In the Eye of the Pedestrian: Exploring the Use of Mobile Eye-Tracking Technology to Measure Pedestrian Perception and Behavior Across Urban Environments

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ABSTRACT

Walking is one of the most sustainable and equitable modes of transportation and the creation of safe and pleasant pedestrian infrastructure is vital for promoting this form of mobility. Understanding pedestrian behaviors, preferences, and perception of the built environment is essential for creating spaces that promote more active modes of transportation. However, the ability to measure these elements in real-world settings was limited until recently, with the introduction of mobile eye-tracking glasses. This thesis establishes an Urban Typologies framework to employ the mobile sensors for research in urban settings. Then, the thesis presents the experimental procedure and initial findings from two case studies that utilize mobile eye-tracking technology and stated-preference surveys to gain insight about the pedestrian experience in different urban environments. The first case study focuses on pedestrian interaction with a temporarily repurposed street in Staunton, Virginia. The second case study uses the glasses to examine variations in pedestrian perception along the same corridor during the daytime compared to the nighttime and explores the influence of lighting conditions. These studies explore the potential of this relatively new technology for this field of research and set the groundwork for future studies that measure attention, perception, and cognition. Having a method to study these elements in a real world setting allows decision makers to evaluate how designs and policies can make safe spaces for pedestrians and alter the urban experience.

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CHAPTER 1: Introduction

1.1 Background and Motivation

Walking is one of the most sustainable and equitable modes of transportation and creating safe and pleasant pedestrian infrastructure is vital for promoting this form of mobility. People often forgo walking when they feel the conditions are unsafe, so understanding pedestrian perception is critical, especially when making decisions regarding the built environment (*1*). As people move through city streets they are exposed to an array of stimuli, both visual and auditory. Attention is directed towards a myriad of cues including people, signage, vehicles, buildings, vegetation, and other visual features of the environment. The decisions made by public actors, like urban planners and transportation engineers, as well as private actors, such as businesses and advertisers, influence the stimuli present in the built environment. The resulting urban environment remains a critical component of facilitating societal functions including access to destinations, interpersonal interactions, and economic activity. Understanding how people interact with their surroundings and environment and which stimuli gain attention can help improve decisions made about infrastructure and the built environment.

Car-centric infrastructure design and driver perspective is often prioritized, especially in the United States. However, as people recognize the numerous benefits associated with walking and other forms of active mobility, there is an increasing interest in creating safe and pleasant spaces for these road users (*2*). Having a methodology to evaluate how changes in the urban environment are perceived is important for these changes to be successful. This thesis focuses on the use of new mobile sensors to evaluate the built environment, through the application of the technology in two urban settings: a repurposed street and a street at different times of day.

Street repurposing is the conversion of vehicle-centered streets to multimodal spaces which support a range of citizen activities and is one strategy that cities have implemented to give more space to pedestrians. Repurposing may take permanent or temporary form. The trend has accelerated in recent years as cities seek to create safer and more accessible public spaces (*3*). This shift in street design often represents a significant change in environmental stimuli and the overall experience of the street. Despite relatively widespread support and adoption, how these different street configurations are directly perceived by individuals, and how those perceptions may be associated with preferences and behavior, remains largely unexamined. The first case study presented in this thesis compares pedestrian perception when a street is open-to-vehicles versus when it is closed-to-vehicles.

Understanding the effect of time of day and lighting conditions on pedestrian safety is also vital for improving conditions. After decades of declining pedestrian fatality in the United States, the numbers have been increasing over the last 15 years (*4*). The rise has mostly been from pedestrian fatalities at night (*4*). Federal data on roadway fatalities demonstrates that the shift in peak times for pedestrian fatalities throughout the year suggest that darkness is the threat rather than people's routines (*4*, *5*). While the cause of this connection has yet to be determined, it highlights the need to gain insight into how pedestrian perception and behavior differs at night. The second case presented in this thesis compares pedestrian perception and behavior when participants walked along the same corridor during the day and night.

Previous research suggests that it is challenging to capture and quantify the pedestrian perspective in real-life settings (*6*), but the two studies presented in this thesis incorporate the use of mobile eye-tracking technology to gain insight about this perspective in different urban environments. Visual behavior is closely associated with underlying cognitive processes, like attention and memory. There is also a strong connection between where we look and our actions in the world (*7*). Studies on visual behavior as it relates to the built environment have previously only been possible in laboratory settings (*8*), due to technological constraints and the complexity of monitoring tasks in their natural environments (*9–12*). Mobile eye tracking technology allows researchers to identify which urban streetscape elements capture individuals' attention, giving insight to how people perceive their surroundings while traveling. This represents a significant advance from simulated screen-based or virtual reality approaches (*13*) and static scenes (*8*, *14*) that have been deployed in the past. The introduction of technology presents an opportunity to do further research about how pedestrians and other people interact with and move through their surroundings. This can inform decision-makers about the types of infrastructure and environmental conditions that are both objectively and subjectively safer and enjoyable for pedestrians and other vulnerable road users. Although, the ability to study more dynamic environments comes with some challenges as the methodological and analysis approach is being developed for the new technology.

1.2 Research Goals

Pedestrian response to differences in streetscape conditions and associated stimuli cuts across a wide range of disciplines including urban planning, transportation design, economic development, marketing and consumer psychology, and environmental psychology. Each of these fields has developed a unique set of questions and methodologies related to human movement in the city. This research explores a holistic approach to understanding human cognition and behavior along streetscapes using shared frameworks and methodologies between these disciplines, specifically considering visual attention and stated preference.

Mobile eye-tracking technology, a sensor technology that detects eye movements and what someone is focusing on, can be used to provide insight about people's perception, cognition and emotional state. This technology has the potential to be applied to various types of infrastructure and built environment conditions in order to evaluate how pedestrians and other users interact and perceive their surroundings. By integrating mobile eye-tracking glasses and pre- and post-experiment surveys, the studies in this thesis explore how to better understand pedestrian response to changes in urban infrastructure design and environmental conditions.

This thesis presents two case studies that incorporate mobile eye-tracking technology to compare pedestrian perception in two real-world settings. The main aims of this thesis are to demonstrate how this technology can be utilized in studies related to the built environment and to establish a framework for this type of study. Some initial findings from the two studies are also presented. The development of streetscape typology to classify the diverse array of stimuli encountered by pedestrians is presented as a part of the research framework. Using this typology, the studies examine differences in perception and visual attention when either the right-of-way or time of day changes along an urban street. As a relatively new technology, there is a lack of established data metrics and methodologies within similar types of studies. However, the knowledge gained from these studies can further develop this type of study and how it can be used to design safer and more vibrant urban environments.

CHAPTER 2: Literature Review

This section summarizes existing literature related to pedestrian safety and perception, eye-tracking analysis, and eye movements. Based on the review of existing literature, the contributions of this thesis are then presented.

2.1 Pedestrian Perception and Safety

The design and quality of urban spaces can create place value through a wide range of benefits including: greater physical and mental health, general fitness, daily comfort from reduced pollution and traffic noise, and happiness and quality of life (*15*). By emphasizing multimodal urban streetscapes that serve as public spaces for people, transportation planners, engineers, designers, and policy makers can reach goals related to creating more livable, safe, and economically vibrant environments, while deemphasizing automobile transportation (*16*).

Pedestrian wayfinding requires attention to traffic signs and signals, traffic rules, and social norms (*17*). The characteristics of the built environment can influence the amount of attention required of these elements and the stress and anxiety associated with a pedestrian's surroundings. There has been a great deal of research that focuses on the physical factors that impact pedestrian safety, such as number of lanes, visibility, raised medians, street trees, and land-use patterns (*18–20*). However, there is limited research on the perception of safety and environmental conditions and studies that have examined perception often rely on participant surveys (*2*). Understanding subjective perception of the safety of conditions and infrastructure is critical for both creating walkable spaces that do not cause fear and anxiety, and for promoting walking as a chosen mode of transportation.

2.2 Eye-tracking Analysis

Until recently, studies of visual exploration processes have only been possible in laboratory settings. The emergence of more portable wearable devices (smart glasses, sensors, cameras, etc.) allow researchers to map visual attention and collect data from the first-person perspective (*21*). Research involving mobile eye-tracking is being used more frequently outdoors, providing a deeper understanding of how people relate to real-life environments, but there is a lack of studies that consider the built environment from the perspective of those who walk in it (*22*). Hasan and Hasan (*23*) concluded in their 2022 study that most research on pedestrian safety using sensors and augmented reality focuses on a specific domain, usually not suitable for the real-world setting. Limitations in laboratory studies, including the inability to expose participants to the same level of visual and non-visual stimuli in a lab based study as you would find in the real world, demonstrate the need to be cautious about generalizing lab-based findings in the real world (*7*). Furthermore, experimentation with smart glasses has been identified as necessary in understanding pedestrians' changes in focus during their walking experience (*24*). In this fashion, using smart glasses for data collection allows researchers to obtain reliable data on pedestrians' behavior (*22*).

Mobile eye tracking is an evolution of lab-based eye tracking that allows researchers to measure how focus and other eye movements change in real-world settings like outdoor urban environments (*13*, *25–30*). Eye tracking data indicates how visual information is processed so it provides insight into pedestrians' perception and cognition (*29*). Research has found that pedestrian viewing behavior is highly targeted, seeking information from the environment that aids them in walking around safely (*27*). One study that focused on the visual attention process of pedestrians in relation to architectural work found that time spent looking at the building did not relate to the walked route (*25*). Additionally, ground floors have been found to receive more visual engagement than upper floors (*28*), while other elements of the urban environment, like street edges, are key aspects of the urban experience as they receive the most visual attention (*28*). When walking on a typical car-occupied street, visual attention is mostly focused on the walked side of the street. However, if the street is pedestrianized, then the visual attention is distributed nearly equally between both sides of the street (*28*). Another study found that the path walked is also important, and that most of the visual attention on the target path happens at close distances (*30*). Overall, these studies demonstrate that pedestrians utilize visual information to move safely and interact with the street environment. However, these studies do not examine how attention varies in a given environment, when cars are either present or absent, and when lighting conditions differ at different times of day.

2.3 Eye Movements and Metrics

High visual acuity is restricted to the fovea, a small area at the center of the retina, so for humans to gather quality visual information, eye movement is essential. Visual acuity significantly decreases beyond the fovea, so it is necessary to use eye movement to focus the fovea on the visual target (*31*). The point of gaze is defined as where one is looking, and can be analyzed with eye tracking data with respect to the visual scene (*32*). The two fundamental components of eye movements are saccades and fixations. A visual fixation is essentially a period when the gaze remains focused on a specific location (*31*). This thesis focuses on fixation data and video recordings in order to determine the relationship between participants' attention while walking in the two different scenarios.

Saccades are the rapid movements of the eyes that abruptly change the point of fixation. Due to this fast movement, the eyes are not able to acquire new information. The average duration of a saccade is between 20 and 40 ms, whereas fixations occur when the eyes remain in one place and are able to acquire new information from the visual array (*33*). Fixations usually last between 50 to 600 ms and can be used to make inferences about cognitive processes and attention (*33*). When working with dynamic stimuli in real-world settings, eye movements beyond fixations and saccades need to be considered. Vergence eye movements align the fovea on visual targets at different distances. When trying to focus on moving objects, smooth pursuit movements keep the fovea aligned with the visual target. Finally, Vestibular Ocular Reflex (VOR) compensates for head movements by stabilizing the fovea on an element of interest even when the head or body is moving (*34*). When eyes are stabilizing, they are still gathering information. These movements are attempts to stabilize the fovea on an object of interest and can potentially extract information. Understanding these movements is important when deciding the velocity threshold to filter the recorded eye tracking data (as discussed in section 3.2).

While the increasing use of eye-tracking devices in experiments related to vulnerable road users speaks to the promise of this type of data, there are some inconsistencies in the metrics used (*35*). There are numerous approaches to analyzing eye-tracking data and there have not been enough studies of this type to have a standard for which metrics are best, or most applicable to, this emerging field. Metrics can be categorized into general metrics and AOI-related metrics. General metrics, fixation duration and fixation dispersion being two of the most common, can be used to infer mental workload and stress levels (*35*). Whereas, AOI-related metrics, such as fixation duration and fixation count, provide insight about attention, visual search patterns, and hazard detection (*35*).

