Eye Movements: Measuring Fatigue and Attention in Natural and Urban Scenes

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Exposure to nature can improve affective and cognitive states, reducing stress and arousal. Across four experiments, I measured eye movements when viewing natural and urban environments in the laboratory, recording changes in visual exploration and fatigue. My dissertation formally investigates the relationship between affective preference and visual exploration. For the first time, I gathered data from microsaccades to measure changes in fatigue and arousal while people view natural and urban environments. Natural scenes involved longer and more frequent fixations than urban scenes. I measured blink rates and microsaccade slopes as eye movement indicators associated with arousal and fatigue. These measures indicated that viewing natural scenes involved lower arousal than urban scenes. For static natural and urban scenes, preference was associated with increased fixation count. In experiment 2, I found that fractal complexity influences visual exploration and preference. More complex scenes elicited shorter saccades and were more pleasant, especially for urban scenes. In experiment 3, I contrasted different types of natural and urban environments. I showed that historic architecture was preferred to modern architecture, and that it involved lower fatigue and more exploratory eye movements. In experiment 4, I showed that differences in visual exploration and arousal between natural and urban scenes remained significant when using video stimuli, and when depleting attention beforehand using a sustained attention task. As eye-tracking grows in popularity for measuring experiences in architectural and natural environments, these experiments provide a valuable resource for understanding the relationship between eye movements, affective processing, and fatigue.

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Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

The biophilia hypothesis argues that people have an innate desire to connect with nature. In the environmental psychology literature, the beneficial effects of spending time with nature have been well documented through hundreds of studies (Spano et al., 2023; Stier-Jarmer et al., 2021; Twohig-Bennet & Jones, 2018). These effects include affective (McMahon & Estes, 2015), cognitive (Stevenson et al., 2018), and physiological (Gaekwad et al., 2022; Yao et al., 2021) benefits. Some of the pioneering work in this field starts with research with surgery patients, where being able to view greenery from a hospital window results in faster recuperation than looking at a brick wall (Ulrich, 1984). From an aesthetic standpoint, it is well established that people prefer looking at images of nature compared to other types of stimuli (Kaplan et al., 1972; Ulrich, 1983). Views of nature in the workplace can reduce feelings of stress (Lottrup et al., 2013) and improve employee health and cognitive ability (Gritzka et al., 2020; Kaplan, 1993). Laboratory and field studies measuring physiological arousal in myriad environments via skin conductance, heart rate, and salivary cortisol show that exposure to nature can reduce levels of stress (Gaekwad et al., 2022; Valtchanov et al., 2010).

In day-to-day lives, most people live in cities and may not experience the level of nature exposure that would be optimal for them. Living in cities is associated with worse mental health outcomes (Peen et al., 2010; Ventriglio et al., 2020). The divergence between built environments and people's innate preferences may help explain impacts on health (de Vries et al., 2003; Gullone, 2000). To alleviate this, there has been a major push in recent years to include more natural features in urban environments (Andreucci et al., 2021; Beatley & Newman, 2013).

1.1 Attention Restoration Theory (ART)

One major proposed benefit of exposure to nature is improvements in attention. In environmental psychology, attention restoration theory (Kaplan & Kaplan, 1989; Kaplan, 1995, 2001) is one of two major theories explaining the positive impact of viewing nature – the other being stress restoration theory (Ulrich, 1984). An important concept in ART is ‘directed attention’: a mechanism for maintaining focus and avoiding distractions, requiring cognitive effort and highly affected by fatigue. Directed attention allows someone to pay attention to a certain stimulus for a long period of time. An example given by Kaplan (1995) is intense work on a project. In the modern day, a person would have to avoid the distraction of checking social media or a loud Zoom meeting from someone nearby, while maintaining concentration on their task. Under ART, directed attention is the resource that allows people to accomplish this. The effects of fatigue on directed attention are substantial. Kaplan argues that ‘any prolonged mental effort leads to directed attention fatigue’. He claims that evolution would not have selected for the ability to continuously attend to one stimulus for a prolonged period of time. Evolution would prefer vigilance – the ability to scan the environments for threats or opportunities – not hyperfocus on one specific area. Tunnel vision of this kind would be a vulnerability that threats could exploit. This explains why humans have definite capacity limits for directed attention. Directed attention is not only depleted by the tasks that people undertake but also affected by the environments where people reside. In modern environments, many distractions in the physical environment must be ignored to carry out the tasks people genuinely find important or interesting. For example, to succeed in a job interview in a major city, you must first arrive at the interview location. This might involve travelling through many crowded and congested streets, ignoring the sounds of vehicles moving, people talking, alarms and horns blaring as you try to remember your pitch for the interviewer. You then must enter the building itself and find your way to the right room, while trying not to be too distracted by all the goings-on in a busy office. The need to ignore these distractions involves using directed attention, which becomes fatigued even before the interview begins. Kaplan (1995) argues that when directed attention is impaired, people become more easily distractable, struggle to inhibit impulses, perform worse at planning, and experience more irritability.

The other major component of ART is the concept of ‘fascination’, which is broken down into a ‘hard’ and a ‘soft’ version. Kaplan (1995) describes fascination as a form of attention that does not require effort, it is ‘involuntary’. The difference between hard and soft fascination is the degree they demand attention and allow for mental reflection. Hard fascination involves highly attention-demanding stimuli, while soft fascination is less intense and allows for other thoughts and mental reflection. An example of hard fascination is watching a car race with many competitors– a very noisy environment demanding that attention is paid to following the cars. Soft fascination would include a peaceful nature walk – an activity in a location with eye-catching natural features but not overly demanding to process. Soft fascination allows space to think about things other than the stimulus immediately present. Both hard and soft fascination involuntarily grab attention. By contrast, directed attention requires effort and is often under voluntary control. ART proposes that directed attention recovers much more effectively during activities involving soft fascination compared to hard fascination. Soft fascination is superior at what ART describes as ‘being away’ – the ability to escape demands on directed attention. Meta-analyses of published studies find that natural stimuli are more effective than urban stimuli at restoring attention after it has been depleted (Ohly et al., 2016; Stevenson et al., 2018), though effects may be larger for real environments compared to virtual ones.

An important, highly cited work investigating the cognitive impact of nature exposure was conducted by Berman and colleagues (Berman et al., 2008). In the first experiment of this paper, participants completed the Positive and Negative Affect Schedule (PANAS), a backwards digit-span task, and then a directed-forgetting task lasting 35 minutes, fatiguing participants. Participants then went for a 50- to 55-minute walk in a nearby arboretum or the city’s downtown, equal in length, followed by another backwards digit-span task and the PANAS. Berman et al. found a significant improvement in digit-span performance after the nature walk, but not when walking through downtown. In the second experiment, participants viewed pictures for 10 minutes instead of physically going on walks and also completed the Attention Network Test (ANT), a task involving reacting to an arrow presented at the centre of the screen and indicating its direction (Fan et al., 2002). After viewing natural images, there was an improvement in performance on the digit-span task, and on incongruent trials for the ANT. There was no significant improvement after viewing urban images. It is quite surprising that 10 minutes of viewing images would be able to improve attention in a similar way as physically going to a natural environment. If this body of work holds true, that simply viewing images of nature is enough to improve depleted attention, nature could very readily be prescribed to alleviate some of the fatigue that people experience every day.

1.2 Stress Recovery Theory (SRT)

The other major theory explaining the beneficial impact of natural environments is Stress Recovery Theory (SRT) (Ulrich, 1983; Ulrich et al., 1991). One of its major starting points is the position that affective responses precede other cognitive processes (Zajonc, 1980). When experiencing nature, the following steps are proposed to occur. First, the observer has an initial affective state which directs attention and influences what subsequently is perceived. A natural scene is perceived and reaches consciousness, with the immediate reaction being an affective one. These affective responses include changes in arousal. This reaction motivates behaviour, including approach-avoidance decisions. Afterwards, there are cognitive appraisals of the scene, which can be accompanied by memories and other learned associations.

SRT is described as a ‘psycho-evolutionary’ account, with preference being one of a range of affective responses to natural environments. The evolutionary component of this theory includes the idea that the initial affective responses to natural stimuli have been adapted over the millennia of evolution, quickly motivating approach-avoidance decisions. The example Ulrich (1983) gives is viewing a venomous snake – humans rapidly engage in avoidance behaviour without requiring much cognitive activity. However, this response is associated with significant costs: negative emotions, and a reduction in energy from heightened arousal. Once the threat passes, restoration becomes the adaptive need. Natural environments that are high in qualities important for well-being (i.e. an area with water) allow for restoration to occur. Energy must be recovered so that future energy-intense behaviours (i.e. gathering food or water) can be undertaken. The now-adaptive state would involve a reduction in arousal and reduced fear and other negative emotions. In unthreatening natural environments, restoration should occur quickly. Ulrich argues that this ability to be restored by unthreatening natural environments was evolutionarily favourable for human beings, allowing restoration of depleted energy reserves and a return to more neutral emotional states, improving physical and psychological well-being. Thus, SRT argues that the reason why nature is preferable to people than urban environments is because people have evolved in natural environments and are adapted to using pleasant, natural sights as a tool to reduce stress, and feel more positive emotions.

1.3 Perceptual fluency

One major difference between natural and urban environments is their level of processing fluency, which is the ease of processing a given stimulus (Joye & van den Berg, 2011). Gist recognition of natural scenes is faster for natural scenes than urban scenes (Greene & Oliva, 2009; Rousselet et al., 2005). At a glance, people can accurately recognize natural elements extremely quickly. The structural information of a scene provides information allowing the observer to determine whether it can be traversed, or if there are places to seek refuge from threats (Kaplan, 1992). A place's affordances can be gleaned from its spatial layout (Oliva & Torralba, 2001), which influence possible actions in an environment while making survival decisions (i.e. running away from a threat into a cave, entering a forest to climb a tree). These approach-avoidance decisions need to be made rapidly. The Perceptual Fluency Account (PFA) proposed by Joye and van den Berg (2011) argues that differences in restoration between natural and urban environments can be explained by differences in perceptual fluency. Since natural environments have higher processing fluency than urban environments, they require less cognitive resources to process, which is proposed to explain why nature is more effective at restoring depleted attention. It is argued that perceptual fluency is itself responsible for aesthetic pleasure, that the more fluently an object can be processed, the greater the level of aesthetic pleasure (Reber et al., 2004). Recent work has drawn doubt on this relationship, finding that for aesthetic processing of photography, processing fluency is negatively related to interest (Vissers & Wagemans, 2023). In this study, the relationship between pleasure and fluency depended on the condition – high-fluency photographs were preferred when participants were asked to immediately rate them, while low-fluency photographs were preferred when participants were asked to generate a title and then provide an aesthetic rating.

1.4 Nature and visual exploration

The primary focus of my dissertation is the relationship between ART and visual processing of natural and urban environments. Several studies have found differences in visual exploration when people view images of natural or urban environments (Batool et al., 2022; Berto et al., 2008; Franek et al., 2018; Valtchanov & Ellard, 2015). The first work on this was done by Berto and colleagues (Berto et al., 2008), who measured the mean fixation count and saccade count, along with the total distance of visual exploration while people were viewing different photographs on a computer. Pictures in this study consisted of low fascination and high fascination colour images. The aim in this study was to test whether attention restoration theory could predict changes in eye movement patterns. Stimuli were rated on the Perceived

Restorativeness Scale (Hartig et al., 1997), which measured how psychologically restorative they are. Components of the PRS measured being away, fascination, coherence, and compatibility. Using this approach, Berto et al. created a set of greyscale stimuli varying in perceived restorativeness, to compare how attention restoration potential would affect eye movement behaviour. High fascination scenes consisted of natural environments such as lakes and rivers, while low fascination scenes consisted of built environments such as industrial areas and housing. Results from this study indicated that there were significantly more fixations on low fascination than high fascination images, while there was no difference in the number of saccades. The mean eye movement distance traversed was significantly higher for low fascination than high fascination images. Based on this data, Berto and colleagues argue that there are different types of attentional patterns engaged for fascinating compared to non-fascinating scenes. They propose that there were fewer fixations on natural scenes because there were fewer distractions present. They argue that the fact there are fewer fixations on natural scenes suggests that people were not compelled to examine natural features in a detailed way and could easily continue viewing the rest of the scene. In their theory, Berto and colleagues suggest that natural scenes are more restorative because the inhibitory system is not engaged during viewing. Since nature in ART involves soft fascination, it does not require attentional effort to disengage from natural objects unlike built environments. Thus, Berto and colleagues draw a direct connection from visual exploration to affective processing of natural and urban scenes.

The next major study investigating visual exploration of natural and urban scenes was carried out by Valtchanov & Ellard (2015). In this study, participants were presented with greyscale natural and urban images using a head-mounted display, while also varying spatial frequency information. They found that there were more fixations on urban scenes than natural scenes, consistent with Berto et al. (2008). However, the eye travel distance measure did not show any difference between natural and urban scenes, and they argue that it may not be a reliable measure. Interestingly, Valtchanov & Ellard found that mean fixation durations were longer for natural scenes compared to urban scenes. Thus, while people make more fixations overall on urban scenes, each fixation lasts a shorter period of time compared to a natural scene. Based on this data, the authors agreed with Berto et al. that visual attention varies between viewing nature and urban environments. Valtchanov & Ellard also found that blink rates significantly varied by scene content, with nature scenes involving a lower blink rate than urban scenes. This study interprets blink rates as a measure of cognitive load, arguing that viewing natural scenes should induce a more relaxed state, improving attention. It follows previous studies showing higher blink rates in tasks involving higher cognitive load: talking to another participant vs. reading quietly (Bentivoglio et al., 1997); increasing the number of digits present for a digit-sorting task (Siegle et al., 2008); vocalizing mental arithmetic instead of performing it silently (Schuri & von Cramon, 1981).

Work by Franek and colleagues (Franek et al., 2018) used eye-tracking to measure responses to natural and urban environments using colour images, while also including urban stimuli that varied in attractiveness. This contrasts with previous studies, which compared relatively unattractive urban environments with attractive natural environments (Berto et al., 2008; Valtchanov & Ellard, 2015). This study was influenced by work on the restorative potential of built environments, which shows that myriad urban places such as museums (Kaplan et al., 1993; Packer & Bond, 2010), modern urban developments (Karmanov & Hamel, 2008), and historic architecture (Hidalgo et al., 2006) can improve mood and reduce stress. Stimuli in this study consisted of buildings in contemporary Western cities, historic architecture, and natural scenes, with pilot testing indicating that perceived restorativeness was higher for historic architecture than modern buildings. There were significantly more fixations, longer fixation durations, and greater eye travel distance in both the modern urban and old city images compared to the nature scenes, but they did not vary from each other. Perceived restorativeness was positively correlated with mean fixation durations and negatively correlated with the mean fixation count. Eye travel distance was only significantly correlated with one of the perceived restorativeness factors, a negative correlation with coherence. While historic architecture was subjectively considered to be more restorative than modern city buildings, there were no significant differences between the two categories in the eye movement data reported.

Two studies compared eye movement data while viewing either urban scenes (Batool et al., 2021) or natural scenes (Batool et al., 2022) with subjective ratings of preference. Using a pile sorting task, participants identified their three most preferred and three least preferred scenes. Eye movements for the three most and three least preferred scenes across all participants were compared. When rating urban scenes, the fixation count and saccade count were higher for most preferred compared to least preferred views, while fixation durations and saccade amplitudes did not vary significantly. Exploratory gaze behaviour was associated with greater preference for urban scenes. When rating natural scenes, there were no significant differences between most preferred and least preferred scenes on the fixation count, saccade count, or fixation durations. However, when comparing preferences made within participants, there were significant differences. Participants' gaze for their three most preferred natural scenes involved a higher fixation count and saccade count compared to their least preferred scenes, with no effect on fixation duration.

One recent between-subjects study investigated differences in eye movements when viewing either urban environments or green infrastructure such as parks, green roofs, and greenways (Fu & Xue, 2023). They measured nature-relatedness (Nisbet et al., 2009) as an individual difference variable, a scale evaluating participants' connection to nature. They also included a backwards digit span task as a measure to test attention. They found an improvement in performance on the digit span task for participants viewing green infrastructure compared to urban environments. Participants viewing green infrastructure made fewer fixations, fewer saccades, longer average fixations, and longer total saccade amplitudes compared to participants viewing urban settings.

1.5 The control of eye movements

There are two major explanations for how the visual system decides how long fixations should be: direct control, and indirect control theories (Henderson & Pierce, 2008; Rayner et al., 1998). Direct control explanations indicate that real-time information from the current area being fixated is used to make decisions about when to complete a fixation and begin a saccade towards the next object. Indirect control argues that fixation durations are influenced by the global task, with different tasks involving different eye movement parameters. An internal process is proposed to keep fixations and new saccades occurring at a consistent pace.

Studies proposing a link between ART and eye movements invoke direct control theories. Under this theory, fixations on natural scenes are longer because natural scenes are more fascinating. The greater interest in natural scene content prolongs those fixations. Urban scenes have more fixations and more saccades because the urban scenes have more competing distractors that demand attention. Each individual fixation does not last as long, because other scene regions contain important information that must be fixated. These generally use free-viewing protocols (Batool et al., 2022; Berto et al., 2008; Franek et al., 2018; Valtchanov & Ellard, 2015). In some of these studies, instructions explicitly inform participants not to memorize information. “You should look freely at the photographs, don’t try to memorize any detail because this is not a memory task and no task related to the photograph contents will occur at the end of the eye movements recording” (Berto et al., 2008) or “View an image with composure. Do not try to remember its content or its details” (Franek et al., 2018).

Visual exploration is influenced by the type of task being carried out. Broadly, when participants freely look at scenes without having to search for an object, they make longer fixations. One study investigated the effect of task on fixation durations and saccade amplitudes during the first 6 seconds of viewing, contrasting search, memory, pleasantness (rating after scene), and a free-viewing task (Mills et al., 2011). There were longer fixation durations for free-viewing and memory tasks compared to search and pleasantness conditions. There were also larger saccades in the free-viewing condition than the other conditions. In another study, a preference judgment condition was compared with search and memorization conditions (Nuthmann, 2017). The preference judgment task involved similar fixation durations to the memory task, and both were longer than the search task. In real-world settings, free-viewing is most similar to what people experience when walking down a street or exploring nature. We might engage in visual search when trying to find a building or a street, but most of the time, we walk from one place to another without a constant search process. Consistent with the literature, my work also uses a free-viewing method.

There is much work to be done to understand why natural scenes are explored differently than urban scenes. Is nature broadly preferred and processed differently than all types of urban environments, or does architectural style have an impact? How does scene complexity influence visual exploration? And how strongly are differences in explorations – fixations and saccades – related to affective impressions? I address these gaps in the literature through my experiments in this dissertation.

1.6 Overview of current studies

The aims of the experiments in my dissertation were to test how people visually explored natural and urban scenes, and whether visual exploration as measured through eye-tracking related to cognitive and affective experience. Could I use fixations and saccades as a proxy for fatigue or attention restoration? Were there other eye-tracking measures that were a better indicator for changes in fatigue or arousal? Moreover, was exposure to natural images or videos sufficient to create a noticeable improvement in attention?

In Study 1, I aimed to replicate previous findings about the differences between natural and urban stimuli in visual exploration using eye-tracking with images presented on a computer. Consistent with previous research, I found that eye movement measures of visual exploration such as fixation duration and saccade amplitude varied between natural and urban stimuli, such that natural scenes had larger fixations and saccades (Srikantharajah & Ellard, 2022). I contrasted blink rates between natural and urban scenes to measure changes in arousal and fatigue.

In Study 2, I expanded the scope of the work using a different set of images to include microsaccadic measures, which have been shown in the literature to have properties directly relevant to measures of interest such as cognitive load and fatigue. Study 2 compared high complexity and low complexity natural and urban scenes, measuring changes in visual exploration, affective and cognitive processing.

In Study 3, I replicated Study 2 using colour stimuli, to attempt to account for the effects of colour on visual exploration when comparing nature with urban environments. Study 3 contrasted different scene content. I compared water and greenery scenes, along with historic architecture and modern architecture.

And finally, in Study 4, I used a modified version of Berto's (2005) paradigm directly depleting participants' attentional capacity using the SART to measure changes in fatigue after viewing natural or urban video stimuli. I measured changes in fatigue during the SART using eye movement measures, identifying if there was a similar time-on-task effect for the SART as that found in experiments 1-3 for scene viewing.

Using eye-tracking, this dissertation explored a wide range of questions facing environmental psychology. Why do we prefer nature to urban places? How do we explore different types of places? How does architectural style and complexity influence how we feel? Across four studies, I replicate differences in visual exploration – fixations and saccades – when viewing natural scenes compared to urban scenes. A major novel finding was that blink rates were higher when viewing natural scenes, indicating a reduction in arousal. Measuring microsaccadic patterns for the first time in the context of viewing the built environment, I found converging evidence for a reduction in arousal when viewing nature compared to urban stimuli. Finally, my studies demonstrated preferences for higher complexity and historic architecture vs. lower complexity and modern architecture, along with differences in visual exploration.

Chapter 2: Experiment 1 – Fixations, saccades and blinks during scene processing

2.1 Introduction

Experiment 1 aimed to replicate previous findings about eye movements when viewing natural and urban scenes (Berto et al., 2008; Franek et al., 2018; Valtchanov & Ellard, 2015) to confirm their reliability. This experiment was previously published in the Journal of Vision

(Srikantharajah & Ellard, 2022). In this experiment, I asked: do natural scenes vary from urban scenes in how people explore them? In experiment 1, I presented participants with images of natural and urban scenes on a computer screen for 20 seconds each, while asking participants to freely view each scene. I tested whether ratings of pleasantness were correlated with eye movement metrics such as fixation count, fixation duration, saccade count, and saccade amplitude.

