that make noise (open can, clatter of glasses, plates, chairs)
Moving things	Church bells
Different street surfaces under vehicles	Water (fountain, weir, canals, water wheel, river)
Music (street musicians, from buildings, ...)	Sirens (police, ambulance, ...) and alarm signals
Aircraft (helicopter, drone, ...)	Machines (cash machine, parking machine, ...)
Playground	Park
Horns, bells	Brakes, accelerations
Water pipe	Vehicles in tunnel
Wind	Wind noise (trees, flags, ...)
Exhaust air, air conditioning	Acoustic signals at traffic lights
Construction site	

4 Urban Sound Mapping

We formalise a taxonomy for urban sound mapping for pedestrian wayfinding and a conceptual framework for mapping such data in GIS. In Section 4.1 we develop the taxonomy with classes, sub-classes, and properties. We describe the mapping in the field using GIS (Section 4.2).

4.1 Taxonomy and conceptual Model for Sound Mapping

For the purposes of urban sound mapping we develop a taxonomy and define sound classes and sub-classes (Section 4.1.1) as well as properties of each sound class (Section 4.1.2). We consider a taxonomy with two levels – level 1 (sub-classes) and level 2 (classes), being the most common number of levels in classifying sounds (Jimenez et al., 2018).

4.1.1 Definition of Sound Classes and Sub-classes

We analysed the results from the online studies (Section 3.1) and the focus-group interview (Section 3.2) to define the classes for sound mapping. We merged the results and identified 14 different sound classes and sub-classes (Table 4).

Table 4. Taxonomy with sub-classes.

Class	Sub-classes
Aircraft	Airplane, Helicopter, Drone, Other
Animal noise	Chirping, Barking, Quacking, Cooing, Other
Human noise	Conversations, Voices, Shouts, Children, Other
Music	Street Musician, Stereo system, Speakers, Building, Other
Object	Opening cans, Dishes, Moving chairs, Water pipe, Other
Place	Park, Playground, Construction site, Other
Religious facility	Church, Cathedral, Other
Signal	Horn, Bicycle bell, Other bell, Accessible pedestrian signal, Gate signal, Other
Siren	Police, Ambulance, Other
Traffic	Tram, Car, Truck, Bus, Scooter, Bike, Train, Other
Vehicle on road surface	Asphalt, Cobblestone, Rail, Other
Ventilation system	Air condition, Exhaust air, Other
Water area	Fountain, Channel, Weir, Water wheel, River, Other
Wind noises	Flags, Trees, Other

Most classes of other taxonomies are similar to our classes (Table 5). Jimenez et al. (2018) consider a class effects including sub-classes "beep" and "boing". Salamon et al. (2014) consider a similar sub-class "backing up (beeping)" in the class mechanical (mechanical→Motorised Transport→Road→Truck→Fire engine→Backing up (beeping)). We consider these sounds in the class signals. Salamon et al. (2014) summarise a number of our classes in one class mechanical but distinguish between several sub-classes again having sub-classes (see Salamon et al. (2014) for an overview).

4.1.2 Definition of Properties of Sub-classes

The classes alone do not provide enough information for the detailed analysis of sounds. We identified the properties *temporary*, *loudness*, and *notes* as important to be captured in sound mapping.

Temporary This property provides information whether this sound source possesses a temporal component (e.g., time of the year (seasons) or time of the day (Baus et al., 2007)). Most of the sounds in an urban environment have seasonal dependencies (e.g., wind or water areas) or time dependencies (e.g., human noises, music, or traffic noise). The temporary field is of the type integer (0 for no temporary dependency and 1 for the opposite).

Loudness Loudness can be measured at a quantitative scale, e.g., by using levels from 0 (whispers are understandable without problems) to 5 (harmful sounds) (Baus et al., 2007). We define an integer field for loudness to be able to report the exact decibel value of the sounds.

Notes Notes is an important property, being especially important for the details not captured in the sub-classes, maybe because they were not thought of before starting the mapping. To describe details, a description can be inserted in the free-text-field notes.

