Soundscapes as Urban Transformation:

Introducing a notational language that represents the shifting relationships between sound, space, and movement

by

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Abstract

Even though we have advanced technology that can reveal the complexity of cities, urban planners typically turn to the physical attributes of the built environment alone to design them. Instead, this research views cities as a system of continuous, temporal changes that determine how people actually experience and move through cities in their everyday lives. I argue that sound -- an integral experience of cities often treated as no more than urban pollution -- conveys vital information about the practices, events, boundaries, and characters of neighborhoods and streetscapes. Urban sound is ubiquitous, yet we have not developed an adequate language to describe it. Through a case study in Cambridge, Massachusetts, I introduce a computational tool that can be used to understand and represent temporal, sonic changes occurring during different phases of the COVID-19 pandemic. More broadly, this work offers a notational system as a new language for representing the changing relationships between sound, space, and movement that embodies the complexity of the urban environment.

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All images created by the author unless otherwise noted.

PART I: Introduction

Cities are not simply comprised of what we see. An important part of our experience in cities is what we hear, what we smell, and how we move in space. Sound, smell, and movement are temporal events that are not usually considered integral to the planning process. These events bring continual change, as with the passing of cars, the smell of fresh grass, and someone playing guitar on the street. By focusing on the built environment alone, we are left with a distorted or inadequate sense of what actually constitutes city life. More specifically, urban planners need to recognize that transformations are taking place all around us. Transformations that look only at the built environment are often represented over large periods of time, such as when an area in the city is redeveloped, constructed, or demolished. This keeps us from making informed decisions that improve living conditions. Furthermore, how can we prepare our cities for climate change if our models do not account for the temporal pace, auditory complexity, and other unfixed dimensions of urban life?

Additionally, even if we understood the complex nature of cities, we currently don't have a language for describing transformations in urban soundscapes, an integral part of cities. The thesis sees the temporal dimensions of a city as a system of temporal changes, focusing on changes in the urban soundscape, *soundscape transformations*, and how those relate to the urban space, *spatial transformations*, and consequently how they affect the ways we move in the space, *movement transformations*. A computational analysis methodology is developed to identify and analyze changes in the urban soundscape, which incorporates clustering algorithms to show how different sound clusters change over time and how those changes are related to space and movement. The thesis introduces a notational system to visualize the changing soundscapes and their shifting relationships to space and movement that shape different walking experiences.

To test the methodology developed in this thesis, Harvard Square in Cambridge, Massachusetts, was used as a case study during the different phases of the COVID-19 pandemic. More specifically, a specific walking route around Harvard Square was used to capture how the different phases of the pandemic changed the soundscape, the spatial conditions, and the walking experience at street level over time. Visual and audio data in the form of 360-video and 360-sound recordings and geolocation data were collected and captured over three months in the afternoons and evenings. These data then are used to demonstrate the implementation of the notational system and digital interface that can identify, compare and visualize the spatial and soundscape and movement transformations. Urban planners, policymakers, and real estate can use this tool to understand how the different policy decisions changed the urban space, the soundscape, and the everyday experience of the residents of the Harvard Square area.

The thesis is structured in four parts, Introduction, Background, Soundscapes as Urban Transformation, and Conclusion and Future Work. In the Background chapter, I discuss the problem of looking only at the built environment in urban planning and how that leads to dismissing temporality in cities. Then, I present different approaches to studying temporal aspects of urban spaces. As an integral part of temporality in cities, I discuss the concept of soundscape, from the sound being only conceived as urban noise pollution in the context of cities to using soundscape as a way to understand the temporal dimensions of the environment.

In part three, I introduce my thesis and the methodology that is developed, as well as the case study of the changing walking experience in Harvard Square during COVID-19. This chapter introduces the clustering of different sounds in the soundscape, the notational system, and the interface. Finally, I demonstrate the application of my thesis in the Findings, in which I show examples of different comparisons. Lastly, in the Conclusion and Future Work chapter, I discuss the conclusion from this work and potential applications and future steps.

PART II: Background

Looking only at the Built Environment

Jane Jacobs (Jacobs 1961), already in the 1960s, warned about the consequences of oversimplifying “the kind of complex problem the city is” and relying on models of cities or dream cities that have nothing to do with reality. She referred to the “modern orthodox planning” of the early 20th century, but her arguments are still very timely.

“The pseudoscience of city planning and its companion, the art of city design, have not yet broken with the spe-cious comfort of wishes. familiar superstitions, oversimplifications, and symbols. and have not yet embarked upon the adventure of probing the real world.”

Even though today we would like to be more scientific by collecting more and more data using them to create our models of cities, and to “understand” how cities work better, we are still oversimplifying the kinds of problems cities present. We still carry remnants of our orthodox planning past as we look at the city from a top-down view. In particular, the majority of the planning field studies place in cities by looking only at the built environment.

More recently, cities and municipalities are looking at technology to help solve city problems. The development of digital twins in the future, presented as a form of advanced technology, is an example of this. Digital twins are digital 3D models of entire cities, and planners hope to run simulations of new policies or infrastructure projects and preview their potential impacts before deciding in the real world.[1] But, even in this digital context, cities are seen only through their physical characteristics. Yet, cities respond to a changing world, and so should our ways of understanding and representing them.

[1] *Bloomberg.Com*. 2022. “How Cities Are Using Digital Twins Like a SimCity for Policymakers,” April 5, 2022. https://www.bloomberg.com/news/features/2022-04-05/digital-twins-mark-cities-first-foray-into-the-metaverse.

Different Approaches to Studying Temporality in Cities

Temporal events are integral to our everyday experience in cities. But what constitutes an event? According to Varzi and Casati (Varzi and Casati 2008), there are various definitions of an event in terms of time and location. Events are four-dimensional entities that extend through time as well as space and that endure through time by being partially located at each moment of their existence, according to the revised definition of what constitutes an event. Events are defined by their temporal and spatial parts (spatiotemporal), and according to Gibson (Gibson 1975), time can be perceived through the happening of events. Therefore, we can only perceive change through a series of temporal events.

The temporality of urban spaces as defined by the tempo of city life has been discussed by many academics. According to Torsten Hagerstrand, the recurring everyday-life activities that meet and intersect in time and place define the temporality of urban space (Pred 1977). Lefebre (Lefebvre and Regulier 2004) introduced the concept of rhythmanalysis, suggesting that urban places are polyrhythmic fields of interaction shaped by recurring practices, actions, and other events that are synchronized in time and space. Anne Buttimer (Buttimer 1976) talked about synchronizing recurring events within a time-space framework, and she described social urban space as a "multilayered dynamic complex" made up of timespace rhythms.

More specifically, Jane Jacobs (Jacobs 1961) discussed the dynamics of streetscape referring to it as “an intricate sidewalk ballet” that is “choreographed” by the different everyday rhythms and movements of people, that create recurring patterns. These recurring rhythms are orchestrated by daily routines, such as stores open and close, the delivery of services and goods, the movement of people, and constitute the city and streetscape life. This, according to David Seamon (Buttimer and Seamon 1980), offers the distinct experience of New York's streets and reveals the dynamics of everyday life, which are determined by the density and activities of people at any given time and place.

One of the ways to capture and untangle the dynamics of everyday life, is sound. But how can sound help us understand and capture the temporal events that create different rhythms in the everyday life of cities?

Urban Soundscapes

Sound in Cities and Noise Pollution

The vast majority of urban studies, when they refer to 'soundscape' they, focus on how to control noise pollution in cities. Noise pollution in cities is a growing problem as urban environments become more and more densely populated. According to the EU and WHO, noise pollution is defined as noise levels above 55dB Lden and 50dB Lnight. In their report, they show that 65% of Europeans in major cities are exposed to high noise levels, which has an impact on their health.[2]

This strictly quantitative approach to understanding sound in the context of cities has proven ineffective in policymaking since it only considers physical measurements and ignores human perceptions of sound. Most city policies are insufficient, as they primarily aim for maximum noise weighted levels and hence focus on physical measurements, ignoring human noise experiences. Assessing the sound quality of an urban area appears to be more complex than just a simple measurement of the sound pressure level as it relies on the content of the sound and the context in which it is perceived (Raimbault and Dubois 2005). One of the main difficulties is the controversy around the defintion of noise, as it is determined of the human perception, the meaning of the sound and preferences of people that are exposed to it.

Since all types of pollution require effective management, measurement, and evaluation, a comprehensive perspective that incorporates the broader subject of urban comfort is now required to assess the impact of urban sounds on people (Raimbault and Dubois 2005). To address this, a more holistic approach to measuring and evaluating urban sound is needed.

[2] *Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living Well, within the Limits of Our Planet' Text with EEA Relevance*. 2013. *OJ L*. Vol. 354. http://data.europa.eu/eli/dec/2013/1386/oj/eng.

Soundscape as a quality assessment of our environment

Soundscape can be regarded of as an alternative to strictly quantitative ways for overcoming the limitations of noise pollution measurements, that can offer a more holistic approach to urban sound quality (Brigitte Schulte-Fortkamp 2002). Current urban soundscape research is more subject-centered, with the goal of gaining new knowledge regarding the negative consequences of noise on health and well-being. Distinguishing between soundscapes that bring quality to an environment and those perceived as disturbing improves urban development (Skånberg and Öhrström 2002; Stockfelt 1991; B Schulte-Fortkamp and Lercher, 2003).

The Soundscape

The soundscape, also known as the acoustic environment, is a recognized and aesthetic collection of sounds in a certain place (Schafer 1993; Augoyard and Torgue 2006). In his book “The Tuning of the World”, he used the notions of lowfi and hi-fi soundscapes to investigate the different textures of sounds in the acoustic urban surroundings. As defined through his fieldwork, low-fi soundscapes are characterized by foggy and blurry sounds, while hi-fi soundscapes consist of sounds that are distinct and precise.

Sounds in a hi-fi soundscape have the property that their "frequencies can be heard distinctively" and hence are not masked by background noises and other sounds (Schafer 1993). Therefore, the distinction between foreground and background noises is clear (Wrightson 2000.). These sounds collide and reverberate in terms of their frequency and rhythm, resulting in various acoustic colorations. As a result, an auditory and rhythmic equilibrium similar to that of a "natural soundscape" is achieved (Krause 1992).

Acoustic colorations are described as "echoes and reverberations that occur as sound is absorbed and reflected from surfaces within the environment" (Augoyard and Torgue 2006). They provide valuable insight on the physical nature and scale of spaces. In the case of hi-fi soundscapes, the acoustic colorations of hi-fi soundscapes are generally defined by repetition and resonance. Recurring sound events make environments distinctive; therefore repetition is important in determining the context in which sounds are generated (Augoyard and Torgue 2006).

Moreover, acoustic colorations of hi-fi soundscapes can convey information about the temporal dimensions of a city's life, the character and cultural identity of a place as sounds emerge from places and their everyday social activity and routines. As a result, the walking experience is defined and enhanced through the repetition and resonance of acoustic colorations (Wunderlich 2013).

How sound influences our everyday walking in cities

Recent research (Cornwell et al. 2020) shows that sounds have a large impact on the way we walk as they control temporal and spatial aspects of walking. Sounds that are produced during walking may convey temporal information about the timing of key events in the gait cycle. Footsteps, for example, signal the important shift from leg swing to stance every time the feet make contact with the ground. In this regard, urban sounds may also act as spatial landmarks for managing components of walking, such as body posture and orientation (Karim et al. 2018).

The impact of sound in the walking experience becomes even more apparent in the case of people that suffer from hearing loss. Hearing loss can deprive the neurological system of important sensory information for controlling certain aspects of the walking. Research indicates that people suffering with hearing loss tend to walk slower and have difficulty walking longer distances. (Viljanen et al. 2009; Li et al. 2013). This point contradicts the notion that visual information is the most useful sensory feedback when navigating an urban environment, as auditory input is equally as important to the walking.

Soundscape as a way to understand temporal dimensions of the environment

Sound can be also seen as a way to overcome the limitations of visual information when trying to acquire more knowledge of the world. For example, we are using sound in our everyday life to decide whether we should cross a street or not. It is so fundamental in the way that we navigate in cities that autonomous vehicles are designed to have an artificial noise in order to alarm pedestrians (Moore, Currano, and Sirkin 2020). Sound is such an integral part of the way we try to learn about the world and our environment that humans use it all the time without having to think about it.

In some cases, we use sound to understand one of the most complex environments that exist, our universe. Space is a place full of dust, and although light is the main way through which scientists try to measure distances and make up a model of our universe, this approach has its limitations, as dust blocks light from reaching Earth. To overcome this problem scientists in NASA developed a project called “The tuning in the sounds of space”[3] and use sound, by measuring the sound waves, to understand

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[3] https://www.nasa.gov/audience/forstudents/5-8/features/F_Tuning_in_Sounds_of_Space_5-8.html

the distance of a star, a planet, or a different galaxy. In a different context, marine biologists also use sound to study changes in coral reefs due to climate change. Researchers study underwater soundscapes to determine the health of a coral reef [4], as healthy ones tend to be ‘noisy’, since fish also communicate through sound. So why can’t we use sound to determine whether our cities are “healthy” or not?