2.2 Hypotheses

I predicted that people would make more fixations and have longer fixations on natural scenes than urban scenes, consistent with previous studies (Berto et al., 2008; Franek et al., 2018; Valtchanov & Ellard, 2015). Past studies have shown mixed results for the saccade count, with one study finding no differences between natural and urban scenes (Berto et al., 2008) and another study claiming that natural scenes involve a reduced saccade count (Batool et al., 2022). I tried to resolve this question in this study. While several previous studies have measured total eye travel distance to mixed effect (Berto et al., 2008; Valtchanov & Ellard, 2015), experiment 1 measured mean saccade amplitudes. I hypothesized that natural scenes would involve larger saccades on average than urban scenes. Urban scenes are often more cluttered than natural scenes, with many fixations in neighbouring areas required to effectively parse information. With less clutter in natural scenes, the average saccade would be larger, since information is not as closely clustered together.

2.3 Methods

2.3.1 Participants

50 undergraduates with normal or corrected-to-normal vision from the University of Waterloo participated in this study in exchange for course credit. The study was approved by a university ethics committee and all participants provided informed consent before participating. Due to technical issues, 8 participants were missing eye-tracking data for some trials and were excluded. The final sample consisted of 42 participants (88% female). A post-hoc power analysis was conducted using the pwr package in R (Champely et al., 2020). The sample of 42 provided 81.6% power to identify a moderate effect size of $d = 0.5$ at a significance level of .025. .025 was chosen as the significance level for this power analysis to reflect follow-up t-tests following a main ANOVA.

2.3.2 Design

This study employed a within-subjects design in which scene type (Natural, Urban) and visual field (Control, Central, Peripheral) were manipulated. I only report results from the control condition, where scenes were presented to the entire visual field. The central and peripheral conditions were for questions about the impact of the visual field on visual exploration. Those questions about the visual field are out of the scope of my dissertation, which focuses purely on visual processing under normal visual conditions. For comparisons between early trials (the first sixth of the experiment) with late trials (the last sixth of the experiment), comparisons include data across visual conditions, rather than being exclusive to the control condition. This is because limiting the analyses to only full vision would adversely affect the number of trials available for comparison in the early and late blocks. All other comparisons include data only from the control condition.

2.3.3 Stimuli

The stimuli for this study consisted of 90 natural and urban scenes (see Figure 1). Images were from the SUN database (Xiao et al., 2014) and Flickr. Natural scenes included bodies of water, mountains, forests, and deserts. Urban scenes included streets, buildings, skylines of cities, and railways. All scenes were converted to grayscale in MATLAB. Spatial frequency and luminance were controlled for using the SHINE toolbox (Willenbockel et al., 2010). Average pixel intensity and RMS contrast were then calculated. Average pixel intensity was identical across all images at 105.2. Similarly, RMS contrast was identical across all images at 16.8.

Scenes were presented on a CRT monitor with a refresh rate of 100 Hz, with a horizontal radius of 14.8° and vertical radius of 11.1°. All images were 1024 x 768 pixels. Participants viewed each scene while resting their head on a chinrest, with a distance of 71.5 cm from the screen. Out of the 90 scenes presented, thirty belonged to the control condition, in which visual field was not manipulated. There were 15 natural scenes and 15 urban scenes in this condition. The results discussed are from this subset. Data from the central and peripheral visual conditions are reported in Appendix A. Stimuli for all studies are available on an OSF repository (https://osf.io/6mw7y/?view_only=344d083702b24b43a25f57277e921a33).

Figure 1. Sample images from the Experiment 1 dataset. Left is an urban scene, right is a natural scene.

2.3.4 Procedure

An SR Eyelink 1000 eye-tracker recorded gaze binocularly at 1000 Hz. Participants completed a 9-point calibration at the start of the experiment. At the start of each trial, participants were required to fixate a fixation cross located at the centre of the screen. When gaze was identified on the fixation cross, the scene was presented. If gaze could not be identified at the centre of the screen, another calibration was carried out. Each scene was presented for a total of 20 seconds. Scene order was randomized. Participants free-viewed scenes, with their instructions being to simply explore the scene as they like, while keeping their eyes on the screen. If participants were looking away from the screen, the scene would disappear until their gaze returned to the monitor. After each scene, participants answered a 7-point Likert item measuring pleasantness, using the word pair unpleasant-pleasant. Participants would press the space bar when ready to continue to the next scene. Two self-paced breaks were scheduled for participants after the thirtieth and sixtieth trials to alleviate fatigue. Participants would press the space bar when ready to continue the study.

2.3.5 Data analysis

Data analysis was conducted using R. Fixations and saccades were detected using the Eyelink's online parser. This parser identifies saccades with deflections in eye position larger than 0.1° using a minimum velocity threshold of 30°/s and an acceleration threshold of $8000°/s^2$, maintained for at least 4 ms. Blinks consisted of periods where there was no pupil information. Fixations or saccades were discarded if they occurred within a 100 ms interval of a blink. Fixations were removed if they were either shorter than 80 ms or longer than 1000 ms. Fixations or saccades that only occurred in one eye were removed. Trials with a total blink time greater than 20% of trial length were excluded. On average, 6.3 trials were removed per participant, comprising 7% of the total dataset.

2.4 Results

Tables 1 and 2 summarize results contrasting natural vs. urban scenes (Table 1) and early vs. late trials (Table 2).

Measure	***M* (Natural)**	***M* (Urban)**	***p***	***d***
Fixation count	38.6 (1.6)	42.6 (1.7)	< .001	.89
Saccade count	45.7 (1.5)	49.5 (1.5)	< .001	.96
Fixation duration	299.5 ms (7.3)	284.5 ms (5.5)	< .001	.74
Saccade amplitude	6.1° (0.2)	5.5° (0.2)	< .001	.86
Pleasantness	5.1 (0.1)	4.6 (0.1)	< .001	.80

Blinks	6.7 (0.5)	6.3 (0.5)	.012	.41

Table 1. Means, *p*-values, and effect size for natural and urban scenes in Experiment 1. Standard error in brackets.

Measure	***M* (Early)**	***M* (Late)**	***p***	***D***
Blinks	4.1 (0.4)	5.3 (0.5)	.003	.49

Table 2. Means, *p*-values, and effect size for early (first sixth of the experiment) and late trials (last sixth) in Experiment 1. Standard error in brackets.

2.4.1 Fixation count and saccade count

Scene type had a significant impact on the fixation count ($t(41) = 5.75$, $p < .001$, $d = .89$) on each scene. As predicted, people made significantly fewer fixations ($M = 38.6$) on natural scenes than urban scenes ($M = 42.6$). The saccade count was significantly affected by scene content ($t(41) = 6.25$, $p < .001$, $d = .96$). People made fewer saccades on natural scenes ($M = 45.7$) than urban scenes (49.5).

2.4.2 Fixation duration

Scene type had a significant effect on fixation duration, $t(41) = 21.40$, $p < .001$, $d = .74$. Consistent with the literature, people made longer fixations on natural scenes ($M = 299.5$ ms) compared to urban scenes ($M = 284.5$ ms).

2.4.3 Saccade amplitude

Scene type significantly impacted saccade amplitudes, $t(41) = 5.56$, $p < .001$, $d = .86$. Consistent with the hypothesis, natural scenes ($M = 6.1°$) involved larger saccades than urban scenes ($M = 5.5°$).

2.4.4 Pleasantness

As expected, natural scenes ($M = 5.1$) were rated higher than urban scenes ($M = 4.6$) on pleasantness, $t(41) = 5.21$, $p < .001$, $d = .80$. Pearson correlational analyses tested the claim that eye movement metrics capture changes in liking for a stimulus (Figures 2 and 3). Across all valid trials, pleasantness was positively correlated with fixation count ($r = .09$, $p = .003$) and saccade count ($r = .09$, $p = .003$). There was no relationship between pleasantness and fixation durations ($r = -.04$, $p = .19$), saccade amplitudes ($r = .06$, $p = .055$), or blink rate ($r = -.03$, $p = .26$). Exploratory analyses ($\alpha = .025$) tested whether correlations between eye movement metrics and pleasantness varied between natural and urban scenes. Fisher's Z-transformation tests found no significant differences between natural and urban scenes for the correlations between pleasantness and any eye movement metrics, all *p*s > .18.

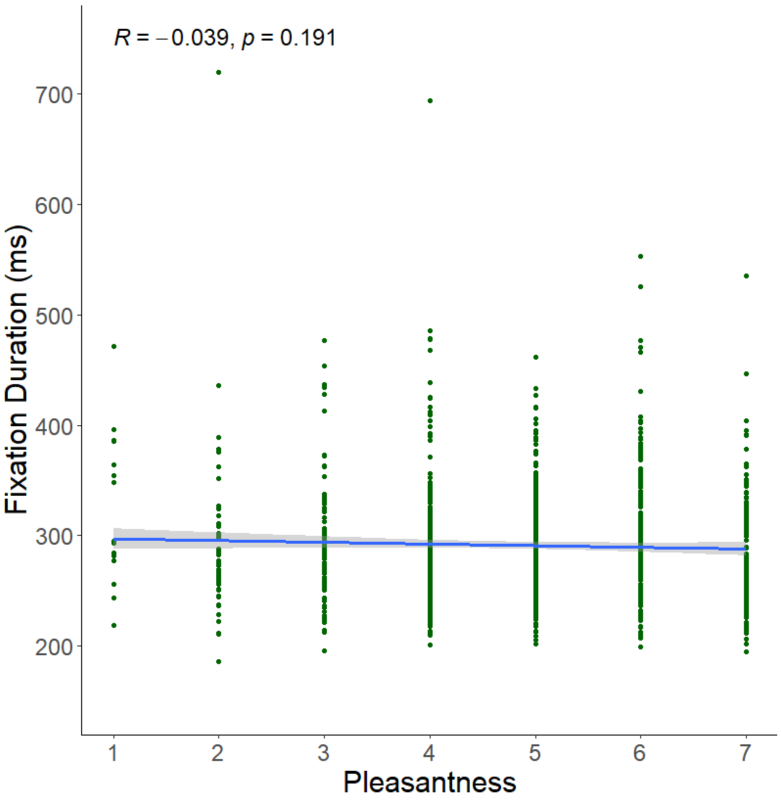

Figure 2. Fixation duration by pleasantness. Green dots represent ratings of pleasantness and their associated fixation duration for each scene. Regression line in blue, with standard error in grey.

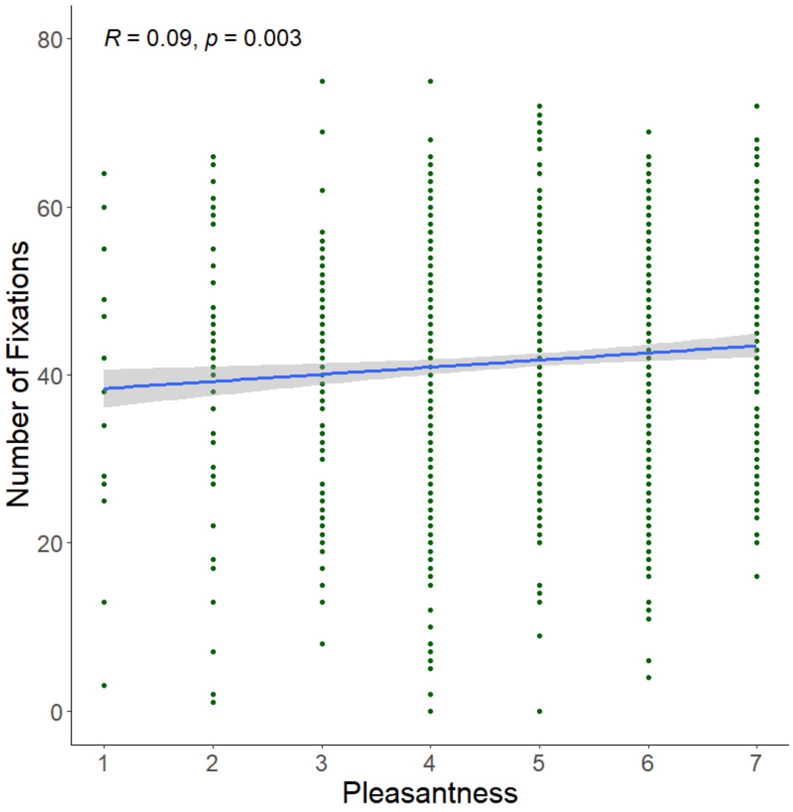

Figure 3. Fixation count by pleasantness. Green dots represent ratings of pleasantness and the fixation count for each scene. Regression line in blue, with standard error in grey.

2.4.5 Blink rate

Surprisingly, natural scenes (*M* = 6.7) involved a larger blink rate than urban scenes (*M* = 6.3), *t*(41) = 2.63, *p* = .012, *d* = .41. There was a time-on-task effect, with blink rates significantly increasing from early (first sixth of the experiment) trials (*M* = 4.1) to late (last sixth of the experiment) trials (*M* = 5.3), *t*(41) = 3.20, *p* = .003, *d* = .49.

2.5 Discussion

This study demonstrated that visual exploration of natural scenes involves fewer fixations and saccades than urban scenes. It also demonstrated that natural scenes involve longer average fixations, consistent with previous research (Berto et al., 2008; Franek et al., 2018; Valtchanov & Ellard, 2015). This work expanded on the literature by showing that saccade amplitudes are larger for natural scenes than urban scenes. According to attention restoration theory, natural environments are considered inherently fascinating and draw involuntary attention, allowing directed attention resources to replenish while involuntary attention wanders. Natural scenes do not involve effort or directed focus to view, unlike urban scenes which contain more distractions. The challenge for ART is validating the relationship between these eye-tracking visual exploration measures and changes in attention or affective processing.

2.5.1 Eye-tracking, attention, and preference

The differences in fixation and saccade patterns between urban and natural scenes are theorized to reflect attentional demands (Berto et al., 2008). Berto interprets a lower number of fixations on natural scenes as indicating that people "people do not pause long to study these attractive features but continue viewing other aspects of the scene". A second explanation given in the same paper is the interpretation of higher fixation count on urban scenes as indicating a more effortful attentional process. In this theory, urban scenes are more complex and perceptually challenging, thus engaging attention through demanding many fixations without allowing attentional resources to be restored. The fact that I found, consistent with the literature, that natural scenes involve longer fixations than urban scenes would seem to disprove the account that people are not pausing long on attractive features. In fact, other researchers interpret this finding for mean fixation durations (i.e. Franek et al., 2018) as reflecting greater interest in a stimulus. This interpretation draws on studies from face perception which find that the total fixation duration (Leder et al., 2016; Maner et al., 2003; Mitrovic et al., 2018) and mean fixation duration (Kerzel et al., 2024; Leder et al., 2010; Silva et al., 2016) is longer for more attractive faces. One challenge is that total fixation duration on attractive faces is influenced by the total number of fixations being made.

One of the main questions in this study was whether eye movement differences index changes in soft fascination. To resolve this question, the current experiment directly tested whether preference for an image was associated with fixation count, saccade count, fixation durations, and saccade amplitudes. I found that pleasantness of an image was not significantly correlated with fixation duration or saccade amplitudes. I also found that pleasantness was positively correlated with fixation count and saccade count, an effect in the opposite direction as what Berto et al. (2008) proposed. This presents a major challenge for the ART account of eye movements during natural and urban scene viewing. As Joye et al. (2013) point out, the commonly used measure for fascination includes the item ‘my attention is drawn to many interesting things’. A place with many interesting things to view could easily involve shorter fixations on more things compared to a place that is less fascinating. My data are consistent with studies of face processing, which find a higher fixation count on attractive faces (Leder et al., 2016; Silva et al., 2016). Goller et al. (2019) presented participants with faces or paintings and found that total fixation duration and fixation count were higher for stimuli higher in aesthetic preference, while results for mean fixation duration were mixed. Using landscapes, Scott et al. (2020) find that people make longer fixations on images of the Great Barrier Reef rated high on perceived beauty compared' to low-rated images. In another study involving landscapes, Huang & Lin (2020) find that landscape preference was associated with larger total fixation count but had no relationship with fixation duration. Nature clearly draws attention.

2.5.2 Interpreting blink rates

Contradicting previous research (Valtchanov & Ellard, 2015), this experiment found a higher blink rate for natural compared to urban scenes. Valtchanov & Ellard (2015) found higher blink rates for urban scenes, which was proposed to reflect higher cognitive load present when viewing urban scenes. A key factor in interpreting these varied results is that increases in blink rates are associated with a variety of cognitive factors (Cruz et al., 2011). For example, visual fatigue is associated with increased blink rate when performing long tasks on a visual display terminal compared to using paper (Kaneko & Sakamoto, 2001; Mourant et al., 1981). Task difficulty when operating aircraft in the military inversely correlated with blink rate (Stern & Skelly, 1984). Fatigue related to time-on-task is associated with increased blink rates (Luckiesh & Moss, 1937; Stern, 1994). This time-on-task effect is consistent with findings from experiment 1, where blink rates increased from early to late trials. The higher blink rates during trials in the last sixth of the experiment reflect increased fatigue. Importantly, drowsiness is commonly associated with increased blink rate (Abe et al., 2011; Barbato et al., 2000; Barbato et al., 2007;

Crevits et al., 2003; Shiferaw et al., 2018; Slama et al., 2018). Blink rates are higher during the evening than during the day (Barbato et al., 2000). During sleep deprivation studies, blink rates increase as people reach the time where they normally go to sleep (Barbato et al., 2007; Cajochen et al., 1999). People who are sleep-deprived have higher blink rates the day after compared to people who are well-rested when performing a variety of activities, ranging from a prosaccade task (Crevits et al., 2003), a matching task (Slarna et al., 2018), or driving a vehicle (Shiferaw et al., 2018). One possibility is that the relaxing quality of viewing nature is causing people to feel a lower state of arousal during this experiment, resulting in an increased blink rate while viewing nature. Studies show that viewing nature can reduce levels of arousal, measured by changes in biomarkers including heart rate (Benz et al., 2022; Lanki et al., 2017; Laumann et al., 2003), and skin conductance (Korpilo et al., 2024; Ulrich et al., 1991; Valtchanov et al., 2010). A relaxation effect of nature can be found for audio stimuli, with some studies showing that listening to nature sounds is associated with improved sleep quality (Nasari, 2018; Williamson, 1992). Several studies show that nature exposure reduces levels of salivary cortisol (Antonelli et al., 2019; Hunter et al., 2019; Kobayashi et al., 2019), a hormone used as a stress indicator. Cortisol plays an important role in regulating sleep, with cortisol levels declining throughout the day. That stated, my finding that viewing nature involves a higher blink rate requires more clarification, and the following experiments in my dissertation will help to resolve that relationship.

2.5.3 Validating the relationship between ART and eye movements

Understanding the relationship between ART and eye-tracking data requires further evidence. That there exist reliable differences (fixation count, fixation duration) in how people explore natural and urban scenes is replicable, as experiment 1 shows. Yet the interpretation of these eye-tracking findings, that fixation or saccade patterns necessarily reflect attentional changes requires further evidence. In Experiment 1 I did not find a significant correlation between pleasantness of an image and fixation duration or saccade amplitudes. There are many alternative possibilities. Differences between natural and urban settings in human perception take many forms. Perhaps these eye movement differences are primarily the result of changes in affective processing. Or perhaps these differences are simply a record of visual exploration patterns, indicating nothing more than how people gather information. Previous studies using natural and urban stimuli to validate the relationship between eye-tracking data and affective processing have found mixed results. While one study found a significant positive correlation between perceived restorativeness of stimuli and average fixation duration (Franek et al., 2018), that same study did not find any eye movement differences between restorative old city buildings compared to less restorative modern buildings. Neither preferred urban or natural stimuli show significantly longer average fixation durations compared to less preferred urban or natural stimuli (Batool et al., 2021; 2022). There is more work to be done to test whether longer fixations on natural stimuli compared to urban stimuli reflect affective preference, rather than being caused by some other factor.

Another question I must ask is about the impact of viewing nature on people. The claim in ART is that viewing nature restores people's attentional states. Does the data gathered from eye-tracking, changes in the number of fixations and saccades, or the length and amplitude of the same, really reflect a decline or improvement in attentional capacity? The data from blink rates suggest that arousal is lower when viewing nature. The purpose of the following experiments is to validate the assumptions made in interpreting eye movement patterns when viewing natural and urban scenes, testing them against possible alternatives.

Chapter 3: Experiment 2 - Visual complexity and visual processing

3.1 Introduction

Patterns in fixation duration and saccade amplitudes may be a result of the type of information in an image. We explore scenes differently based on what they contain. Prior work shows that scenes with more objects elicit shorter fixations with reduced saccade amplitudes than scenes with fewer objects (Unema et al., 2005). The authors argue that with more objects in the scene, the average distance between objects decreases, and competition between objects for attention increases. The proximity effect reduces saccade amplitudes, as a lower distance has to be travelled before viewing the next object of interest. They argue that the decrease in fixation durations can be explained by two factors. The proximity of objects may reduce the time involved before another object generates a fixation, and there may be an overall change in the scanning strategy, de-emphasizing longer fixations. Pannasch et al. (2008) analyzed eye movement data for the first 6 seconds of viewing a scene, replicating the findings for saccade amplitudes, while finding no effects for fixation duration. Another factor influencing fixation duration and fixation count is the level of openness in a scene (Dupont et al., 2014). Landscape scenes rated higher in openness have longer fixations and a lower number of fixations and saccades.

Thus, the differences between natural and urban images with regards to fixations and saccades may be due to natural scenes containing different information than urban scenes. Metrics like fixation durations or fixation counts might not actually be related to the changes in attentional resources that ART proposes. A scene can elicit a higher number of fixations and a reduced average fixation duration without being particularly fatiguing or distracting. People view countless stimuli every day. An urban scene may present a higher visual load than a natural scene because of differences in complexity, openness or the number of objects it contains, but that does not need to cause a reduction in attentional capacity. The human visual system should not be overtaxed by mere scene viewing, especially in experimental set-ups where each scene is only being viewed for less than half a minute. Unless people are overtaxed or stressed beforehand, simply viewing natural or urban environments should not have much of an impact on attentional capacity. From an evolutionary standpoint, it would not be adaptive for the visual system to be drained just by free-viewing a stimulus for twenty seconds. The visual system should adapt to processing the increased information present in urban scenes without being mentally fatigued or experiencing a loss in attentional resources.