2.4 Conclusions from the literature review and paper contributions

This review of literature focused on pedestrian perception of their surroundings, the use of eye-tracking technology, and the eye movements and metrics that can provide insight. While the use of eye-tracking has been used across disciplines for many years, the lack of literature about research that has utilized mobile sensors, especially in built environment conditions, shows the novelty of mobile eye-tracking technology. This is largely due to the addition of mobile sensors to track eye movements being a relatively recent development, however the technology demonstrates a high potential for pursuing research related to pedestrian perception and cognition in real-world settings. Many of the studies that have begun to incorporate this technology to the built environment and transportation related studies have been done from the perspective of drivers, whereas fewer have focused on the pedestrian perspective (*36–38*). This thesis contributes to the current state of knowledge by examining two studies that have used this technology to evaluate changes in urban infrastructure and environmental conditions from the pedestrian perspective, and exploring possible analysis approaches that can help with the development of a more standardized process for this type of research. A better understanding of pedestrian's interaction with infrastructure types and their perception of urban spaces can assist engineers, planners, and decision makers in creating safer spaces and promoting more active and sustainable modes of transportation.

CHAPTER 3: Mobile Technology and Research Framework

Both studies presented in this thesis utilize Mobile Eye-Tracking Technology and a similar research framework to examine pedestrian perception in different urban environments. This chapter describes the aspects of the research design framework, the technology, and analysis approach that were used for both studies.

3.1 Urban Typology Framework

Urban environments are made up of physical and social elements that make cities and streetscapes dynamic spaces. This thesis identifies these elements as Urban Typologies that help to categorize and understand the role different types of urban stimuli play within the urban fabric of cities. The identified Urban Typologies can be found in **Figure 3.1**. The two studies in this thesis determined specific categories suited to the research questions that build off of this framework. The specific categories selected for the two studies can be found in **Table 4.2** and **Table 5.2** . While this thesis examines variations related to a repurposed street and different times of the day, this framework could be applied to various other conditions in urban spaces and tailored to the specific research questions.

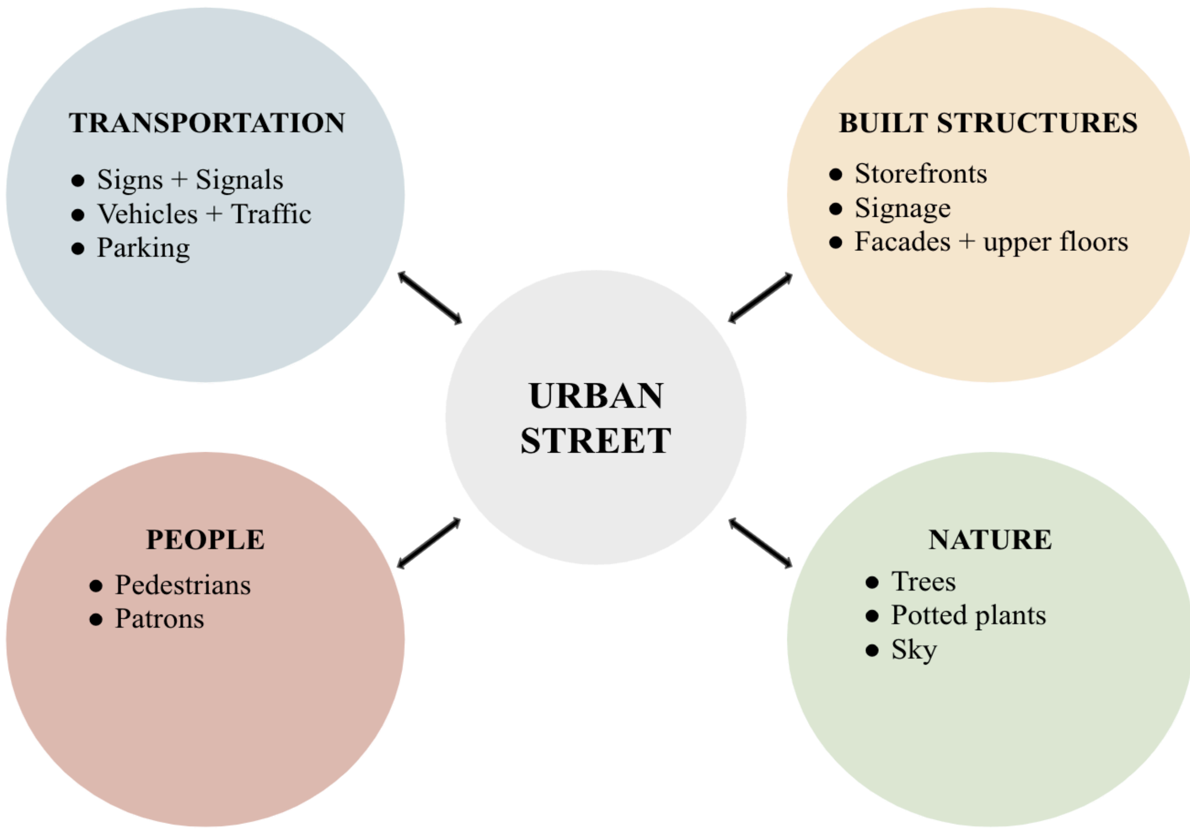


Figure 3.1: Urban Typology of Stimuli

3.2 Tobii Pro Eye-Tracking Glasses

Identified categories, based on the Urban Typologies, were used to better understand which elements were gaining pedestrian attention and how this differed between scenarios, by assigning fixation data collected from the mobile eye-tracking glasses as an Area of Interest (AOI). An AOI is defined as the region that may be observed in a scene or object, and allow the eye tracking data to be linked to those segments or objects (*25*). The Tobii Pro Glasses 3 were used for both studies and can be seen in **Figure 3.2**.

Figure 3.2: Tobii Pro Glasses 3 (source: Tobii.com)

The Tobii Pro Glasses 3 sample participants' eye movements at 100 Hz and are equipped with a forward facing point-of-view camera with recording resolution of 1920 x 1080 pixels, a sampling rate of 25 frames per second, and a diagonal field of view of 106 degrees. Even though it has a slightly smaller field of view than the human eye, the glasses can portray which elements gain pedestrians' attention. Further recording capabilities of the glasses include 16-bit mono audio recording, and gyroscope and accelerometer movements sampled at 100 Hz. The resulting data outputs include the users' gaze and fixations, pupils' position, pupils' diameters, and video with sound from the smart glasses' camera, linear acceleration, and rotational velocity among others.

3.2 Tobii Pro Lab Software

During the replay of recordings, the Tobii Pro Lab software uses the Gaze Filter, an eye movement classification algorithm, to process and classify the gaze data, which is then superimposed on the videos (*39*). The Velocity-Threshold Identification (I-VT) fixation classification algorithm uses velocity of the directional shifts of the eye to classify the data, and is measured in visual degrees per second. When samples are above a determined threshold, they are classified as a saccade. Similarly, when samples fall below the threshold, they are classified as fixations. The algorithm can be customized to the needs of researchers, however the recommended presets available are the Tobii I-VT (Attention), Tobii I-VT (Fixation), and Raw Gaze Filters. The Tobii I-VT (Attention) filter is optimized for wearable eye trackers and created for dynamic situations when the subject is moving (*40*). Thus, the Attention filter, with a threshold of 100 degrees/second, was used in this study. This threshold allows VOR and smooth pursuit movements to be included instead of limiting analysis to fixations. As discussed in section 2.3, people are still gathering information with these movements. Therefore, using the Attention filter means that any fixation metrics in this study could be described as "foveal stabilization" metrics. However, the term fixation will still be used throughout this thesis.

The Tobii Pro Lab software identifies the location of fixations that fall within the threshold (described above) for each relevant frame, and superimposes it on the forward-looking video recordings, as seen in **Figure 3.3.** From the video recordings, physical elements that attracted participants' visual attention were manually classified into one of areas of interest (AOI) for analysis. In static studies, AOIs can be identified on the image themselves. However, with dynamic studies like this one, the fixations within the video have to be remapped as an AOI on a static image to be able to analyze the fixations. The gaze data mapping in Tobii Pro Lab allows researchers to map gaze data onto a snapshot with AOIs (**Figure 3.4**). The AOIs of each study were added to a snapshot with the AOI tool and fixations were manually remapped as AOIs for analysis on the frequency and duration of each category. For both studies, all recordings were manually analyzed by one researcher to limit the influence of different interpretations and human bias on the AOI classification between participants and scenarios. After all fixations have been remapped, metrics, such as fixation duration and fixation count, can be exported from the software for analysis. The process used for each experiment is described in their respective chapters.

Figure 3.3: Examples of fixations superimposed onto recordings in Tobii Pro Lab

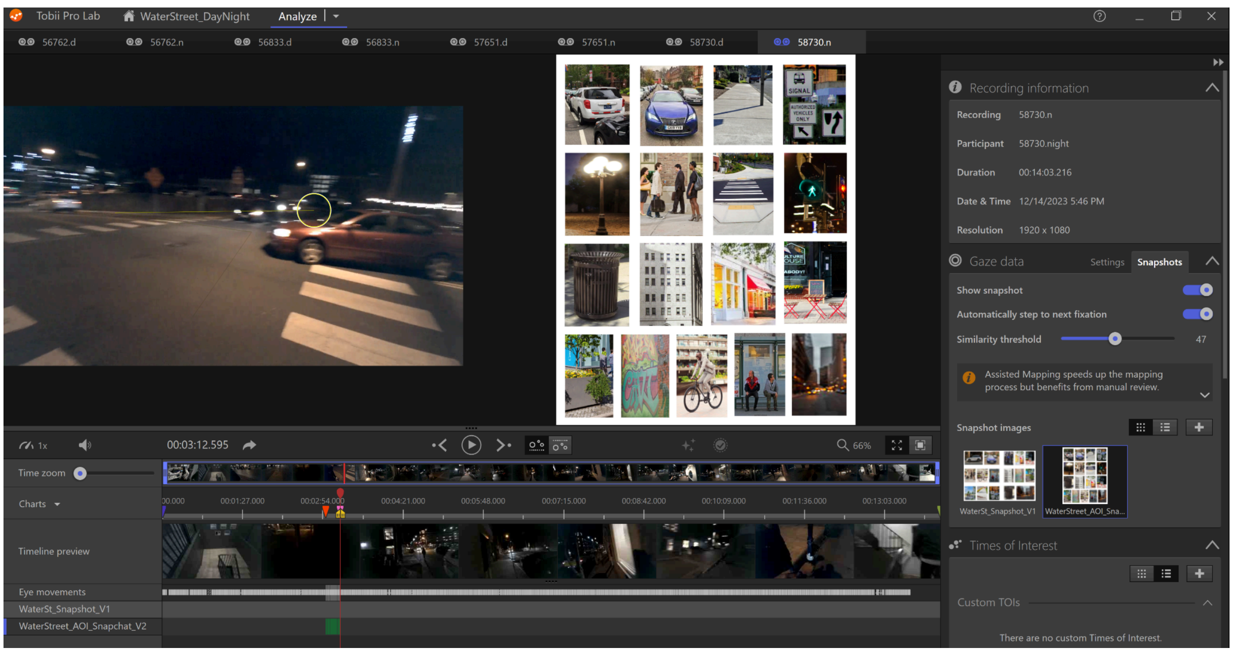


Figure 3.4: Tobii Pro Interface and Remapping Snapshot (right)

CHAPTER 4: Variations In Pedestrian Perception Along a Repurposed Urban Street

This chapter presents the experimental design and findings of a pilot naturalistic pedestrian experiment conducted on a commercial street in Staunton, Virginia. An initiative to repurpose the main commercial street to be closed to vehicles on weekend days, while remaining open to vehicular traffic the rest of the week, allowed for the experiments to be conducted to measure variations in the pedestrian experience between the two scenarios. Mobile eye-tracking technology enabled insight into the pedestrian experience. Stated preference survey responses provided further insight into the pedestrian experience. This study examines how individual attention and perception changes between automobile-centric and repurposed, pedestrian-only streetscapes on a commercial street that temporarily limits vehicle access. Temporary closures of the main commercial corridor in the city of Staunton, Virginia on select days allow for a quasi-experimental approach, examining differences in open and closed street configurations while holding other aspects of the built environment relatively constant. This represents a unique opportunity to understand the differences in human perception to a range of stimuli along the same corridor.