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4 https://dosits.org/people-and-sound/investigate-marine-animals/how-is-sound-used-to-study-coral-reefs/

PART III: Soundscapes as Urban Transformation

1. Introduction

Different dimensions make up a city, shape our everyday experience, and how a city change. These dimensions are more temporal and often not considered in urban design, planning, and policymaking. For example, our urban experience is shaped by our sensory experience of a place and a series of temporal events that trigger different reactions/ interactions, such as a very loud passing car, the smell of fresh grass, and someone playing guitar on the street. An important part of our experience is what we see in the cities and what we hear, what we smell, and how we move in space. Sound, smell, and movement are integral parts of these temporal events shaping our cities and everyday experiences.

The thesis focuses on the study of temporal transformations that have a significant impact on how people experience cities in their daily lives. This research looks at the temporal dimensions of a city as a system of temporal changes, focusing on changes in the urban space, *spatial transformations*, and the urban soundscape, *soundscape transformations* and how those changes affect the ways we move/walk in the space, *movement transformations*.

At the time that this thesis was being developed, the COVID-19 global pandemic broke out. Countries around the world enforced lockdowns and asked people to stay at home while cities were emptied of life in the streets. The global economy and infrastructure were stalled. During that time, cities were undergoing major temporal transformations as everyday life was changing rapidly. Cities around the world had to create new policies and measures to address temporal changes in the everyday life in cities due to the global pandemic. In these unprecedented times, people spent most of their time in their houses, while a walk was the only way to interact with the city.

To test the methodology developed in this thesis, Harvard Square, in Cambridge, Massachusetts was used as a case study during the implementation of the Reopening Massachusetts plan. More specifically, a specific walking route around Harvard Square was used to capture how the different phases of the pandemic changed the soundscape, the spatial conditions, and the walking experience at street level over time.

Visual and audio data in the form of 360-video and 360-sound recordings and geolocation data were collected and captured over three months in the afternoons and evenings. These data then are used to demonstrate the implementation of the notational system and digital interface that can identify, compare and visualize the spatial and soundscape and movement transformations. Urban planners, policymakers, and real estate can use this tool to understand how the different policy decisions changed the urban space, the soundscape, and the everyday experience of the residents of the Harvard Square area.

This chapter will discuss the thesis methodology for analyzing changes in the soundscape, urban space, and movement. I also demonstrate the implementation of the methodology in the Harvard Square case study and show how we can use the visual notational system that I developed and the interface to compare different phases of COVID-19.

2. Methodology

In this section, I discuss the methodology of this thesis that consists of a series of steps described as follows:

[Step 1] Determining the time period for establishing the comparative model

[Step 2] Deciding on a location to study

[Step 3] Designing of a walking route to study the walking experience

[Step 4] Specifying the recording methodology for data collection

[Step 5] Performing qualitative analysis to identify spatial transformations

[Step 6] Developing the soundscape analysis to identify sound clusters

[Step 7] Introducing the notational language representation for visualizing the shifting relationships between sound, space and movement

[Step 8] Implementing the notational language on a digital interface to create data-driven visualizations of the walks

[Step 9] Evaluating the findings of the comparison

2.1 TIME PERIOD: COVID-19 Pandemic

To study these temporal events, we need a more *dynamic* way to capture and represent these events over time. Furthermore, to identify temporal transformations, we need a comparative model, a way to compare, and a basis upon which we will make these comparisons. There are multiple ways to compare, different scales of transformation, and different units we can use to measure change. An important component of this methodology is defining the timeframe/period in which the transformations will be studied. Following the period, defining the smallest increment of time that we want to compare is also important. Lastly, the frequency of the walks for data collection is also crucial.

On March 11, 2020, the World Health Organization (WHO) declared the novel coronavirus (COVID-19) outbreak a global pandemic[5]. In Massachusetts, Gov. Charlie Baker declared a state of emergency on March 10, 2020, as cases of COVID-19 began to spike. Starting in March 2020, Massachusetts was in lockdown for about three months, while restaurants, businesses, companies, and schools were closed.

Two months later, the state of Massachusetts developed a four-phase approach, *Reopening Massachusetts plan*[6], to responsibly reopen the Massachusetts economy amidst the COVID-19 pandemic. The phased reopening plan was driven by public health guidance, and the goal was to progressively allow businesses, services, and activities to resume while protecting public health and limiting a resurgence of new COVID-19 cases. The plan centered around Mandatory Workplace Safety Standards that were applied across all sectors and enterprises and sector-specific protocols tailored to individual sectors and activities. Each phase of the reopening was guided by public health data and key indicators that were continually monitored for progress and were used to determine advancement to future phases. Industries, sectors, and activities that presented lower risk were allowed to reopen in earlier phases. Those that presented greater risk opened in later phases.

Phase I ("Start") of the plan began on May 18, 2020, and allowed manufacturing facilities, construction sites, and places of worship to re-open. Hospitals and community health centers were able to begin to provide high-priority preventative care, pediatric care, and treatment for high-risk patients. Under a staggered approach, additional Phase 1 sectors of the economy were permitted to open effective May 25 including lab space, office space, limited personal services (including hair salons, pet

[5] https://www.euro.who.int/en/health-topics/health-emergencies/coronavirus-covid-19/news/news/2020/3/who-announces-covid-19-outbreak-a-pandemic

[6] https://www.mass.gov/info-details/reopening-massachusetts

grooming, car washes, and retailers could offer remote fulfillment and curbside pick-up for all retailers).

Massachusetts moved to **Phase 2 ("Cautious")** in June, allowing additional lower risk businesses to reopen, including retail, childcare facilities, restaurants (with outdoor table service only), hotels and other lodgings, personal services without close physical contact, youth and adult amateur sports, and driving and flight schools. In **Step 2 of Phase II**, restaurants were permitted to open for indoor table service, and close-contact personal services, including nail care, skincare, massage therapy, and personal training. Health care providers also incrementally resumed in-person elective, non-urgent procedures, and services, including routine office visits, dental visits, and vision care subject to compliance with public health and safety standards.

On July 6, the Commonwealth proceeded to **Phase III ("Vigilant")** based on a sustained decline in key public health data, such as new cases and hospitalizations. A broad range of sectors was permitted to open, again subject to compliance with industry-specific rules concerning capacity and operations. The Phase III, Step 1 sectors included movie theaters and outdoor performance venues; museums, cultural and historical sites; fitness centers and health clubs; certain indoor recreational activities with low potential for contact; and professional sports teams (without spectators) became eligible to reopen. In October, indoor performance venues were permitted to open, and certain industries saw their capacity limits increase.

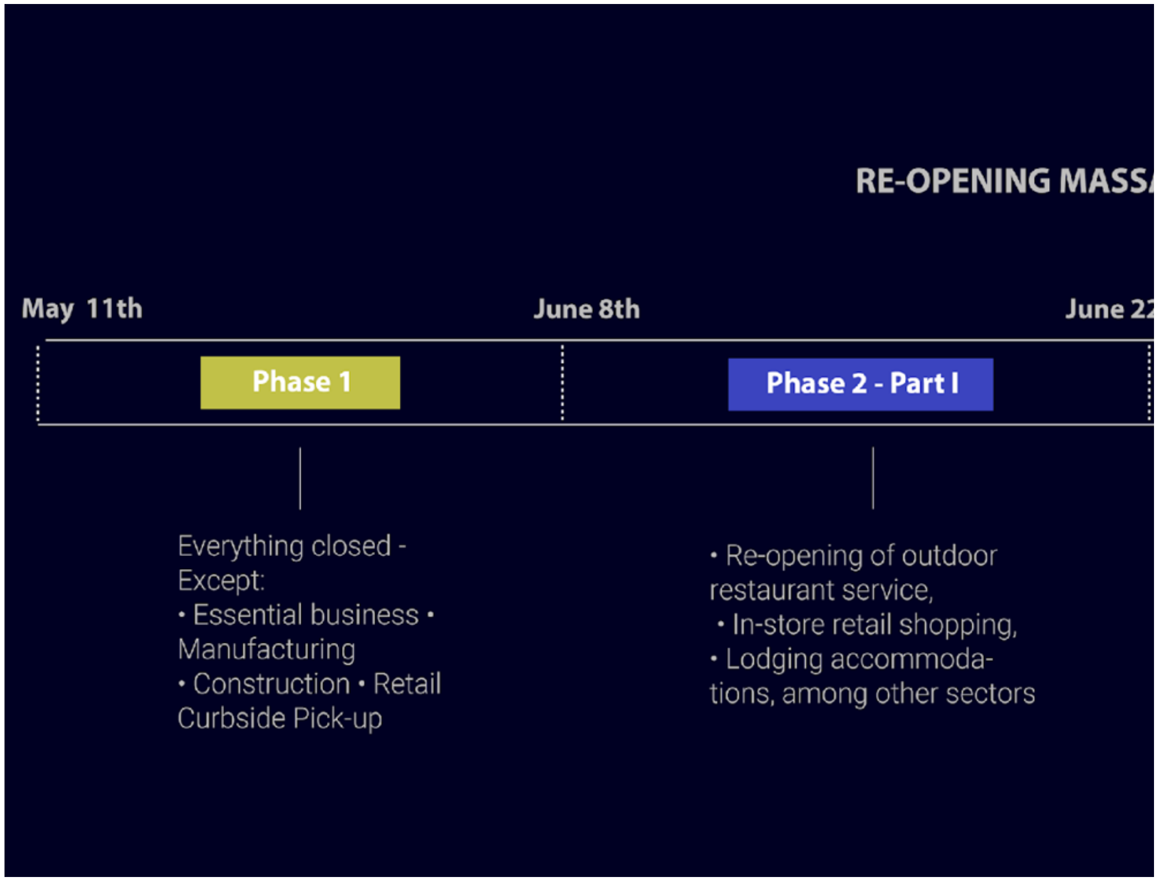

Figure 01: Overview of the phases of Re-opening Massachusetts Plan.

2.2 LOCATION: Harvard Square, Cambridge

Harvard Square is one of the most vibrant and historical areas in Cambridge, Massachusetts. Located right next to Harvard University, at the intersection of Massachusetts Ave, Brattle St., and John F. Kennedy St., Harvard Square functions as a commercial center for Harvard students and residents of western Cambridge as well as the western, northern neighborhoods, and inner suburbs of Boston. The area is served by Harvard station, a major subway station and bus transportation hub which makes the square well connected with other central parts of Cambridge and Boston. To locals, Harvard Square also refers to the entire neighborhood surrounding this intersection for several blocks in each direction and serves as an important landmark.

One of the unique characteristics of Harvard Square is its high pedestrian traffic which makes it a gathering place for not only the residents but also street musicians, street performers, and tourists. This high pedestrian traffic is due to the variety of different services that the square offers, from restaurants and bars to museums, and theaters, as well as important research and educational institutions, such as Harvard University

and Tufts. In addition, some of the locally-run historical businesses with unique styles contribute to the area's historical and unique character that makes Harvard Square a unique attraction for tourists as well. Some examples include: Leavitt & Pierce tobacconists (est. 1883), Laflamme Barber Shop (est. 1898), Harvard Book Store (est. 1932), Cardullo's Gourmet Shoppe (est. 1950), Charlie's Kitchen (est. 1951), the Brattle Theater (est. 1953), the Hong Kong Chinese restaurant (est. 1954), Club Passim (est. 1958), Café Pamplona(est. 1959), Mr. Bartley's Burger Cottage (est. 1960), Million Year Picnic comics (est. 1970), Algiers Coffee House (est. 1970), and Grendel's Den (est. 1971).

Following the global pandemic outbreak, all activities were stopped, and universities in Massachusetts, such as Harvard University, asked the students to evacuate the campuses. Starting in March 2020, Harvard Square went through different phases of transformation as the Reopening Massachusetts plan was implemented in the area.

The thesis focused on all three phases of the Reopening plan and started recording the changes in June 2020 until the end of August.

2.3 WALKING ROUTE: East-West Harvard Square

The thesis studies temporal transformations in the walking experience of everyday life on a daily scale. In the framework of this research, the unit of comparison is defined as a *walking event* where the start and end of the walking event are the start and end of a walk from point A to point B.

A recurring walk from point A to point B is used as the primary method for collecting data about the walking experience in an urban environment. Each walking event constitutes a series of temporal events that influence our sensory experience. In the context of this research focus, *an event is defined as a change in the urban environment*.

To capture and study the different phases of temporal transformations in Harvard Square and how the everyday experience in the city changed during all three phases of the reopening, walking was chosen as the primary way to map these changes. The spatial boundaries of a walk are defined by the space that is in the left, right, and the front side of the body, the walking space. In particular, these boundaries are defined by the sidewalk's space, which can be described as the boundary between the sidewalk and the street and the boundary between the sidewalk and the building or a park. Spatial transformations that occur in the walking space have an immediate impact on the walking experience.