3.1.1 Preference and visual exploration

People may engage differently with natural and urban scenes depending on their level of preference for those scenes. Urban scenes that are more interesting might involve more visual load because there are more items to look at, compared to less interesting urban scenes. A highly fascinating urban scene with higher visual load may potentially have a restorative effect. Perhaps visual exploration and fixation and saccade patterns are influenced by both the increase in visual load and the level of fascination. Prior studies (Batool et al., 2021; 2022) did not find any significant effects of preference on fixation durations for natural scenes or for urban scenes.

Urban scenes that were higher in preference involved higher fixation counts than less preferred urban scenes (Batool et al., 2021). For natural scenes, the effect of preference on fixation counts was not significant (Batool et al., 2022). More work is required to determine how preference relates to visual exploration.

3.1.2 Visual complexity

One explanation for why nature is especially fascinating is visual complexity, which has an inverted-U relationship with aesthetic appreciation (Berlyne 1968, 1971). People prefer environments with intermediate levels of visual complexity compared to environments that are either very high or very low in complexity (Berlyne, 1971; Imamoglu, 2000; Spehar et al., 2003). Spehar et al. (2016) found a similar preference for intermediate complexity in a study rating preference for images that were greyscale, black-and-white, or only included edges, while Friedenberg & Liby (2016) showed that this preference applied to texture patterns. This inverted-U relationship between complexity and preference does not only apply to visual stimuli, as it also holds true for music (Chmiel & Schubert, 2017). Natural environments often involve moderate visual complexity (Redies et al., 2012; Tolhurst et al., 1992). Images of buildings or facades are slightly more complex than natural scenes, while urban streets without cars or people are similarly complex as natural scenes (Braun et al., 2013). Moderately complex environments can attract attention without being too visually demanding. Attention restoration theory states that these environments invoke soft fascination, allowing directed attention to wander.

Visual complexity consists of both the number of elements present, and the structure and order of visual information across different magnification levels of the scene. The self-similarity of a visual pattern at different scale levels can be quantified by the fractal dimension (*D*), which represents fractal complexity (Mandelbrot, 1982). The fractal dimension is a widely used measure, with application ranging from quantifying the complexity of molecules (von Korff & Sander, 2019), plants (Corbit & Garbary, 1995), and architecture (Ostwald & Vaughan, 2016). The fractal dimension is highly correlated to other measures of complexity such as RMS contrast and perceived complexity (Kacha et al., 2013; Robles et al., 2021; Robles et al., 2023).

One study (van den Berg et al., 2016) compared viewing time on natural scenes with urban scenes while varying the magnification of those scenes to understand how fractals influenced perception at different scale levels. Participants viewed unmodified natural scenes longer than unmodified urban scenes, but they rated both scene categories similarly in perceived complexity. Buildings with more ornamentation were viewed longer than buildings with less ornamentation. However, with increased magnification, viewing times for urban scenes decreased, while viewing times for natural scenes increased. This is because when magnified, natural scenes would involve higher levels of complexity because of their fractal structure, compared to urban scenes. Another study (Franek et al., 2019) tested how differences between urban scenes and natural scenes are related to fractal complexity by manipulating levels of fractal complexity between stimuli. Natural scenes consisted of two categories of forests – ones with foliage and ones without foliage, operating under the idea that scenes with foliage would have a higher fractal dimension. Tests of fractal dimension for their stimulus set found that natural scenes had a higher fractal dimension than urban scenes, but there was no significant difference between natural scenes with and without foliage. Thus, their manipulation of complexity within the natural scene category was not successful. Eye movement data in this study revealed a higher fixation count on urban scenes compared to all natural scenes, and a higher fixation count on natural scenes without foliage than ones with foliage. There were also longer fixation durations on both types of natural scenes compared to urban scenes.

Dupont et al. (2017) investigated how levels of urbanization in landscapes and complexity influence eye movement behaviour using a free-viewing task. Complexity was measured using spectral entropy, which uses an image's power spectrum to identify the level of order and regularity present (Zaccarelli et al., 2013). A Fourier transformation decomposes images into a spectrum of frequencies. Entropy measures randomness or complexity within this frequency spectrum. Dupont et al. (2017) give the example of an image including only a few colours having lower entropy than an image with many colours present due to the difference in variety within pixels. Using a sorting method, landscapes were classified by participants as 'rural', 'semirural', 'mixed', 'semi-urban', and 'urban'. This sort was validated by calculating the percentage of area in images for each category that was covered by buildings or concrete surfaces. These classifications were correlated to spectral entropy scores, with entropy highly correlated to the percentage of urbanized area present in an image. Rural, semi-rural, and mixed landscapes had a lower number of fixations than semi-urban or urban landscapes. The saccade count was lower for semi-rural and mixed landscapes than urban landscapes but did not vary between rural and urban landscapes. After excluding rural landscapes, the authors found that increased levels of complexity were associated with more fixations and saccades. However, the choice to exclude rural landscapes from this analysis means that a significant amount of information is missing.

Liu et al. (2021) analyzed the relationship between landscape complexity in urban green space, visual preference and eye movements. Complexity was measured subjectively by participants and scenes were categorized into low, medium, and high complexity groups. Complexity was positively correlated with preference for all settings, which included lawns, paths, plazas, and waterscapes. There was no effect of setting type on fixation duration or the fixation count. There were more fixations on high complexity images than low or medium complexity images. Fixation durations on high complexity images were shorter than low complexity images and did not vary from medium complexity images. Moreover, neither fixation count nor fixation duration significantly predicted preference ratings.

Huang & Lin (2020) presented participants with mountain, aquatic, open, and forest landscapes varying in fractal complexity. They found that fractal complexity was associated with increased fixation duration, but only for mountain and forest landscapes. Lower complexity landscapes were preferred to higher complexity landscapes. Landscape preference was associated with larger total fixation count but had no relationship with fixation duration.

3.1.3 Microsaccades

While previous studies testing the differences between natural and urban scenes in eye movement behaviour have largely focused on fixation and saccade data, microsaccadic behaviour may be even more insightful in measuring visual and cognitive load. Microsaccades are small saccades shorter than 1° (Martinez-Conde et al, 2009; Martinez-Conde et al., 2013), sharing a common neural generator to saccades (Otero-Millan et al., 2008). The purpose of microsaccades is to enhance visual perception during fixations. Two important measures are microsaccade rate and the slope of the microsaccade peak velocity-magnitude relationship. The microsaccade rate is the number of microsaccades that occur per second of fixation (Otero-Millan et al., 2008). The slope of the microsaccade peak velocity-magnitude relationship indicates changes in microsaccade peak velocity as a function of its magnitude. This metric is preferred to using either microsaccade peak velocity or magnitude because peak velocity increases as magnitude increases.

3.1.3.1 Microsaccade rate

Microsaccade rate is useful because it varies as a function of visual and cognitive load. While there is some mixed evidence, the general pattern is that microsaccade rate increases under tasks involving higher visual load and decreases during tasks involving higher cognitive load. Prior studies on microsaccade activity show that microsaccade rates (Otero-Millan et al, 2008; McCamy et al., 2014) are higher during free-viewing tasks compared to viewing a blank scene. Microsaccade rates are altered by task difficulty depending on whether it is a visual or cognitive demand. One study found that microsaccade rates decreased with increased task difficulty on a mental arithmetic task (Siegenthaler et al., 2014). In a simulated driving task, a dual-load task involving visual search resulted in a higher microsaccade rate than a low load control task (Benedetto et al., 2011). In another study, mental load and visual load were both manipulated, using an n-back task with either letters or abstract visual figures (Schneider et al., 2019). This study found an increase in microsaccade rate for stimuli with higher visual load (abstract figures), while changes in mental load from varying the n-back level did not affect microsaccade rate. Another study manipulated mental load through mental arithmetic with a hard (count backwards by 17 from a presented number) and easy (count backwards by 2 from the number) condition, along with a control condition in which no arithmetic was required (Krejtz et al., 2018). There was a null effect for microsaccade rates between the difficult and easy conditions. Another study with three separate task phases (calculation, post-calculation, and control) found that microsaccade rates only decreased during the calculation phase as task difficulty increased (Gao et al., 2015). The suppression of microsaccade rates is argued to be due to nonvisual cognitive processing and is a function of task difficulty. Increasing working memory load also suppresses microsaccade rates (Dalmaso et al., 2017). In a dual task study manipulating the difficulty of a visual search and mental arithmetic task, microsaccade rates increased when the visual search task was highly difficult and decreased when the mental arithmetic task was highly difficult (Krueger et al., 2019). They argue that microsaccade rate reflects the processing resources given to a visual task.

There are mixed results in the literature about the relationship between emotionally arousing stimuli and microsaccadic rates. One study (Chen et al., 2021) involved a pro- and anti-saccade task, instructing participants to look at or look away from a peripheral stimulus while unpleasant, neutral, and pleasant auditory stimuli from the International Affective Digitized

Sound (IADS) database were presented. There were no differences in microsaccadic rates by emotional condition (Chen et al., 2021). Another study (Kashihara et al., 2014) presented people with emotional, neutral, or pleasant stimuli from the International Affective Picture System (IAPS) and also included a condition with images scrambled. They compared changes in microsaccade rates after the stimulus to rates prior to stimulus presentation. In all conditions, there was an initial suppression of microsaccade rates in the first 100-200 ms post-stimulus, followed by an increase 300-600 ms post-stimulus. However, in the 300-600 ms period, microsaccade rates were lower for negative emotional stimuli compared to scrambled, positive, or neutral stimuli. In another study (Krejtz et al., 2020), participants selected between two diamond-shaped cues, which were presented after an emotional stimulus (aversive, erotic, or neutral). Participants could view up to 6 cues before making a decision. This study found no effect of emotional condition on microsaccade rate. As more cues were viewed, microsaccade rates decreased more strongly for aversive stimuli compared to neutral stimuli, but did not vary from the erotic condition. The authors interpret this effect to indicate that as participants get closer to having to decide, more cognitive effort is required, particularly when viewing emotional stimuli.

Lange et al. (2017) measured changes in microsaccade rate while participants listened to instrumental music excerpts from a variety of genres for 60 seconds each. After listening to each excerpt, participants rated their experience on valence, arousal, liking, familiarity and absorption. Microsaccade rate was inversely associated with absorption, liking, and valence, and was positively associated with arousal. Lange et al. argue that the reduced microsaccade rate reflects more attention being paid to the music when experiencing states of higher absorption. A follow-up study involving listening to audiobooks found a positive relationship between microsaccade rates and self-reported arousal, but no effect for absorption, liking, or valence (Lange et al., 2022). A study employing a speech-in-noise task (Contadini-Wright et al., 2023) found that microsaccade rates were lower during a more difficult listening condition than an easy listening condition, reflecting allocation of attention under higher cognitive load. In this study, the drop in microsaccade rates only occurred during the time period where the keywords being searched for were presented.

3.1.3.2 Microsaccade peak velocity-magnitude slopes

The slope of the microsaccade peak velocity-magnitude relationship is a measure of mental fatigue. Di Stasi et al. (2013) describe mental fatigue as 'the mental tiredness generated by time-on-task and task complexity'. In a two-hour simulated air traffic control task, mental fatigue caused by time-on-task is reflected by the microsaccade peak velocity-magnitude relationship, while there was a null effect on microsaccade rate (Di Stasi et al., 2013). As time-on-task increased, the slope of this relationship decreased, indicating that the velocity of microsaccades was decreasing relative to their magnitude, due to mental fatigue. However, there was no effect of task complexity on microsaccade peak velocity-magnitude slopes. In a study using a two-hour simulated driving task, microsaccade peak velocity-magnitude slopes decreased as driving time increased (Di Stasi et al., 2015). There is mixed evidence for whether mental arithmetic tasks elicit a time-on-task effect reducing microsaccade peak velocity-magnitude slopes, with one study (Siegenthaler et al., 2014) finding a significant effect and another finding a null effect (Krejtz et al., 2018). However, neither of these studies found any effect of task difficulty on the slope of this relationship, consistent with Di Stasi et al. (2013). Another study found a similar time-on-task effect reducing microsaccade peak velocity-magnitude slopes with a pro- and anti-saccade task (Chen et al., 2021). Interestingly, this study did not find a difference in microsaccadic slopes in conditions varying by emotional arousal.

In experiment 2, I manipulated fractal complexity to identify how differences between natural and urban scenes on eye movement metrics (fixations and saccades) and affective appraisals varied due to scene complexity. As in experiment 1, I tested whether ratings of pleasantness were correlated to eye movement metrics. Experiment 2 expanded on the literature by using microsaccadic measures such as microsaccade rate and microsaccade slopes to evaluate mental fatigue and arousal in scene viewing, identifying whether a time-on-task effect existed.

3.1.3.3 Luminance and spatial frequency

The approach taken in experiment 2 involves colour stimuli without controlling for luminance or spatial frequency, unlike experiment 1. Eye-tracking studies that vary screen luminance find that microsaccade rates are lower under high luminance conditions (Benedetto et al., 2014; Chen et al., 2021; Zhang et al., 2020), though luminance does not impact microsaccade slopes (Chen et al., 2021). When viewing objects, microsaccade rates are higher when high spatial frequency information is available compared to when only low spatial frequency information is present (Craddock et al., 2017). Other studies suggest that tasks that require high visual acuity – threading a virtual needle (Ko et al., 2010) or viewing a Snellen chart (Intoy & Rucci, 2020) – involve a reduced microsaccade rate. The experiments in this dissertation do not involve tasks that require high acuity, since they are free-viewing tasks without a specific need to search for, identify or manipulate an object.

3.2 Hypotheses

Consistent with data from a pilot study (see section 3.3), I predicted that higher complexity scenes would be rated as more pleasant than lower complexity scenes. I expected to replicate the results from Experiment 1, that natural scenes should have larger fixation durations, larger saccade amplitudes, fewer fixations, and fewer saccades than urban scenes. Consistent with the literature (Chen et al., 2021; Di Stasi et al., 2013), the slope of the microsaccade peak velocity-magnitude relationship should decrease with time-on-task. I expected that microsaccade rates would be higher for urban scenes compared to natural scenes, as urban scenes would contain more objects and details, representing a higher visual load.

3.3 Methods

3.3.1 Participants

50 undergraduate students (70% female) from the University of Waterloo with normal or corrected-to-normal vision participated in the experiment. Trials were defined as invalid when over 25% of the trial (> 5 seconds) was spent looking away from the monitor or blinking. On average, 1.9 trials (SD = 3.3) were excluded per participant, comprising 2.3% of the dataset.

Invalid trials resulted in the participant being excluded from the final dataset when they consisted of over 20% of all trials for that participant. 0 participants were excluded under this criterion. A post-hoc power analysis indicated that a sample size of n = 50 provided 93% power to identify an effect size of d = 0.5 at a significance level of .025. Participants provided written, informed consent prior to the experiment. The study had been approved by a University of Waterloo ethics committee.

3.3.2 Design

This study used a similar experimental design as experiment 1, with a slightly smaller stimulus set (84 scenes vs. 90 scenes).

3.3.3 Stimuli

84 images of natural and urban scenes (Figure 4) were collected from the SUN database (Xiao et al., 2010) and from Flickr. As in experiment 1, natural scenes consisted of forests, bodies of water, mountains, and deserts, while urban scenes consisted of city streets, skylines, building facades, roadways, and parking lots. Scenes were converted to greyscale using ImageJ (Schindelin et al., 2015). Both natural and urban scenes were divided into high and low fractal complexity subcategories. Average pixel intensity and RMS contrast were then calculated in MATLAB. Welch's two-sample tests contrasted levels of pixel intensity by complexity and scene type. Pixel intensity was significantly lower for high complexity natural scenes ($M = 82.7$) than low complexity natural scenes ($M = 122.3$), $t(39.9) = 4.83$, $p < .001$. There were no

significant differences in pixel intensity between high complexity urban ($M = 121.3$) and low complexity urban ($M = 110.9$) scenes, $t(36.5) = 0.18$. RMS contrast did not vary by levels of complexity for natural scenes (high complexity $M = 56.0$, low complexity $M = 53.5$), $t(39.6) = 0.65$ or urban scenes (high complexity $M = 57.2$, low complexity $M = 56.7$), $t(34.3) = 0.15$, $p = 0.88$. Analyses of fractal complexity were carried out using the FracLac plugin (Karperien, 2013) for ImageJ. Two-sample Welch's *t*-tests were carried out to validate the sorting of groups by complexity. Low complexity natural ($D = 1.69$) scenes were significantly less complex than high complexity natural ($D = 1.83$) scenes, $t(23.5) = 6.37$, $p < .001$. Low complexity urban ($D = 1.67$) scenes were significantly less complex than high complexity urban ($D = 1.83$) scenes, $t(25.7) = 8.12$, $p < .001$. There were no differences in fractal complexity between low complexity natural and urban scenes ($t(40) = 0.22$, $p = 0.83$) or between high complexity natural and urban scenes ($t(37.4) = 0.16$, $p = 0.88$). Stimulus size was equalized at 1920 x 1200 pixels, with a horizontal radius of 22.4° and vertical radius of 14.0°. Stimuli were presented on an LCD monitor with a refresh rate of 60 Hz at a viewing distance of 65 cm. Participants rested their head on a forehead and chinrest while viewing each stimulus.

Figure 4. Images from the Experiment 2 stimulus set. Images in the left column represent high complexity scenes, while images in the right column represent low complexity scenes. Images in the top row are natural scenes, while images in the bottom row are urban scenes.

3.3.3.1 Pilot testing

Pilot testing was conducted to evaluate whether the natural scenes in the stimulus set were more restorative than the urban scenes, using the fascination and being away subscales of the PRS-11 (Pasini et al., 2014). Since attention restoration theory argues that natural and urban scenes vary in the type of fascination they elicit, the fascination subscale was the focus for statistical testing. In the pilot study, participants ($n = 20$) viewed each scene for 20 seconds and then responded to the fascination subscale in the PRS-11. Both natural and urban scenes were subdivided into high and low complexity categories. A two-way ANOVA tested how stimulus type (natural, urban) and complexity (low, high) affected fascination. Stimulus type ($F(1,19) = 53.94$, $p < .001$, $\eta^2_p = .74$) and complexity significantly affected fascination ($F(1,19) = 104.31$, $p < .001$, $\eta^2_p = .85$), with a significant interaction ($F(1,19) = 53.67$, $p < .001$, $\eta^2_p = .74$). Natural scenes ($M = 7.0$, SD = 1.2) were higher in fascination than urban scenes ($M = 4.3$, SD = 1.1).

Planned comparisons indicated that high complexity (*M* = 7.2, SD = 1.2) natural scenes were significantly more fascinating than low complexity (*M* = 6.8, SD = 1.2) natural scenes, $F(1,19) = 4.72$, $p = .043$, $\eta^2_p = .20$. For urban scenes, complexity was associated with a significant difference in fascination, with high complexity (*M* = 5.4, SD = 1.4) scenes higher in fascination than low complexity (*M* = 3.2, SD = 1.0) scenes, $F(1,19) = 142.00$, $p < .001$, $\eta^2_p = .88$. This interaction suggests that the effect of complexity on fascination is greater for urban scenes than natural scenes. This stimulus set allowed me to test how eye movement patterns relate to the differences in fascination between natural and urban scenes, and between high complexity and low complexity urban scenes. In particular, it let me test how differences in fascination within urban scenes relate to visual exploration and fatigue.

3.3.4 Procedure

The procedure of this study was mainly identical to experiment 1, similarly using control, central, and peripheral visual conditions. With the exception of early vs. late trial comparisons, all data analyses reported here are from the control condition. There were 14 natural scenes and 14 urban scenes in this condition. Data from the central and peripheral conditions are reported in Appendix A. Instead of thirty scenes for each of the three visual conditions, there were twenty-eight scenes per visual condition. For each visual condition, fourteen natural scenes and fourteen urban scenes were presented, with each group further subdivided into high (seven) and low (seven) complexity categories. Scenes were presented in a randomized order, with visual condition and complexity level also randomized. Two breaks were scheduled during the study after the twenty-eighth and fifty-sixth trials. Participants were instructed to freely explore the scenes and told that they would answer a question after each scene. This question was a 7-point Likert item measuring pleasantness, using the word pair unpleasant-pleasant.

3.3.5 Data analysis

An SR Eyelink 1000 eye-tracking system recorded eye movements binocularly at 1000 Hz. Fixations, saccades, and blinks were detected using the built-in Eyelink algorithm. Saccades and microsaccades fall along the main sequence in the microsaccade-saccade continuum, with highly correlated amplitudes and peak velocities (Bahill et al., 1974; Zuber et al., 1965). Microsaccades were defined as saccades with an amplitude < 1° of visual angle (Rolfs, 2009; Martinez-Conde et al., 2013) and were identified using a velocity-based algorithm (Engbert & Kliegl, 2003) using the Microsaccade Toolbox for R (Engbert et al., 2015). A detection threshold of $\lambda = 4$ and minimal duration over six velocity samples (6 ms) was employed to compute microsaccades using the Engbert & Kliegl algorithm (Benedek et al., 2017; McCamy et al., 2012). Saccades were defined in this study as being 1° or greater in size. All saccades identified through the Eyelink algorithm that were smaller than 1° were removed. To avoid detecting overshoots as microsaccades, an intersaccadic interval of 10 ms was employed (Hung et al., 2023), with any microsaccades occurring less than 10 ms after a previous saccade or microsaccade removed from the dataset. Saccades, microsaccades, or fixations that were not binocular were removed. Saccades, microsaccades or fixations that started before scene presentation in a trial were removed. Any fixations longer than 1000 ms or shorter than 80 ms were removed. Trials where the total blink time was equal to or greater than 5 s (25% of the trial length) were excluded from the dataset. On average, 1.9 trials (SD = 3.3) were excluded per participant, comprising 2.3% of the dataset. When violations of sphericity occurred, a Greenhouse-Geisser correction was applied for repeated-measures ANOVAs.