4.1 Methodology

4.1.1 Experimental process

Given prior findings, we expect that when closed to traffic, a repurposed street will enable pedestrians to shift their attention away from vehicles and traffic to focus on social, economic, built, and natural features of the environment. To assess this, a naturalistic pedestrian quasi-experiment was designed to have participants walk up and down four blocks of Staunton, Virginia's primary commercial corridor, East Beverly Street, between Market Street and Lewis Street. Beverly Street is a two-lane, one-way (westbound) corridor with permitted parallel parking along the south side. Motivated by COVID-19 safety measures, Beverly Street has been closed to vehicular traffic during select hours since June of 2020. Typically, the repurposing of the street occurs April through October, starting Fridays at 4pm until Mondays at 7:30am, as part of the "Shop & Dine Out in Downtown" initiative. The initiative was a measure set by the City of Staunton to support local business owners that could not fully reopen their businesses indoors at the beginning of the pandemic, and provided outdoor space for seating and extra space for pedestrian mobility. Street closures extend four blocks, but all five minor streets that cross Beverly Street remain open to traffic. Temporary in-ground bollards located along the intersections of both ends of the corridor are used to close off the corridor and provide safety and guidance for both drivers and pedestrians. Additionally, official city vehicles typically block street ends, and the City of Staunton makes five local parking garages free of charge when Beverly Street is closed to vehicles. **Figure 4.1** shows Beverly Street in both operation scenarios: while it is open to vehicular traffic and when it is open to pedestrian traffic exclusively.

Figure 4.1: (Left) Beverly Street while it is open to vehicular traffic (source: Google Street View). (Right) Beverly Street while it is open to pedestrians only.

During times that Beverly Street was closed to vehicular traffic, multiple shops, restaurants, businesses, and pop-up vendors set up outside with tents and designated spaces for outdoor dining, shopping, and playing stations for children in the spaces usually designated for vehicular use. The experiment occurred over two separate weekdays, on Thursday evenings when Beverly Street remained open to vehicles, and on Friday evenings when Beverly Street was reserved for pedestrian-only use. These days were chosen for data collection since they are both weekdays and operationally similar. Still, as a quasi-experiment occurring across multiple days, environmental conditions, including weather and crowds, varied. Weather and outdoor conditions were important considerations, as the experiments could not be carried out in the rain. Rain would obstruct the view through the smart glasses' lenses, and shops and restaurants would not set up furniture and tents outside, even if vehicular traffic were restricted on Beverly Street, which would introduce major variations in the urban environment in the closed-to-vehicles scenario.

In an attempt to avoid extreme changes in light conditions between scenarios, participants were scheduled at similar times for both experiments, between 4:30 pm to 8:30 pm, to the extent possible. All experiments took place in June and July of 2022. A pilot experiment was conducted at the beginning of June 2022, with 5 researchers and city employees.

Participants were emailed a brief description of the tasks required for the experiments and participation requisites, including the consent form and a pre-experiment survey eliciting sociodemographic and activity data (e.g., walking, driving, or time dedicated to physical activity) (See Appendix A for full set of questions). Participants were instructed to meet with the researchers at the meeting point on South Market Street (**Figure 4.2**), about 75ft. from Beverly Street. After completing the pre-experiment survey, researchers assisted the participants with putting on the wearable sensors and briefed them regarding their use. These included the Tobii Pro Glasses 3 and a Fossil electrocardiogram (ECG) smartwatch. The glasses recorded video, sound, and eye-tracking data, while the smartwatch gathered participants' heart rate. Before leaving the meeting point to start the experiment, the smart glasses were calibrated to each participant to ensure data collection accuracy.

In addition to verbal explanations by the researchers, a map of the test route was shown to the participants. The study route required participants to walk westbound from the intersection of Beverly Street and Market Street to the intersection of Beverly Street and Lewis Street on the south sidewalk, cross Beverly Street on that intersection, walk eastbound to the initial intersection of Beverly Street and Market Street on the north sidewalk, and cross Beverly Street until the start location of the test was reached, approximately 8 city blocks (**Figure 4.2**). The pre-defined walking path remained constant throughout the phases of the test, regardless of whether Beverly Street was open or closed to vehicular traffic. The order in which participants walked the open-to and closed-to-vehicle scenarios was random, to avoid any bias that might emerge from the novelty or excitement of participating in such an experiment. Participants walked each street scenario once on a Thursday and once on a Friday.

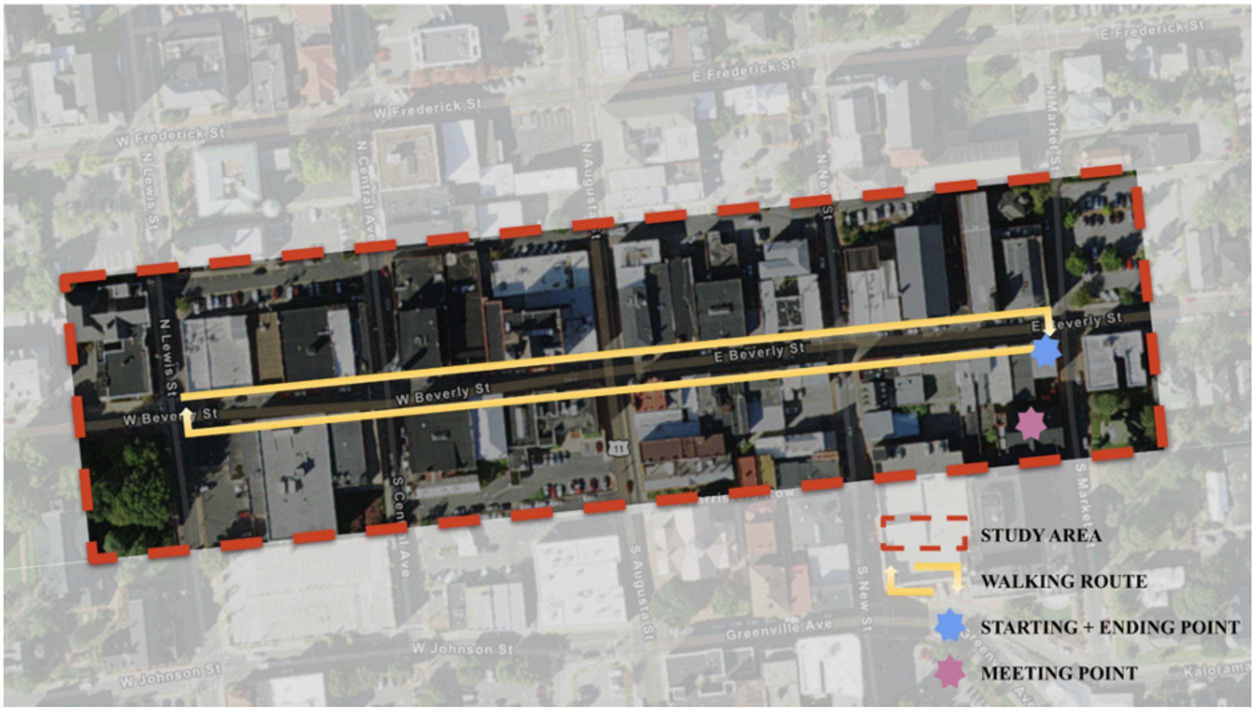


Figure 4.2: Walking route on Beverly Street in Staunton, VA

Once participants returned to the meeting point, they were asked to complete a post-experiment survey (See Appendix B for the full set of questions). This survey was only administered once participants had completed both scenarios of the experiment. The post-test survey assessed the participants' subjective ratings of the environment for the open/closed conditions.

4.1.2 Participants

In total, 12 participants completed both scenario experiments. Recruitment for the experiment took place via email in identified interest groups within the Staunton area, universities, businesses along the Beverley Street corridor, social media, and word of mouth with the help of employees of the City of Staunton. Participants were required to be at least 18 years of age and could not wear glasses on the days of the test (contact lenses were allowed) as the smart glasses could not be put on over regular eyewear. Participants who could not walk without assistance were excluded from the study, since the navigation and behaviors of pedestrians with disabilities in urban environments was considered out of the scope of this small sample study. All participants received compensation in the form of a gift card for their time. **Table 4.1** shows descriptive statistics of all participants.

Table 4.1: Descriptive Statistics of Participants

	TOTAL SAMPLE (N=12)	
	Frequency	%
GENDER		
Male	4	33.3%
Female	8	66.7%
RACE AND ETHNICITY [a]		
White/Caucasian	12	100.0%
Asian/Pacific Islander	1	8.3%
Hispanic/Latino	1	8.3%
AGE		
18-29	1	8.3%
30-39	4	33.3%
40-49	2	16.7%
50-59	4	33.3%
60-69	1	8.3%
70+	0	0.0%
EDUCATION LEVEL		
High School/GED	0	0.0%
Some College (no degree)	1	8.3%
Associate's degree	0	0.0%
Bachelor's degree	5	41.7%
Graduate degree	6	50.0%
EMPLOYMENT		
Full-time	6	50.0%
Part-time	3	25.0%
Student	1	8.3%
Self Employed	1	8.3%
Unemployed	1	8.3%
INCOME		
Less than $50,000	1	8.3%
$50,000 - $100,000	6	50.0%
$100,000 - $200,000	3	25.0%
More than $200,000	1	8.3%
No answer	1	8.3%
TRAVEL BEHAVIOR (previous week) [a]		
Driven or ridden in a car	11	91.7%
Walked	12	100.0%
Ridden a bike	3	25.0%
Taken transit	2	16.7%

[a] Participants where able to select all that apply

4.1.3 Eye-Tracking Analysis

Front facing video recordings with eye-tracking data, heart rate data, and survey data were collected for each participant. From the video recordings, physical elements that attracted participants' visual attention were manually classified into one of thirteen areas of interest (AOI) for analysis, based on the urban typologies identified in **Figure 3.1**. The thirteen categories used for this study are listed in **Table 4.1.** With this segmentation and following the process described in Chapter 3, the duration individual elements were fixated upon can be assessed (*25*). Analysis for this study focused on total duration of fixation metrics, specifically, the share of time each participant spent visually focusing on each category of urban stimuli.

Table 4.2: AOI Classifications for Experiments in Staunton

Vehicles	*Parked Vehicles*
	Moving Vehicles
People	*Pedestrians*
	Patrons
Stores and Buildings	*Storefronts*
	Sidewalk Signs and Other Sidewalk Set-ups
	Non-Storefront Buildings
Traffic Elements	*Traffic Lights*
	Traffic Signs
Other	*Miscellaneous Infrastructure*
	Sidewalk or Ground
	Natural Elements
	Blurry or Undetermined

However, gaze data was not continuously recorded throughout as factors like the fit of the smart glasses, the shape of the participants' faces, and the outside environment (e.g., the glare from the sun) impacted data collection. The percentage of valid data collected ranged from 34%

to 90% across all the recordings. However, the mean data validity across all recordings was 72%. Out of the 24 total recordings, 20 had more than 60% validity. The four recordings with less than 60% validity are still included in the analysis due to the small sample size of the study but do raise the need for research on sufficient thresholds for data validity and analysis. Additionally, the average duration spent walking on the predetermined route while open-to-vehicles was 10 minutes and 7 seconds, whereas the average duration in the closed-to-vehicles environment was 9 minutes and 32 seconds. The sample size of this pilot study limits the ability to compare statistical significance of any differences.

3.1.4 Survey Data

Data included in **Table 4.1** were elicited from the pre-test questionnaire and includes gender, age ranges, educational attainment, race/ethnicity, and employment status. The participant group is relatively homogeneous in terms of economic status, race/ethnicity, and education level. Of the 12 participants, 8 were female and 4 were male, and the groups' mean age was 42.8 (ranging from 19-64 years old). Participants were instructed to select all race or ethnicity options that applied. All participants identified as White/Caucasian (with one participant also identifying as Hispanic/Latino and one identifying as Asian/Pacific Islander). All participants had at least some college education and 11 had either a bachelor's or graduate degree. During the week prior to the experiment, all 12 participants had walked somewhere and 11 had used an automobile.

In the pre-test questionnaire, five participants reported vision impairments that ranged from wearing glasses or contacts, glasses for seeing in the distance, occasional blurry vision, and regular nearsightedness. No participant reported color blindness. In relation to the eye-tracking glasses, most participants found the eye-tracking glasses to be comfortable with minimal impact on behavior or vision (**Figure 4.3**). On a scale of 1-5 where 5 represents the glasses being comfortable, participants' mean response was 3.58. When asked about vision impairment due to the glasses (where 5 represents a high level of impairment), the mean response was 1.58. Lastly, the impact of the glasses on participant behavior is evenly distributed and had a mean of 2.58. Participants were allowed to elaborate beyond their numerical answer and some participants mentioned feeling more cognizant of their visual focus at the beginning of the experiment, however many also mentioned that their vision returned to being more instinctive as the experiment progressed. Other than some slipping, the glasses were described as feeling like heavier sunglasses, however there was mention of feeling sensitive to how others perceive the glasses and being more self-conscious while wearing the glasses.