4.2 Sound Mapping in the Field

We used the App ArcGIS Collector (Collector, 2022) to map sound information, a tool enabling data collection in the field. We needed a map containing layers of different sounds in the urban environment. We describe the transfer of the classes from the taxonomy into sound layers (Section 4.2.1) and the procedure to map sound (Section 4.2.2).

4.2.1 From a Taxonomy to an editable WebMap

We prepared an editable layer in the GIS for the classes to setup a WebMap and created a field named *type* defining the sub-classes. We defined fields for the properties temporary, loudness, and notes. In a preceding experiment we tried to map the "borders" of sound. It turns out that the sounds do not stop suddenly but are getting quieter and quieter until they cease to be audible. Additionally, they mix with new emerging sounds. Thus, identifying borders of sound polygons is difficult or even unfeasible. Because of these reasons we decided to use point geometry and to map the sound as a point ("sound-peak") at the location where it is most audible or being produced.

For the data collection we additionally defined a layer named "others" since there might be sound classes occurring that we had not thought of previously. We included "other" as a possible sub-class for all the classes, to be able to map the types of sound as accurately as possible.

After defining the layers, we prepared the map for data collection. For each class and sub-class we specified a symbol. These are the symbols that ArcGIS Collector used for

Table 5. Comparison of our taxonomy with other classifications of sounds.

Taxonomy Sounds	Gemmeke et al. (2017)	Jimenez et al. (2018)	Salamon et al. (2014)
Aircraft	-	-	Mechanical
Animal noise	Animal sounds	Nature	Nature
Human noise	Human sounds	Human	Human
Music	Music	Music	Music
Object	Sounds of things	-	-
Place	-	-	Mechanical
Religious facility	Sounds of things	-	Mechanical
Signal	Sounds of things	-	Mechanical
Siren	Sounds of things	Urban	Mechanical
Traffic	Sounds of things	Urban	Mechanical
Vehicle on road surface	Source-ambiguous sounds	-	Mechanical
Ventilation system	-	-	Mechanical
Water area	Natural sounds	-	Nature
Wind noises	Natural sounds	-	Nature
-	-	Effects	Mechanical

the mapped sound-peaks. We uploaded the map in ArcGIS Online, a cloud-based mapping and analysis solution used to share data and to collaborate (Online, 2022). ArcGIS Collector was given access to the map via ArcGIS Online and the map could be shared for sound-peak collection.

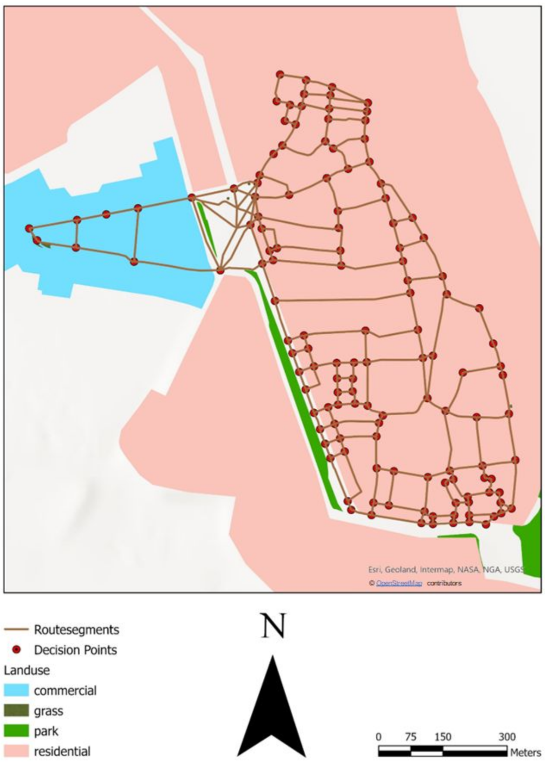

Figure 1. Landuse in the investigation area.

4.2.2 Procedure

Sound-peaks were collected within the project seminar "The sonorous city – modelling landmarks with GIS". Five students of this seminar (in the following called *sound-mappers*) mapped sound-peaks in the investigation area. This process was closely monitored by the instructor, i.e., the corresponding author.

A part of Augsburg was selected as investigation area (Figure 1). The investigation area includes a variety of urban infrastructures with different land uses. There is a commercial area with a number of shops and restaurants, but also green spaces (grass and park), and residential areas.