3.4 Results

Tables 3 and 4 summarize results contrasting natural vs. urban scenes (Table 3), and early vs. late trials (Table 4). Table 3 reports η^2_p values instead of *d* values since these tests are from two-way ANOVAs with stimulus type (natural, urban) and complexity (low, high) as factors.

Measure	***M* (Natural)**	***M* (Urban)**	***p***	**η^2_p**
Fixation count	47.1 (1.3)	49.3 (1.2)	< .001	.23
Saccade count	49.6 (1.2)	49.5 (1.1)	.76	.00
Fixation duration	275.6 ms (5.5)	267.4 ms (4.9)	< .001	.21
Saccade amplitude	6.7° (0.2)	6.5° (0.2)	.012	.12
Pleasantness	5.3 (0.1)	4.6 (0.1)	< .001	.50
Microsaccade slope	0.85 (0.05)	0.95 (0.08)	.080	.01
Microsaccade rate	0.58 (0.06)	0.64 (0.07)	.024	.10
Blinks	6.6 (0.4)	6.3 (0.4)	.061	.07

Table 3. Means, *p*-values, and effect size for natural and urban scenes in Experiment 2. SE in brackets.

Measure	***M* (Early)**	***M* (Late)**	***p***	***D***
Microsaccade slope	0.89 (0.04)	0.72 (0.04)	.002	.46
Microsaccade rate	0.38 (0.05)	0.71 (0.08)	< .001	.79
Blinks	4.1 (0.4)	5.4 (0.5)	.002	.46

Table 4. Means, *p*-values, and effect size for early and late trials in Experiment 2. SE in brackets.

3.4.1 Fixation count and saccade count

A repeated-measures ANOVA tested how scene type and complexity affected the fixation count (see Figure 5). Consistent with experiment 1, there was a significant effect of scene type ($F(1,49) = 14.72$, $p < .001$, $\eta^2_p = .23$), with fewer fixations on natural scenes ($M = 47.1$) than urban scenes ($M = 49.3$). There was no significant effect of complexity ($F(1,49) = 1.00$, $p = .32$, $\eta^2_p = .02$). The interaction between scene type and complexity was not significant ($F(1,49) = 1.21$, $p = .28$, $\eta^2_p = .02$). Exploratory simple effects tests ($\alpha = .025$) examined if complexity affected fixation count separately for natural and urban scenes. For natural scenes, there were no significant differences in fixation count between high complexity ($M = 47.1$) and low complexity ($M = 47.1$) scenes, $F(1,49) = 0.00$, $p = .99$, $\eta^2_p = .00$. Fixation count did not significantly differ between high ($M = 49.8$) and low ($M = 48.7$) complexity urban scenes, $F(1,49) = 1.80$, $p = .19$, $\eta^2_p = .04$.

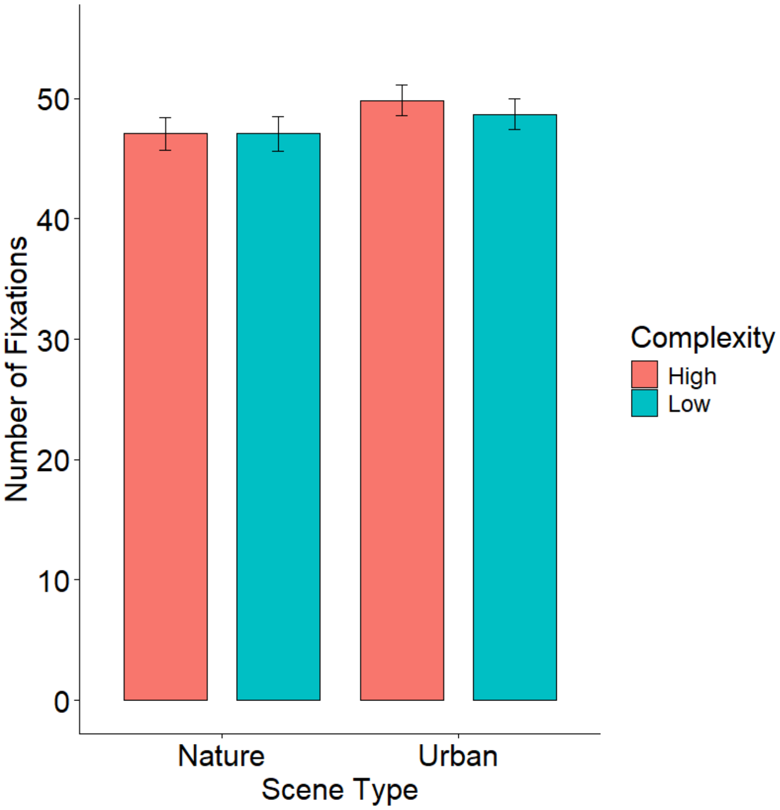

Figure 5. Number of fixations by scene type and complexity. Red bars indicate high complexity scenes, while blue bars indicate low complexity scenes. Error bars indicate one standard error. * represents $p < .025$.

A repeated-measures ANOVA tested how scene type and complexity affected the saccade count (Figure 6). Unlike experiment 1, I did not find any significant differences in the saccade count in natural ($M = 49.6$) and urban ($M = 49.5$) scenes, $F(1,49) = 0.09$, $p = .76$, $\eta^2_p = .00$. There was a significant effect of complexity ($F(1,49) = 5.48$, $p = .023$, $\eta^2_p = .10$), with more saccades on high complexity ($M = 50.2$) than low complexity scenes ($M = 48.9$). The interaction between complexity and saccade count was not significant ($F(1,49) = 1.52$, $p = .22$, $\eta^2_p = .03$).

Exploratory simple effects tests (α = .025) found no significant differences in saccade count for natural scenes between high complexity (*M* = 50.0) and low complexity (*M* = 49.3) scenes, *F*(1,49) = 0.89, *p* = .35, η^2_p = .02. For urban scenes, high complexity (*M* = 50.4) scenes involved significantly more saccades than low complexity (*M* = 49.6) scenes, *F*(1,49) = 6.59, *p* = .013, η^2_p = .12.

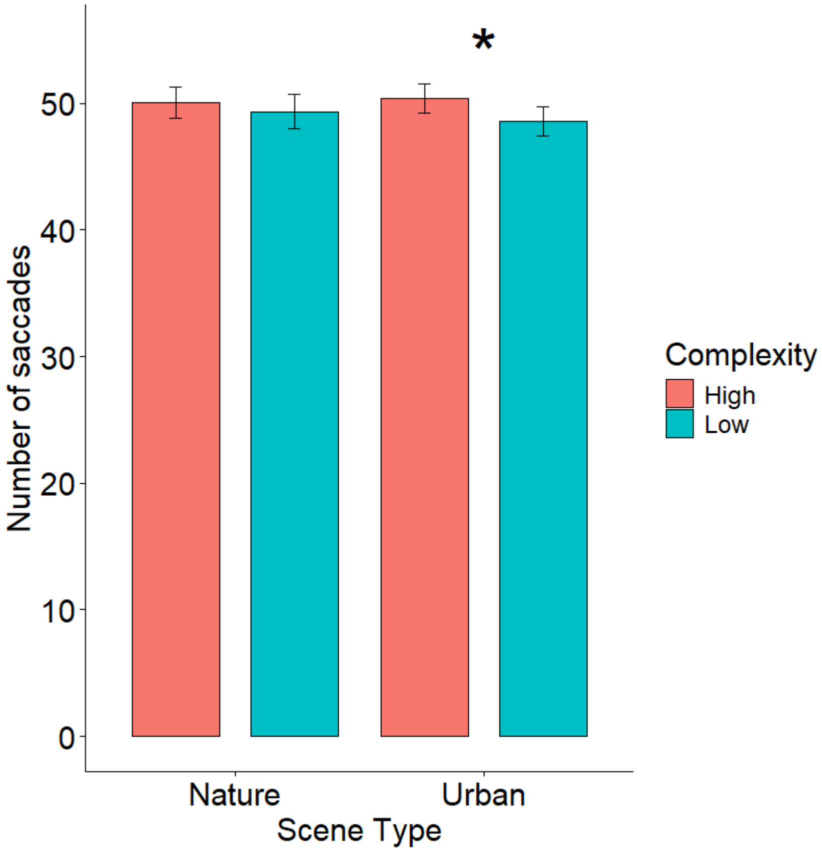

Figure 6. Saccade count by scene type and complexity. Red bars indicate high complexity scenes, while blue bars indicate low complexity scenes. Error bars indicate one standard error. * represents *p* < .025.

3.4.2 Fixation duration

A repeated-measures ANOVA tested how scene complexity and scene type influenced fixation durations (Figure 7). There was no main effect of complexity ($F(1,49) = 0.89$, $p = .35$, $\eta^2_p = .02$) and a significant effect of scene type ($F(1,49) = 12.86$, $p < .001$, $\eta^2_p = .21$) on fixation durations. Consistent with experiment 1, fixation durations were longer for natural scenes (M = 275.6 ms) than urban scenes (M = 267.4 ms). There was no significant interaction effect ($F(1,49) = 0.84$, $p = .36$, $\eta^2_p = .02$). Exploratory simple effects tests ($\alpha = .025$) were carried out to see if scene type affected fixation duration at different levels of complexity. There were no differences between high (M = 275.2 ms) and low (M = 275.2 ms) complexity natural scenes ($F(1,49) = 0.00$, $p = .99$, $\eta^2_p = .00$). This is consistent with Franek et al. (2019), who also did not find any difference in fixation durations between higher complexity natural scenes with foliage and lower complexity natural scenes without foliage. High (M = 265.9 ms) and low (M = 269.0 ms) complexity urban scenes did not significantly vary ($F(1,49) = 1.70$, $p = .20$, $\eta^2_p = .03$).

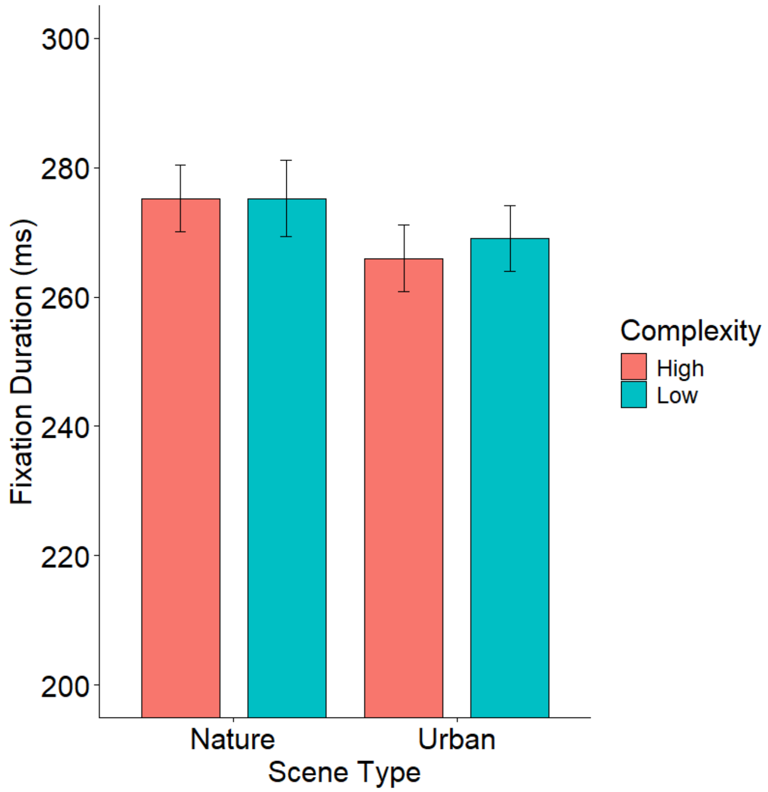

Figure 7. Mean fixation durations by scene complexity and scene type. Red bars indicate high complexity, while blue bars indicate low complexity. Error bars indicate one standard error.

3.4.3 Saccade amplitude

For saccade amplitudes (Figure 8), there was a main effect of scene type ($F(1,49) = 6.76$, $p = .012$, $\eta^2_p = .12$) and a significant effect of complexity ($F(1,49) = 4.76$, $p = .034$, $\eta^2_p = .09$). The interaction was not significant ($F(1,49) = 1.24$, $p = .27$, $\eta^2_p = .03$). Natural scenes involved significantly larger saccades ($M = 6.7°$) than urban scenes ($M = 6.5°$). Low complexity scenes involved larger saccades ($M = 6.6°$) than high complexity ($M = 6.5°$) scenes. Exploratory simple effects tests ($\alpha = .025$) found no significant differences between high complexity ($M = 6.6°$) and low complexity (*M* = 6.8°) natural scenes (*F*(1,49) = 4.95, *p* = .031, η^2_p = .09). There were also no significant differences between high and low complexity urban scenes (*M*s = 6.5°, 6.5°, *F*(1,49) = 0.62, *p* = .44, η^2_p = .01).

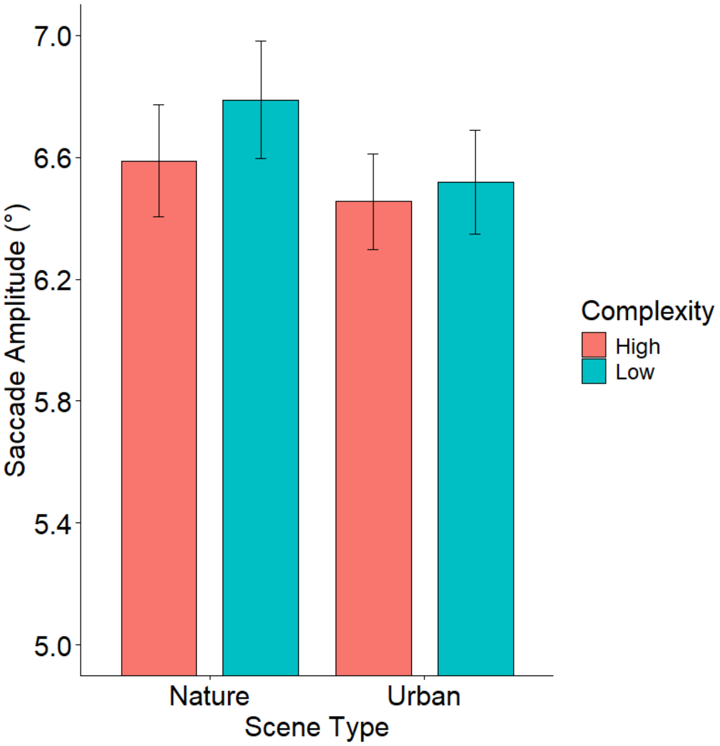

Figure 8. Mean saccade amplitudes by scene complexity and scene type. Red bars indicate high complexity scenes, while blue bars indicate low complexity scenes. Error bars indicate one standard error.

3.4.4 Pleasantness

We found a significant effect of complexity (*F*(1,49) = 5.17, *p* = .027, η^2_p = .10) and scene type (*F*(1,49) = 48.73, *p* < .001, η^2_p = .50) on ratings of pleasantness (Figure 9). As expected, natural scenes (*M* = 5.3) were preferred to urban scenes (*M* = 4.6). High complexity scenes (*M* = 5.0) were preferred to low complexity scenes (*M* = 4.9). There was a significant interaction effect ($F(1,49) = 16.81$, $p < .001$, $\eta^2_p = .26$). Simple effects tests ($\alpha = .025$) indicated that complexity had a significant effect on pleasantness for urban scenes ($F(1,49) = 20.2$, $p < .001$, $\eta^2_p = .29$), with high complexity urban scenes (*M* = 4.8) perceived to be more pleasant than low complexity (*M* = 4.4) urban scenes. For natural scenes, high (*M* = 5.2) and low (*M* = 5.4) complexity scenes did not significantly vary in pleasantness ($F(1,49) = 1.99$, $p = .17$, $\eta^2_p = .04$).

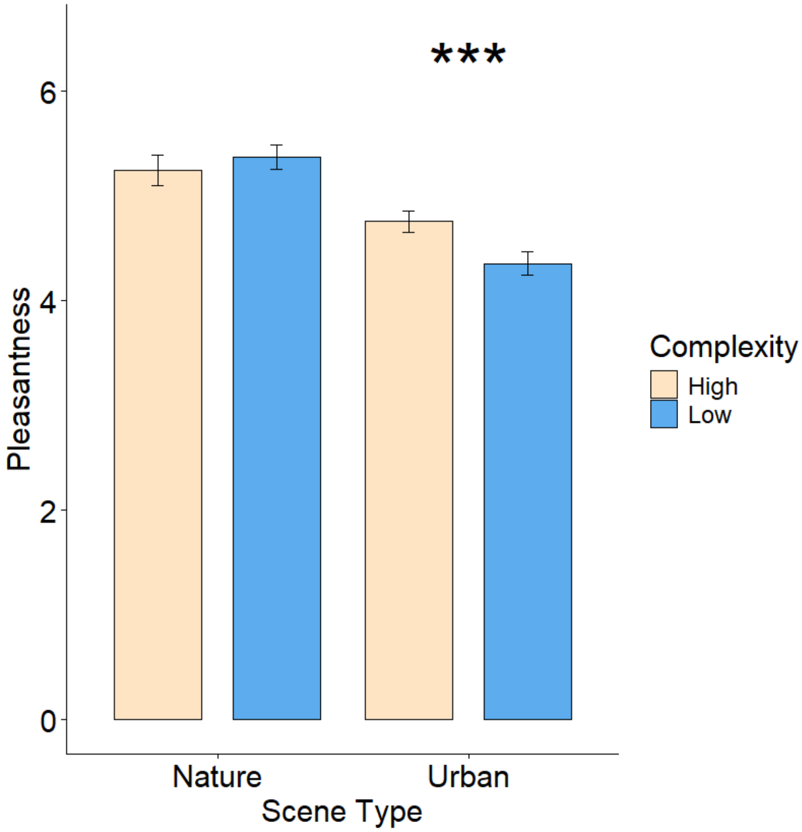

Figure 9. Ratings of pleasantness by scene complexity and scene type. Orange bars indicate high complexity, while blue bars indicate low complexity. Error bars indicate one standard error. *** represents $p < .001$.

Correlation analyses tested relationships between eye movement metrics and pleasantness using data from all valid trials. There was no relationship between pleasantness and fixation durations ($r = .00$, $p = .96$), saccade amplitudes ($r = -.05$, $p = .09$), fixation count ($r = .02$, $p = .55$), saccade count ($r = .01$, $p = .82$), or blink rate ($r = .00$, $p = .99$). There was a significant positive correlation between pleasantness and microsaccade rate ($r = .08$, $p = .002$). Exploratory analyses ($\alpha = .025$) tested whether correlations between eye movement metrics and pleasantness varied between natural and urban scenes. Fisher's Z-transformation tests found no significant differences between natural and urban scenes for correlations between pleasantness and any eye movement metrics, all *p*s > .09.

3.4.5 Microsaccade slope

To evaluate fatigue and arousal during the time course of the study, the first 14 trials (1/6 of the total number of trials) were defined as the early block, while the last 14 trials were defined as the late block. Similar to experiment 1, analyses contrasting early vs. late trials used data from all visual conditions (full vision, peripheral vision, central vision). The other analyses in this experiment only use data from the full vision condition. The purpose of the early vs. late block comparisons is to identify any potential time-on-task effect. In experiment 1, a time-on-task effect was identified for blink rates, and experiment 2 expands on this by measuring microsaccade slopes and microsaccade rates. Previous studies (Chen et al., 2021; Di Stasi et al., 2013; Siegenthaler et al., 2014) found time-on-task effects for microsaccade slopes using information from normal vision.

The slopes of the relationship between microsaccade magnitude and peak velocity were analyzed using a power-law relationship (Di Stasi et al., 2015). Robust linear regressions were performed on the log-transformed data for each participant to obtain the slopes for peak velocity-magnitude relationships, depicted in Figure 10. The regression equations were: ln(peak velocity) = m * ln(magnitude) + b, with m representing the slope and b the y-intercept. As predicted, microsaccade peak velocity-magnitude relationship slopes decreased significantly during late trials ($M = 0.72$) compared to early trials ($M = 0.89$), $t(49) = 3.28$, $p = .002$, $d = .46$. There were no significant differences in microsaccade peak velocity-magnitude relationship slopes when comparing natural ($M = 0.85$) and urban scenes ($M = 0.95$), $t(49) = 1.79$, $p = .080$, $d = .25$. High ($M = 0.92$) and low ($M = 0.90$) complexity scenes did not significantly vary in microsaccade slopes, $t(49) = 0.43$, $p = .67$, $d = .05$.