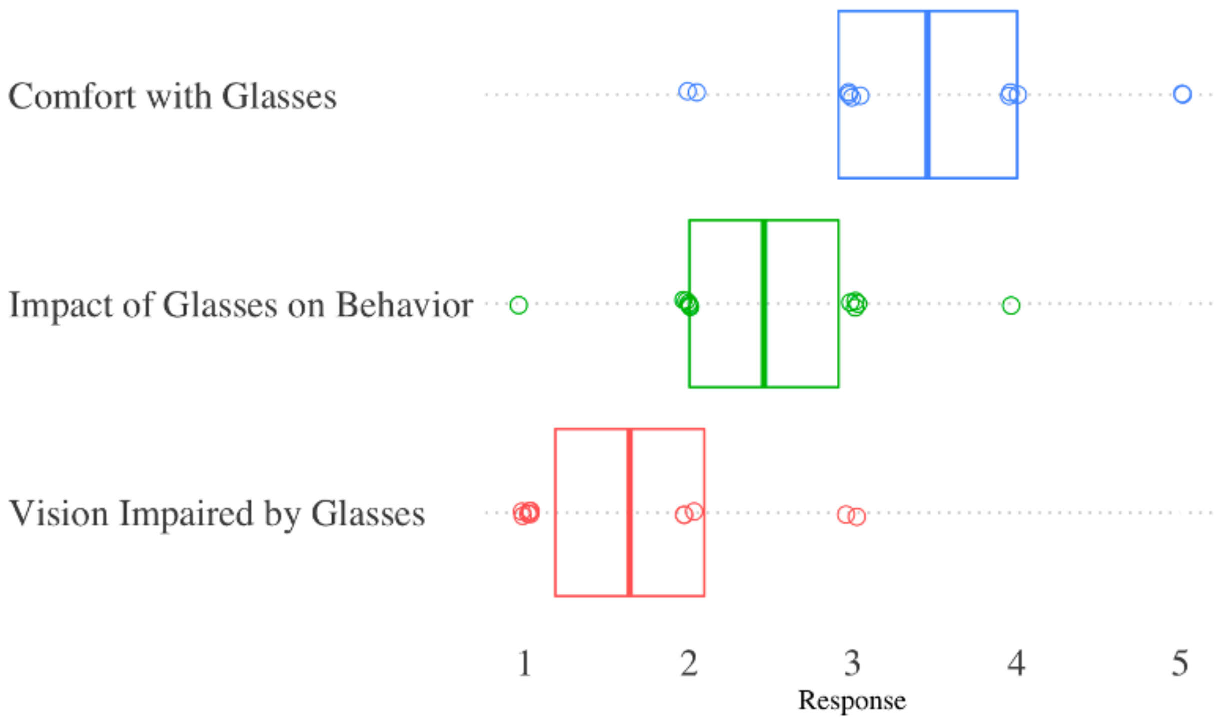


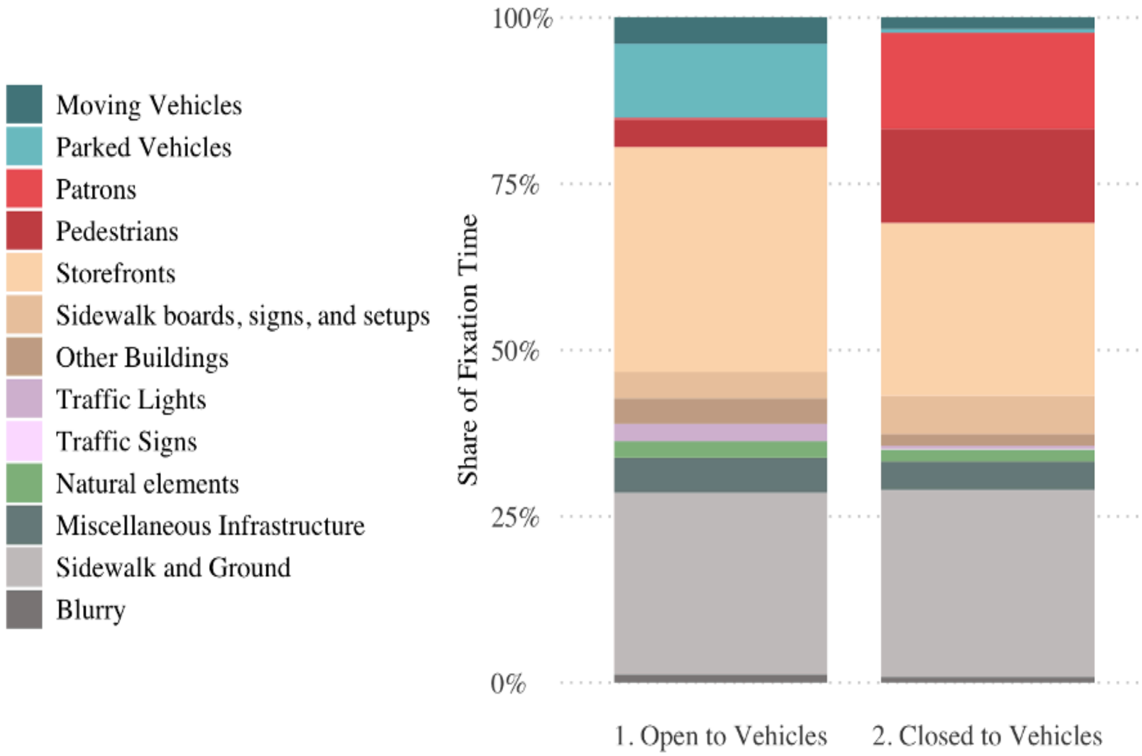
Figure 4.3: Mean of participants' feedback about eye tracking glasses

4.2 Results and Discussion

Identifying eye movements as fixations and remapping the urban elements that gained participant's attention as one of the urban typology categories allowed for the comparison of participant attention when the street was open-to-vehicles and closed-to-vehicles. The share of total fixation time, the share of total walk time (from the start to finish of the walking route), and the share of total captured valid recording time (also from start to finish of the walking route but only the amount of time recorded to account for any time associated with invalid data) were calculated. The analysis found that, on average, 41.8% of total time on the walking route was associated with identified fixations, while 58.2% of total time was not. For the total captured valid recording time, 54.4% of the time was associated with identified fixations and 45.6% was not. The share of total fixation time visualizes the differences between scenarios most clearly and can be seen in **Figure 4.4**.

Cars and people were the categories that experienced the largest shift in attention between scenarios. The average of all participants' share of fixation time spent focusing on moving or parked vehicles decreased from 15.1% to 2.3% in the closed-to-vehicles scenario, compared to when the street is open-to-vehicles. In part, this difference is likely due to the lack of vehicles parked along Beverly Street during the closed-to-vehicles scenario, as the street parking spaces were repurposed to space for dining and walking. Thus, participants only encountered vehicles at the cross-streets. Whereas the average of all participants' share of fixation time spent focusing on people (including other pedestrians as well as people utilizing temporary infrastructure set up by the shops) increased from 4.5% to 28.6% of total fixation time. This shift is supported by the post-experiment survey responses. While the survey analysis results are not presented in this thesis, it was found that participants felt more socially involved and engaged during the closed-to-vehicles scenario on average. The survey also indicated that most participants felt safer and more compelled to visit the area for recreation and visiting businesses.

The share of fixation time spent focusing on storefronts decreased from 33.8% in the open-to-vehicles setting to 25.9% when vehicles were restricted. However, the shifted attention towards people sitting in the shops' temporary infrastructure leads to interaction with the shop services. For example, participants' attention was also focused on the food being eaten by people in the temporary dining spaces. There was also a slight increase in the share of time spent focused on sidewalk boards, from 4.0% to 5.9%. Despite the decrease in the share of fixation time spent looking at the physical storefront, there was an overall increase in the share of time spent interacting with the spaces and services of the shops along the corridor. The share of time participants spent focusing on traffic lights and signs decreased from 2.7% of fixation time to 0.5%. The share of fixation time spent focusing on the sidewalk or ground remained similar between the two scenarios (27.4% and 28.3%). Similarly, the share of fixation time on miscellaneous infrastructure also remained similar between the two scenarios. Lastly, the share of fixation time spent focusing on natural elements, such as plants, trees, or sky, decreased from 2.5% to 1.8% on average. It is worth noting that the number of natural elements present on the route is limited and consists mostly of potted plants in front of shops.



	Open-to-Vehicles Mean	Closed-to-Vehicles Mean
Moving Vehicles	3.94%	1.75%
Parked Vehicles	11.11%	0.59%
Patrons	0.30%	14.41%
Pedestrians	4.19%	14.17%
Storefront	33.77%	25.92%
Sidewalk boards, signs, and setups	4.01%	5.88%
Buildings	3.76%	1.79%
Traffic Light	2.68%	0.30%
Traffic Sign	0.00%	0.23%
Nature	2.49%	1.78%
Miscellaneous Infrastructure	5.18%	4.18%
Sidewalk and Ground	27.39%	28.29%
Blurry	1.18%	0.74%

Figure 4.4: The mean share of fixation time for all participants when Beverly Street was Open-to-Vehicles and Closed-to-Vehicles

Generally, individual behavior followed similar trends to the findings described above. However, each participant displayed unique individual behaviors that were consistent between scenarios, which can be seen in **Figure 4.5**. For example, some participants spent more time with their heads down focusing on the sidewalk or ground in both scenarios. Additionally, some participants were exceptions to the general findings. Two participants slightly increased the share of fixation time spent focusing on moving cars, which was likely due, in part, to spending a longer period waiting to cross at the cross streets. All participants decreased the share of fixation time on parked cars.

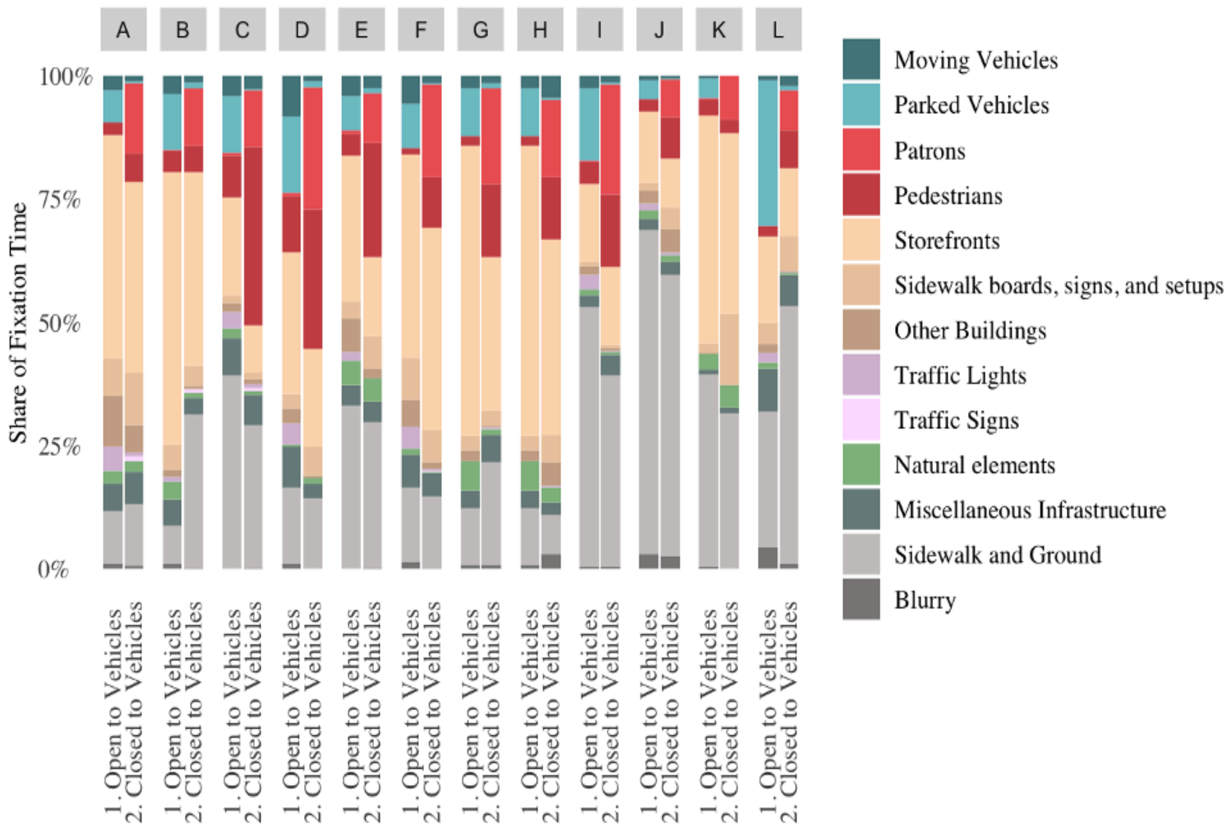


Figure 4.5: The share of fixation time on each urban typology by participant

CHAPTER 5: Variations In Pedestrian Perception at Different Times of Day

This chapter presents the experimental design and findings of a naturalistic pedestrian experiment conducted on a downtown commercial street, Water Street, which runs parallel to the downtown pedestrian mall, in Charlottesville, Virginia. The 2018 Pedestrian Safety Action Plan identified the Water Street corridor as a priority corridor due to the pedestrian crash risk (*41*). This study builds on the framework discussed in Chapter 3 and developed in the pilot study. Mobile sensor technology enabled data collection about the pedestrian experience and behavior. In addition to the cognitive and physiologic response data collected, data about environmental conditions was also collected. Stated preference survey responses provided further insight into the pedestrian experience. The study aimed to explore the use of mobile eye-tracking to examine variation in the pedestrian experience during daytime and nighttime scenarios.