The on-site mapping was performed over two weeks in June and July 2022. The sound-mappers examined the investigation area. They recorded each sound-peak using a dedicated mobile recording device. In a preceding experiment we investigated tools for sound recording. The Zoom H1n (Zoom, 2022) showed the best quality regarding disturbing noises such as wind. At each sound-peak the sound-mappers started the Zoom to record for 5 - 10 sec.

After opening ArcGIS collector as well as the prepared WebMap, the map centres on the location of the sound-mapper. There is an "add"-button to select the class and sub-class as well as to capture the location of the sound-peak. Values for the properties temporary, notes, and loudness can be captured by filling out a form. While the sound-mappers assessed whether a sound is temporary or not, loudness was measured using a mobile phone decibel app. After entering the values the mapped sound-peaks and the property values were shared via a checkmark and were then available in the WebMap.

4.3 Data and Software Availability Section

We provide the data of the Figures as well as the results of the studies (Section 3.1). The result of the the mapping via ArcGIS Collector is available as a geodatabase. It includes the layers of the mapped sound-peaks with properties as well as audible sound files. Additionally, we provide all the sounds as .wav- or .mp3-file. The data is available on figshare and accessible via the following DOI: https://doi.org/10.6084/m9.figshare.22109987. Note: the data was collected in German. For this publication everything has been translated to English.

5 Results

Overall, 130 sound-peaks were mapped (Table 6 and Figure 2). We detail the results of the classes and sub-classes (Section 5.1) and take a look at the properties (Section 5.2).

Table 6. Results per class.

Class	No	Decibel			
		Min	Max	Mean	Std
Aircraft	1	34	34	34	
Animal noise	11	35	55	41.91	6.58
Human noise	23	32	70	43.13	8.44
Music	8	33	63	44.63	8.60
Object	8	35	49	41.75	4.80
Place	3	46	120	75.67	39.12
Religious facility	5	30	67	43	14.54
Signal	7	46	62	52.17	5.85
Siren	1	48	48	48	
Traffic	43	24	85	52.02	14.28
Vehicle on road surface	6	44	82	53.83	14.29
Ventilation system	1	38	38	38	
Water area	10	43	61	49.70	5.52
Wind noises	3	38	62	50.67	12.06

5.1 Results per Class

Some classes include more sound-peaks than expected – while in others there are not many sound-peaks. Most of them are part of the class traffic, which is typical for a downtown area with streets populated by cars, buses, and trams (Table 6).

Aircraft The sound of an airplane was mapped once with relatively low decibel (34, compare Section 5.2). Augsburg is not located in an airport corridor. Thus, the sound of aircraft is not constantly around. In the focus-group interview (Section 3.2, Table 3) drones and helicopters were mentioned – however, these sounds were not noticeable during mapping.

Animal noise We reported eleven animal noises such as chirping and cooing. Especially pigeons are typical animals for inner city areas and there are places, where doves frequently occur. They may be useful wayfinding aids to let the traveller understand where the place is and to maintain orientation.

Human noise There are numerous human noises in an inner city area. We mapped 23 of the most outstanding ones. These included noises connected to buildings such as kindergartens, restaurants, nursing homes, or residential buildings. Noises on the street were mapped such as the crying of a baby, people on the phone, and general noises of pedestrians. Koutsoklenis and Papadopoulos (2011) reported people entering or leaving a shop as an important auditory cue used for wayfinding by individuals with visual impairments – other human noises were not mentioned. Human noises in front of a restaurant or noises at busy places can help individuals to understand that they are approaching a busy street and to avoid collisions with other people.

Music We mapped eight sound-peaks stemming from music. Music is often connected to a building such as a music store or a school giving music classes. Music connected to shops can help to find the entrance or to understand that there is a building (Koutsoklenis and Papadopoulos, 2011). We mapped two street musicians, which can be helpful aids in case they are connected with places or street intersections (e.g., pedestrian zone).

Object We mapped eight sound-peaks of objects (Table 6). Most sounds came from rattling dishes, but also from moving chairs, a rustling plastic bag, and a goods trolley. Most noises were related to buildings such as restaurants, kindergartens, or market stalls.