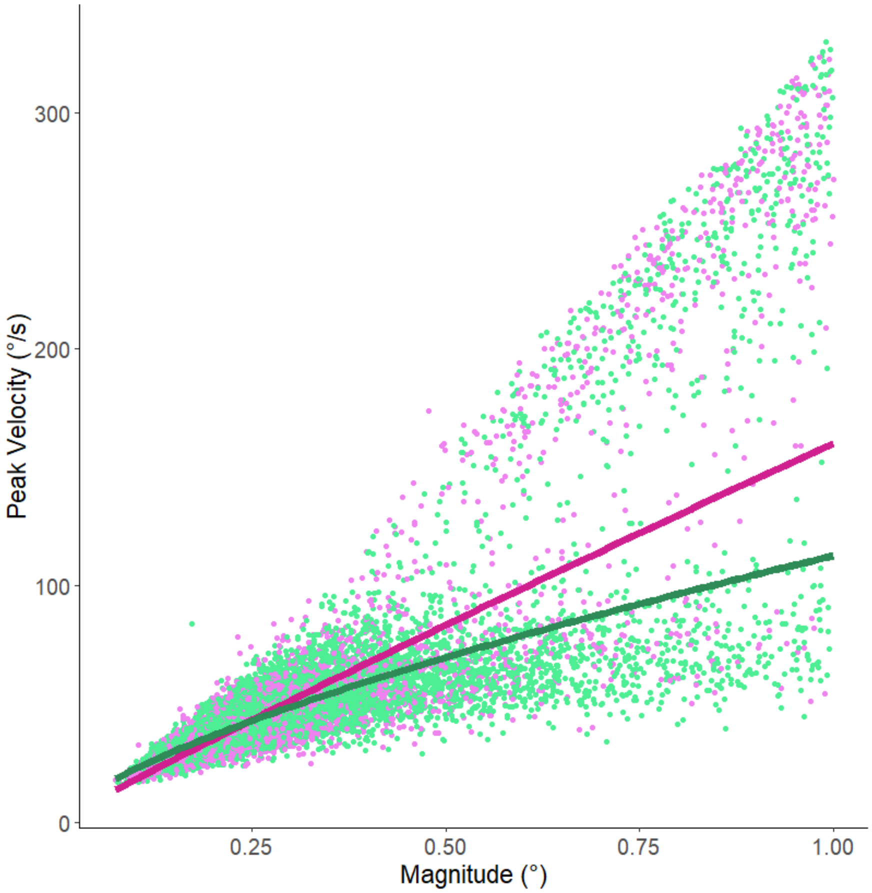

Figure 10. Effect of time in the experiment on the microsaccade peak velocity-magnitude relationship. Purple dots indicate early trials (the first sixth of the experiment) while green dots indicate late trials (the last sixth of the experiment). Each dot represents one microsaccade. The curves are power law fits for early and late trials across all participants.

The distribution of microsaccadic slopes varies in this study when compared to some previous studies (Chen et al., 2021; Di Stasi et al., 2013; Di Stasi et al., 2015), where microsaccades rarely have peak velocities greater than 100 °/s. Martin et al. (2020) report data more similar to what is found in my study, with the microsaccadic main sequence including a cluster of microsaccades above 200 °/s. Krejtz et al. (2018) also report microsaccades up to 200 °/s.

3.4.6 Microsaccade rate

As per McCamy et al. (2014), the microsaccade rate for a trial was defined as the number of microsaccades divided by the total fixation duration in that trial. A repeated-measures ANOVA found a significant effect for scene type on microsaccade rate ($F(1,49) = 5.50$, $p = .024$, $\eta^2_p = .10$), while complexity was not significant ($F(1,49) = 0.91$, $p = .34$, $\eta^2_p = .02$). As shown in Figure 11, microsaccade rates were lower for natural scenes ($M = 0.58$) than urban scenes ($M = 0.64$). There was also no significant interaction effect ($F(1,49) = 0.05$, $p = .83$, $\eta^2_p = .00$). Microsaccade rates were also higher during late trials ($M = 0.71$) compared to early trials ($M = 0.38$), $t(49) = 5.56$, $p < .001$, $d = .79$. Microsaccade rate was negatively correlated with fixation count ($r = -.06$, $p = .035$), fixation durations ($r = -.19$, $p < .001$), and saccade amplitudes ($r = -.14$, $p < .001$).

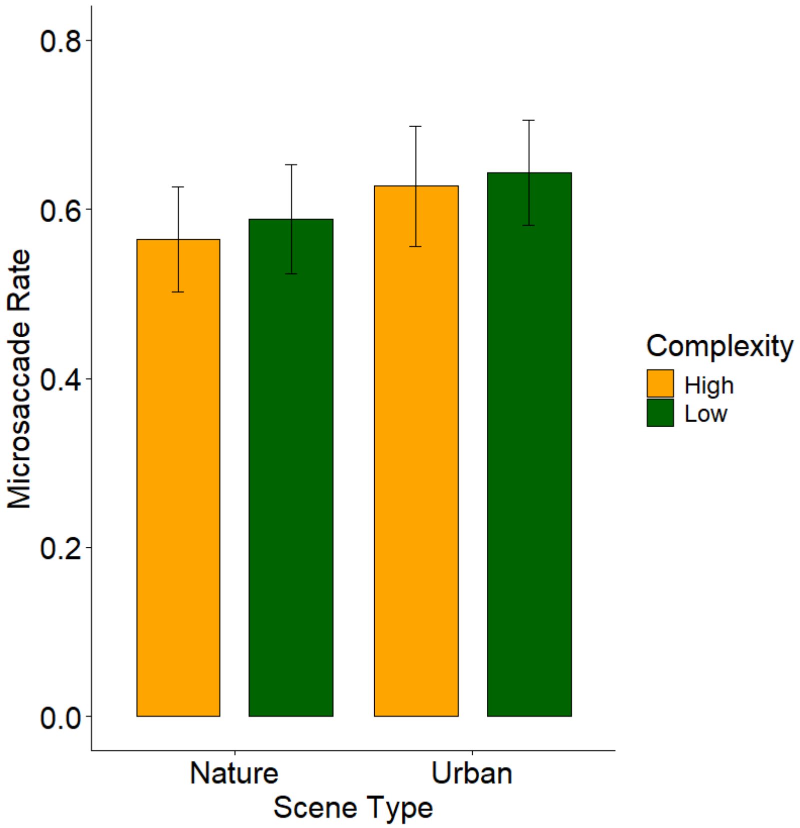

Figure 11. Microsaccade rate per second by scene type and complexity. Orange bars indicate high complexity, while green bars indicate low complexity. Error bars indicate one standard error.

3.4.7 Blink rate

I tested whether complexity and scene type predicted blink rates (Figure 12). There was no effect of complexity ($F(1,49) = 0.23$, $p = .63$, $\eta^2_p = .01$) or scene type ($F(1,49) = 3.69$, $p = .061$, $\eta^2_p = .07$). Experiment 2 does not replicate the finding from experiment 1 that viewing natural scenes ($M = 6.6$) involves more blinking than urban scenes ($M = 6.3$), though the result is in the same direction. There was no interaction effect ($F(1,49) = 1.66$, $p = .20$, $\eta^2_p = .03$). Consistent with experiment 1, blink rates significantly increased from early trials ($M = 4.1$) to late trials ($M = 5.4$), $t(49) = 3.26$, $p = .002$, $d = .46$.

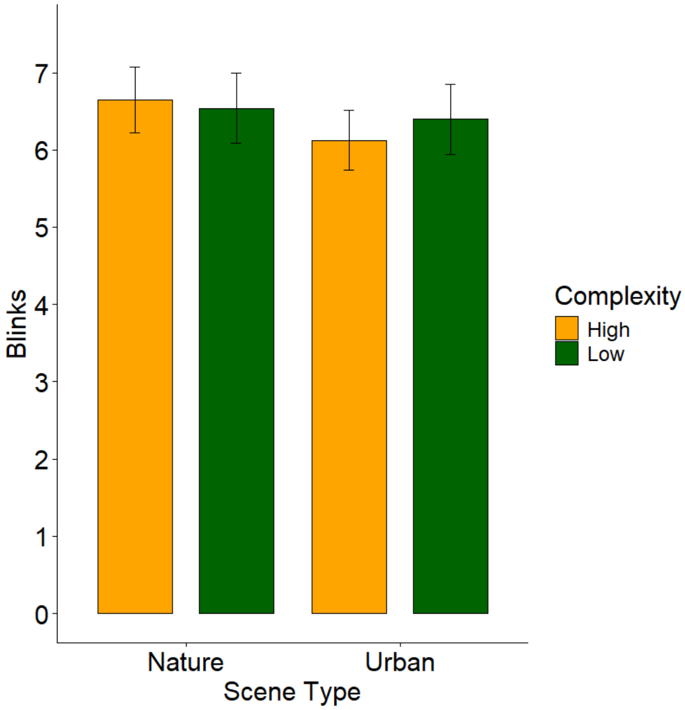

Figure 12. Mean number of blinks per trial by scene type and complexity. Orange bars indicate high complexity, while green bars indicate low complexity. Error bars indicate one standard error.

3.5 Discussion

The goals of this study were to identify (1) how complexity influences eye movements, (2) how preference influences eye movements and (3) whether microsaccades reflect visual load and fatigue in scene viewing. I replicated findings from previous studies that natural scenes involve fewer overall fixations and longer fixation durations than urban scenes (Berto et al., 2008; Franek et al., 2018; Valtchanov & Ellard, 2015; Srikantharajah & Ellard, 2022). Consistent with study 1, saccade amplitudes were larger for natural scenes than urban scenes. However, I was unable to replicate the effect of scene type on saccade count. More work is required to identify whether saccade count varies between natural and urban scenes.

3.5.1 Complexity and visual exploration

I predicted that scenes with higher fractal complexity would involve a higher fixation count and shorter fixation durations. The results from this study did not bear out this prediction. In contrast to previous studies (Dupont et al., 2017; Franek et al., 2019; Liu et al., 2021), I found no significant effects of complexity on fixation count, or on fixation durations. Instead, I found an impact of complexity on saccade amplitude, with smaller saccade magnitudes on more complex scenes. Previous studies indicated varying relationships between complexity and fixations, though they have several issues. Dupont et al. (2017) found an increase in fixation and saccade count by complexity measured by spectral entropy, but only after excluding rural landscapes from this analysis, which were low in complexity and had increased fixations and saccades compared to mixed (rural and urban) landscapes. Franek et al. (2019) measured complexity using fractal dimension, comparing urban scenes (D = 1.80) with natural scenes without foliage (D = 1.83) and natural scenes with foliage (D = 1.86). There was a lower fixation count for natural scenes with foliage compared to natural scenes without foliage, and no differences in fixation durations. However, natural scenes with foliage were not significantly higher in fractal dimension than natural scenes without foliage in this study. Moreover, their lower complexity condition (nature scenes without foliage) still had a high fractal dimension (D = 1.83), similar to the high complexity condition in my study (D = 1.83). The lower complexity scenes in my study were less complex (D = 1.68) than the scenes in the Franek et al. (2019) study, which may explain the different results.

Liu et al. (2021) measured complexity using subjective reporting by participants, separating an image set into high, medium, and low complexity groups. High complexity images involved a higher fixation count than low and medium complexity images and reduced fixation durations compared to low complexity images. Fractal dimension and subjective ratings of complexity are correlated, so the tool for measuring complexity may not be the cause of these differences (Kacha et al., 2013; Robles et al., 2021; Robles et al., 2023). In my study, people explored highly complex scenes by making smaller saccades, rather than altering their fixation patterns. Information from highly complex scenes was acquired in places located closely together. In less complex scenes, information is gathered from more distant places. A main reason for these differences may simply be the stimulus set, with my study including different stimuli compared to previous studies (Dupont et al., 2017; Franek et al., 2019; Liu et al., 2021). The stimuli in Liu et al. (2021) consisted of urban greenspace, Franek et al. (2019) used urban scenes and forests with and without foliage, while Dupont et al. (2017) used rural-urban landscapes. My experiment included a much larger variety of scenes, including forests, bodies of water, mountains, deserts, city streets, skylines, building facades, roadways, and parking lots. The advantage to my experiment is that my higher vs. lower complexity conditions include a greater variety of stimuli. In a study where a participant is only presented with scenes of a certain type of content, patterns of visual exploration may change as people acclimatize to the information being presented. A lower complexity scene may involve less visual exploration, with less fixations being made, as it is less compelling than a previously presented higher complexity scene with the same content. A study with a broader variety of scenes is less likely to face this issue, since the content of scenes is less predictable. Trial-by-trial variation in scene content can forestall effects of acclimatization on visual exploration.

Liu et al. (2021) argue that fixation count and duration should be treated as measures of the difficulty of scene processing. Based on the data from experiments 1 and 2, I would argue that fixation count, saccade count, fixation duration, and saccade amplitudes reflect the process of exploring a scene, not its difficulty. Higher complexity scenes had more details that are worth foveating, located closer together, inducing more saccades. While complexity itself affected visual exploration, it did not explain the differences that exist between exploring natural and urban scenes. In other words, natural scenes were not explored differently from urban scenes because of differences in their complexity. Even after controlling for complexity, significant differences in visual exploration were found between natural and urban scene content. There is something inherent to natural scene content, other than pure differences in fractal complexity, which drives different patterns of visual exploration. The processing fluency account (Joye & van den Berg, 2011) may play a role here. Since human beings are adapted to a natural environment, extracting visual information from the natural context would not require as many fixations, explaining the reduced fixation count. This would also explain why complexity induces a higher saccade count for urban scenes, but not for natural scenes.

3.5.2 Preference and visual exploration

As expected, I found that natural scenes were evaluated as being significantly more pleasant than urban scenes. I tested whether these differences were due to complexity, as urban settings are more complex than natural settings. Even after accounting for complexity, natural scenes were evaluated as being more pleasant than urban scenes. Higher complexity scenes were more pleasant than lower complexity scenes, but this was significantly impacted by scene type. There were no differences in ratings of pleasantness by complexity for natural scenes, with only urban scenes varying in pleasantness by complexity. High complexity urban scenes were more pleasant than low complexity urban scenes. These patterns for pleasantness were identical to ratings of fascination from pilot testing, where natural scenes were rated more fascinating compared to urban scenes, and high complexity urban scenes rated more fascinating than low complexity urban scenes. This suggests that creating higher complexity is important when designing pleasant urban environments. Nature is enjoyed regardless of complexity. Yet urban settings that lack complexity, that are less fascinating, may fail to engage people, and suffer from disinterest. Built environments may need to provide people with features and interesting details to look at and explore.

In attention restoration theory, it is proposed that these differences in eye movement patterns reflect attentional patterns. According to Berto et al. (2008), lower fixation counts on high fascination scenes reflects less effort involved during viewing. Natural scenes are proposed to be more restorative because they do not engage the inhibitory system as much compared to urban scenes. They do not require as many fixations and saccades, and each fixation is allowed to occur for longer. Subsequent studies (Franek et al., 2018) claim that longer fixation durations occurring on natural scenes reflect aesthetic appreciation, drawing from face processing studies about the association between liking and fixations on attractive faces (Leder et al., 2016). Marin & Leder (2022) found that changes in arousal for scenes are associated with eye movement differences. Arousal was positively associated with fixation count and inversely associated with fixation duration. Similarly, Gomez et al. (2019) also found a positive relationship between arousal and fixation count in a study using the IAPS, though fixation count was also inversely associated with pleasantness. Similar to the previous study, experiment 2 found no correlation between pleasantness and fixation durations or saccade amplitudes. Unlike experiment 1, the correlations between pleasantness and fixation counts and saccade counts were not significant in experiment 2. The most reliable finding in the literature (Goller et al., 2019; Huang & Lin, 2020; Leder et al., 2016; Scott et al., 2020; Silva et al., 2016) is that pleasantness is related to higher fixation counts, which experiment 1 showed but was not replicated in experiment 2. It is surprising that this finding was not replicated in this experiment, but there have been other studies which have found a null effect (Liu et al., 2021) or found that fascination is inversely related to fixation count (Franek et al., 2018). An important caveat is that the correlation between fixation count and pleasantness in experiment 1 is relatively small (r = .09). Changes in the stimuli used or the number of trials may suffice for a small significant correlation to disappear in another experiment. It is clear that more data are required to clearly determine the nature of the relationship between aesthetic preference and fixation count on a scene.

3.5.3 Microsaccades, fatigue and visual load

In attention restoration theory, voluntary attention to avoid distractions and maintain attention increases mental fatigue (Kaplan, 1995). In previous studies involving simulated driving and mental arithmetic (Di Stasi et al., 2015; Siegenthaler et al., 2013), microsaccade peak velocity-magnitude slopes have been used to index mental fatigue. Increased microsaccade rates reflect higher visual load (Benedetto et al., 2011; Krueger et al., 2019; Schneider et al., 2019), but not mental load. Fractal complexity has been related to cognitive load, measured through gait kinematics (Burtan et al., 2023). In this study, images were projected onto a wall, and people walked towards those images while the velocity of movement was measured. Images would have an intermediate fractal complexity consistent with images of nature, or have low or high complexity. Intermediate complexity images involved a higher mean velocity than low complexity images, though they did not vary from high complexity images. This is similar to findings contrasting walking towards projected nature images compared with urban images, where stride times are faster for nature (Burtan et al., 2020). The slower velocity for urban images or low complexity images indicates slower processing speed for those images. This study followed the perceptual fluency account (Joye & van den Berg, 2011) explaining why there are processing advantages for natural stimuli over urban stimuli. Human beings have evolved in a natural context, and through millennia of evolution, have become specialized for visual processing for natural scenes. Since natural scenes mostly comprise of intermediate fractal complexity, there is a processing advantage for intermediate fractal complexity compared with other levels of complexity.

In experiment 2, I found that microsaccade rates were higher for urban scenes than natural scenes, though I found no effect of complexity on microsaccade rates. It is challenging to explain higher microsaccade rates on urban scenes by differences in complexity, if complexity itself is unrelated to microsaccade rates. Even though I controlled for fractal complexity, urban scenes will still have more objects to parse. Since increased microsaccade production is related to more informative scene regions (McCamy et al., 2014), urban scenes may be eliciting more microsaccades because there is more detailed processing required with a greater number of objects. In general, scenes with more objects involve shorter fixations and smaller saccades compared to scenes with fewer objects (Unema et al., 2005). Experiment 2 also found a significant positive relationship between microsaccade rate and pleasantness. In a study using musical stimuli, there was an inverse relationship between microsaccade rate and self-rated absorption and liking (Lange et al., 2017). One likely reason for this difference is because visual behaviour is different when viewing visual stimuli compared to listening to music. Absorption in music involves disengaging from visual stimuli, while absorption in landscape images will naturally involve paying close visual attention to their features. I found an increase in microsaccade rate between early and late trials, suggesting a time-on-task effect. This is consistent with other studies which found a similar time-on-task effect for microsaccade rate for both easy and difficult mental arithmetic tasks (Siegenthaler et al., 2014) and in a pro- and anti-saccade task (Chen et al., 2021). However, it is inconsistent with another study (McCamy et al., 2014), which only found an increase in microsaccade rate over time for a visual search task, and not free-viewing natural scenes.

In attention restoration theory, the increase in fixation count for urban scenes and reduction in average fixation duration is interpreted to indicate that there is less soft fascination occurring. It is important to distinguish whether indicators such as microsaccade rate, fixation duration, and fixation count are mainly representing exploratory behaviour, mental fatigue or visual load. Since the goal is to test the claims of ART during scene viewing, it is necessary to use eye movement measures that are directly linked to fatigue. The microsaccade peak-velocity magnitude slope data are crucial to these questions, as it provides a direct link between visual behaviour and mental fatigue. In previous studies measuring the impact of time-on-task on fatigue, participants would carry out highly demanding air traffic control (Di Stasi et al., 2013) or driving tasks (Di Stasi et al., 2015) for two hours. In our study, participants merely free-viewed scenes for a period of around forty-five minutes. Nevertheless, I found that microsaccade peak velocity-magnitude slopes significantly decreased during late trials compared to earlier trials, showing that participants became more fatigued over the course of time. Although I did not find a significant effect of scene content on microsaccadic slopes, microsaccade slopes were numerically lower (p = .080) for natural scenes compared to urban scenes. I was able to replicate the findings from experiment 1 that blink rates increased from early to late trials. The blink rate difference between natural and urban scenes was not significant (p = .061) in experiment 2, but the effect was in the same direction. To lend credence to the interpretation of blink rates as a measure of fatigue and arousal, it is important to have consistent findings between blink rates and microsaccade slopes in how people experience natural and urban scenes.

Experiment 2 established that the differences in visual exploration between natural and urban scenes were not due to differences in complexity between those scenes. Natural scenes involved fewer fixations, longer fixations, and larger saccades, even after accounting for the effect of fractal complexity. Fractal complexity did not influence fixation count or fixation duration and only affected saccades. For urban scenes, higher complexity was associated with a higher saccade count and shorter saccade amplitudes. There is something integral to natural scene content that results in reliably different patterns of scene exploration compared to viewing urban scenes. In previous studies (Valtchanov & Ellard, 2015), viewing urban scenes is described as more fatiguing than natural scenes, because urban scenes have higher blink rates. Both experiments 1 and 2 of my dissertation show the opposite pattern. In experiment 1, blink rates were significantly higher for natural scenes, and in experiment 2, blink rates are higher for natural scenes but not significant. The microsaccade slope data are consistent with blink rates, showing smaller slopes when viewing natural scenes, indicating greater fatigue. At this point, my data does not support the idea that viewing urban scenes is inherently more fatiguing than viewing natural scenes. They hint at the opposite relationship, that people experience lower arousal while viewing nature compared to viewing urban scenes. However, it is difficult to extrapolate too much into the blink rate and microsaccade slope data from experiment 2, since those results were not significant. More data are needed to resolve this question, which experiments 3 and 4 will provide.

Chapter 4: Experiment 3 – Visual exploration using colour stimuli

4.1 Introduction

In experiment 2, I followed previous eye-tracking research (Chen et al., 2021; Di Stasi et al., 2013; Siegenthaler et al., 2014) in using the slope of the microsaccade peak velocity-magnitude relationship as a measure of fatigue. I validated that there is a time-on-task effect increasing fatigue, with microsaccadic slopes declining over the course of the study between early and late trial blocks. It was noteworthy that simply viewing scenes on a screen repeatedly over the course of a 45-minute study was sufficient to elicit this time-on-task effect. Berto et al. (2008) claim that differences in visual exploration such as fixation count between viewing natural and urban scenes reflect changes in attention, and that people make fewer fixations on natural stimuli because viewing natural stimuli is less effortful than urban scenes. Kaplan (1995) defines fascination as involving effortless, involuntary attention. Berto et al. (2008)'s interpretation is that the pattern of less frequent, long fixations on natural scenes reflects soft fascination, where an attractive and interesting scene can be viewed without intensely demanding attention on specific details. Experiments 1 and 2 present a challenge to these claims. It is true that natural and urban scenes vary in visual exploration, consistent with previous research (Berto et al., 2008; Valtchanov & Ellard, 2015; Franek et al., 2018). Natural scenes involved longer and fewer fixations, and larger saccades. However, experiment 2 found no relationship between pleasantness and any eye-tracking metric. In experiment 1, pleasantness was associated with an increase in fixation count, an opposite relationship to what Berto et al. (2008) propose. Yet natural scenes were consistently rated as more pleasant than urban scenes.