5.1 Methodology

5.1.1 Experimental process

The design of this naturalistic pedestrian within-subject study included having participants walk up and down four blocks of a downtown corridor in Charlottesville, Virginia, Water Street, between 2nd Street SW and 4th Street SE. Water Street is a two-lane corridor with permitted parallel parking along the north side. **Figure 5.1** highlights the study area of Water Street. Daytime experiments occurred between the hours of 9am-4pm and nighttime experiments occurred between the hours of 5:30pm-9pm. Experiments took place on weekdays, Tuesday-Thursday, over the course of six weeks in November and December of 2023. These days were chosen for data collection to minimize operational differences that might occur during weekend days. Participants were scheduled for both a daytime and nighttime experiment. There was a pilot experiment conducted in October 2024 with 4 student researchers.

Figure 5.1: Water Street Corridor with the Study Route Highlighted

As a quasi-experiment occurring across multiple days, environmental conditions, including weather and crowds, varied. While some outdoor conditions were impossible to control for entirely, experiments were not carried out in the rain given that rain would obstruct the view through the smart glasses' lenses. Data about the environmental condition was also tracked for each participant. This included audio, lux level (lightings), temperature, and air quality data. While this paper focuses on the eye tracking data, all sensors and data tracked during the experiment can be found in **Figure 5.3.**

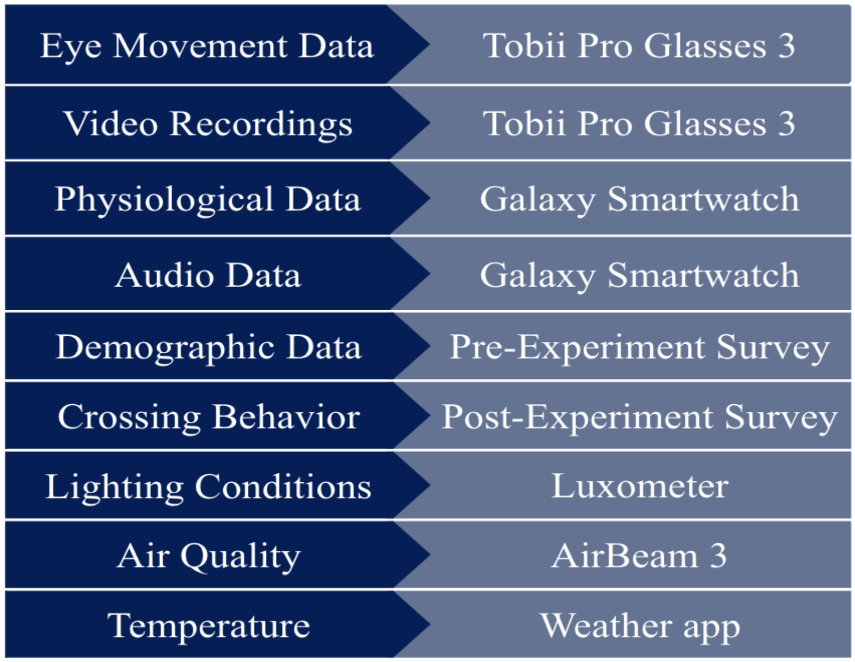


Figure 5.2: The type and method of data collection

Participants were emailed a short description of their tasks and a copy of the consent form before their scheduled time. Participants were instructed to meet the researchers at the Meeting Point (**Figure 5.3**), UVA's Environmental Institute, to prepare for the experiment, about 300 ft from the study's route on Water Street. During their first experiment only, participants signed the consent and filled out a pre-experiment survey eliciting information related to socio-demographics, activity (e.g. walking, driving, or time dedicated to physical activity), and familiarity with the area (See Appendix C for full set of questions). After completing the pre-experiment survey, researchers assisted the participants with putting on the wearable sensors and briefed them regarding their use. These included the Tobii Pro Glasses 3 and a Galaxy smartwatch. The glasses recorded video, audio, and eye-tracking data, while the smartwatch gathered participants' heart rate. Before leaving the meeting point to start the experiment, the smart glasses were calibrated to each participant to ensure data collection accuracy. Data collection from the smart watch was started at the starting point of the route.

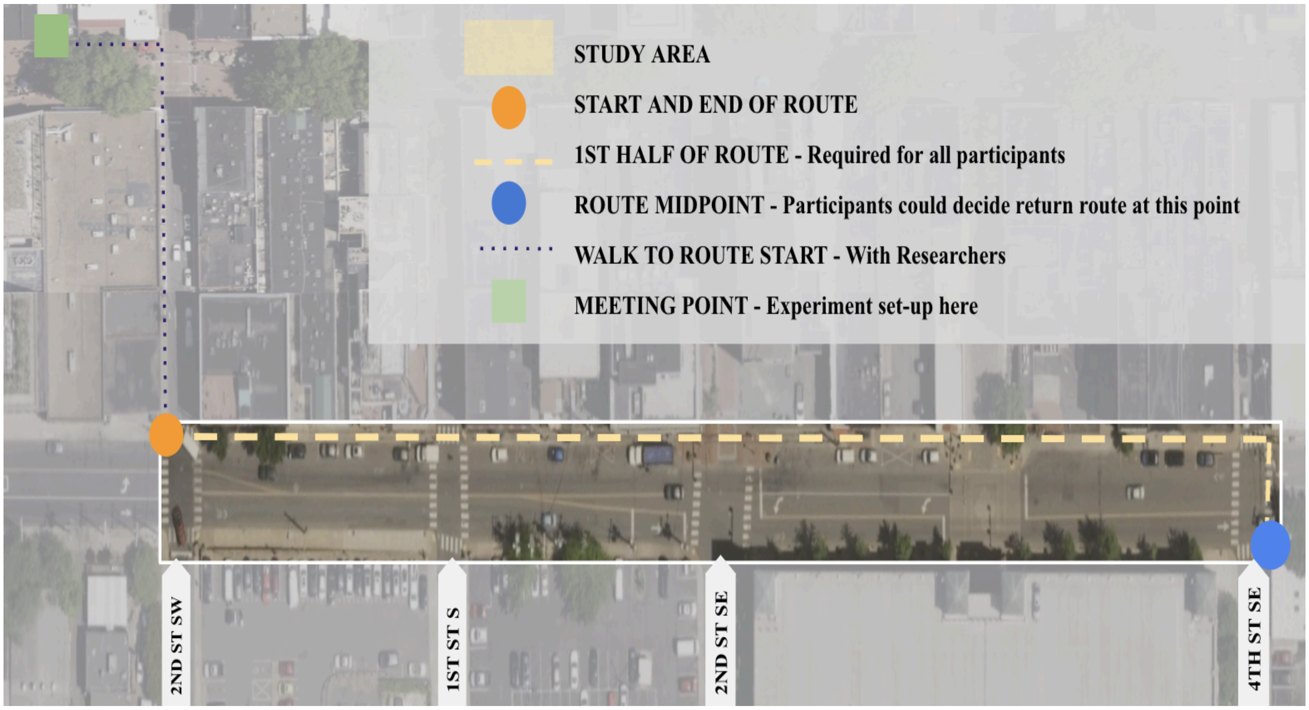


Figure 5.3: Water Street Study Area and Route

In addition to a verbal explanation by the researchers, participants were shown a map of the experiment route and a member of the research team walked with them to the starting point of the route (**Figure 5.2**). The study route required participants to walk eastbound from the intersection of Water Street and 2nd Street SW to the intersection of Water Street and 4th Street SE on the north sidewalk, cross Water Street at the second crosswalk of that intersection, and then walk westbound along the corridor to the initial intersection of Water Street and 2nd Street SW. After the initial crossing at Water Street and 4th Street SE, participants were instructed to cross back over Water Street and return to the starting point, however they would do so under normal conditions and could choose any point along the route where they would normally choose to cross. Regardless of where they crossed, the total route was approximately 8 city blocks and took most participants between 6-10 minutes to complete. The pre-defined walking path, and allowing participants to cross back at any point that they chose on the way back, remained constant throughout both experiment scenarios. The order in which participants walked the daytime and nighttime scenarios was random in an attempt to avoid any bias that might emerge from a change in familiarity of the route and the novelty or excitement of participating in such an experiment. Once participants returned to the meeting point, they were asked to complete a post-experiment survey after the completion of both scenarios (See Appendix D for full set of questions included). The post-experiment survey assessed the participants' subjective safety ratings of the daytime and nighttime conditions. It also asked them to identify locations where they felt particularly safe or unsafe along the route, indicate where they chose to cross back across Water Street, and provide their reasoning for their choice.

5.1.2 Participants and Data Collection

In total, 63 participants completed both scenarios of the experiments. Recruitment for the experiment was done via email, fliers, and word of mouth. Identified interest groups within the Charlottesville and Albemarle area, University of Virginia departments, city staff, and other community members were contacted in order to recruit participants. Participants were required to be at least 18 years of age and could not wear glasses on the days of the test (contact lenses were allowed) as the smart glasses could not be put on over regular eyewear. Participants also had to be able to walk the 8 blocks without assistance. All participants received compensation in the form of a gift card for their time. **Table 5.1** shows descriptive statistics of all participants.

Table 5.1: Descriptive Statistics of Participants

	TOTAL SAMPLE (N=63)	
	Frequency	%
GENDER		
Male	28	44.4%
Female	35	55.6%
RACE AND ETHNICITY [a]		
White/Caucasian	49	77.8%
Asian/Pacific Islander	9	14.3%
Hispanic/Latino	3	4.8%
Black/African American	2	3.2%
American Indian/Native American	1	1.6%
Other	2	3.2%
AGE		
18-29	21	33.3%
30-39	11	17.5%
40-49	14	22.2%
50-59	9	14.3%
60+	8	12.7%
EDUCATION LEVEL		
High School/GED	2	3.2%
Some College (no degree)	3	4.8%
Associate's degree	1	1.6%
Bachelor's degree	20	31.7%
Graduate degree	37	58.7%
EMPLOYMENT [a]		
Full-time	26	41.3%
Part-time	9	14.3%
Student	18	28.6%
Self Employed	10	15.6%
Unemployed	3	4.8%
Stay-at-Home Spouse	2	3.2%
Retired	7	11.1%
INCOME		
Less than $25,000	6	9.5%
$25,001 - $50,000	15	23.8%
$50,001-$75,000	8	12.7%
$75,001-$100,000	10	15.9%
$100,001-$150,000	7	11.1%
$150,001-$200,000	9	14.3%
More than $200,000	6	9.5%
No answer	2	3.2%

[a] Participants were able to select all that apply

5.1.3 Eye-Tracking Analysis

Front facing video recordings with eye-tracking data, heart rate data, and survey data were collected for each participant. From the video recordings, physical elements that attracted participants' visual attention were manually classified into one of thirteen areas of interest (AOI) for analysis, based on the urban typologies identified in **Figure 3.1.** The seventeen categories used for analysis are listed in **Table 5.2,** and the used process described in Chapter 3. With this segmentation, the duration individual elements were fixated upon can be assessed (*25*). Examples of the AOI classification used in this study within Tobii Lab can be seen in **Figure 4.4.**

Table 5.2: AOI Classifications

Vehicles	*Parked Vehicles*
	Moving Vehicles
Transportation + Crossing Infrastructure	*Non-Pedestrian Transportation Infrastructure*
	General Pedestrian Infrastructure
	Lighted Crossing Infrastructure
	Unlighted Crossing Infrastructure
Lighting	*Non-Transportation Lighting Features*
People	*Pedestrians*
	Bicyclists
	Other People (Patrons, Waiting for a bus, etc.)
Storefronts and Buildings	*Storefronts*
	External Store Infrastructure
	Non-Storefront Buildings
	Public Art
Other	*Nature (Trees, Sky, etc.)*
	Miscellaneous Infrastructure (garbage bins, newsracks, etc.)
	Blurry or Undetermined

Figure 5.4: Examples of AOI Classification Categories

There was a lot of variation in data validity across experiments. Gaze data was not continuously recorded throughout and was impacted by factors such as environmental conditions (e.g., the glare from the sun) and the fit of the glasses. Due to the influence of the sun and glare, the biggest difference was between the daytime and nighttime scenarios. The mean data validity across all recordings was 73.5%, with a mean of 63.8% validity during the daytime and 83.2% at night.