Place We mapped only construction sites for places. One was connected to a building. In the focus-group interview (Section 3.2, Table 3) playgrounds and parks were mentioned as important sound sources. In the investigation area there are park areas (Figure 1) and one official playground. However, there were no noises reported there.

Religious facility We mapped five sound-peaks from church bells. Sometimes the sound was clearly connected to a building, since the church was nearby and visible, or it was reconstructed where the sound stemmed from. Sometimes the sound was audible but the source was incomprehensible resulting in differences in loudness (Table 6, decibel).

Signal Most of the mapped signals were traffic controls with accessible pedestrian signals. This sound source is a good cue as a location reference and is found to be most useful for wayfinding after car passing (Koutsoklenis and Papadopoulos, 2011). Other signals, found in the investigation area, were car horns and the ring of a cell phone. Thus, car horns, even though very plausible, seem to be somehow overrated.

Siren After the focus-group interview (Section 3.2, Table 3) we expected to map a number of ambulances and po-

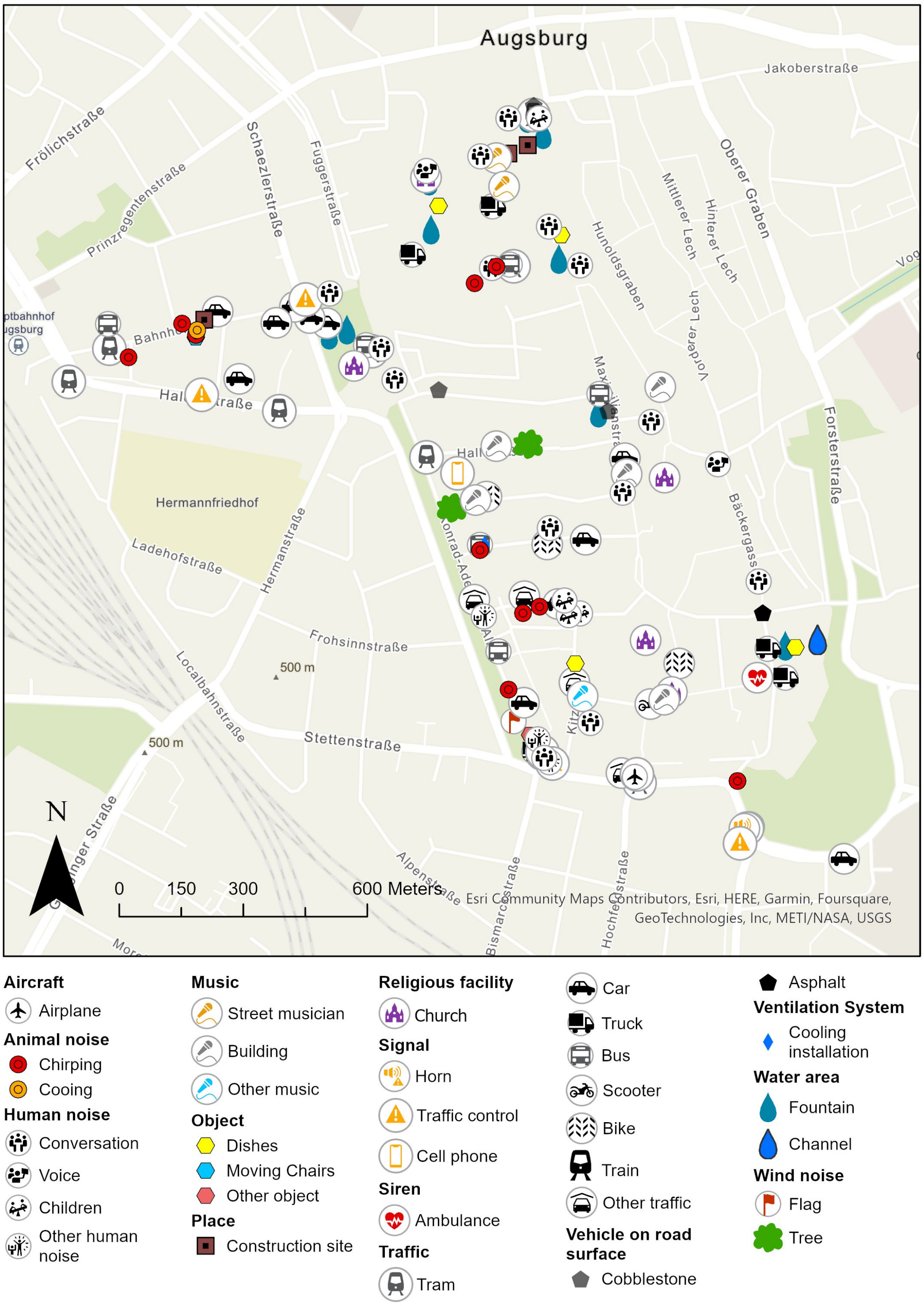

Figure 2. Results of urban sound mapping.

lice sirens. However, only one ambulance was around during mapping. Police stations and hospitals are not located within the investigation area. Thus, sirens only appear in case something has happened within the area requiring an ambulance or a police car.

Traffic For traffic we mapped the largest number of sound-peaks. This is typical for downtown areas. There are a lot of sounds around stemming from cars, trams, trucks, and buses. This is in line with Koutsoklenis and Papadopoulos (2011) who found car passing, street traffic, and bus passing as the three most significant auditory cues for wayfinding.

Vehicle on road surface Here we mapped sounds not stemming from the traffic itself but that the car makes in connection with the road surface. Overall we identified six sound-peaks stemming from vehicles on road surfaces (Table 6), mainly sounds from vehicles on cobblestones and on asphalt. In one instance the sound overlapped with music. Especially the sound of vehicles on cobblestones can be a useful sound for wayfinding since it gives not only information about the direction of cars but also about distance and the direction of the street (Koutsoklenis and Papadopoulos, 2011).

Ventilation system One air condition was mapped for the class ventilation systems – one of the few temporally independent sounds, since it is connected to a building and constantly there. It could be a good hint for blind people to understand that there are (larger) buildings around.