The walking route was selected to include the streets that have the most pedestrian traffic and the majority of different services and local landmarks that can be found in this area. Moreover, because most of these businesses were affected by different phases of the Reopening Massachusetts plan, it provided an opportunity to examine temporal changes during different phases of the pandemic. The specific walking route that was chosen started at the intersection of Dana St and Massachusetts Ave, walking on Massachusetts Ave towards Harvard Sq., passing by Hong Kong restaurant, Harvard Book Store, Cardullo's Gourmet Shoppe, Mr. Bartley's Burger Cottage, Leavitt & Pierce tobacconists, and Harvard University, cycling around Brattle St. and passing by Brattle Theater, and ending up at the intersection of Dana St and Massachusetts Ave again by walking on Mt Auburn St.

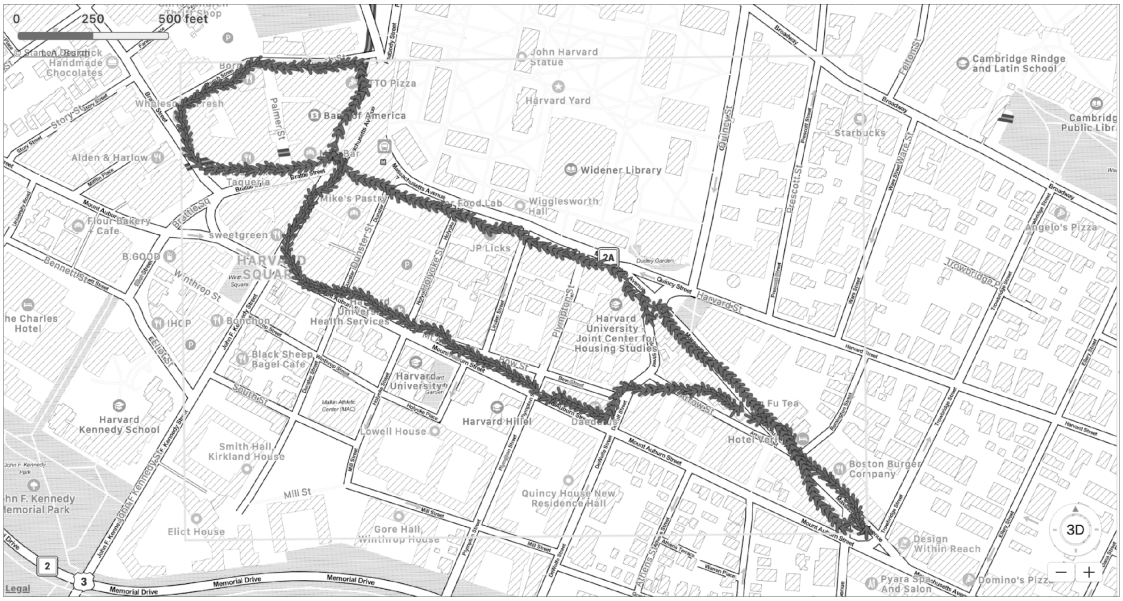

Figure 02: The walking route around Harvard Square.

2.4 AUDIO-VISUAL RECORDING

An important part of this study is the data collection methodology. The methodology has some key parameters that need to be determined based on the case study. These parameters include the overall time period of the study of transformations, the frequency by which the walks should be performed, the time(s) of the day to be studied, and the recording equipment that should be used. To understand how the different phases affected everyday life in the area of Harvard Square, data were collected for all different phases, starting with Phase I on June 7th until September 1st of Phase III Step 1.

I walked the same route every day, as the goal of the research was to investigate how the different phases affected everyday life in the city. The sectors that were affected by the different phases have different operating hours, for example, bars would open after 6pm or certain restaurants open only several days of the week, therefore the walk was performed twice a day. Recordings were collected in afternoons and evenings, at 12pm which is lunch time, and 8pm which is dinner time, as those times are typically the busiest times of the day and pedestrian traffic is intensified. The following section describes the recording equipment.

To record the soundscape, spatial, and movement transformations, a combination of different devices was used. Sound is captured by a handheld audio recorder with a built-in ambisonic microphone, recorder, and decoder that captures what is called “spatial audio”. The device contains four microphones that point in four directions, resulting in a 360 mapping of the soundscape.

Space was recorded by using a 360 camera and recording a full-length video of the walk. The video format was preferred as it records space over time. The 360 video allows capturing in a better way the space surrounding the person that walks, as it simultaneously records the space from all different angles. The camera was mounted together with the audio recorder on a handheld stick that was held right above a person’s head.

The movement was recorded by using a GPS tracking device that can be installed on a mobile phone. The tracking device creates a point with specific coordinates and for each point, it collects information about the exact location, speed, timestamp, orientation, and duration. The GPS device was attached to the lower part of the left arm.

To decrease the amount of noise/inconsistency in the data collection process, I created a set of instructions that should be followed each time that someone walks that route. The repetitive process is the following:

Mapping Instructions

1. After mounting the camera and the recorder make sure the orientation is correct. (see photo)
2. Make sure that the orientation of the recorder attached to the phone is correct. (see photo)
3. Open the apps on the phone.
4. Open the audio recorder and the camera. Make sure the camera is on video mode!
5. At 20:00 pm press start at the GPS app, at the same time start at video recording and then the audio recorder.
6. Lastly, press start at the recorder on the phone.
7. Start walking.
8. If you see an open store with an open door or window
1. Stop walking
2. Stand at the entrance or next to the opening of the store (boundary)
3. Record for approximately 30 seconds
9. If you see someone entering or exiting a store
1. Stop walking
2. Follow the person and get as closest as possible to the boundary (entrance)
3. Record for approximately 30 seconds

For the period of three months that contained data from phase I, phase II step one, phase II step two, and phase III step one, a dataset of 172 audio recordings or 86 hours of audio, 172 video recordings and 172 GPS recordings were created. In addition, a dataset that consisted of a list of businesses along the walking route was created, including information about the status of the businesses (open or closed) and the type of physical changes that happened during the different phases of the pandemic as observed in every walk.

2.5 ANALYSIS OF SPATIAL AND MOVEMENT TRANSFORMATIONS

Temporal changes as a system

This thesis argues that temporal changes in cities should be studied as a system consisting of spatial soundscape and movement transformations and focuses on studying their shifting relationships.

Spatial transformations can take the form of a changing sidewalk, a changed facade, adding a new space outdoors, completely demolishing a building, etc. Spatial transformations can include removing or demolishing a part of the building environment or changing or modifying the building environment by adding new features or new spaces.

These spatial transformations have a particular impact on the environment's soundscape in two ways: a spatial transformation changes the physical characteristics of a space, such as the materials, dimensions, or arrangement, and this consequently changes the sounds produced in that space. The second way corresponds to a spatial transformation that changes how a space is used and the kind of activities that take place in space. Different activities produce completely different sounds that can ultimately change the soundscape fundamentally.

The movement has a dual dynamic relationship with space and sound. On the one hand, spatial and soundscape transformations can affect the way we move in space. Different spatial and auditory experiences evoke a spectrum of different feelings in people that influence how they move. For example, when walking in a park and listening to the calming sound of birds singing, we tend to relax and move at a slower pace. On the other hand, how fast or slow we move affects the sound that is produced and how it's perceived.

2.5.1 Spatial Transformations & Qualitative Analysis

Spatial transformations in the context of the case study are defined as any kind of physical changes in space that are directly affected and are in contact with the walking route. More specifically, the thesis focuses on transformations that occur on the boundary between the sidewalk and street or the sidewalk and the building, the boundaries that define the “walking space”. In the case study, this translates into changes that are directly related to the COVID-19 policies. To identify the different spatial transformations for each place in the walking route, photos from the video recordings of each walk for each phase were saved in a table.

By qualitatively inspecting the table, three types of spatial transformations were identified. These include: (1) the extension of sidewalk-street boundary by adding an outdoor dining and sitting area, (2) the transparent boundary of sidewalk-building due to the fact that openings (doors and windows) remained open for better air circulation, and lastly (3) the conversion of openings to transaction places. In this last type of transformation, a new spatial typology emerged as entrances were converted to cashier spaces where people would pay and pick up their orders. Spatial transformation type (1) emerged as a result of phase two step one, while type (3) was a consequence of phase one and lasted until the beginning of phase two step two. In phase two step two onwards, transformations of type (3), openings as cashier spaces were converted to type (2), they just remained opened and the transaction took place in the interior space. These three types of spatial transformations had a significant impact on the types of sounds that emerged and generated the footprint of the different phases on the soundscape.

2.5.2 Movement Transformations & Quantitative Analysis

To analyze the changes in the movement, I used the GPS data from the tracking app. The tracking app generates a point with latitude and longitude coordinates and records how long it takes to go from one point to the next. The smallest increment is three seconds which corresponds to approximately two footsteps at my normal walking pace. The pace of the walk can vary from one person to another as it depends on the different body types and ways of walking. In this thesis, the walking pace is used as the relative time scale for each walk. Changes related to COVID-19 phases would affect the walking pace, which would result in longer or shorter walks.

Figure 03: Photos of the three spatial transformations types from top to bottom: type (1), type (2) and type (3).

	Putnam Square	Boston Burger Company	Hokkaido Ramen Santouka Harvard Square	Hong Kong	Harvard Book Store	Tatte Bakery & Cafe	Zinnia Jewelry	Leavitt & Peirce Inc	Harvard Shirt Shop	Harvard Square point 1
Phase 1										
Phase 2 - Part I										
										
Phase 2 - Part II										
Phase 3										
Time of										

Figure 04: The table showing the spatial transformations for each business in the walking route over the COVID-19 phases.

Milk Bar Harvard Square	Crimson Corner	Bluestone Lane Harvard Square Cafe	Felipe's Taqueria	Gap	Cardullo's Gourmet Shoppe	Russell House Tavern	The Harvard Shop	Tasty Burger
								
								
								
								
								

2.6 SOUNDSCAPE ANALYSIS: SOUND CLUSTERING

To analyze the types of sounds found in the 86 hours long audio dataset, and understand how the soundscape changed over the different phases, I followed a more exploratory computational approach. Typically computational sound studies use machine learning models to classify different sounds. Although there are many pre-trained models available, none of them uncover the complexity and variety of sounds found in an urban soundscape. More importantly, urban sounds are difficult to analyze as they are not produced in a 'sterilized' interior environment. Urban sounds always contain multiple sounds that occur at the same time as well as background noise from vehicles, and this makes it hard to separate distinct sounds and classify them. Recent computational approaches that use models that were developed for urban sound are oversimplifying the types of sounds in their analysis to fit the limited number of classes provided such as in the case of UrbanSound8K (Salamon, Jacoby, and Bello 2014) and ESC-50 (Piczak 2015) datasets.

To overcome this limitation and to be able to explore the soundscape space, instead of using a machine learning model with predefined classes, I used unsupervised machine learning method to identify sound clusters across the different phases in all of the walks, followed by a qualitative process of evaluating the type clusters that were found.

The size of the audio segment

The first step of the process is to segment each audio file into smaller increments such that we can identify different sound events within an audio file. One of the challenges is choosing the size of the audio segment. The audio segment should be small enough to reduce the complexity of analyzing multiple sounds captured within the same clip, but at the same time, it should be long enough so that we can infer what kind of sound occurs. In the context of this case study, in order to isolate, after trying out different sizes, 96 seconds was chosen as the most appropriate size for the audio segmentation. This size allowed for one sound to be clearly identifiable while reducing the co-occurrence of multiple sounds to a range between one to four. This was also helpful in the validation process of clustering as it was easier and quicker to check whether a cluster is salient or not.

Sound representation in computers

To analyze the audio segments in order to find the sound clusters, we first need to find sounds that are similar/close to each other. To measure how similar or dissimilar one sound is to another, we need a representation, so the second step is to build a representation for each audio segment.

One approach to constructing a representation is to use sound features, certain characteristics that make sounds distinct. Sound features include: the duration, the fundamental frequency, the harmonics of the sound, or the loudness. However, each of these features supports a particular objective. We can not use the duration to differentiate between different sounds. For this purpose, we would need to look at the fundamental frequency.

Sound is represented in computers as a 1-d vector of discrete values, which are the digitized version of pressure fluctuations received by a microphone. The temporal waveform representation is a sequence of pressure amplitude measurements across time. The DFT (discrete Fourier transform) is another sound representation that lets us see the signal's frequency content. Because sounds have a duration, the DFTs may be stacked to build a matrix that records the frequency's change through time.

There is a fourth representation which is the one used in the methodology of this thesis: the embedding. An embedding is derived from a neural network and "is a representation of a topological object, manifold, graph, field, etc. in a certain space in such a way that its connectivity or algebraic properties are preserved" [7]. On a high-level, an embedding gives us a "summary" of a collection of sound features.