5.2 Results and Discussion

All eye movements within the attention threshold discussed in section 2.5 were remapped in the Tobii software as the urban elements that gained participant's attention. Analysis, using the seventeen AOI categories discussed in 5.1.3, allowed for the comparison of participant attention when walking the corridor during the day and at night. On average, 52.8% of the total route time was associated with fixations. The initial analysis presented in this section includes the mean share of fixation duration across all participants and the mean total fixation duration (normalized to account for differences in data validity).

Similar to the repurposed street study described in Chapter 4, the share of total fixation duration was calculated from 'Total Fixation Duration' to visualize the differences between scenarios (**Figure 5.5**). Analyzing the data using this metric showed the largest increases in attention at night were on both moving and parked vehicles and on lighted crossing infrastructure and general lighting features. The other transportation infrastructure categories, all of which were unlighted, all experienced decreases. Storefronts and other buildings all experienced an increase in attention at night as well, likely in part due to the lighting of many of the storefront windows. There was also a large decrease in attention on natural elements, such as trees and sky, at night. While the share of fixation duration that was determined to be too blurry to classify was minor, it should be noted that there was a large increase in frames that were within the I-VT threshold that were too blurry to determine at night due to the dark conditions of the video.

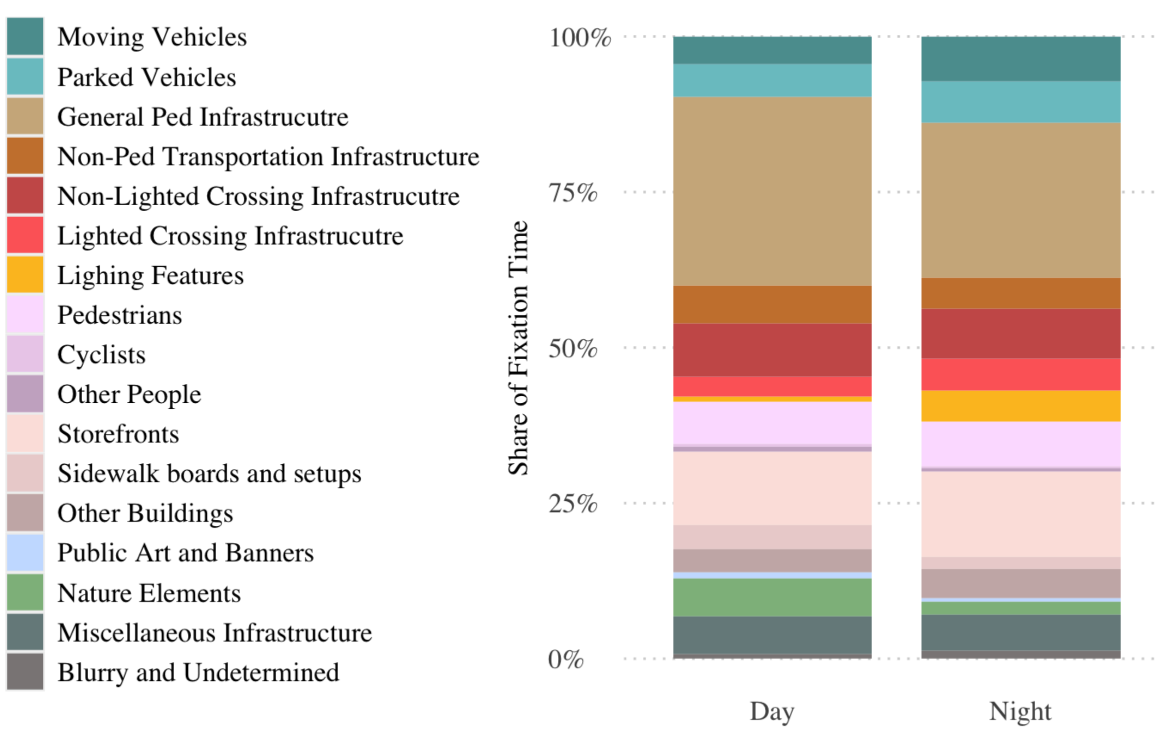


Figure 5.5: The mean share of fixation duration for all participants during the Day and Night Scenarios

Participant ages ranged from 20 to 88 years old and the fixation duration data was disaggregated by age group to explore differences across this range, which can be seen in **Figure 5.6.** Most notably, there was an increase in attention to general pedestrian infrastructure (mostly consisting of sidewalks) with age. Based on some conversations with participants, one possibility for this increase is a greater concern about sidewalk conditions and tripping as people get older. There was little variation when data was separated by gender.

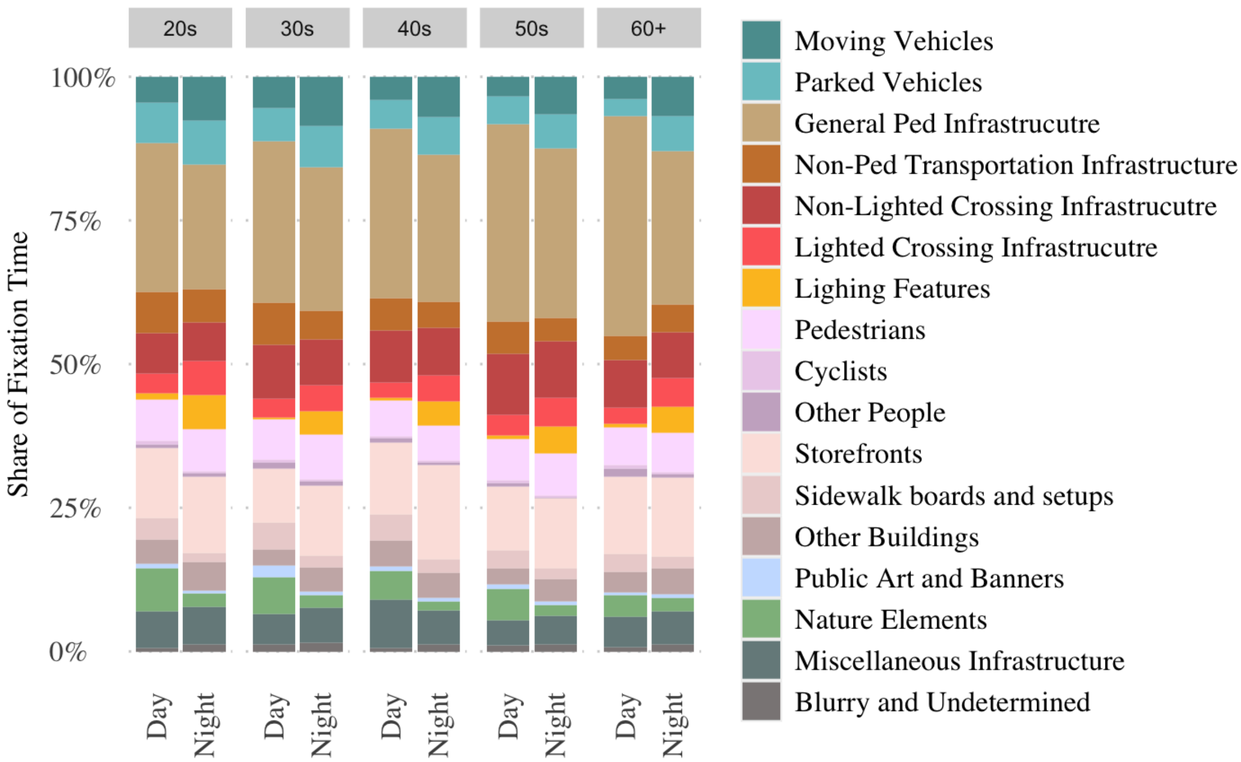


Figure 5.6: The mean share of fixation duration by age group during the Day and Night Scenarios

While share of fixation duration is one of the most commonly used metrics to look at visual attention, total fixation duration was also analyzed in order to further examine the extent of the variation between the scenarios. However, as mentioned previously, there was a large difference in data validity between the day and night scenarios. Thus, the mean total fixation duration data had to be normalized in order to compare this data, which can be seen in **Figure 5.7**. While all of the other categories varied in a similar direction in both types of data, the only classification that differed was Pedestrians. On average, both scenarios experienced a notable increase of attention on moving and parked vehicles, lighted crossing infrastructure, and general light features. There was a slight increase at night when analyzing the share of fixation time, but a decrease at night when using the total fixation duration data. While the findings from this study are far from conclusive, the data does begin to demonstrate trends between the day and the night condition.

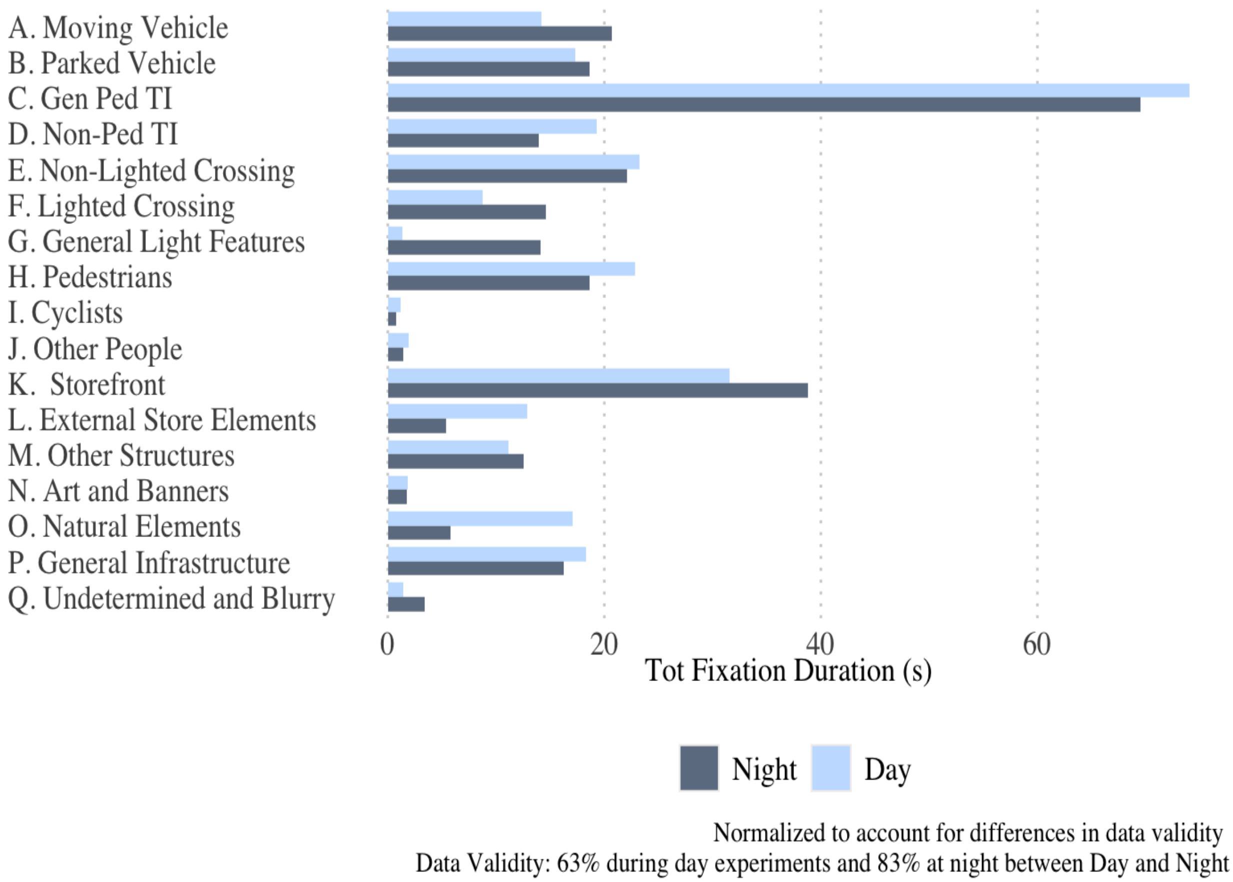


Figure 5.7: The mean total fixation duration for participants by Day and Night (normalized for differences in data validity)

CHAPTER 6: Conclusion

6.1 Summary of Results

The two studies presented in this thesis explore the visual response and preference of pedestrians to illustrate how mobile eye-tracking technology can be used to better understand pedestrian interaction with the built environment in the different urban settings. While there are various directions that future analysis could go to find conclusive results, these studies establish a framework based on identified urban typologies that can be applied to various urban environments.