Water area The canals and fountains in Augsburg are a core part of the historic water management. We expected to hear a number of water noises stemming from water wheels or weirs. Most of the mapped water areas in the investigation area are fountains. Although there are a number of channels, they do not emit as much noise.

Wind noise We found wind noises in the investigation area stemming from trees and flags on flagpoles. Wind is one of the nature-related sounds (together with animal noises and water areas). Although they are to some extent unstable, since they are dependent, e.g., on weather conditions, they can be a good source to maintain orientation.

We classified the sounds into the classes and then, again, into sub-classes. The sub-class used the most often with eleven occurrences was car from the class traffic. An important sub-class was "other", since this was used for all the sounds previously not been thought of. This sub-class was most commonly used for traffic with five selections. These include waste removal, tractor, and motorcycle. The sound motorcycle is commonly appearing but hadn't been thought of during the focus-group interview. Overall, there were not many sub-classes missing for sound mapping in Augsburg.

5.2 Results Properties

This subsection takes a look at the property values, the limitations of the properties, and the resulting difficulties.

Temporary Most of the sounds have a daily or seasonal dependency. The few not temporary exceptions include traffic controls with accessible pedestrian signals (although they are not constantly permitting noise, they are available the whole day) and noises from air conditions. All the other noises have high temporal dependencies and differ only in their manifestation (seasonal, daily, quarter-hourly, e.g., church bells).

Loudness We measured noises in the range of 24 (traffic, motorcycle) and 120 (place, construction site) decibel (Table 6). The quietest sound-peak was aircraft (mean = 34 decibel). Place was considered the loudest with a mean = 75.67. Thus, there are a number of influencing factors when measuring the volume of sounds, e.g., nearness plays a role. In case the measurement for the noise of the motorcycle would have been taken at closer distance the number of decibel would be higher. According to Statista (2022) a passing motorcycle at two meters distance can reach 100 decibel. This is also true for a passing ambulance, which can easily reach a volume of 120 (Statista, 2022), but was only measured at 48 decibel. There were even not measurable sounds (traffic controls with accessible pedestrian signals, a rustling plastic bag).