This presents a challenge to claims invoking ART to explain how different patterns in visual exploration reflect changes in effort due to fascination. Berto et al. (2008) describe natural scenes as being attractive and interesting, arguing that nature's attractive features do not require as many fixations as urban scenes. They claim that a higher fixation count indicates that there are more distracting features in a scene that demand attention. My data from experiments 1 and 2 do not support this interpretation. In experiment 1, pleasantness was associated with a higher fixation count, consistent with work from face processing (Leder et al., 2016; Silva et al., 2016), and landscape studies (Huang & Lin, 2020; Scott et al., 2020), while experiment 2 found a null effect. Pleasant, attractive features draw attention not because they are distracting, but because they are fascinating and interesting to look at. One possibility is that the type of stimulus may play a role. The claims of ART are based on an evolutionary account, suggesting a processing advantage for nature because of humanity's evolution in natural settings. In those settings, nature was experienced in colour, not in black-and-white. Using colour images, Franek et al. (2018) find that the restorative scales of being away (escaping demands on visual attention) and fascination (the attractiveness or interest in a scene) are both associated with lower fixation count and higher fixation durations. Yet other studies (Liu et al., 2021) either find no relationship between pleasantness and either fixation count or fixation duration, or a different relationship where both fixation count and fixation duration increase with beauty (Scott et al., 2020). Huang & Lin (2020) find an increase in fixation count and a null effect for fixation duration by preference for landscapes. Clearly, more work must be done to clarify these relationships. One of the key distinguishing factors between nature and urban settings are the colours present. Experiments 1 and 2 both use black-and-white images. It is possible that a contrast using colour images would show a different pattern of results compared to experiment 2. Appreciation of a natural stimulus is likely to be higher under full colour compared to black-and-white. These conditions will allow the relationship between aesthetic appreciation and fixation metrics to be further clarified.

4.1.1 Greenspace vs. bluespace

Both greenspace (Twohig-Bennett & Jones, 2018) and bluespace (White et al., 2020) – lakes, coasts, rivers - have been associated with aesthetic preference and cognitive restoration. Several studies have compared the two directly in terms of preference and visual exploration. A number of studies have found that bluespace may be preferred to greenspace (White et al., 2010) and have greater benefits on health (Garrett et al., 2019). Living closer to the coast is associated with improved health and well-being (Gascon et al., 2017) and can have greater benefits to mental health when compared to living near greenspace (Garrett et al., 2019; McDougall et al., 2022). However, the McDougall et al. (2022) study also found that greenspace was more predictive of general health than bluespace. One study (Liu et al., 2021) found no difference between lawns and waterscapes in preference, also using an eye-tracking method. Nordh et al. (2011) found using images of small parks that grass, trees, and water features were all significantly predictive of restorativeness. Another study using images of waterfront parks found that aesthetic preference was positively correlated with size of waterscape elements, negatively correlated with hardscape elements, and not significantly correlated with plantscape area (Zhou et al., 2023). Colour composition can be related to both preference and fixation metrics when viewing landscapes, depending on their content (Huang & Lin, 2020). Landscapes with greater variety in colour are associated with higher preference and higher fixation counts. Forest landscapes with more magenta-green variation were associated with higher preference and total fixation count. Aquatic scenes with more blue content were preferred, though this did not affect fixation count or durations.

It will be useful to identify whether preferences for natural scenes based on natural content are related to eye movement data. Do people explore bodies of water differently than greenspace? Are there differences in blink rates and microsaccade slopes based on natural scene content?

4.1.2 Architectural styles

One critique of previous studies investigating ART is that there is a need to be more nuanced when contrasting urban and natural environments. Urban environments can be aesthetically pleasing and restorative as well. It is imperative to design pleasant urban environments, since that is where the majority of people live and spend our time. From a visual perspective, it will be interesting to identify if the content of an urban environment affects visual exploration, separately to how it may affect preference. One factor that may influence preference is architectural style. Historic architecture can be preferred to modern architecture, especially modern developments that are lacking in visual complexity. Comparing old city and modern urban environments, Franek et al. (2018) did not find any differences in fixation count or fixation durations, even though the old city images were perceived to be more restorative. Using 360-degree videos presented in virtual reality, Mouratidis & Hassan (2020) found that historic architecture high in ornamentation was evaluated more positively than modern architectural streetscapes and public squares. Much more research is required to understand how people visually explore scenes based on architectural style. This experiment aims to address this gap in the literature by testing how architectural style and categories of nature influence aesthetic appreciation, in addition to visual exploration and fatigue.

4.2 Hypotheses

I predicted that natural scenes would be preferred to urban scenes, and historic architecture preferred to modern architecture. I expected historic architecture to involve more fixations and saccades than modern architecture, since there would be more ornaments and interesting features to make more fixations. I expected a time-on-task effect similar to study 2, with a decrease in microsaccadic slopes, increased blink rates and increased microsaccadic rates from early to late trials.

4.3 Methods

4.3.1 Participants

51 undergraduate students (74.5% female) from the University of Waterloo with normal or corrected-to-normal vision participated in the experiment. The study had been approved by a University of Waterloo ethics committee. Trials were defined as invalid when over 25% of the trial (> 5 seconds) was spent looking away from the monitor or blinking, or if there were less than 10 fixations made during the trial. On average, 2.0 trials were excluded per participant, representing 2.4% of total trials.

4.3.2 Design

This study used a similar experimental design to experiment 2. Colour stimuli were used instead of black-and-white stimuli. Stimuli were not equalized on luminance and spatial frequency, similar to experiment 2.

4.3.3 Stimuli

Eighty-four images of natural (*n*=42) and urban (*n*=42) scenes (Figure 13) were collected from the SUN database (Xiao et al., 2010) and from Flickr. Natural scenes consisted of scenes involving water (*n*=21) or greenery (*n*=21). Scenes with water consisted of rivers, waterfalls, icebergs, and oceans. Greenery scenes included forests, meadows, and fields. Urban scenes consisted of historic (*n*=21) architecture or modern (*n*=21) architecture. Historic architectural scenes included more ornaments and often included materials such as brick or stone. Modern architectural scenes were mostly unornamented, often including materials such as glass or steel. The fractal dimension of scenes was computed using the same methods as in experiment 2. Scenes with water (*D* = 1.75), greenery (*D* = 1.79), historic architecture (*D* = 1.78), and modern architecture (*D* = 1.78) did not vary in fractal complexity (F(3,80) = 1.33, *p* = .27, $\eta^2 = 0.05$). Average pixel intensity and RMS contrast were calculated in MATLAB. Welch's two-sample tests contrasted levels of pixel intensity by complexity and scene type. Water scenes (*M* = 120.8) had a higher mean pixel intensity than greenery (*M* = 100.0), *t*(37.2) = 2.72, *p* = .010, while historic architecture (*M* = 121.3) did not significantly vary from modern architecture (*M* = 131.2), *t*(39.0) = 1.46, *p* = .15. RMS contrast did not significantly vary by nature type (water *M* = 57.1, greenery *M* = 61.9), *t*(36.2) = 1.45, *p* = .16 or architecture style (historic *M* = 61.7, modern *M* = 67.3), *t*(36.8) = 1.45, *p* = .15.

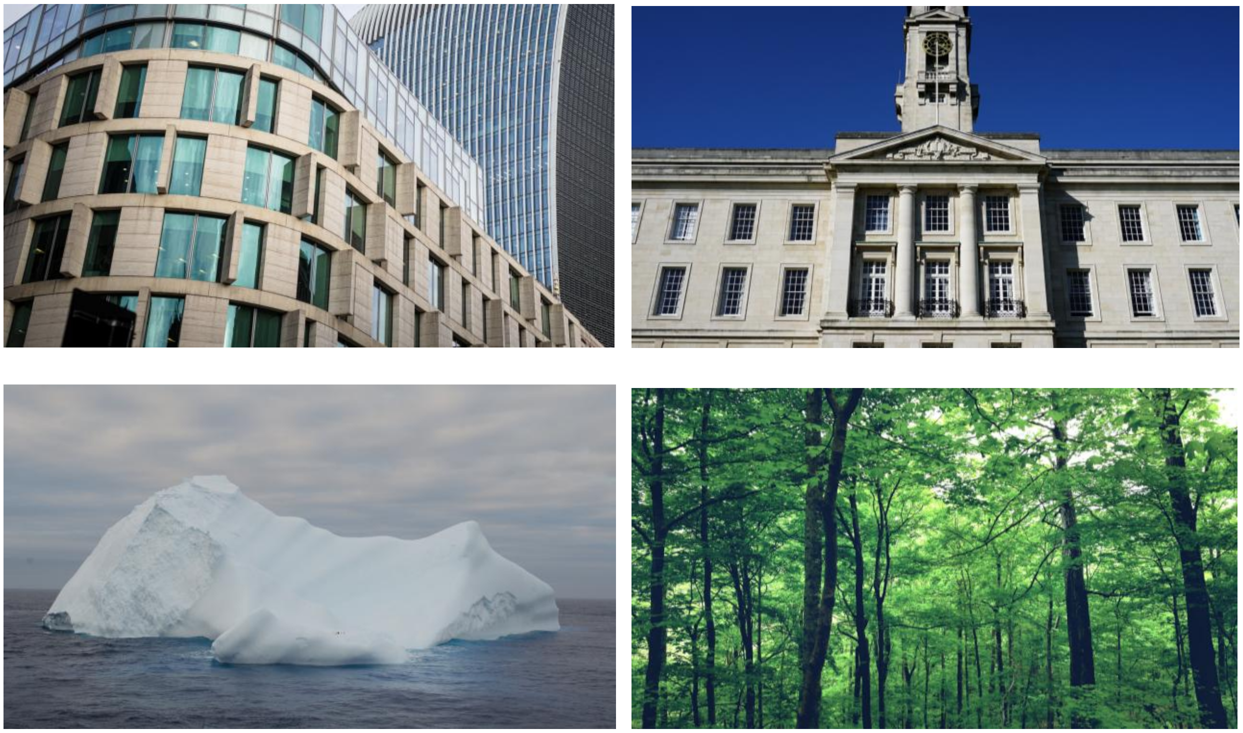

Figure 13. Images from the Experiment 3 stimulus set. Examples of modern architecture (top-left), classical architecture (top-right), water (bottom-left), and greenery (bottom-right) scenes are shown.

4.3.4 Procedure

The procedure of this study was identical to experiment 2, with control, central and peripheral visual conditions. With the exception of early vs. late trial comparisons, analyses reported here involve the data from the control condition (similar to experiments 1 and 2). There were 14 natural scenes and 14 urban scenes in this condition. Data from the central and peripheral visual conditions are reported in Appendix A.

4.4 Results

Tables 5 and 6 summarize results for this study contrasting natural vs. urban scenes (Table 5), and early vs. late trials (Table 6).

Measure	***M* (Natural)**	***M* (Urban)**	***p***	***d***
Fixation count	46.4 (1.2)	48.0 (1.3)	< .001	.48
Saccade count	48.3 (1.1)	48.4 (1.2)	.82	.03
Fixation duration	282.7 ms (4.7)	274.7 ms (4.4)	< .001	.60
Saccade amplitude	7.0° (0.2)	6.8° (0.2)	.038	.30
Pleasantness	5.3 (0.1)	4.6 (0.1)	< .001	.94
Microsaccade slope	0.86 (0.03)	0.95 (0.03)	.009	.38
Microsaccade rate	0.46 (0.04)	0.51 (0.04)	.024	.33
Blinks	8.2 (0.7)	7.7 (0.7)	.031	.31

Table 5. Means, *p*-values, and effect size for natural and urban scenes in Experiment 3.

Measure	***M* (Early)**	***M* (Late)**	***p***	***d***
Microsaccade slope	0.92 (0.04)	0.80 (0.04)	.023	.33
Microsaccade rate	0.37 (0.04)	0.48 (0.05)	.014	.36
Blinks	5.7 (0.6)	5.8 (0.6)	.82	.03

Table 6. Means, *p*-values, and effect size for early and late trials in Experiment 3.

4.4.1 Fixation count and saccade count

A paired *t*-test revealed a significant effect of scene type on fixation count ($t(50) = 3.44$, $p = .001$, $d = .48$), with fewer fixations on natural scenes ($M = 46.4$) than urban scenes ($M = 48.0$). Exploratory comparisons ($\alpha = .025$) examined differences by scene category (Figure 14). There were no significant differences between water and greenery scenes (*M*s = 46.9, 46.1, $t(50) =$

1.18, *p* = .24, *d* = .17), but there were significantly more fixations on historic architecture (*M* = 49.8) than modern architecture (*M* = 46.1), *t*(50) = 6.26, *p* < .001, *d* = .88.

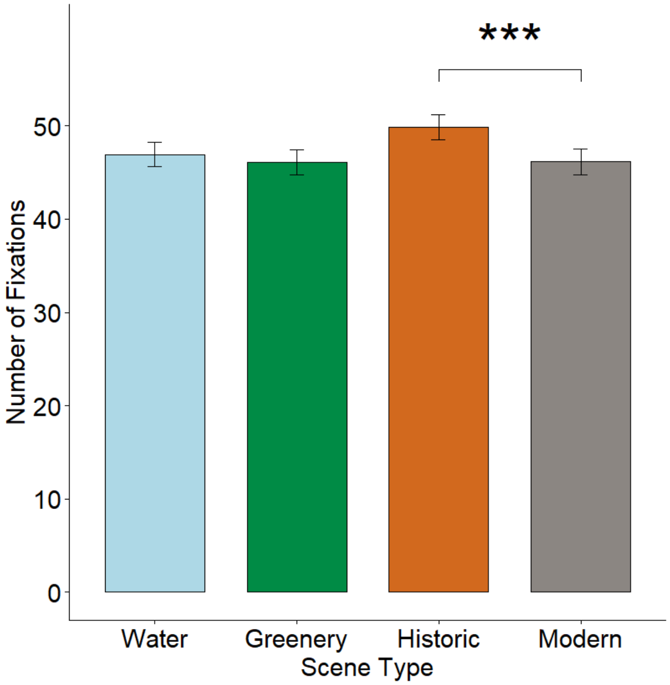

Figure 14. Fixation count by scene type. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error. *** represents *p* < .001.

A paired *t*-test did not find any significant effect of scene type on saccade count (*t*(50) = 0.22, *p* = .82, *d* = .03). Natural scenes (*M* = 48.3) did not significantly vary from urban scenes (*M* = 48.4). Exploratory comparisons (α = .025) found no significant differences between water and greenery scenes (*M*s = 49.0, 47.8, *t*(50) = 1.85, *p* = .071, *d* = .26), while historic architecture (*M*

= 49.2) had significantly more saccades than modern architecture (*M* = 47.6), *t*(50) = 3.05, *p* = .004, *d* = .43.

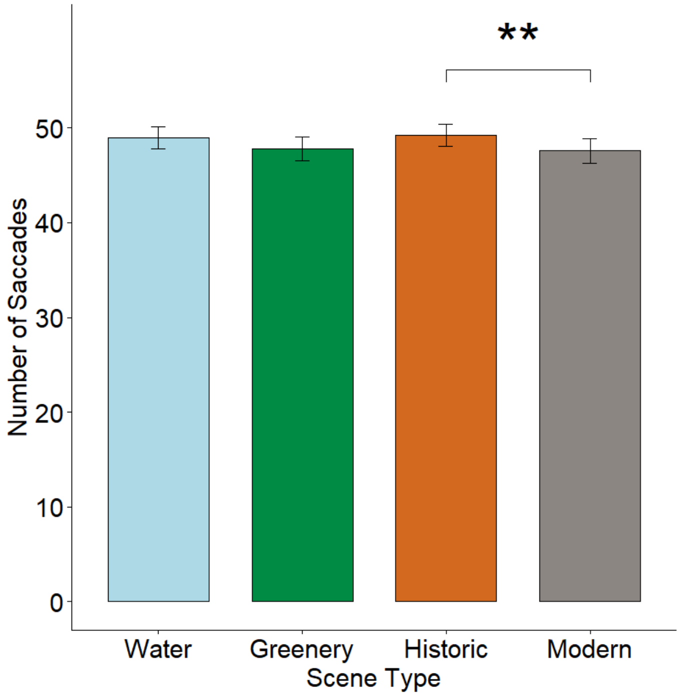

Figure 15. Saccade count by scene type. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error. ** represents *p* < .01.

4.4.2 Fixation duration

Consistent with experiments 1 and 2, a paired *t*-test found that fixation durations were significantly longer for natural (*M* = 282.7 ms) scenes compared to urban (*M* = 274.7 ms) scenes, *t*(50) = 4.26, *p* < .001, *d* = .60. Exploratory comparisons (α = .025) found that fixation durations were significantly shorter for water compared to greenery (*M*s = 279.2, 285.2 ms, *t*(50) = 2.62, *p*

= .012, *d* = .37), and shorter for historic (*M* = 268.5 ms) than modern (*M* = 281.0 ms) scenes, *t*(50) = 5.23, *p* < .001, *d* = .73.

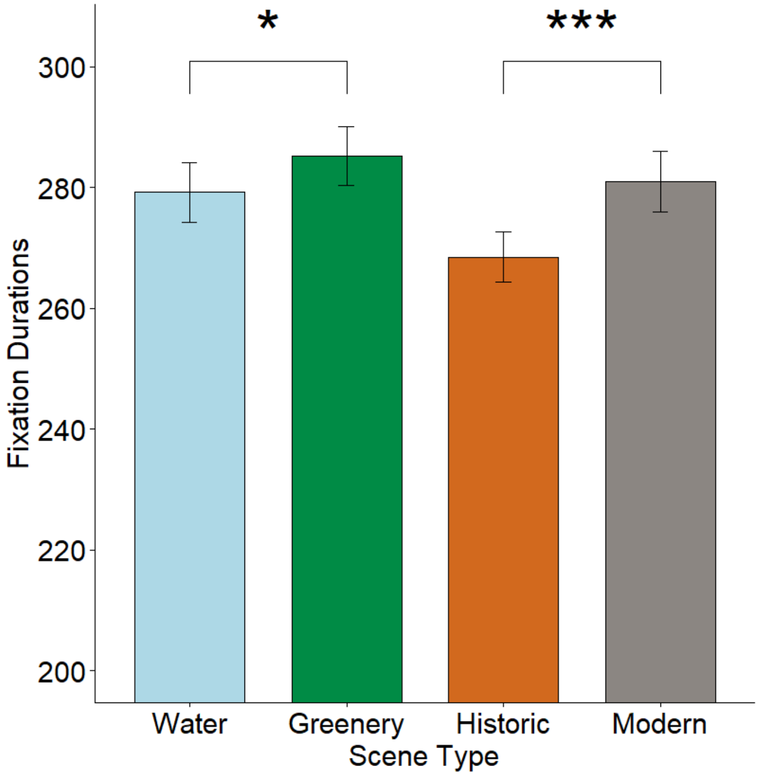

Figure 16. Mean fixation durations by scene type. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error. * represents *p* < .025, *** represents *p* < .001.

4.4.3 Saccade amplitude

Consistent with experiments 1 and 2, a paired *t*-test found that mean saccade amplitudes were significantly larger for natural (*M* = 7.0°) scenes compared to urban (*M* = 6.8°) scenes, *t*(50) = 2.13, *p* = .038, *d* = .30. Exploratory comparisons (α = .025) found that water scenes involved larger saccades than greenery (*Ms* = 7.1, 6.8°, *t*(50) = 3.01, *p* = .004, *d* = .42), while historic (*M* = 6.7°) and modern (*M* = 6.9°) scenes did not significantly vary, *t*(50) = 1.95, *p* = .056, *d* = .27.

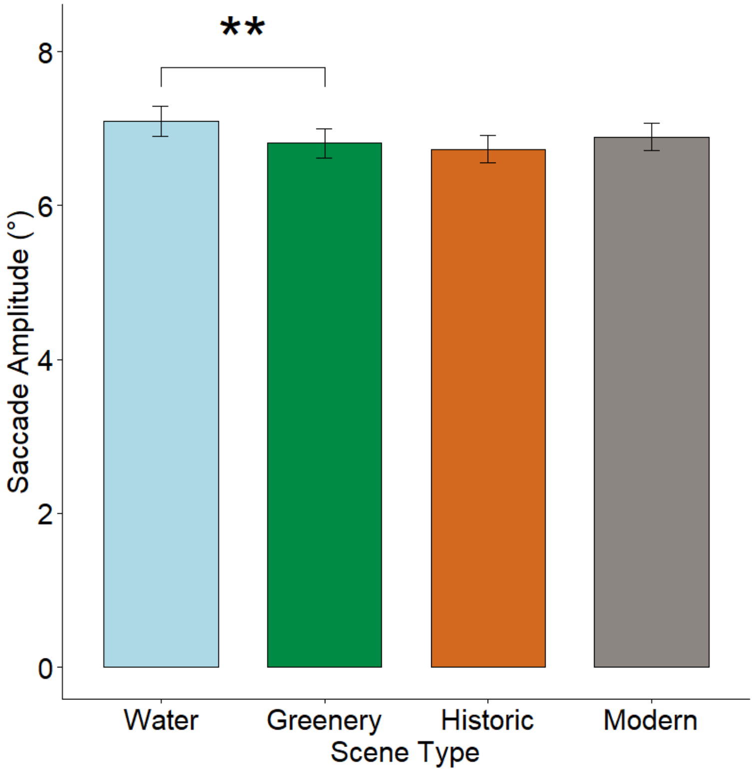

Figure 17. Mean saccade amplitudes by scene type. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error. ** represents *p* < .01.