We extract embeddings on each audio clip of the dataset so that an audio clip is represented by an N-dimensional vector, where N depends on the model chosen. For this case study, Yamnet[8], a large pretrained neural network model trained on Google's Audioset (Gemmeke et al. 2017) data to identify sound events, is used to analyze the audio segments. The final output is a dataset of an embedding (a 1024-dimensional vector per audio file.

Dimensionality reduction

It is difficult to understand the meaning of the embedding itself since we are not used to understanding spaces that have more than 3 dimensions. Therefore, we need to use some dimensionality reduction technique to project the 1024 vectors into a 2-dimensional space. This will be the third step in the analysis process.

Principles for determining the clusters

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[7] "Embedding -- from Wolfram MathWorld." n.d. Wolfram MathWorld. Accessed May 19, 2022. https://mathworld.wolfram.com/Embedding.html.

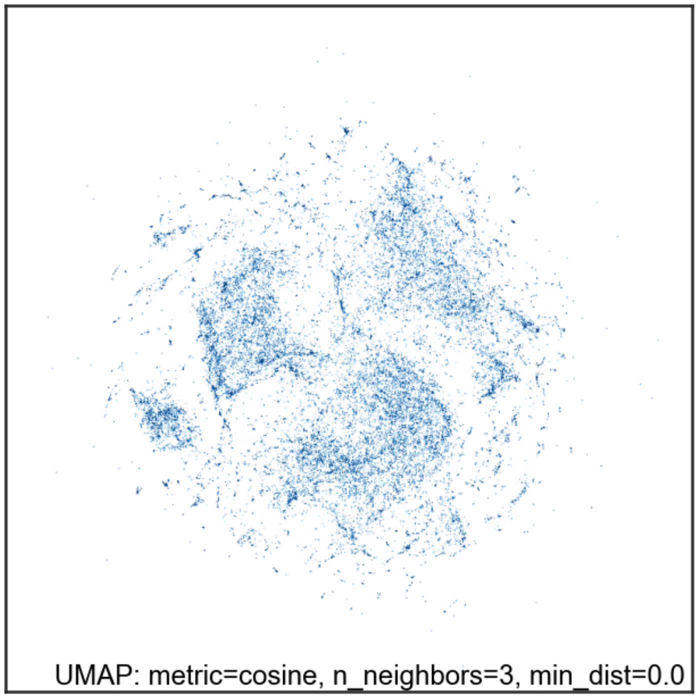
[8] M. Plakal and D. Ellis, "Yamnet," Jan 2020 available online: https://github.com/tensorflow/models/tree/master/research/audioset/yamnet

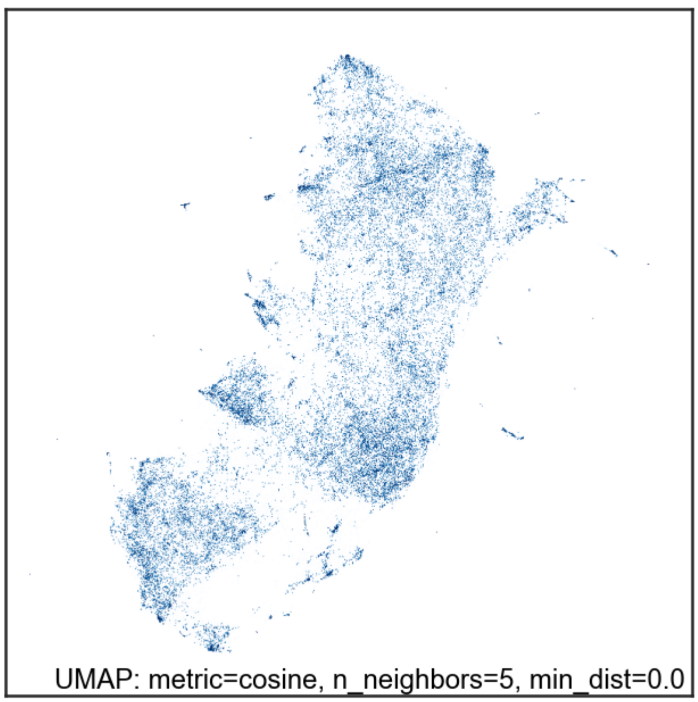
For dimensionality reduction I used the UMAP[9] (McInnes, Healy, and Melville 2020) algorithm and iteratively arrived at the following parameter settings: 5 neighbors, a minimum distance of 0.001, and using the cosine distance metric. I ran fifteen runs to account for UMAP's stochasticity and qualitatively analyzed the output to confirm that my analyses were not based on any artifacts. To identify the sound clusters I chose to used the HDBSCAN[10] algorithm (Campello, Moulavi, and Sander 2013), as unlike K-means, density-based methods work well even when the data is not clean, and the clusters are weirdly shaped, similar to the audio data.

To identify the clusters that are best separating and grouping sounds that are dissimilar or similar respectively, a qualitative iterative process was followed. By executing different runs of the algorithm with different parameters and examining the resulting clusters after each run, I was able to arrive at the following principles to determine the sound clusters that fit best the case study:

1. **The focus of the research --** I was interested to find clusters about sounds that were potentially affected by the COVID-19 phases, such as people talking or sounds that came from interior spaces because the boundary between the buildings and the sidewalk changed. The focus is one of the primary parameters that determine the clustering process.
2. **The minimum size of the cluster** -- Determining the minimum size of a cluster affects how sounds are clustered together. Larger sizes exclude small size clusters. This is also something that should be determined in relation to the scope of the research. In the COVID-19 case study, I was interested in separating a cluster with sounds of people talking from a cluster of sounds of people talking and music in the background since that would indicate the presence of an outdoor dining area.

[9] Uniform Manifold Approximation and Projection for Dimension Reduction
[10] Hierarchical Density-based Spatial Clustering of Applications with Noise Algorithm


UMAP: metric=cosine, n_neighbors=3, min_dist=0.0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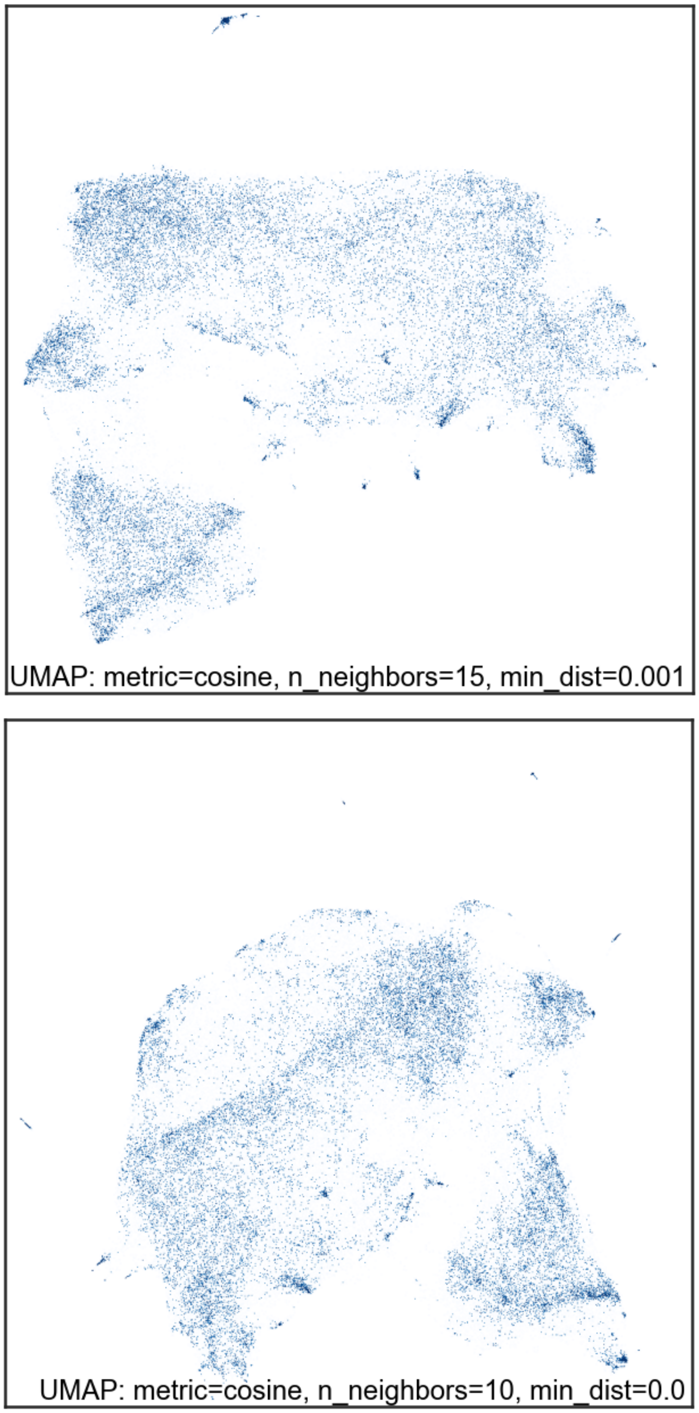


Figure 05: UMAP visualizations of the sound clusters with different parameters.

Figure 06: UMAP visualization of the soundscape during the different phases of COVID-19.

Sound clusters

The results of the iterative qualitative process concluded with initial 400 clusters of various sizes. The clusters were examined in order to characterize the sound clusters with different labels. Some of the clusters that were found include:

Cars passing
Footsteps
Crowd talking
Music from interior space
Music with singing
Music
Construction machines
Bus exhaust
Birds singing
Cashier machines from interior space
Human voices
Human voices with background music
Pedestrian crosswalk lights beeping
Motorcycle passing
Door closing
Train passing
Background noise

Figure 07: Table of a sample from the clusters found.

To produce a more effective comparison, clusters were grouped into larger categories according to a) whether there is the presence of human activity such as people talking or crowd, b) whether the sounds come from interior space, c) the presence of natural sounds such as birds singing or cicadas at night, d) sounds produced by machines, vehicles or engines, cars horning, e) the footsteps and f) the presence of music. By looking at how frequently these clusters appear, in which locations, and their relationship with the spatial transformations, we can start to have a sense of how the soundscape changed over the different phases of the COVID-19.

2.7 NOTATIONAL LANGUAGE REPRESENTATIONS

To represent the shifting relationships between sound, space, and movement, a notational system is introduced. Inspired by the musical scores that show different rhythms and sounds over time, the notation borrows elements such as the staff and bars to depict the changing rhythm of the walking pace, as well as the rhythm of the soundscape over time.

Shape grammars originally developed by Stiny and Gips (Stiny and Gips 1971), offer a rule-based formal approach that captures the temporal aspects of the design process. The notation incorporates shape grammars to translate the design principles of temporal transformations into computational visual rules.

1. Creation Rules

Creation rules consist of a set of rules that describe the initial components of the notation, the staff, the bars, the spatial boundaries of the walk, and the time scale.

1.1. The Staff

The notation has the staff, five parallel lines, with the central line representing the center of the body. We can now split the staff to the left and right spaces of the centerline to show what is happening on the left and right sides as we are walking. The staff is split into two parts; the monochromatic part shows the rhythm of the movement, and the colorful part shows the rhythm of the soundscape.

1.2. Bars

The vertical lines represent the start, end, and stops during a walk. Each stop consists of a vertical line and a triangle. The triangle depicts a local business along the route, for example, “Tatte Cafe”. Its fill property indicates whether the business is open or closed as affected by the Re-opening Massachusetts plan.

1.3. The spatial boundaries of the walk

By creating different weights of lines, we can represent the kind of boundary that we have on the left or on the right side as we walk. The bolder line represents the boundary between the sidewalk and the building, while the lighter line the boundary between the sidewalk and the street.

1.4. Time Scale

Walks vary in total duration. Some walks were longer, some shorter depending on the type of changes that occurred along the walking route. When a change occurred, the walking pace would be slower, and a very short stop would be added to the walk according to the aforementioned methodology. The walking pace provides us the relative time scale for each walk. Two rules describe this time relationship visually:

1.4.1. Adding a stop

Each time we add a stop, we increase the overall time of the walk by an extra time(t’-t).

1.4.2. Removing a stop

Each time we remove a stop, we decrease the overall time of the walk by an extra time (t’-t). For example, even if we compare walks in the same phase, if they are from different days of the week, operational hours of business might vary on a week basis.

2. Transformation Rules

Transformation rules describe the three main types of spatial transformations that were identified in the qualitative analysis of the different phases. Rule (1) represents the extension of sidewalk-street boundary by adding an outdoor dining and sitting area. Rule (2) visualizes the transparent boundary of sidewalk-building due to the fact that openings (doors and windows) remained open for better air circulation, and lastly, Rule (3) represents the conversion of openings to transaction places.