Notes This property was especially helpful for human noises, since for this class it was difficult to identify sub-classes in advance. It was used to provide more details about the noise, e.g., for the sound class human noises with sub-class discussions, the sound-mappers noted: residential buildings, telephone, retirement home, and conversations at restaurants/cafes.

6 Discussion

In the psychological part of our study we demonstrate that sighted people are capable of reporting auditory signals of interest for spatial orientation. It is rather trivial to say that visually-impaired people heavily rely on auditory signals during navigation, while sighted people rather (prefer to) rely on visual information. This type of information was repeatedly shown to be possibly useful information for wayfinding (e.g., Hamburger and Röser (2014); Karimpur and Hamburger (2016)) and we here provide additional (subjective) data on the usefulness and frequency of use of this type of information. Thus, it is possible to at least complement our cognitive maps with additional sensory information.

In the GIS part of our study we could demonstrate that it is possible to systematically map sounds in urban areas to position them in (cognitive) maps. We built our taxonomy based on the online-studies and the focus-group interview. This resulted in 14 classes and corresponding sub-classes. Some of the classes (or sub-classes) could have been created differently. For example, religious facility could be set-up as a sub-class of place. We made this distinction because religious facility is a building, while a place is an areal object (park or playground). The creation of the taxonomy should be structured as an iterative process, alternating the design of the taxonomy with field investigations.

We used point geometry for the layers and mapped sound-peaks. There may be other ways to represent sound fading characteristics. The range of audibility could be estimated and noted and buffers could be created to show the extent of a sound around a source. Sound could also be captured as continuous field by interpolating point-wise samples into a surface. To better estimate the range multiple sound-mappers could estimate this property from different locations. Additionally, multiple distances between the source and different positions of the sound-mappers could be captured. However, this goes beyond the focus of the current work and will be part of future studies.

The next step would be an evaluation with respect to using the taxonomy classes for wayfinding purposes. Golledge (1999) identifies three wayfinding tasks (travel to familiar destination, to explore, and to novel destination) which can be accomplished by a variety of means (e.g., oriented search, following a marked trail, or piloting between landmarks). The mapped sound-peaks can be used together with these means for orientation or wayfinding for both, sighted and visual-impaired persons. Sound-peaks can, e.g., be used for orientation (e.g., street traffic helps individuals to maintain orientation in an urban environment (Koutsoklenis and Papadopoulos, 2011) and together with marked trails by referring to sounds at specific locations of the trail (e.g., to the sound of music or the noise of traffic). Wayfinding by means of piloting between landmarks is a method that is equally applicable with sound landmarks as described in the Introduction. A detailed investigation of these wayfinding means regarding different wayfinding tasks is still outstanding.

As we have seen, there are intersections/places where useful auditory information is present, while at other intersections/places valuable visual information might be absent. That said, it is important to note that Nuhn and Timpf (2022) identified an intersection in their study which did not provide salient visual features (intersection 24, Figure 3). This intersection was included in the current study and valuable auditory information was obtained for this intersection (as well as olfactory information; which is part of a different study not reported here). This includes auditory information from pedestrian signals as well as car traffic.

For such cases it is not necessary to switch from landmark-based learning to any other wayfinding strategy in the absence of visual information. Rather, if adequate, we could stick to our initial learning and representation strategy without changing it but switching the processing modality of the landmark. This brings us to another point: It is very likely that we do not strictly represent our environment on the basis of landmarks but rather use combinations of strategies. Possible strategies in combination with cognitive abilities and personal preferences (including motivational factors) need to be taken into account in this context and implemented into modern navigation devices for suc-