Taking advantage of an opportunity provided by a temporary street repurposing in Staunton, Virginia, the naturalistic quasi-experiment presented in chapter 4 examines the variation that occurs between an open-to and closed-to-vehicles street environment for pedestrians. The findings suggest that participants had a more positive experience when the street was closed-to-vehicles and prioritized pedestrian use. This is based on participants indicating that they felt safer when crossing and navigating, feeling more engaged and socially involved, being more aware of businesses, more compelled to visit the area, and finding the street more attractive. Participant attention shifted to people, both pedestrians also using the sidewalk and patrons of the temporary dining areas, when the need to focus on vehicular elements was reduced. The study presented in chapter 5 focused on variations that occurred in pedestrian perception with different lighting conditions by comparing the experience of walking the same corridor during the day and night. The initial analysis suggests that vehicles and lighted elements experienced the largest increase in attention between the daytime and nighttime conditions.

This thesis presents two versions of AOI classifications, based on the Urban Typology framework. These classifications can adapt to the conditions and research questions of each study, as needed. While there were many similarities between the two, the importance of lighting became clear in the second study comparing daytime and nighttime. Participants were also allowed to cross the street at any point along the study route that they normally would, making crossing infrastructure important to separate out.

There is a need for a more comprehensive model of measuring attention to better understand linkages between pedestrians' attention, perceptions, and cognition (*29*), which could improve our understanding of urban mobility and behavior. This thesis contributes to the current knowledge by proposing the design of an on-site naturalistic walking experiment and exploration of the use of wearable sensors' outputs to assess real-life settings in an urban environment from the pedestrian viewpoint. Being able to capture the pedestrian perspective in a real-world setting, identified in previous research as challenging to capture and quantify (*28*), is a strength of this technology and the studies presented in this thesis. The first-person view of the video recordings allows for interpreting surroundings from their point of view. On-site real-world data collection is advantageous since it has been shown to describe behavior more accurately than that collected in a laboratory setting (*17*). Understanding pedestrian behavior and perception is essential for enhancing urban spaces and infrastructure and the studies presented in this provides a framework and initial analysis that can be used to gain more insight. The desire to give back space to pedestrians was accelerated during the COVID-19 pandemics, but there is continued interest in pedestrian-centered spaces. With the increase in nighttime pedestrian fatalities that the US is experiencing, the need for creating safer spaces and infrastructure for pedestrians and other vulnerable road users is greater than ever. The results from these studies, and future work that builds on this framework, can help inform the choices of communities and decision makers.

6.2 Limitations

The studies presented in this thesis demonstrate the type of research that mobile eye tracking glasses makes possible and provides a framework for future research. However, there are some limitations related to the studies and to the tracking technology that are important to acknowledge.

Some of the main limitations identified for this type of study are the small sample sizes and the demographic representation among the samples. The sample size was particularly limiting in the first case study given that it was a pilot study with only 12 participants. While the second study was able to recruit 63 participants, a relatively large sample size for this kind of study, it was still challenging to find statistically significant results. Originally, the intention was to recruit a large number of senior participants for the second study, but there were many obstacles to this goal. Reaching equal representation across age demographics was already a challenge. First, people who require corrective lenses are not able to participate in the study, unless they can wear contact lenses, due to the eye-tracking glasses technology. Personal glasses do not fit properly under the mobile glasses and the sensors are unable to track eye movements through the personal lenses. This hindered the ability to find eligible participants, especially in the over forty age range. Many people in their forties found it difficult to take time from their children and families, or to find child care, to participate in optional studies. While seniors were often enthusiastic, they were more likely to have vision or mobility issues which made it impractical for them to participate. In addition to these issues, recruitment responsibilities fell entirely to student researchers in their twenties whose network was largely made up of other students their age, some of whom were international students who had a limited network from which to pull older family, friends and neighbors.

While the days selected for the study were intentionally chosen to minimize the differences in the environment beyond the condition being studied (street closure in the first study and time of day in the second study), the real-world setting made differences that were impossible to control for entirely. In the first study, all closed-to-vehicle samples were collected on Fridays, which potentially could include more foot traffic on Beverly Street regardless of the street repurposing. This could also be a factor in the increased social interaction. In the second study, experiments were only completed on Tuesday, Wednesdays, and Thursdays to minimize any differences that might be seen between weekdays and weekend days. The main difference is the time of day and lighting, but there was still some natural variation related to people and vehicles present along the study area.

It is also important to note the impact that the sensors, and awareness of being in a study, might have had. While participants mostly indicated that the glasses were comfortable and did not impact their behavior, the wearable sensing devices could be a potential stress for some participants (*42*). This type of study requires that the technology be set-up, thus it is difficult to entirely ensure that participant behavior is not impacted by the mechanics of the study itself. Similarly, possible survey fatigue should also be considered.

There are also some limitations related to the data collection and analysis. One aspect to consider is that the use of smart glasses with cameras poses potential privacy concerns for individuals not involved in the experiment who are passively recorded (*43*). The validity of eye movement data collection also varies with some environmental conditions, such as glare from the sun. Both studies also relied on manual remapping of the fixations as one of the identified AOI classifications, which introduces potential researcher bias for this part of the analysis. While the eye movement detection validity rates were higher during the nighttime experiments, the video imagery was often more difficult to interpret. The approach used within this study accounts for many issues often experienced within mobile eye-tracking experimentation, Yet, there is still a significant need for the development of more robust detection algorithms (*44*, *45*). Additionally, the manual remapping of fixations as AOIs is not an efficient method. In order for this technology to be scalable and usable for larger sample sizes, an automated classification process is necessary.

6.3 Future Work

While some of the limitations identified above are unavoidable realities of this type of study, the others can inform the direction of future research. This thesis is primarily intended to present the application of mobile eye-tracking technology and provide a framework for future research of this type. Eye-tracking data can provide insight about pedestrians' attention, however further research is necessary to make the connection among attention, perception, cognition, and the behaviors that impact mobility choices and economic activity on urban streets (*29*). There are many avenues for potential future work that are built on the proposed framework. This section highlights some of the next steps and potential future directions.

There is currently no standardized data processing technique or methodology for this type of analysis that would prove valid across multiple experiments. Further research should define standardized methodologies for data analysis and interpretation in the urban planning domain. The second study presented in this thesis (Chapter 5) focuses on initial findings related to attention data, but further analysis is required to fully reveal comprehensive results related to the eye-tracking data. This work can assist in identifying the best analysis approach when using this technology for naturalistic studies related to the built environment. The elements that gained attention, based on the I-VT attention threshold, were classified into the AOI categories related to the Urban Typologies identified in this thesis. However, some fixations are more significant than others and identifying these can be more informative about a person's cognitive processes and how they perceive their environment (*46*). The initial analysis completed for the case studies has not differentiated between differences in type of fixations, such as distance of the elements, that could lead to different levels of cognition and potentially an increased need to detect safety hazards (*47*, *48*). It also might be important to separate elements that actually gained attention from fixations that were more passive or continued. The eye-tracking glasses include a Gyroscope and Accelerometer sensor and records Inertial Measurement Unit data that could be helpful in identifying these differences.

There are also eye-tracking metrics unrelated to AOI identification, such as Mean Fixation Duration and Horizontal and Vertical Variability, that can provide additional information related to stress and anxiety. Stationary Gaze Entropy and Gaze Transition Entropy are additional metrics that could be considered. Further analysis could also focus on pupil diameter, a physiological factor that relates to emotional states and stress.

As discussed in section 2.5, the attention filter was created for dynamic situations when subjects are moving to include “foveal stabilization” movements. However, there has been limited validation of using this threshold in this type of study and this should be examined further given the differences in cognitive processing with the different movements. It would also be useful to validate the real-world experiments compared to those done in a VR setting. Few studies examining human perception of the built environment have used mobile eye-tracking in an outdoor setting and significant differences between laboratory and outdoor environments have been found when using mobile eye-tracking glasses (*28*, *46*, *49*, *50*).

There were also a variety of data types collected during the second study beyond eye-tracking data and further analysis and integration of the data types is needed for a holistic analysis. Combining the visual response with the physiological data can provide important insights about the pedestrian experience. Noise levels, lighting condition, temperature, and air quality data was also collected during experimentation and will be analyzed further. As discussed in the limitations section (6.2), there is also a great need for automating the AOI identification for dynamic, real-world studies. Using an algorithm to make the classification process more efficient will make this technology a more feasible option for larger studies in the future. It will also allow for analyzing, not only what participants are looking at, but what they chose to focus on from all the possibilities in that frame in a much more efficient way.

Mobile wearable sensors are a promising technology in improving the understanding of vulnerable road users by providing easy-to-obtain data and being flexible in their application. Developing the methodology and analysis approach further would allow for the expansion of mobile eye-tracking technology studies being used in various urban settings. Developing the methodology and analysis approach further would allow for the expansion of mobile eye-tracking technology studies being used in various urban settings. The methods utilized in this study have the potential to allow planners, engineers, designers, and policy makers to directly identify how their efforts, such as street repurposing and lighting conditions, alter the urban experience, providing communities with more engaging public spaces, safer streets, and more livable and economically vibrant communities.

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APPENDICES

APPENDIX A. Staunton Pre-Experiment Questionnaire

Thank you for your interest in participating in this experiment. The following questions will ask about you and your transportation habits.

Please provide the participant number given to you in your experiment confirmation email

____

How did you hear about this study?

- o Word of mouth (1)
- o An email (2)
- o A flier (3)
- o Social media (5)
- o Other (4) ____

In the past week, have you _______ (please check all that apply)

- ▢ Walked to a destination or walked for recreation/exercise? (1)
- ▢ Ridden a bike? (2)
- ▢ Taken transit? (3)
- ▢ Driven or ridden in an automobile? (4)
- ▢ None of the above (5)

The following questions ask you about the amount of time you devote to different activities each day.

	Hours (1)	Minutes (2)

On average, how many hours of physical activity do you have each day? (1)		
On average how many hours a day do you use a smartphone? (2)		
On average how many hours do you spend outdoors each day? (4)		
Approximately how much time did you spend walking last week? (5)		

If you have a smartwatch that counts your steps, how many steps on average per day do you take? (put N/A if you don't wear one or count steps with one)

____

Do you have any visual impairments?

o Yes - please explain here (6) ____

o No (7)

Are you color blind?

o Yes (1)

o No (2)

o Not Sure (3)

What is your current employment status?

- o Employed full-time (1)
- o Self-employed (2)
- o Working part time (3)
- o Unemployed (4)
- o Retired (5)
- o Student (6)
- o Stay at home spouse (7)
- o On sabbatical (8)
- o Other (9) ____

What is the highest educational degree you have earned?

- o Less than high school diploma (1)
- o High school/GED (2)
- o Some college (no degree) (3)
- o Associates degree (4)
- o Bachelor's degree (5)
- o Graduate degree (6)

What is your annual household income?

- o $0-$10,000 (1)
- o $10,001-$15,000 (2)
- o $15,001-$25,000 (3)
- o $25,001-$35,000 (4)
- o $35,001-$50,000 (5)
- o $50,001-$75,000 (6)
- o $75,001-$100,000 (7)
- o $100,001-$200,000 (8)
- o $200,000+ (9)

o Prefer not to answer (10)

How many of the following does your household have?

o Bicycles (1) ____

o Electric bicycles (2) ____

o Mopeds or motorcycles (3) ____

o Passenger cars, vans, SUVs, pickup trucks (4)
____

o Motor homes, recreational vehicles, buses, or large trucks (5)
____

What is your marital status?

o Single (1)

o Married (2)

o Widowed (3)

o Divorced (4)

o Separated (5)

Q42 Do you have children (under the age of 18)?

o No (1)

o Yes (2)

Q43 How many children do you have? ________

Q44 What is/are the age(s) of you child/children?

____

Q45 What is your gender?

o Woman (1)

o Man (2)

o Transgender (4)

o Non-binary/non-conforming (5)

o Prefer not to respond (6)

o Other (3) ____

Q46 What is your age?