4.4.4 Pleasantness

Consistent with experiment 2, natural scenes (*M* = 5.3) were more pleasant than urban scenes (*M* = 4.6), *t*(50) = 6.75, *p* < .001, *d* = .94. Water scenes (*M* = 5.1) were less pleasant than greenery (*M* = 5.5) scenes (*t*(50) = 3.11, *p* = .003, *d* = .44), while historical scenes were more pleasant (*M* = 4.8) than modern (*M* = 4.3) scenes, *t*(50) = 3.82, *p* < .001, *d* = .54.

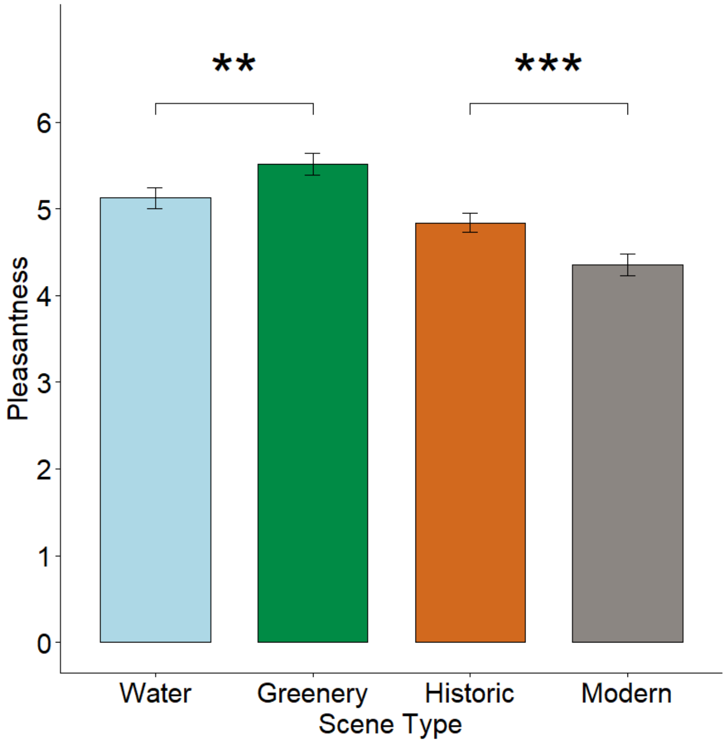

Figure 18. Ratings of pleasantness by scene type. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error. ** represents *p* < .01, *** represents *p* < .001.

Correlation analyses tested relationships between eye movement metrics and pleasantness using data from all valid trials. Pleasantness was not significantly correlated with fixation durations (*r* = .01, *p* = .77), saccade count (*r* = .05, *p* = .085), or microsaccade rate (*r* = -.03, *p* = .22). However, pleasantness was positively correlated with fixation count (*r* = .06, *p* = .030), negatively correlated with saccade amplitudes (*r* = -.12, *p* < .001), and negatively correlated with blink rate (*r* = -.07, *p* = .007). Exploratory analyses (α = .025) tested whether correlations between eye movement metrics and pleasantness varied between natural and urban scenes (Figures 19-23). A Fisher's Z-transformation test indicated significant differences between the correlations between pleasantness and fixation durations for natural (*r* = .05, *p* = .16) and urban (*r* = -0.10, *p* = .011) scenes, *p* = .005. Correlations between pleasantness and microsaccade rate significantly differed between natural (*r* = -.08) and urban (*r* = .05) scenes, *p* = .016. There were no significant durations between correlations for fixation count, saccade amplitude, or blink rate (all *p*s > .19).

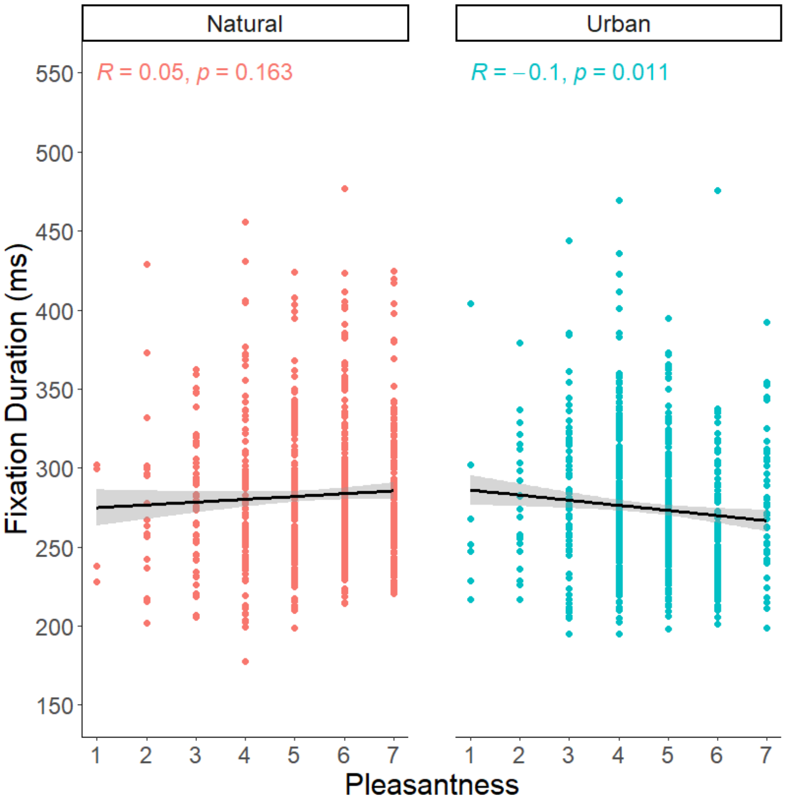

Figure 19. Fixation durations by pleasantness. Red dots represent natural scenes, while blue dots are urban scenes. Correlation line in black, with standard error in grey.

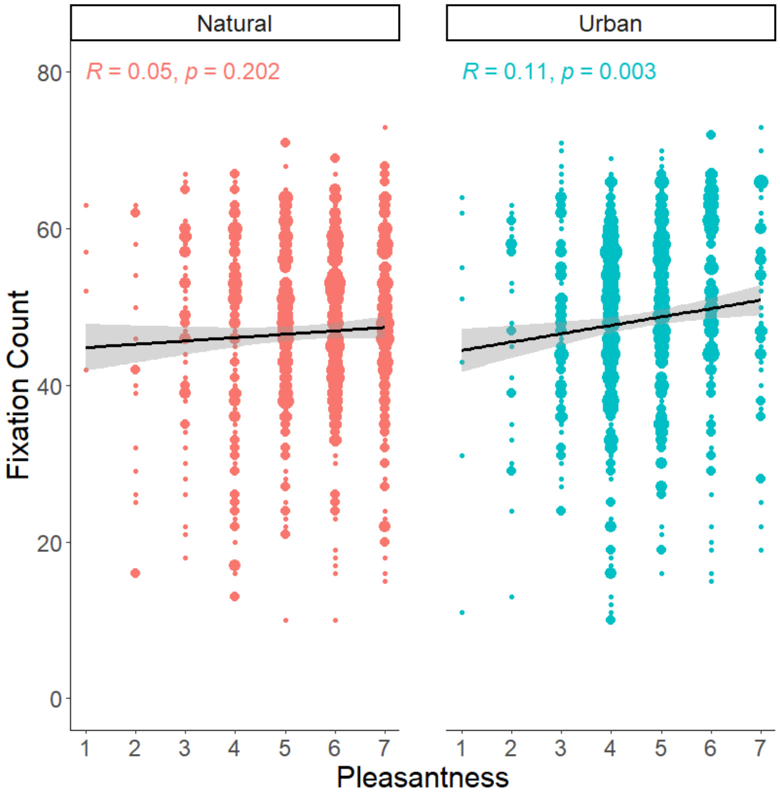

Figure 20. Fixation count by pleasantness. Red dots represent natural scenes, while blue dots are urban scenes. Larger dots represent more frequent occurrences. Correlation line in black, with standard error in grey.

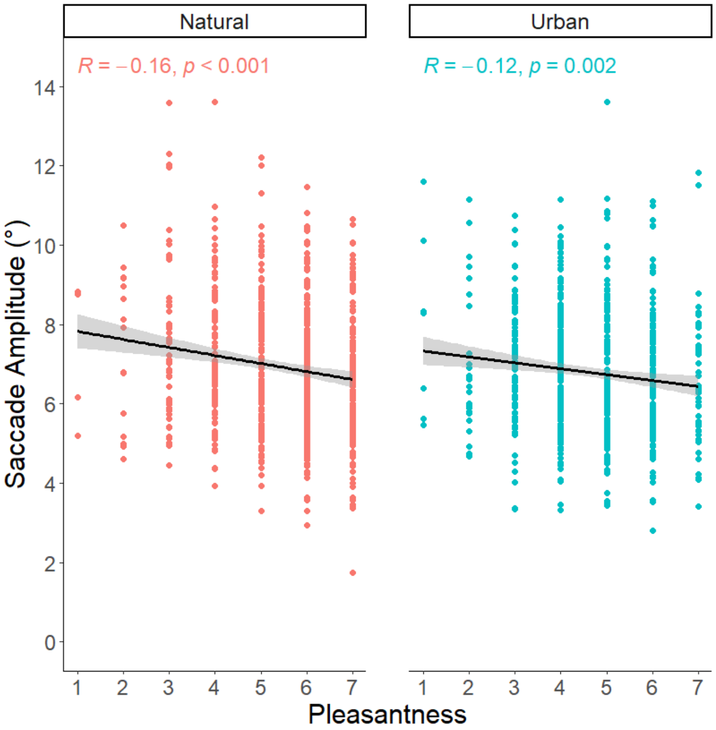

Figure 21. Saccade amplitude by pleasantness. Red dots represent natural scenes, while blue dots are urban scenes. Correlation line in black, with standard error in grey.

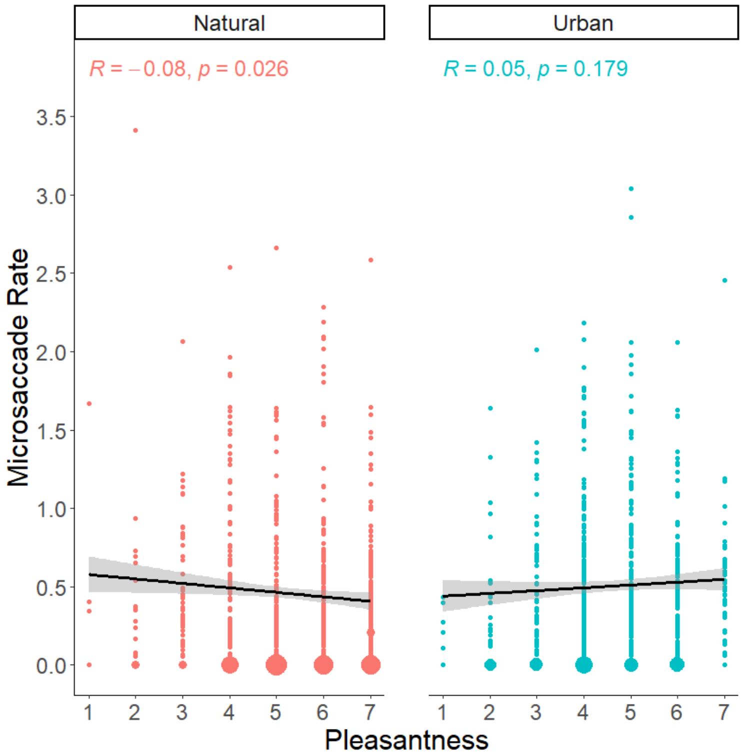

Figure 22. Microsaccade rate by pleasantness. Red dots represent natural scenes, while blue dots are urban scenes. Correlation line in black, with standard error in grey.

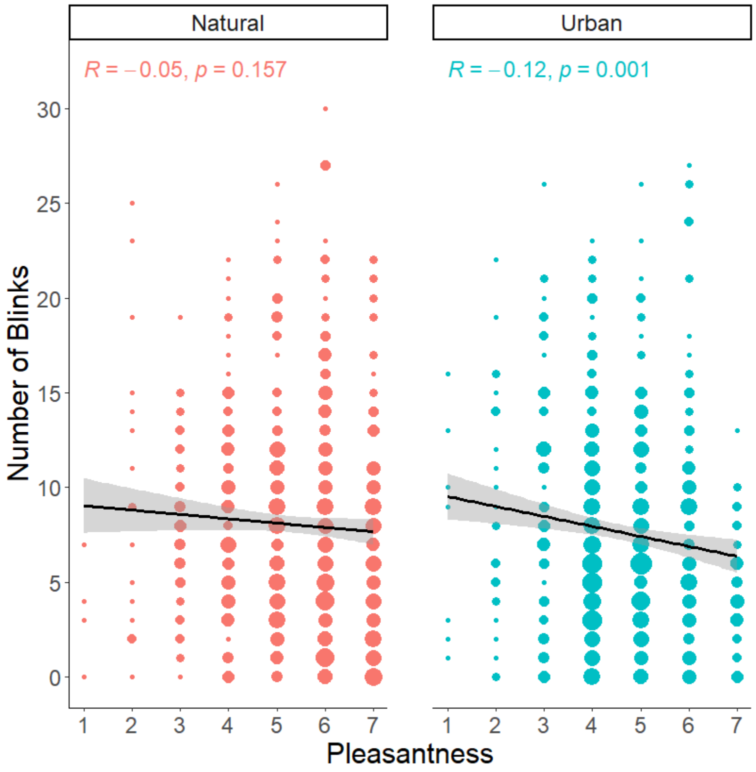

Figure 23. Blink rate by pleasantness. Red dots represent natural scenes, while blue dots are urban scenes. Larger dots represent more frequent occurrences. Correlation line in black, with standard error in grey.

4.4.5 Microsaccade slope

Microsaccade peak velocity-magnitude relationship slopes were analyzed using the same approach as experiment 2. Figure 24 depicts the slopes of the relationship between microsaccade magnitude and peak velocity, showing a similar pattern to experiment 2. One participant did not make enough microsaccades during early trials to estimate this slope and was excluded from this analysis. As predicted, microsaccade slopes significantly decreased during late trials ($M = 0.80$)

compared to early trials (*M* = 0.92), *t*(49) = 2.34, *p* = .023, *d* = .33. Microsaccade slopes were significantly lower for natural scenes (*M* = 0.86) compared to urban scenes (*M* = 0.95), *t*(50) = 2.70, *p* = .009, *d* = .38. Exploratory comparisons (α = .025) found no significant differences in microsaccade slopes between water and greenery scenes (*M*s = 0.87, 0.89, *t*(50) = 0.54, *p* = .59, *d* = .08). However, microsaccade slopes were significantly higher for historic architecture (*M* = 0.98) than modern architecture (*M* = 0.89), *t*(50) = 2.42, *p* = .019, *d* = .34. Figure 25 depicts microsaccade slopes for different scene categories.

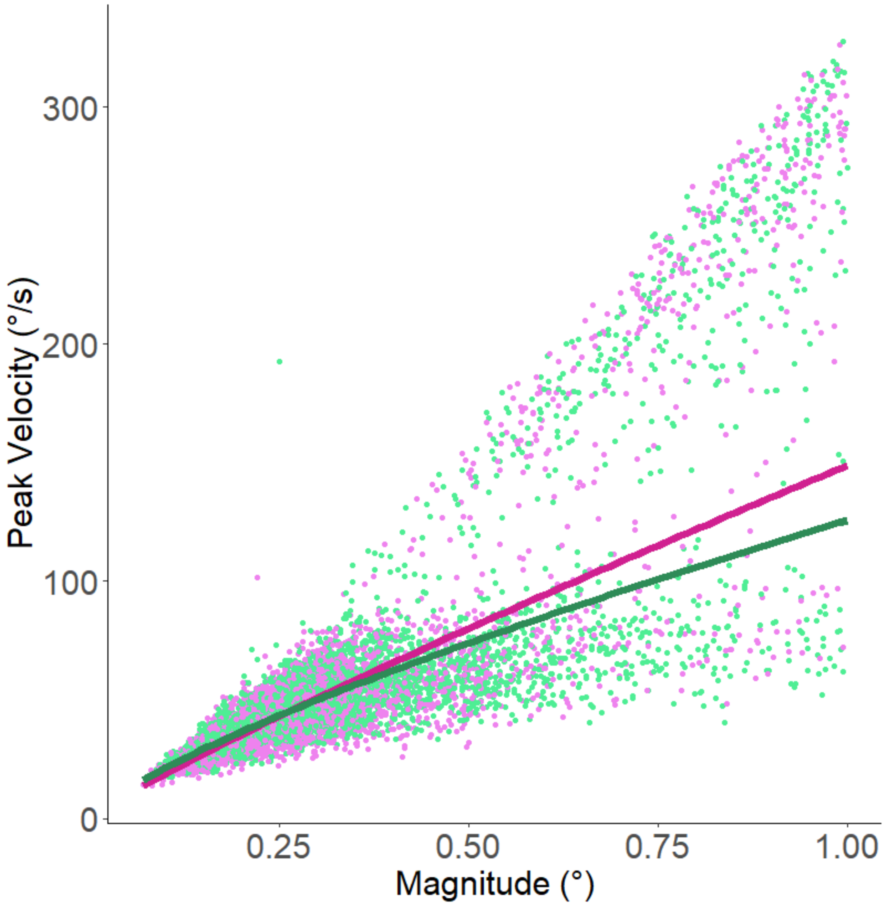

Figure 24. Effect of time in the experiment on the microsaccade peak velocity-magnitude relationship. Purple dots indicate early trials (the first sixth of the experiment) while green dots indicate late trials (the last sixth of the experiment). Each dot represents one microsaccade. The curves are power law fits for early and late trials across all participants.

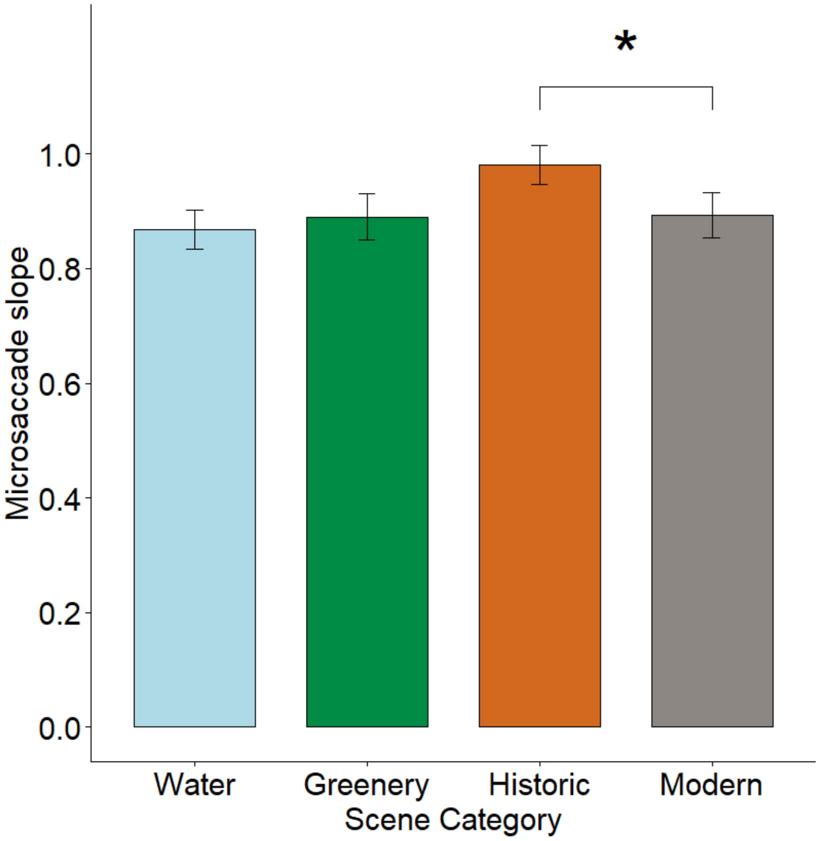

Figure 25. Microsaccade peak velocity-magnitude slopes by scene category. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error. * represents $p < .025$.

4.4.6 Microsaccade rate

Scene type had a significant effect on microsaccade rates (*t*(50) = 2.33, *p* = .024, *d* = .33). Microsaccade rates were lower for natural scenes (*M* = 0.46) than urban scenes (*M* = 0.51). Microsaccade rates were broadly smaller in experiment 3 than experiment 2, yet natural scenes continue to vary from urban scenes. Exploratory tests (α = .025) found no significant differences in microsaccade rates between water (*M* = 0.46) and greenery (*M* = 0.46) scenes, *t*(50) = 0.15, *p* = .88, *d* = .02. There were also no significant differences between historic architecture (*M* = 0.54) and modern (*M* = 0.50) architecture, *t*(50) = 1.33, *p* = .19, *d* = .19. See Figure 26 for microsaccade rates by scene category.

Microsaccade rates were higher during late trials (*M* = 0.48) than early trials (*M* = 0.37), *t*(50) = 2.54, *p* = .014, *d* = .36. As with experiment 2, microsaccade rate was negatively correlated with fixation durations (*r* = -.14, *p* < .001). However, microsaccade rate was positively correlated with saccade amplitudes (*r* = .09, *p* < .001), and was not significantly correlated with fixation count (*r* = -.01, *p* = .68). In experiment 2, microsaccade rate was inversely correlated with both saccade amplitudes and fixation count.