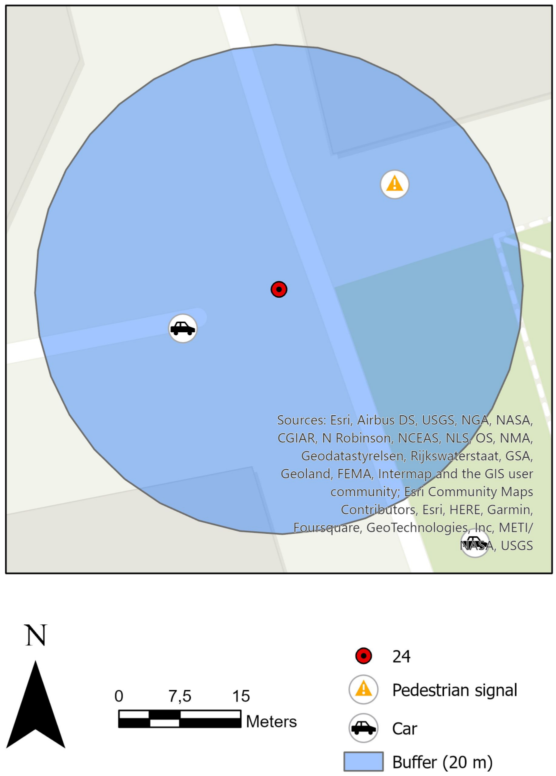

Figure 3. Auditory information at intersection 24.

cessful spatial orientation. Further, we have to be aware that many cities possess totally different properties. Augsburg is full of canals with a high number of bridges (more than Venice for comparison). Other cities may only have a single river running through it or none at all. The sound of water in Augsburg might represent a more valuable information than for other urban environments. This also accounts for other cities and sounds. One example could be air traffic, which did not play any role in Augsburg. For a city like Frankfurt, air traffic noise is permanently present (day and night, even though reduced during the night) in different amounts at different locations/areas, which might at least be helpful for general orientation but could also be helpful for wayfinding. These are just a few examples as well as caveats on the usefulness of sounds in spatial orientation and the mapping thereof. As a consequence, we need to foster further systematic research in this domain. A strategy towards a richer sound taxonomy could be the repetition of the study proposed here in a different environment. This includes the design of an individual taxonomy as well as the mapping to investigate which sounds are really audible. The individual taxonomies could then be merged into an overall taxonomy. With this approach negligible and additional classes could be identified. For example, our sound class place only contains construction sites. However, in another city it could be possible that we would identify other sounding places. If this were not the case, we could consider to integrate construction sites into another class or rename the class places.

Our findings may not only be of relevance for spatial orientation research but also for urban planning and architecture. If we have a better understanding of the underlying perceptual and cognitive processes of landmark-based wayfinding, it could be possible to intentionally encode the most valuable information. This may not only be true at a larger scale like a city but could be implemented at a very small scale such as nursing – and retirement homes, where the residents suffer from different limitations such as perceptual decline (e.g., visual deficits, auditory deficits) and cognitive decline (e.g., dementia).

7 Outlook and Future Work

In this research we propose a taxonomy and a corresponding conceptual model to represent data about urban sounds for pedestrian wayfinding. We collect sound-peaks using this taxonomy and map them.

An important aspect that we have to consider in future work is that the availability of sound can vary considerably over time. Here in this work we did not report sound-peaks at playgrounds. At another time of the day this might be different. Thus, it is necessary to map urban areas for specific time periods. In future work our taxonomy can be extended and additional properties such as daily variations or seasonal dependencies can be captured.

Many of the defined sound classes are not bound to a particular spatial location. For example, animal or vehicles can move and change their location. On the contrary there are static sound sources, e.g., stemming from buildings. This characteristic can be considered as an additional property in a future version of the taxonomy.

In our current study we focused on a single and isolated modality (something we criticised in the Introduction). This was a first attempt at combining psychological approaches and GIS mapping in the domain of auditory information. The next steps will be to add further empirical results from other modalities (i.e., olfaction and haptics) to (1) have a more comprehensive understanding of landmark-based wayfinding; (2) give credit to the multimodal nature of spatial orientation (since navigation is not just a visual process but is rather made up from multiple processes); and (3) being able to provide more user-centred (i.e., adaptive) mobile navigation systems capable of providing a) information that the user is capable of processing (i.e., other than visual information for visually-impaired people and no auditory signals for people with hearing impairments) and b) information that is preferred by the user her- or himself (i.e., cognitive styles). Thus, a major claim is that the navigation system needs to adapt to the user and not the user to the navigation system!

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