3. Sound Rules

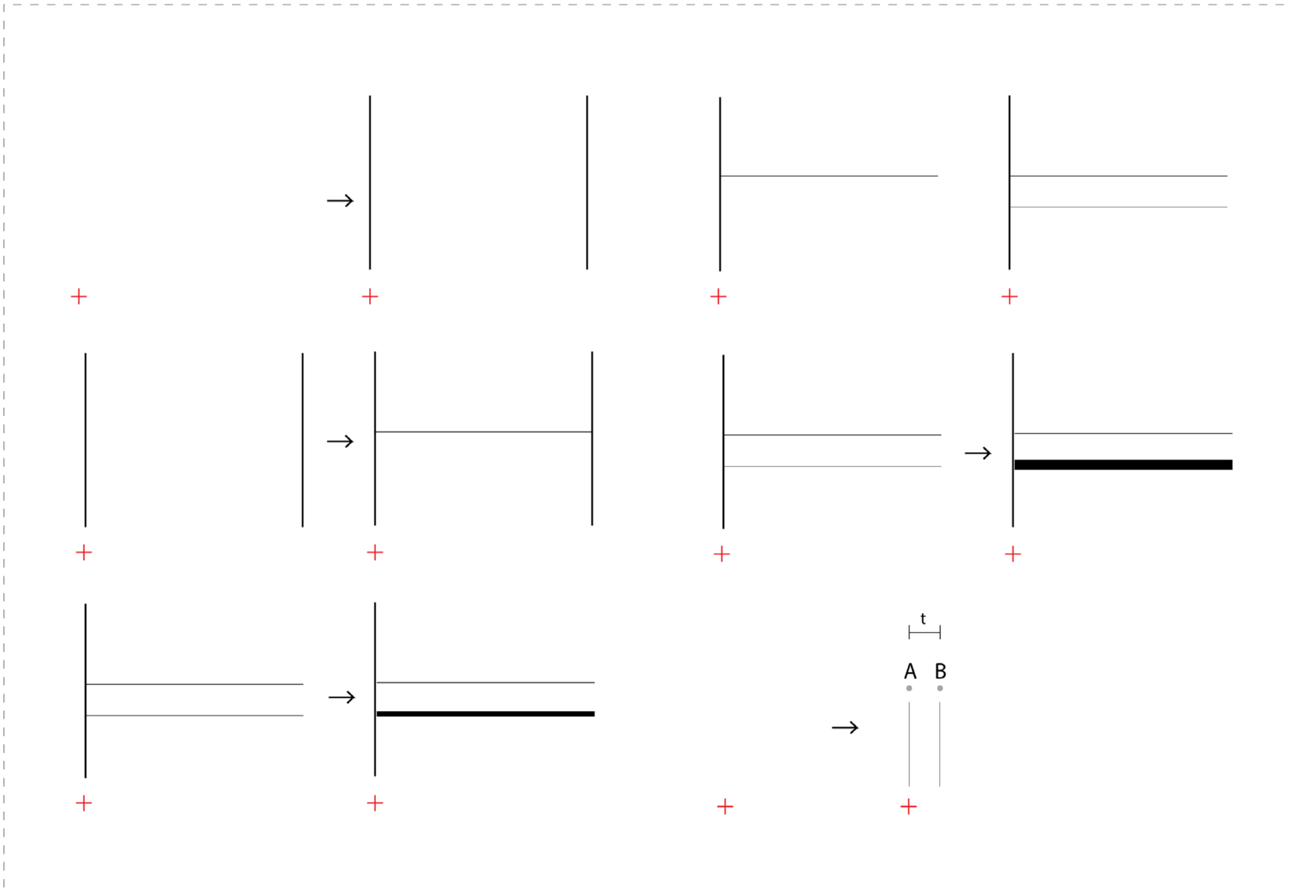
Cluster distribution

To visualize the different clusters that appear in each part of the walk, a coloring rule is developed. We calculate how many times a sound cluster occurs between a part of the walk defined as the distance between a point A and B. Then, for part of the walk, we have a different distribution of clusters and based on the distribution, we sub-divide the matching rectangle accordingly.

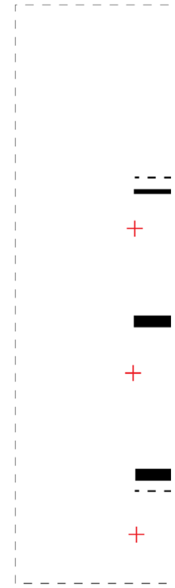
Coloring scale

Clusters that are closer or more similar have similar colors, such as the cluster with sounds of ‘people talking’ and ‘crowd talking’. Another example is the mechanical sounds produced by different kinds of vehicles or machines.

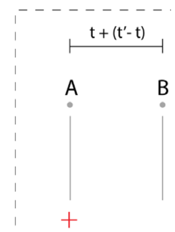
Creation rules



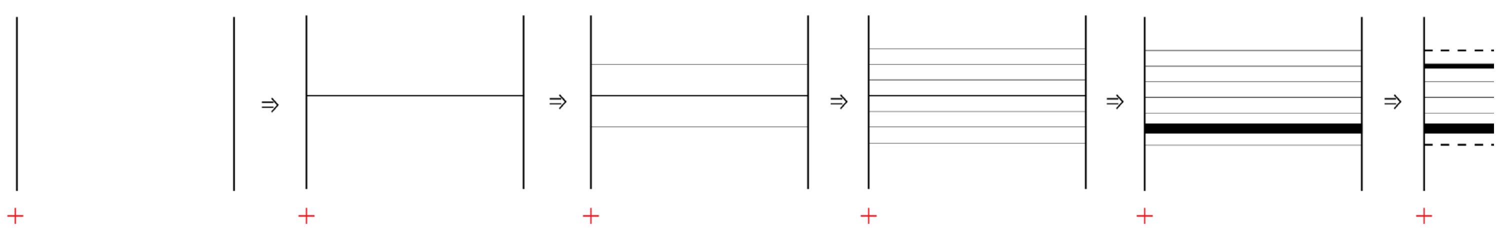
Transforma



Walking Rh



Derivation



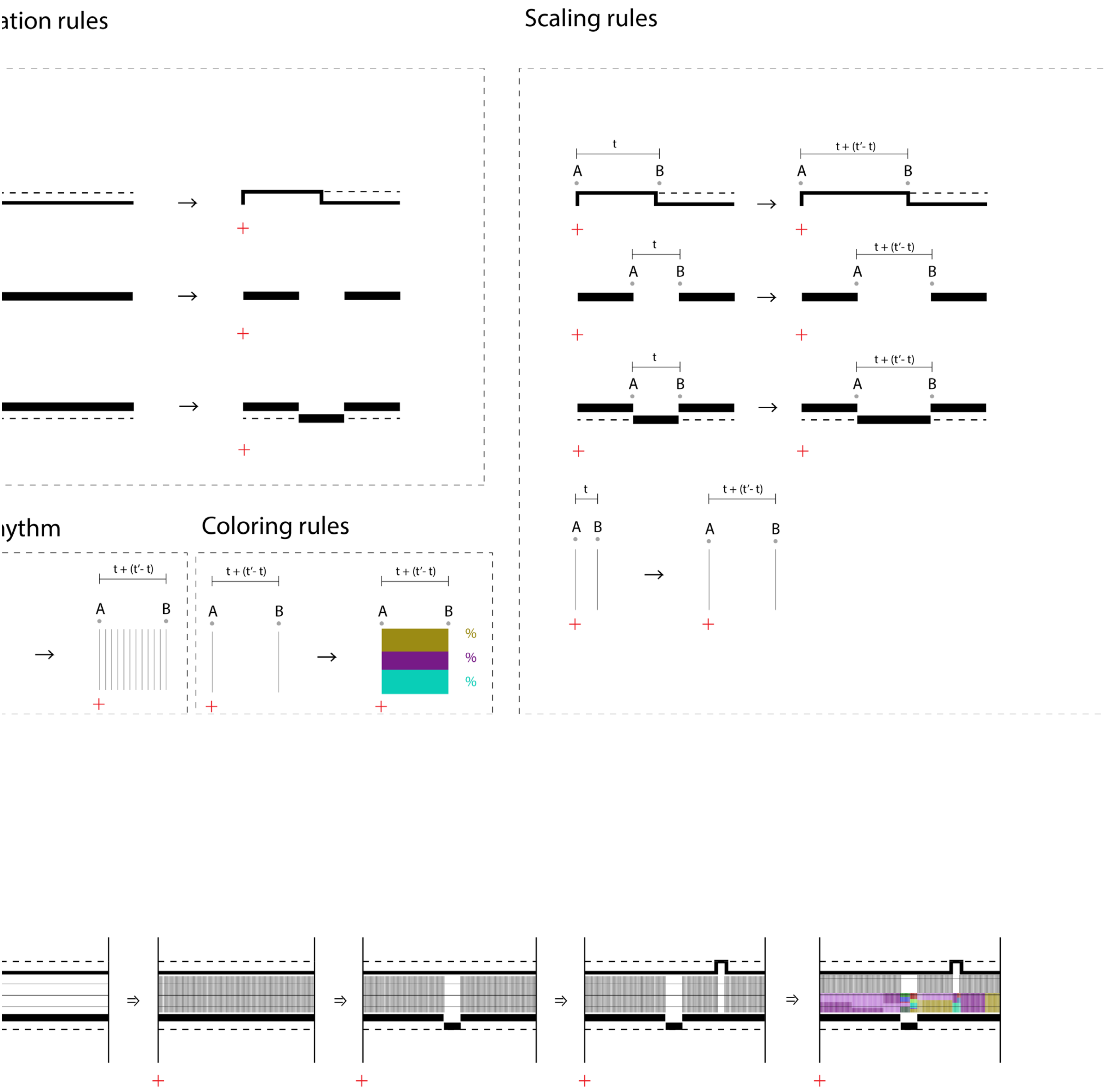


Figure 08: Notational Language Representations. The set of visual rules and a derivation as an example.

2.8 INTERFACE IMPLEMENTATION

To demonstrate how we can use the notational system to compare different walking experiences from the different phases of COVID-19, a digital interface was developed.

Data structure
Each walk is represented as a GeoJson data structure, consisting of line segments that contain different types of information. Each line segment that describes a part of the walk contains multiple sound clusters, information about the duration, the status of the street and building boundary, the phase that it belongs, the geolocation coordinates as well as the location of the closest business.

Design
On the very top of the interface, there is the timeline that includes the dates as well as the phases over three months. Yellow boxes indicate the morning times and blue boxes the evening times. By clicking on one of the boxes, a walk is loaded. Multiple walks can be loaded to perform different comparisons effectively.

On hovering over the black vertical lines, the name of the local business along the route appears. In addition, to more effectively compare the different walks, a connecting thick black line highlights where the business is located in relation to the time-shifting of the different walks. When hovering over the sound rectangles, we can see the name of each cluster and the corresponding distribution percentage. If we choose to click, we can play the sound.