____

Q47 Would you describe yourself as... (Please check all that apply)

▢ American Indian/Native American (1)

▢ Asian/Pacific Islander (2)

▢ Black/African American (3)

▢ Hispanic/Latino (4)

▢ White/Caucasian (5)

▢ Other (6) ____

▢ Prefer not to answer (7)

APPENDIX B. Staunton Post-Experiment Questionnaire

Thank you for your participation in this study. The following questions relate to your experiences and feelings during the study.

Please provide the participant number given to you in your experiment confirmation email:

____

Q1 The following questions relate to your use of the eye-tracking glasses.

	Not At All (1) (1)	(2) (2)	Somewhat (3) (3)	(4) (4)	Very (5) (5)

Did you feel that the eye-tracking glasses impacted your behavior in any way? (1)	o	o	o	o	o
Did the eye-tracking glasses impair your vision in any way? (2)	o	o	o	o	o
Did you feel comfortable wearing the eye-tracking glasses? (3)	o	o	o	o	o

(Optional) Elaborate on your response to "Did you feel that the eye tracking glasses impacted your behavior in any way?"

____

(Optional) Elaborate on your response to "Did the eye tracking glasses impair your vision in any way?"

____

(Optional) Elaborate on your response to "Did you feel comfortable wearing the eye tracking glasses?"

____

How safe did you feel navigating Beverly Street when...

	Not at all safe (1) (1)	(2) (2)	Somewhat safe (3) (3)	(4) (4)	Very safe (5) (5)
it is open to cars (1)	o	o	o	o	o

it is open to pedestrians only (2)	o	o	o	o	o

How safe did you feel crossing the street when...

	Not at all safe (1) (1)	(2) (2)	Somewhat safe (3) (3)	(4) (4)	Very safe (5) (5)
it is open to cars (1)	o	o	o	o	o
it is open to pedestrians only (2)	o	o	o	o	o

How compelled do you feel to visit Beverly Street for recreational purposes when...

	Not at all compelled (1) (1)	(2) (2)	Somewhat compelled (3) (3)	(4) (4)	Very compelled (5) (5)
it operates as normal (1)	o	o	o	o	o
it is repurposed for pedestrian foot traffic (2)	o	o	o	o	o

How socially involved did you feel while navigating Beverly Street when...

	Not at all socially involved (1) (1)	(2) (2)	Somewhat socially involved (3) (3)	(4) (4)	Very socially involved (5) (5)
it operates as normal (1)	o	o	o	o	o
it is repurposed for pedestrian foot traffic (2)	o	o	o	o	o

How aware were you of businesses while navigating Beverly Street when...

	Not at all aware (1) (1)	(2) (2)	Somewhat aware (3) (3)	(4) (4)	Very aware (5) (5)
it operates as normal (1)	o	o	o	o	o
it is repurposed for pedestrian foot traffic (2)	o	o	o	o	o

How compelled did you feel to visit a business on Beverly Street when...

	Not at all compelled (1) (1)	(2) (2)	Somewhat compelled (3) (3)	(4) (4)	Very compelled (5) (5)
it operates as normal (1)	o	o	o	o	o
it is repurposed for pedestrian foot traffic (2)	o	o	o	o	o

How engaged did you feel while navigating Beverly Street when...

	Not at all connected (1) (1)	(2) (2)	Somewhat connected (3) (3)	(4) (4)	Very connected (5) (5)
it operates as normal (1)	o	o	o	o	o
it is repurposed for pedestrian foot traffic (2)	o	o	o	o	o

How attractive do you feel Beverly Street was when...

	Not at all connected (1) (1)	(2) (2)	Somewhat connected (3) (3)	(4) (4)	Very connected (5) (5)
it operates as normal (1)	o	o	o	o	o
it is repurposed for pedestrian foot traffic (2)	o	o	o	o	o

Q13 How close do you live to Staunton, VA?

	0-5 miles (1)	6-10 miles (2)	11-15 miles (3)	16-20 miles (4)	20 or more miles (5)
I live within... (1)	o	o	o	o	o

Have you previously visited Beverly Street when...

	No (1)	Yes (2)
it is operating under normal circumstances (3)	o	o

it is repurposed for pedestrian foot traffic (4)	o	o

How often do you visit Beverly Street when...

	Yearly (1)	Monthly (2)	Weekly (3)	Daily (4)	Never (5)
it is operating under normal circumstances (1)	o	o	o	o	o
it is repurposed for pedestrian foot traffic (2)	o	o	o	o	o

Describe downtown Staunton in three words

____

____

APPENDIX C. Water Street Pre-Experiment Questionnaire

Thank you for your interest in participating in this experiment. The following questions will ask about you and your transportation habits.

Please provide the participant number given to you in your experiment confirmation email:

____

Outreach How did you hear about this study?

o Word of mouth (1)

o An email (2)

o A flyer (3)

o Social media (5)

o Other (4) ____

Q1 In the past week, have you _______ (please check all that apply)

- ▢ Walked to a destination? (1)
- ▢ Walked for recreation or exercise? (2)
- ▢ Ridden a bike? (3)
- ▢ Taken Public Transit? (4)
- ▢ Driven an automobile? (5)
- ▢ None of the above (6)

Q2 What motivates you to walk?

- o I walk for the pleasure of it (1)
- o I walk because it is healthy (2)
- o I walk because I need to access my destinations (3)
- o Other (4) ____

Q3 Which of the following best describes how you usually cross roads ?

- o I always cross at a crosswalk even if it means walking a little further from my path (1)
- o I mostly try to cross at crosswalks but sometimes cross at the first convenient location I see (2)
- o I cross at both crosswalks and convenient locations equally (3)
- o I mostly cross at locations most convenient to me but sometimes try to use crosswalks (4)
- o I only cross at locations most convenient to my path (5)

Q4 The following questions ask you about the amount of time you devote to different activities each day.

	Hours	Minutes
On average, how many hours of physical activity do you have each day?		
On average, how many hours do you spend outdoors each day?		
Approximately how much time did you spend walking last week?		

Q5 If you have a smartwatch that counts your steps, how many steps on average per day do you take? (put N/A if you don't wear one or count steps with one)__________

Q6 How many of the following does your household have?

o Bicycles and E-Bikes (7) ____

o E-Scooters (6) ____

o Mopeds or Motorcycles (24) ____

o Vehicles (passenger cars, vans, pickup trucks) (4) ________________________

Q7 Do you have any visual impairments?

o Yes - please explain here (6) ____

o No (7)

Q8 Are you color blind?

o Yes (1)

o No (2)

o Not Sure (3)

Q9 What is your current employment status?

▢ Employed full-time (1)

▢ Self-employed (2)

▢ Working part time (3)

▢ Unemployed (4)

▢ Retired (5)

▢ Student (6)

▢ Stay at home spouse (7)

▢ On sabbatical (8)

▢ Other (9) ____

Q10 What is the highest educational degree you have earned?

o Less than high school diploma (1)

o High school/GED (2)

o Some college (no degree) (3)

o Associates degree (4)

o Bachelor's degree (5)

o Graduate degree (6)

Q11 What is your gender?

o Woman (1)

o Man (2)

o Transgender (4)

o Non-binary/non-conforming (5)

o Prefer not to respond (6)

o Other (3) ____

Q12 What is your age?

____

Q13 What is your annual household income?

o $0-$25,000 (1)

o $25,001-$50,000 (3)

o $50,001-$75,000 (5)

o $75,001-$100,000 (6)

o $100,001-$150,000 (7)

o $150,001-$200,000 (8)

o $200,000+ (9)

o Prefer not to answer (10)

Q14 Would you describe yourself as... (Please check all that apply)

▢ American Indian/Native American (1)

- Asian/Pacific Islander (2)
- Black/African American (3)
- Hispanic/Latino (4)
- White/Caucasian (5)
- Other (6) ____
- Prefer not to answer (7)

Q15 How close do you live to downtown Charlottesville, Va?

	0-2 miles (1)	2-5 miles (2)	5-10 miles (3)	10-20 miles (4)	20+ miles (5)
I live within... (1)	o	o	o	o	o

Q16 How often do you visit downtown Charlottesville?

	Never been (12)	Have been but don't visit often (13)	Visit a few times a year (14)	Visit a few times a month (15)	Visit a few times a week (17)	Visit everyday (18)
Daytime (1)	o	o	o	o	o	o
Nighttime (2)	o	o	o	o	o	o

Q17 How familiar are you with Water Street during the...

	Not familiar at all (16)	Slightly familiar (17)	Moderately familiar (18)	Very familiar (19)	Extremely familiar (20)
Day time (1)	o	o	o	o	o
Night time (2)	o	o	o	o	o

Q18 Please drag and drop in the box what brings you to the area when you visit the downtown area and rank by frequency:

What brings you to the downtown area?
______ Work (daytime) (1)
______ Work (nighttime) (2)
______ Social and Recreation (daytime) (3)
______ Social and Recreation (nighttime) (4)
______ Shopping (daytime) (6)
______ Shopping (nighttime) (7)
______ Other (5)

Q19 How do you usually get to the downtown area when you come to the area?

o Drive (1)

o Walk (2)

o Bike (3)

o Bus (4)

o Rideshare (i.e. Uber or Lyft) (5)

o Scooter (i.e. VEO) (6)

o Carpool (8)

o Other (7) ____

APPENDIX D. Water Street Post-Experiment Questionnaire

Thank you for your participation in this study. The following questions relate to your experiences and feelings during the study.

Please provide the participant number given to you in your experiment confirmation email:

____

Which scenario of the experiment did you just participate in?

o Daytime (1)

o Nighttime (2)

Q0 How safe did you feel walking along Water Street at this time of day?

	Not at all safe (1) (1)	(2) (2)	Somewhat safe (3) (3)	(4) (4)	Very safe (5) (5)
I felt... (3)	o	o	o	o	o

Q0 How safe did you feel walking crossing Water Street at this time of day?

	Not at all safe (1) (1)	(2) (2)	Somewhat safe (3) (3)	(4) (4)	Very safe (5) (5)
I felt... (3)	o	o	o	o	o

Q1 On the following maps, identify points along the route where you felt the **most unsafe** and/or **uncomfortable**. Click on the map to identify the spot with a red dot. Identify up to three locations - with only one at a time on each of the following maps.

If you never felt unsafe and/or uncomfortable, please leave them blank.

Q1.1a Location 1

Q1.1b What about this location made you feel unsafe and/or uncomfortable?

____

____

Q1.2a Location 2

Q1.2b What about this location made you feel unsafe and/or uncomfortable?

____

____

Q1.3a Location 3

Q1.3b What about this location made you feel unsafe and/or uncomfortable?

____

____

Q41 On the following maps, identify points along the route where you felt the **most safe** and/or **comfortable**. Click on the map to create to identify the spot with a red dot. Identify up to three locations - with only one at a time on each of the following maps.

Q2.1a Location 1

Q2.1b What about this location made you feel safe and/or comfortable?

____

____

Q2.2a Location 2

Q2.2b What about this location made you feel safe and/or comfortable?

____

____

Q2.3a Location 3

Q2.3b What about this location made you feel safe and/or comfortable?

____

____

____

Q3.1 Identify where you crossed from the south side of Water Street back to the north side:

Q3.2 Which of the following best describes why you chose to cross here?

- ▢ The presence of the traffic signal (4)
- ▢ The presence of the stop sign (5)
- ▢ I saw some one else had started to cross at this location (6)
- ▢ The lighting (applicable at night) (7)
- ▢ The amount of traffic (8)
- ▢ This was the first location I felt was feasible or convenient (9)
- ▢ Other (please describe) (10) ____

Q3.3 Please rank which of the factors influenced your choice from most (top) to least (bottom).

______ The presence of the traffic signal (1)
______ The presence of the stop sign (2)
______ I saw some one else had started to cross at this location (3)
______ The lighting (applicable at night) (4)
______ The amount of traffic (5)
______ This was the first location I felt was feasible or convenient (6)
______ Other (please describe) (7)

Q4.1 The following questions relate to your use of the eye-tracking glasses.

	Not At All (1) (1)	(2) (2)	Somewhat (3) (3)	(4) (4)	Very (5) (5)

Did you feel that the eye-tracking glasses impacted your behavior in any way? (1)	o	o	o	o	o
Did the eye-tracking glasses impair your vision in any way? (2)	o	o	o	o	o
Did you feel comfortable wearing the eye-tracking glasses? (3)	o	o	o	o	o

Q4.2 Elaborate on your response to "Did you feel that the eye tracking glasses impacted your behavior in any way?" (Optional)

____

Q4.3 Elaborate on your response to "Did the eye tracking glasses impair your vision in any way?" (Optional)

____

Q4.4 Elaborate on your response to "Did you feel comfortable wearing the eye tracking glasses?" (Optional)