Figure 09: The interface overview (right).

```
{
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  "properties": {
    "duration": 4,
    "phase": "AM_3_1",
    "chunks": [
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        "chunkFilepath": "/Users/elinaoik/Documents/M
        "cluster": -1,
        "xy_umap": [
          7.147198,
          10.448966
        ]
      },
    ],
    "chunkscount": 3,
    "lstclusters": [
      205,
      -1
    ],
    "distribution": {
      "-1": 0.67,
      "205": 0.33
    },
    "placeloc": {
      "lat": "-71.113689",
      "lon": "42.370425",
      "name": "Big Picture Framing-Harvard Square",
      "status": "Closed",
      "bst": "0",
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      "bb_or": "R",
      "bst_or": "L"
    }
  },
  "geometry": {
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      ],
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    ]
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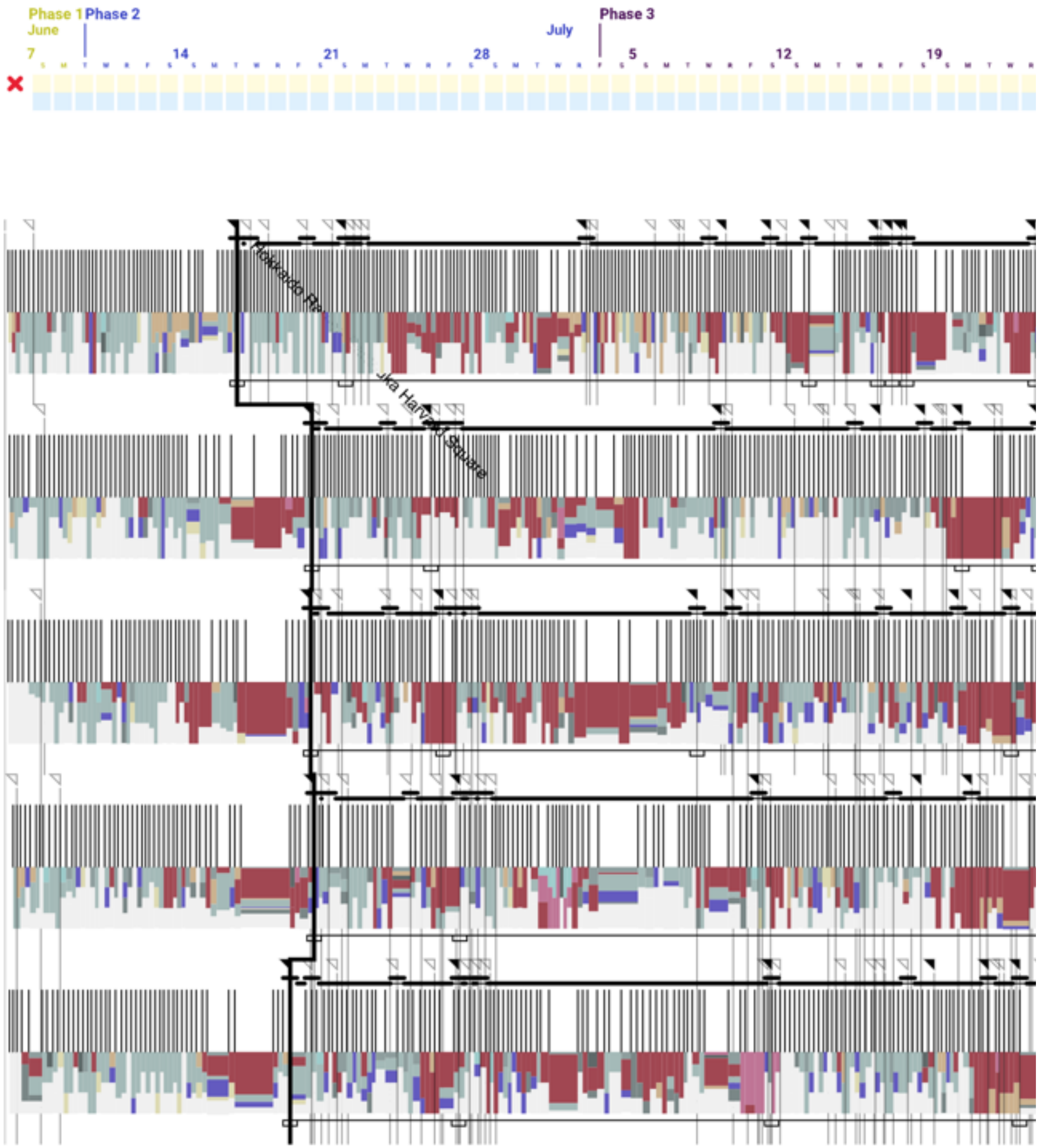
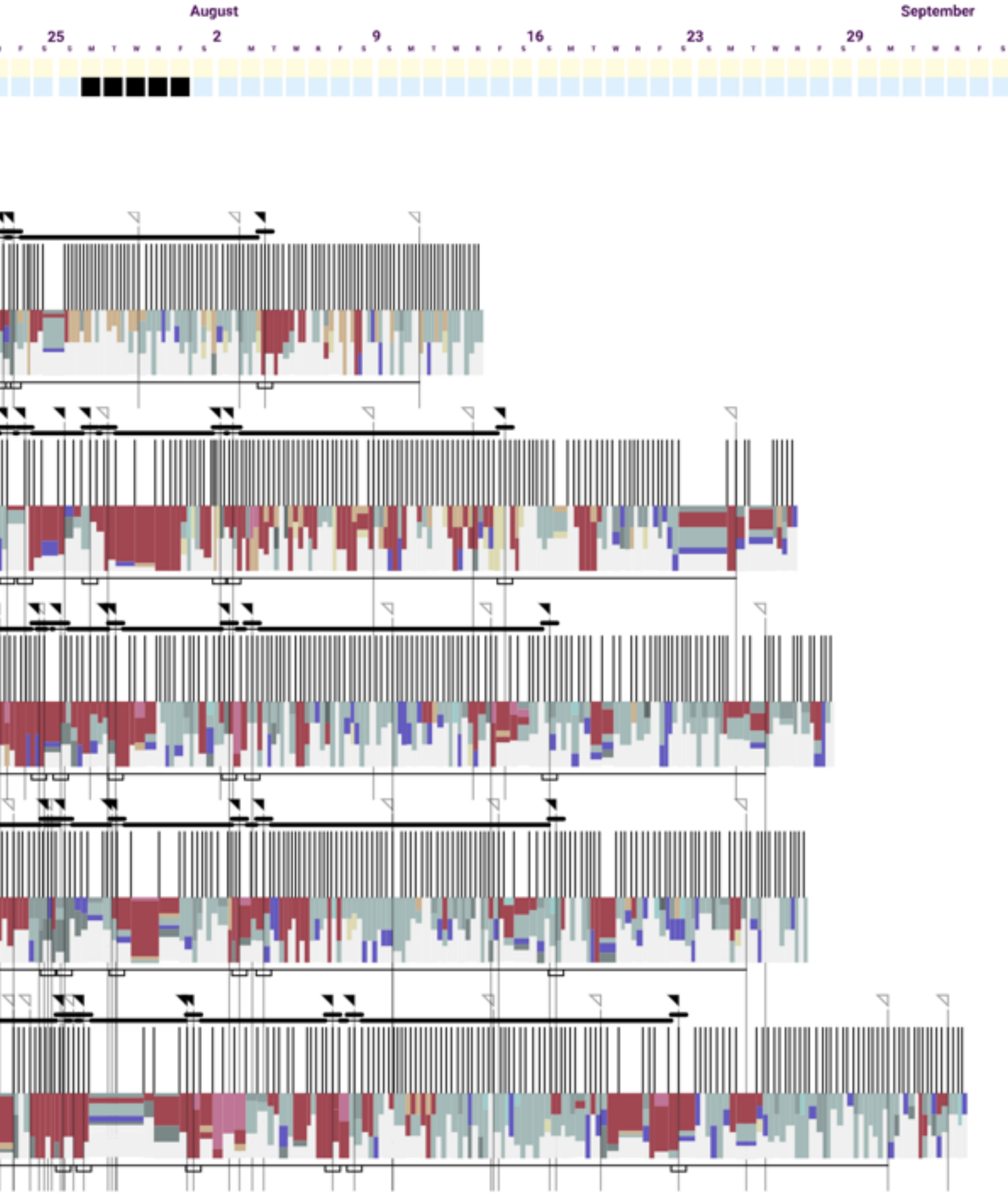


Figure 10: Example of the data structure for the interface.


August
September
25
2
9
16
23
29

2.9 FINDINGS

By using the interface, we can make multiple comparisons. By choosing a different basis upon which we make these comparisons, we can start understanding the different scales of temporality that constitute city life. To identify the temporal transformations in the walking route around Harvard Square for the period of three months that the data was collected, we use a single *walking event,* the start, and end of a walk, as the unit of comparison.

To better understand the temporal changes in the soundscape and how these changes relate to space and the different policies implemented, sound clusters are divided into two main categories, *constants,* and *variants*. Then variants are affected by a set of parameters that trigger changes in the soundscape, and they can be split into two categories, *parameters directly related to the COVID-19 policies* and *parameters that are related to other temporal aspects of a city's life*, such as the day of the week, the time of the day, or the weather. The combination of these parameters generates *different rhythms* that are embedded in the soundscape and that characterize the walking experience.

Parameters that are directly related to the COVID-19 policies result in spatial transformations that trigger changes in the soundscape. Spatial transformations include the keeping of windows and doors open, the conversion of parking lots to dining areas, the waiting lines on the sidewalk, and the conversion of entrances and windows to transaction areas. These changes result in the appearance or absence and increase or decrease of certain sound clusters that were found in the analysis. These clusters inform us about the change in activities that take place in these spaces and are identified in the different comparisons.

1. **The temporality of different COVID-19 phases**

   To identify the changes in the soundscapes related to the different phases of COVID-19 policies, we can compare the same day of the week, in the mornings or evenings in different phases. This approach will reduce differences in parameters related to the temporal aspects of the city's life. For example, it is incorrect to compare a Tuesday in phase two to a Friday in phase three since Tuesday and Friday have completely different rhythms regardless of the phase they belong.

   By looking at three walks from phase one, phase two, and phase three, respectively, we can quickly identify some "big" differences between the different walking experiences. The walking experience in phase one can be characterized by the predominance of natural sounds (sounds of birds indicated with yellow color) and mechanical sounds (sounds of cars), while anthropogenic sounds related to activities are rare and scarce. This is related to the fact that all businesses were closed during the first phase of the pandemic.

In phase two, we can observe that the walking experience is characterized by more variety in terms of sounds. Here can start seeing how the soundscape transforms from a more monotonic rhythm to a more polyphonic one with the emergence of music, human voices, and sounds that come from the interior spaces (indicated with purple). This is, in particular, evident in the busy street sections of the walk around Tatte cafe and Felipe's taqueria that completely transforms from phase one to phase three. As windows and doors remain open and outdoor dining areas are added to the streetscape, the boundary between the public space of the sidewalk and the private space of the building is blurring. This becomes even more apparent in phase three, where we can see more sounds from interior spaces penetrating the soundscape of the walk, while natural sounds (birds) are masked by mechanical sounds (cars).

2. The temporality of the week

By comparing Monday, Tuesday, Wednesday, Thursday, and Friday evenings of a week in phase three, we can identify the different rhythms that characterize the different days of the week. On Mondays, many bars and restaurants are closed, resulting in the decrease or absence of human voices and music clusters in certain parts of the walk. This becomes apparent when looking at the most popular and crowded places on the walk, the Russel House, The Felipe's Taqueria, and the Daedalus. Since the Russell House and Daedalus are only open on Thursdays and Fridays, see the music cluster appearing only these days, while the human voices and interior sounds clusters are also increasing in these local points.

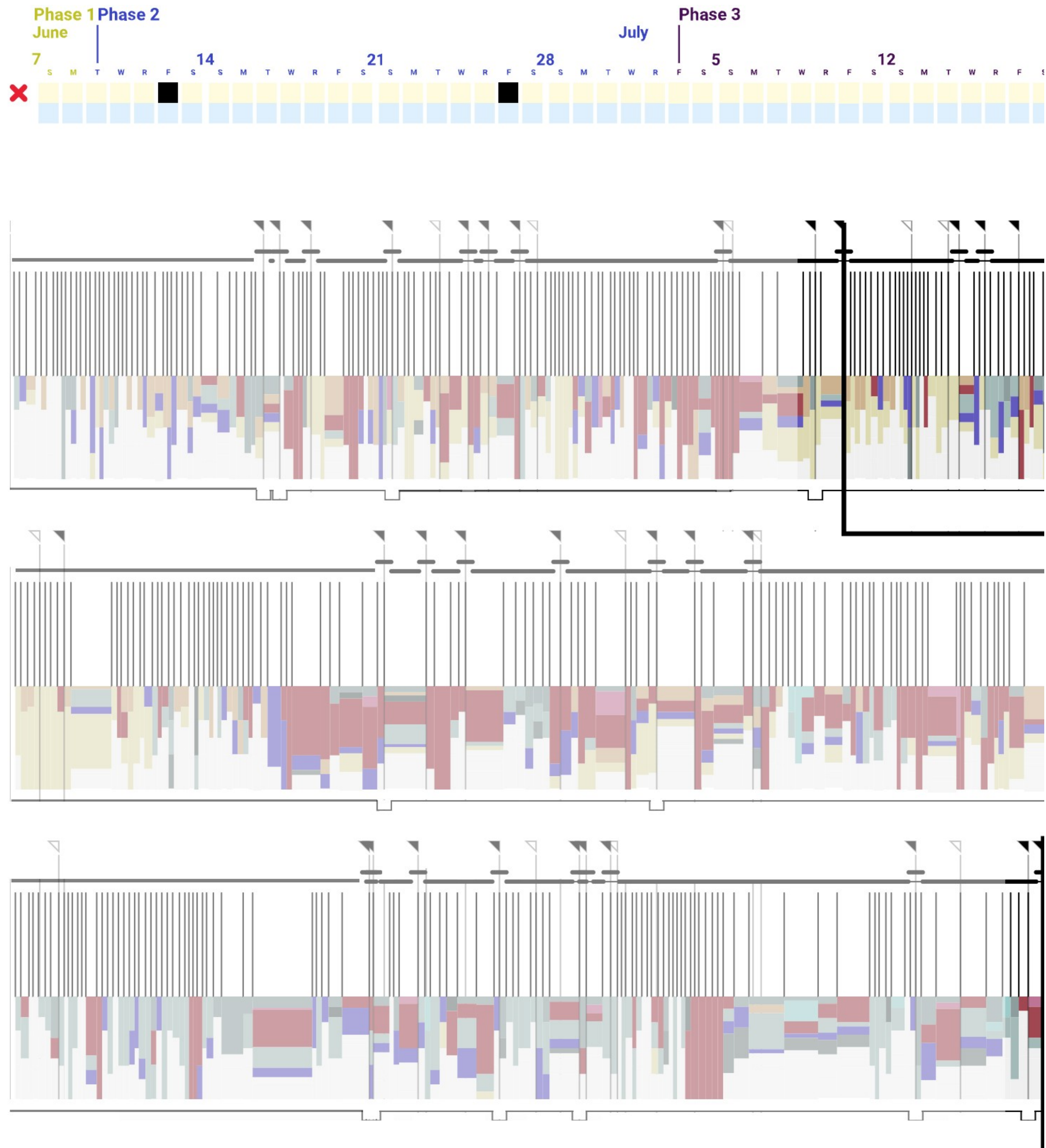
By looking at the walk overall, we can observe the different rhythms for each date. Friday is the longest walk since all of the places are open, while Monday is the shortest since a couple of places are closed. We also see how the rhythm changes in regards to the predominance of natural or mechanical sounds compared to anthropogenic sounds. We can count how often the soundscape switches from the predominance of mechanical/natural to anthropogenic sounds. For example Monday seems to be the quietest day in terms of the anthropogenic sounds, since we see that mechanical sounds are taking the largest chunks of the overall walk, compared to Friday. On Friday, the exact opposite happens; anthropogenic sounds are spread over larger parts of the evening walk.

3. **The temporality of the time of the day**

An important comparison to make when we try to understand the different rhythms of the soundscape is between morning and evening as the city life is completely different, and so is the soundscape. In the mornings, city life consists of daytime activities, and business related to those, from services to cafes to work areas. This increases the number of cars and traffic that constitute mechanical sounds, while the birds are also present when they are not masked by anthropogenic sounds.

By looking at figure we can observe how the different sound clusters that are found reflect the difference between the morning and evening city life. Natural sounds of birds signing predominated most of the parts of the morning walk, while this cluster disappears in the evening walk since birds are sleeping at night. By looking at the soundscape, we can also tell which businesses are open in the mornings only and which are open in the evenings only, such as bars. For example, Tatte Cafe, a very busy area during the morning, is closed in the evening; therefore, the human voices cluster (red color) disappears.

Through the soundscape, and in particular, the clusters that are related to human activities, we also get a feel about which parts of the walk are more busy or more 'loud' in the evenings (Russell House bar) or mornings (Tatte cafe) and which remain busy in both times, such as the Felippes taqueria area.



PHASE 02
Step one

FRIDAY
JUNE 12th

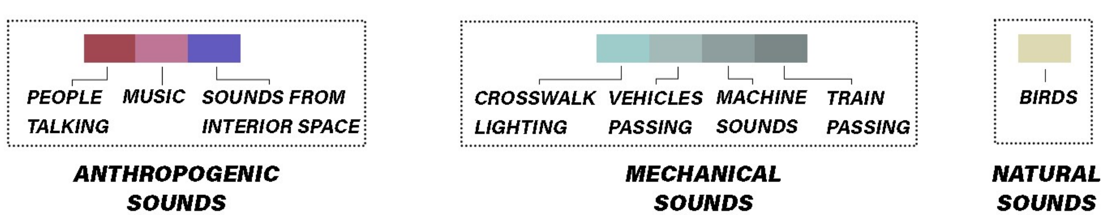
PHASE 02
Step two

FRIDAY
JUNE 26th

PHASE 03
Step one

FRIDAY
JULY 131st

SOUND CLUSTERS



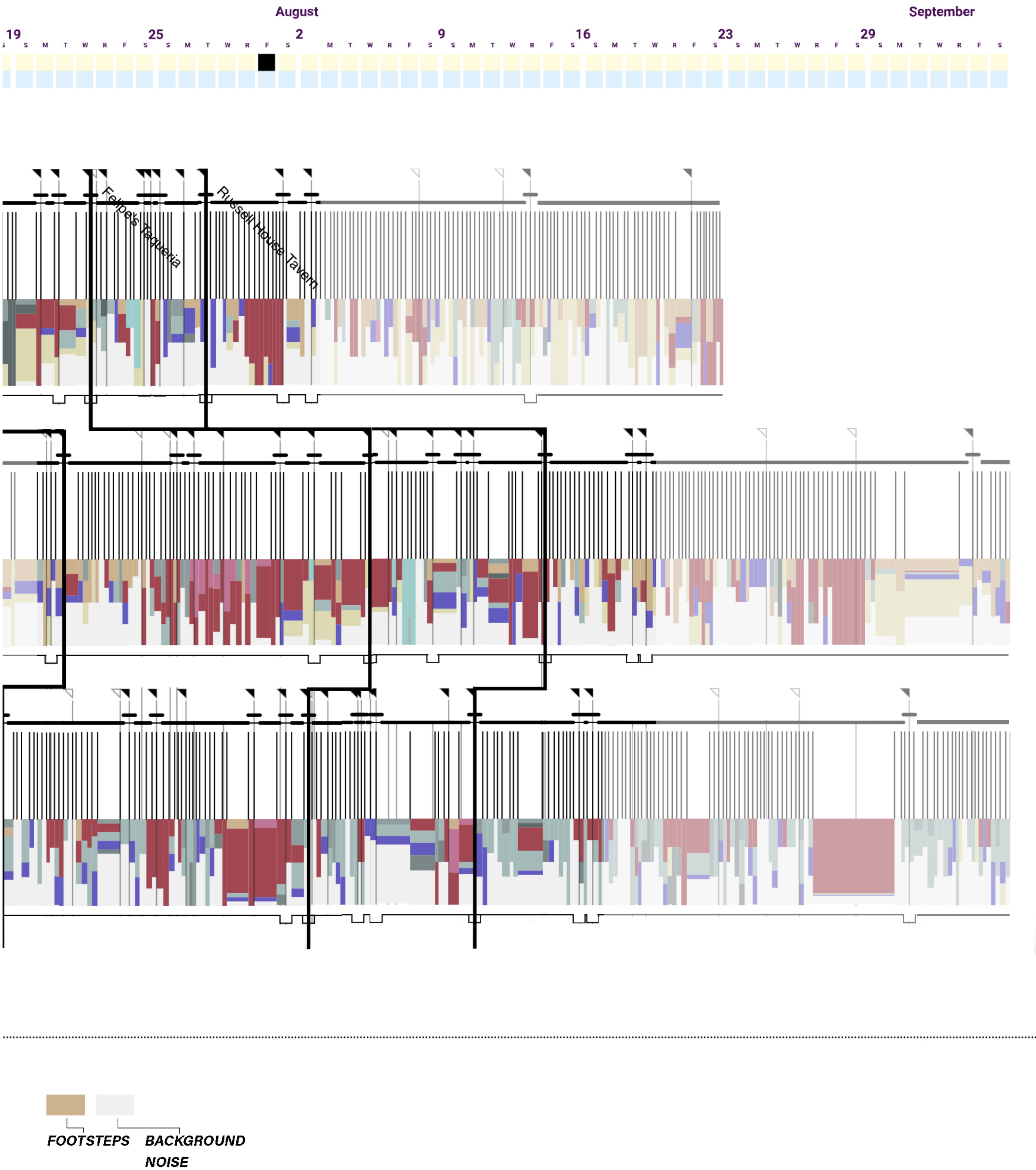
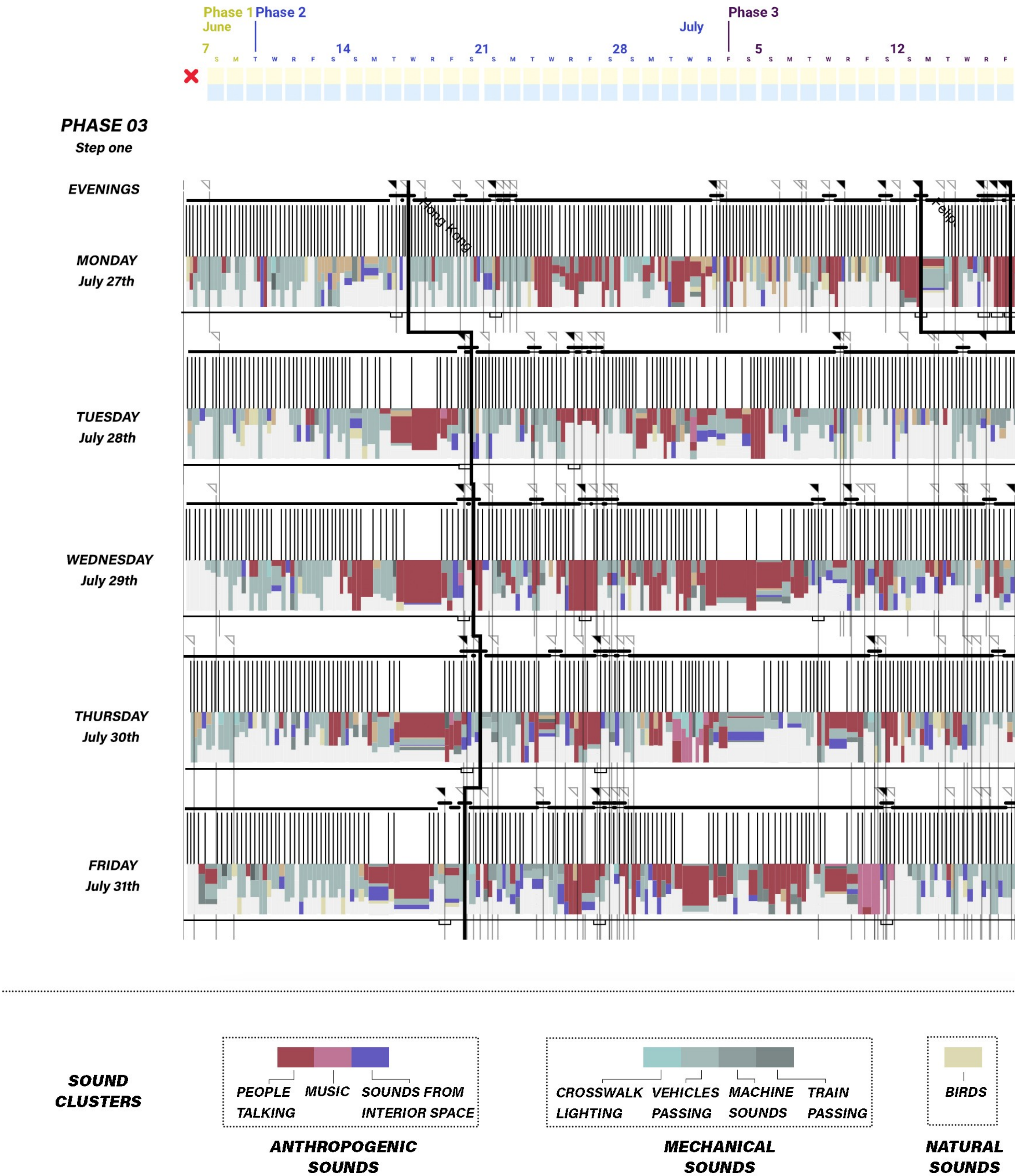


Figure 11: Comparison of walking experiences and soundscapes between the different phases of the pandemic.



Phase 1
Phase 2
June
July
Phase 3
7
14
21
28
5
12
PHASE 03
Step one
EVENINGS
MONDAY
July 27th
TUESDAY
July 28th
WEDNESDAY
July 29th
THURSDAY
July 30th
FRIDAY
July 31th
Hong Kong
SOUND CLUSTERS
PEOPLE TALKING
MUSIC
SOUNDS FROM INTERIOR SPACE
ANTHROPOGENIC SOUNDS
CROSSWALK LIGHTING
VEHICLES PASSING
MACHINE SOUNDS
TRAIN PASSING
MECHANICAL SOUNDS
BIRDS
NATURAL SOUNDS

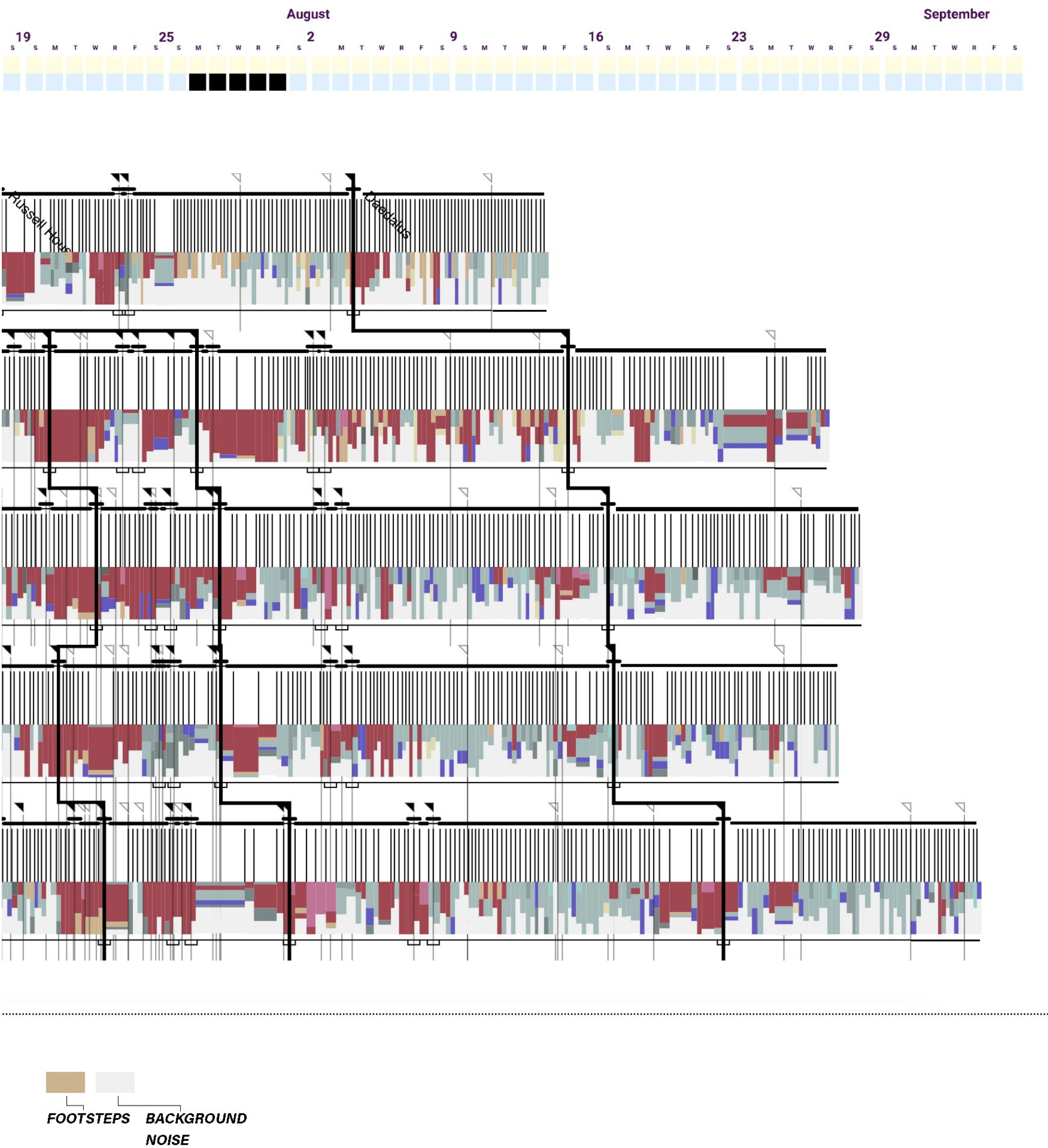
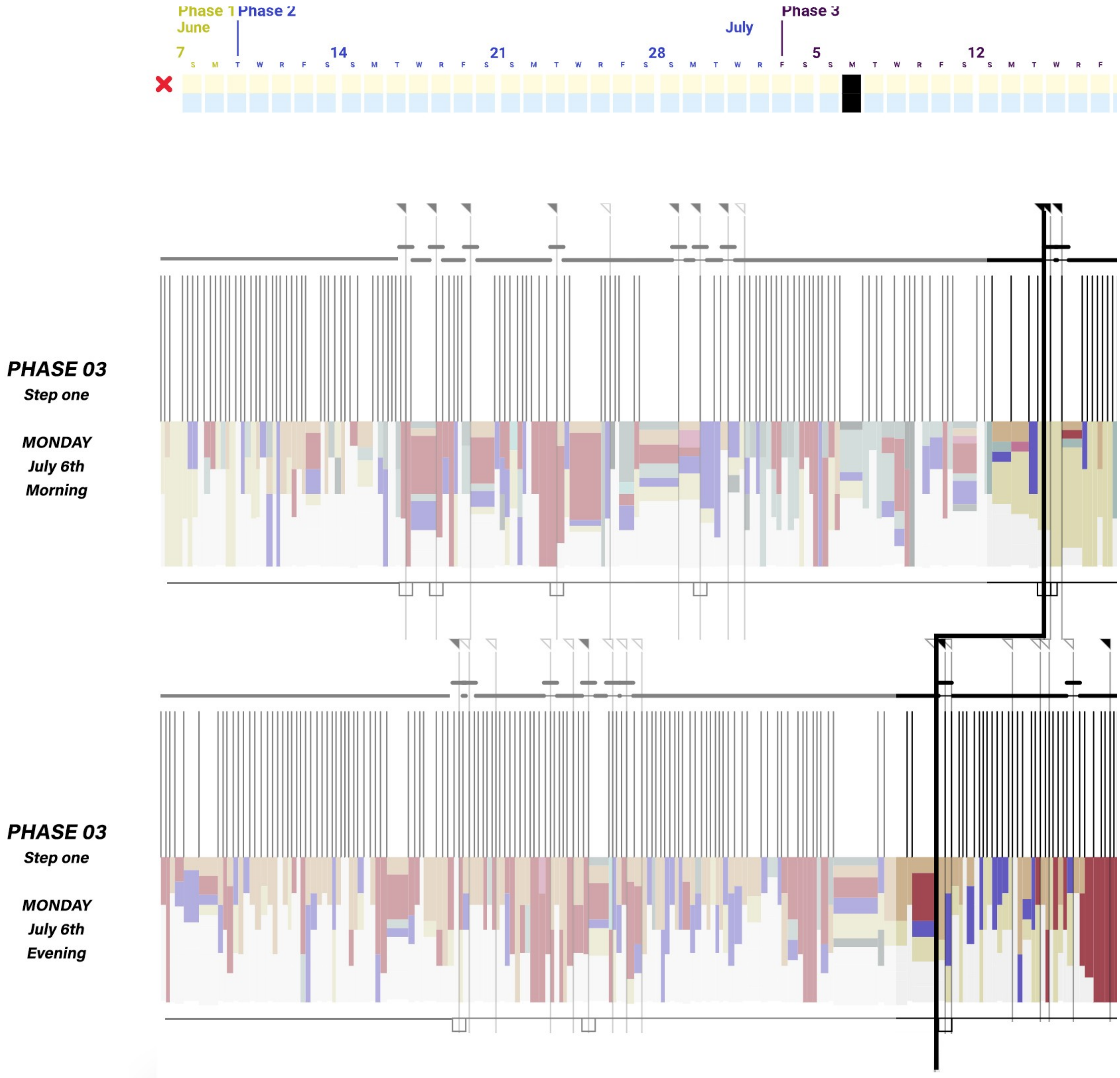


Figure 12: Comparison of walking experiences and soundscapes between the different days of the week



SOUND CLUSTERS

ANTHROPOGENIC SOUNDS: PEOPLE TALKING, MUSIC, SOUNDS FROM INTERIOR SPACE

MECHANICAL SOUNDS: CROSSWALK LIGHTING, VEHICLES PASSING, MACHINE SOUNDS, TRAIN PASSING

NATURAL SOUNDS: BIRDS

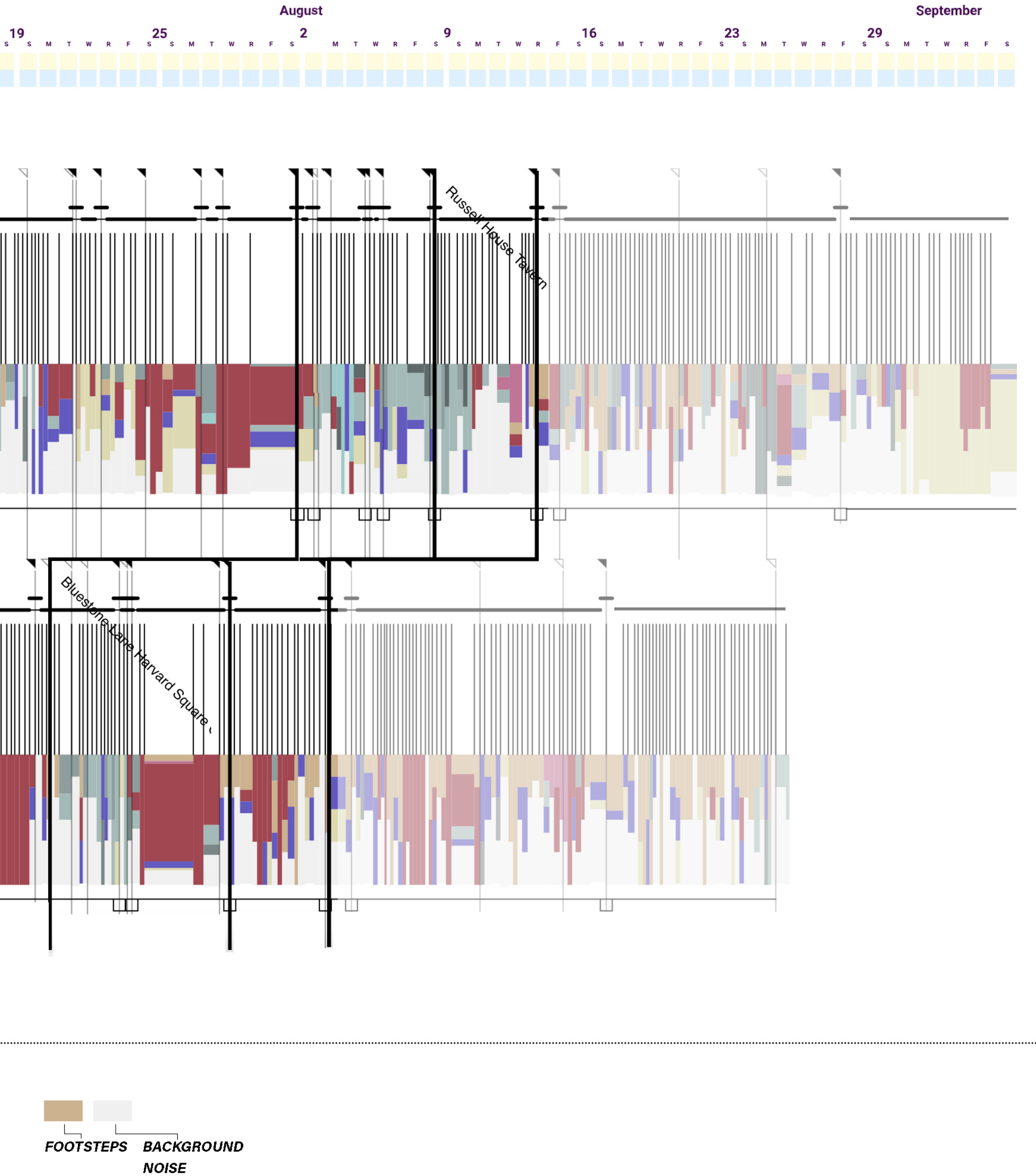


Figure 13: Comparison of walking experiences and soundscapes between the evening and day walk of the same day.

PART IV: Conclusion and Future work

Conclusion

The work presented here demonstrated a process for analyzing and representing the shifting relationships between sound, space and movement. The thesis more notably introduced a notational system as a visual language to describe changes in the soundscape, and showcase the temporal aspects of cities and city life. I provided an example of a digital interface that was developed to illustrate the notational system with the sound. With the case study, I showed how we can use a qualitative clustering approach to extract meaningful insights from the sound that reflect the changes in the city life. Furthermore, I demonstrate how we can use the notational system developed in the thesis to show how everyday life transformed in the area of Harvard Square during the different phases of COVID-19. Lastly, I demonstrate how the system can be used to compare also between different days of the week or different times of the day, a comparison that we can apply to any city to describe and understand its temporal aspects.

Fields such as real estate can benefit from this tool as they can use it to identify areas or locations that attract more people in certain times of the day or different days of the week. They can also use sound to evaluate preferences of a potential client, as soundscape is an integral part of a neighborhood's character. Urban planners and designer can use this tool to design and make policies that not only focus on reducing noise pollution, but to assess the soundscape quality in terms of its different characteristics. How do we design more pleasant soundscapes that contribute to peoples' walking experience? This thesis provides the first step by offering a way to visualize the differences between different soundscapes. With this approach urban planners can learn more about the character of a place or a street, as the soundscape can show the temporal aspects of a neighborhood's character, They can then use it to compare different streets or different neighborhoods and generate representations of the city that are closer to reality. Lastly, designers can use this tool to understand how a design decision that triggers a spatial change can impact the soundscape and the walking experience.

Future Work

The time constraint of this work, didn't allow for further investigation in order to fully unveil the complexity of the urban soundscapes. I see this thesis as a first step towards the understanding of the importance of sound in our everyday experience in cities as well as a first step into building more temporal representations of cities that reflect the city life. An important future research direction could be about looking at how different sounds that are produced at the same time, interact and incorporating these relationships in the clustering methodology as well as in the visual language by forming sound relation rules. Furthermore, the visual rules could be developed to describe other important qualities or characteristics of sounds, such as their textures. Lastly, this work can be applied in different case studies to create a language of soundscape characters that allows us to compare different neighborhoods or different cities.

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PART VI: Appendix

The code can be found here:
https://github.com/elinaoikonomaki/Soundscapes_As_Urban_Transformation