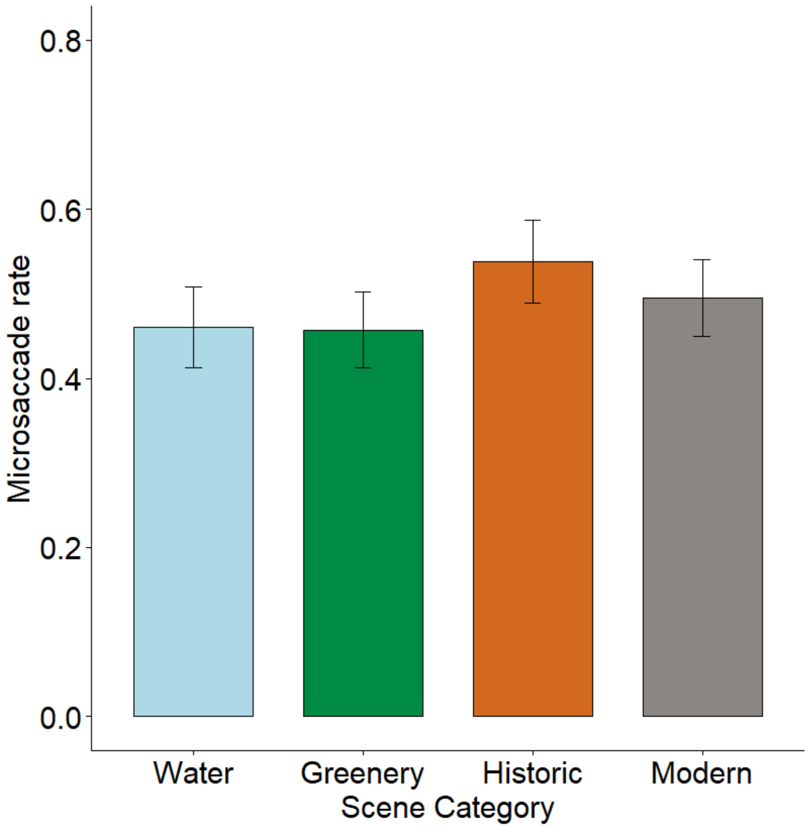

Figure 26. Microsaccade rate by scene category. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error.

4.4.7 Blink rate

Natural scenes (*M* = 8.2) involved significantly more blinks than urban scenes (*M* = 7.7), *t*(50) = 2.23, *p* = .031, *d* = .31. Exploratory tests (α = .025) found that blink rates for water (*M* = 8.2) vs. greenery (*M* = 8.0) scenes (*t*(50) = 1.05, *p* = .30, *d* = .15), and historic (*M* = 7.6) vs. modern (*M* = 7.9) scenes did not significantly differ (*t*(50) = 0.86, *p* = .49, *d* = .12). Surprisingly, blink rates during early trials (*M* = 5.7) did not significantly differ from late trials (*M* = 5.8), *t*(50) = 0.22, *p* = .82, *d* = .03.

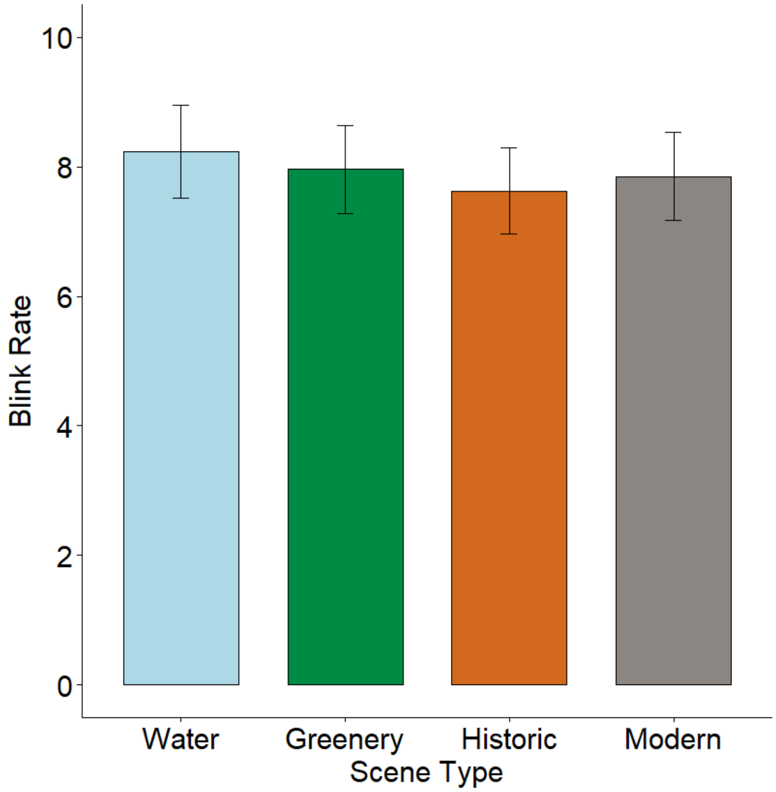

Figure 27. Blink rate by scene category. Blue bars indicate water, green for greenery, orange for historic architecture, and grey for modern architecture. Error bars indicate one standard error.

4.5 Discussion

In experiment 3, I found that differences between natural scenes and urban scenes in visual exploration remained significant when using colour stimuli instead of black-and-white scenes. Natural scenes elicited fewer fixations, longer fixation durations, and larger saccade amplitudes. I found no significant differences between water and greenery scenes on fixation count, saccade count, or microsaccade rates. Water scenes involved shorter fixations and larger saccades than greenery scenes. Scenes with greenery were preferred to scenes with water. This contrasted with previous work (White et al., 2010), where scenes with water are preferred. One potential cause is the duration of presentation – 20 seconds is long enough for participants to both appreciate a scene with water, but also want to look at something with more detail. Naturalness is an appreciated quality by participants, as is detail and visual complexity. While scenes with water did not vary in fractal dimension from greenery, they may have included less details for participants to examine during the 20 second viewing period, thus leading to less appreciation. For urban scenes, as predicted, scenes with historic architecture were preferred to modern architecture, consistent with research using virtual environments (Mouratidis & Hassan, 2020). Historic architecture involved larger microsaccade slopes than modern architecture, indicating that people were less fatigued while viewing historic scenes. As a whole, urban scenes involved larger microsaccade slopes and smaller blink rates than natural scenes. Unlike the predictions of ART, this data suggests that people are less fatigued while viewing urban scenes. Historic architecture involved more fixations, more saccades, shorter fixations, and more microsaccades than modern architecture. One of the advantages of historic architecture is its richness in ornamentation, often involving highly complex and visually interesting patterns. In experiment 2, images with higher fractal complexity were associated with higher pleasantness, especially for urban scenes. However, it is difficult to argue that fractal complexity explains the difference in preference or visual exploration for historic architecture over modern architecture in experiment 3, since the fractal complexity of historic and modern scenes did not vary in this study. Even when holding fractal complexity constant, historic architecture is preferred to modern architecture. This is similar to experiment 2, where natural scenes were preferred to similarly complex urban scenes and involved a different pattern of visual exploration. The main difference is that historic architecture involved more fixations than modern architecture, while in experiment 2 natural scenes involved fewer fixations than urban scenes.

4.5.1 Visual exploration

Experiment 3 provided more evidence about the relationship between visual exploration patterns and affective processing. There were significant correlations between eye movement metrics and ratings of pleasantness, unlike experiment 2 where only microsaccade rate was significantly correlated with pleasantness. The fixation count was positively correlated to perceived pleasantness of a scene, as in experiment 1. Pleasantness was also negatively correlated with saccade amplitude and blink rate. As in Experiment 2, there was no correlation between fixation duration and pleasantness. However, natural scenes and urban scenes varied significantly in how fixation duration related to pleasantness. For natural scenes, there was a significant inverse relationship between fixation duration and pleasantness, while for urban scenes, this relationship was in the opposite direction, though not significant. One difference between experiment 3 and experiment 2 (which found no relationship between visual exploration and preference) and experiment 1 (where only fixation counts and saccade counts were related to preference) is the use of colour stimuli instead of black-and-white scenes. That stated, ratings of preference for natural (*M*s = 5.1, 5.3, 5.3) and urban (*M*s = 4.6, 4.6, 4.6) scenes were remarkably consistent across experiments 1-3.

However, the correlations found in this study contradicted the claims made by attention restoration theory in relation to visual exploration. According to ART theorists, scenes higher in fascination involve a lower fixation count, due to having fewer distractions present (Berto et al., 2008). Experiment 3 found the opposite, that pleasant scenes were associated with a higher fixation count. This finding was consistent with face processing studies (Leder et al., 2016; Silva et al., 2016), and landscape studies (Huang & Lin, 2020; Scott et al., 2020). Moreover, the experiment contradicted the claim that longer average fixations represent greater liking for a stimulus (Leder et al., 2016; Scott et al., 2020), and its interpretation in the ART literature to indicate that natural scenes are fixated for longer because of greater aesthetic appreciation (Franek et al., 2018). In experiments 1-3, there was no correlation between fixation duration and pleasantness of a scene. Moreover, for natural scenes, I found in experiment 3 that appreciation is negatively correlated with fixation duration. One possible reason why this study varied from previous studies (Leder et al., 2016; Scott et al., 2020) on the relationship between fixation durations and affective processing is because their high-beauty images involved images with species of fish and turtles, or attractive human faces, whereas all images in my study were devoid of either animal or human life. Animals and faces are natural objects of interest where people make longer fixations. Interesting scenes in those studies would involve longer fixations on animals or faces, while in my study, visual exploration on pleasant landscapes did not have those focal objects of interest for extended fixation.

4.5.2 Microsaccades, blink rate, and fatigue/sleepiness

Results for microsaccadic measures in experiment 3 were consistent with experiment 2. I once again show a time-on-task effect for microsaccade slopes, indicating increased fatigue as people reach the latter period of the study. Microsaccade slopes were also significantly lower when viewing natural scenes compared to urban scenes. In experiment 2, the difference between natural and urban scenes on microsaccade slopes was not significant, but it was in the same direction. The magnitude of this effect in experiment 2 ($d = .25$) was smaller than experiment 3 ($d = .38$). Consistent with the data on microsaccade slopes, blink rates were significantly higher when viewing natural scenes compared to urban scenes, as in experiment 1. In experiment 2, the blink rate difference was not significant, but it was in the same direction ($d = .24$ vs. $d = .31$ in experiment 3). Based on these results, I argue that exposure to nature by looking at images on a computer for a long period of time can reduce levels of arousal and/or induce drowsiness. Increased blink rate is associated with drowsiness and reduced arousal (Abe et al., 2011; Barbato et al., 2000; Barbato et al., 2007; Crevits et al., 2003; Shiferaw et al., 2018; Slama et al., 2018). Converging evidence for nature's effect on reducing arousal comes from studies measuring heart rate (Benz et al., 2022; Lanki et al., 2017; Laumann et al., 2003), and skin conductance (Korpilo et al., 2024; Ulrich et al., 1991; Valtchanov et al., 2010). The decrease in microsaccade slopes when viewing nature – an indicator of fatigue – is consistent with a reduction in arousal. There is also a time-on-task effect for microsaccade rate, with both experiments 2 and 3 showing an increase in microsaccade rate over time. A number of previous studies also find an increase in microsaccade rate by time-on-task (Chen et al., 2021; Di Stasi et al., 2015; Siegenthaler et al., 2014), while one finds a null effect (Di Stasi et al., 2013). Interestingly, I found in both experiments 2 and 3 an effect where there was a higher microsaccade rate on urban scenes than natural scenes. While some previous studies relate microsaccade rates to visual load (Benedetto et al., 2011; Krueger et al., 2019; Schneider et al., 2019) or cognitive load (Dalmaso et al., 2017; Gao et al., 2015; Schneider et al., 2019; Siegenthaler et al., 2014), I argue that neither explanation fits the present results. It is difficult to argue for visual load as the explanation, since complexity in experiment 2 was not significantly related to microsaccade rates. In a free-viewing task, the cognitive load of viewing an urban scene also should not be noticeable different from viewing a natural scene, as participants are free to look at anything that they wish and are not instructed to do anything specific. There are no additional demands on memory, or deeper cognitive reflection required in a free-viewing task. In both experiments 2 and 3, microsaccade rates across all scenes were inversely correlated with fixation durations. In experiment 2, they were inversely correlated with saccade amplitudes, but the opposite pattern occurred in experiment 3. Meanwhile, microsaccade rates did not significantly correlate with fixation count in experiment 3, after being inversely correlated with fixation count in experiment 2. More data are necessary to clarify the relationship between microsaccade rate and visual exploration. This relationship is important because one possibility is that microsaccade rates are higher for urban scenes because of the underlying patterns in visual exploration involved in viewing urban scenes. Since microsaccades are higher in regions of a scene that are more informative (McCamy et al., 2014), microsaccade rate might be higher for urban scenes because they are more content-dense, containing more objects and less open space.

4.5.3 Eye-tracking and visual preference

Eye-tracking studies comparing natural and urban scenes show that visual exploration of natural scenes varies from urban scenes. The experiments in my dissertation expanded on the literature by employing different eye movement metrics, providing further evidence. I argue that previous studies err in their claims connecting differences in visual exploration to preference. Berto's (2008) highly influential study argues that fixation count is smaller for high fascination scenes because those scenes are 'viewed with less effort' and suggests that a higher fixation count on low fascination scenes indicates an inability to disengage from distractions. The optimal approach is to empirically correlate eye movement metrics with preference data. Experiments 1-3 showed an entirely different pattern than what differences in visual exploration suggested. Natural scenes involved fewer fixations, longer fixations, and larger saccades than urban scenes. People had greater aesthetic appreciation of natural scenes than urban scenes. However, aesthetic appreciation in experiment 2 had a null relationship to all these eye movement metrics, while in experiments 1 and 3, preference was positively correlated with a higher fixation count. Other studies measuring preference for natural scenes find a positive correlation between fixation count and aesthetic preference (Huang & Lin, 2020; Scott et al., 2020) or a null effect (Liu et al., 2021). Moreover, the data on fixation count for experiments 1 and 3 were consistent with that found in the face processing literature, where attractive faces are fixated more frequently (Leder et al., 2016; Silva et al., 2016). If attention restoration theory is to be invoked to explain differences in fascination or preference when viewing stimuli, it should use data directly correlating preference with eye movement behaviour. The claim that longer fixations on natural scenes represents greater liking (Franek et al., 2018) is not supported by any of experiments 1-3. Other studies (Huang & Lin, 2020; Liu et al., 20201) also report a null finding for the relationship between scene preference and fixation duration. In experiment 3, preference was inversely correlated with the size of saccade amplitudes. This is the opposite pattern from what is found between natural and urban scenes, where natural scenes involve a smaller fixation count and greater saccade amplitude.

A remaining challenge is explaining why natural scenes involve smaller fixation counts, longer fixations, and larger saccades, if this is not particularly related to affective processing. The data from these experiments pose further questions. Even while including fractal complexity as a measure being manipulated in experiment 2, these differences in visual exploration remained between natural and urban scenes. Neither is the variety of colours present in natural and urban scenes the cause, as using colour scenes in experiment 3 instead of black-and-white scenes did not change differences in exploration. None of the scenes in any of these experiments have human beings or animals present in them, so visual processes related to viewing faces or creatures are not a factor.

Chapter 5: Experiment 4 – Visual exploration and depleted attention

5.1 Introduction

One possible reason why my experiments do not show the same relationship between visual exploration and affective measures as what Berto et al. (2008) proposes is because the attention restoration effect requires attention to be depleted in the first place. For natural stimuli to restore attentional resources, a depletion of attention has to occur first. In experiments 1-3, there was only one continuous task, that is, viewing scenes for 20 seconds at a time. The effect of nature on attention, and its relationship with affective processing, may be different when people's attentional resources are fatigued.

5.1.1 Attention restoration and the SART

One highly influential study (Berto, 2005) argues that merely viewing natural scenes can restore depleted attention capacity, compared to viewing urban scenes. For experiment 1 in that study, participants first completed 240 SART (Sustained Attention to Response Task) (Robertson et al., 1997) trials, followed by viewing either 25 restorative or nonrestorative images on a computer screen for 15 seconds each, followed by another set of 240 SART trials. Images were rated by a separate group of participants using the Perceived Restorativeness Scale to create restorative and nonrestorative image categories. The main finding from the study is that reaction times for the SART decreased after viewing natural scenes, a major finding that has been cited (as of writing) almost two thousand times. Berto (2005) argues that improved reaction times on this sustained attention task reflect restoration of initially depleted attentional resources after exposure to nature. Several follow-up studies have found mixed results for similar studies about viewing nature on restoring attention or direct replications, with some studies finding a similar effect (Lee et al., 2015) and other studies showing null results (Cassarino et al., 2019; Hicks et al., 2020; Neilson et al., 2021).

Other than the replicability of the results from Berto (2005), one can challenge the methodology itself. In this paradigm, the SART is a task measuring attention and it is also the task that depletes attention. One possibility is that participants' reactions after viewing nature have more to do with the attentional differences caused by undergoing the SART than anything specific about the natural or urban scene they had previously viewed. If the SART depletes attention, then by measuring the SART after viewing nature, what is being measured is a period in which attention is bound to decline. If SART performance is better after viewing nature vs. urban scenes, there could be several possible mechanisms. Viewing nature could increase the amount of attentional resources present before doing the SART. Alternatively, nature might increase resilience when carrying out the sustained attention task. Yet another possibility is that attentional resources might be restored by the act of viewing natural scenes, but in a temporary way. Any temporary change in attention or fatigue would not be captured by a test that occurs after viewing a natural or urban stimulus. If the goal is to measure changes in attention, it would be much better to use a measure of attention that can be gathered while people are viewing the natural or urban stimulus, rather than after that experience.

5.1.2 Eye movements during the SART

In the previous experiments in my dissertation, I have related measures from eye movements to visual exploration and arousal during natural and urban scene viewing. I have also shown that time-on-task effects indicating fatigue during scene viewing can be indexed using microsaccade slopes, replicating work from other studies which used a variety of different tasks (Chen et al., 2021; Di Stasi et al., 2013; Siegenthaler et al., 2014). In experiments 1-3, I demonstrated how eye movements differ between viewing natural and urban scenes, and how they related to both affective judgments and time-on-task fatigue effects. The purpose of experiment 4 was not to replicate Berto's (2005) study of attention restoration using the SART; this would require a greater sample size than what my study involved. Instead, the purpose of the experiment was to use eye tracking to measure changes in fatigue and arousal during a fatiguing task (the SART) and any differences caused by viewing natural and urban videos afterwards. A plethora of studies have employed eye movement measures such as blink rate or microsaccade slopes to measure changes in fatigue and arousal using diverse tasks such as driving (Di Stasi et al., 2015; Shiferaw et al., 2018; Stern, 1994), flying aircraft (Morris & Miller, 1996; Qin et al., 2020; Stern & Skelly, 1984), or cognitive tasks in the laboratory (Crevits et al., 2003; Siegenthaler et al., 2014; Slarna et al., 2018). A major goal of experiment 4 was to apply these well-validated eye movement measures to the SART experience. Would the SART cause changes in eye movements related to fatigue? Were these time-on-task changes similar to what experiments 1-3 showed while people passively view scenes? Moreover, would differences between scene exploration and its relationship to affective processing remain when scenes are viewed after people are fatigued?

This study expanded on the Berto (2005) methodology by using eye movements as measures of visual exploration and fatigue while people are looking at different scene content, rather than just measuring changes in the SART afterwards. I measured fatigue while people are looking at nature or urban videos. Due to the vast differences in visual exploration between free-viewing scenes and a sustained attention task where focus is on a centrally presented number, it would not have been meaningful to compare fixation durations, saccade amplitudes, or fixation counts between looking at videos and performing the SART. By virtue of the task, the SART would have involved longer fixations, shorter saccades, and less frequent fixations. The eye movement data I focused on when comparing the SART to videos in experiment 4 were microsaccadic slopes and blink rate. One important factor is that the previous experiments all involved static natural or urban scenes. Maffei & Angrilli (2019) found that when viewing a nature video, blink rates decreased, and arousal was rated relatively neutral. It was important to replicate the differences found in experiments 1-3 using video stimuli, to show that the changes in blink rates or microsaccade slopes while viewing nature were not merely caused by the mode of presentation.

5.2 Hypotheses

Natural scene content should have been preferred to urban scene content. I expected a time-on-task effect, with SART performance being worse for the final SART trial compared to the first SART trial. I also expected microsaccade slopes to decrease over time and an increase in microsaccade rates due to a fatigue effect when undergoing the SART. I expected to replicate the findings from the prior experiments for how fixation count, fixation duration, and saccade amplitude differ between natural and urban scenes.

5.3 Methods

5.3.1 Participants

50 undergraduate students from the University of Waterloo with normal or corrected-to-normal vision participated in the experiment. The study had been approved by a University of Waterloo ethics committee. Eye movement recordings from 1 participant were excluded due to technical issues. Data from 5 participants were excluded due to having too many trials with insufficient fixations (less than 20% of the trial spent fixating), or excessive blinking resulting in unusable microsaccade data, leaving a final sample of 44 participants (79.5% female).

5.3.2 Procedure

Participants completed 225 trials of the SART in 3 blocks, with each block lasting close to 5 minutes. These SART trials involve presentation of a number between 1 and 9, with participants instructed to press the space bar if a non-target number is presented. Participants were instructed to give equal importance to speed and accuracy during the task. Figure 28 depicts the order of events in the study. Each number was presented for 250 ms, followed by a mask with a diagonal cross for 900 ms. The target was always the number 3. All numbers were presented at an equal frequency with one in nine trials involving the target number. The font size for numbers varied, with 5 possible fonts. The first and second blocks were followed by a 1-minute rest period. After the third block was completed, participants viewed one of two videos of natural or urban scenes on the computer screen, lasting for 5 minutes. They then rated the video on a 7-point scale measuring pleasantness, followed by a 1-minute break. Afterwards, they underwent another 3 blocks of the SART comprising a total of 225 trials, with 1-minute breaks after the fourth and fifth block. Following the last SART block, participants viewed the other video for 5 minutes, followed by the pleasantness scale. The total experiment lasted close to one hour. This study employed a within-subjects design. The order of video presentation (whether a natural video or an urban video was presented first) was counter-balanced between participants. However, due to an error in the counterbalancing, most participants (31 nature vs. 13 urban in the final sample) ended up viewing the natural video first. To account for this, presentation order is included as a variable in tests comparing natural and urban videos.

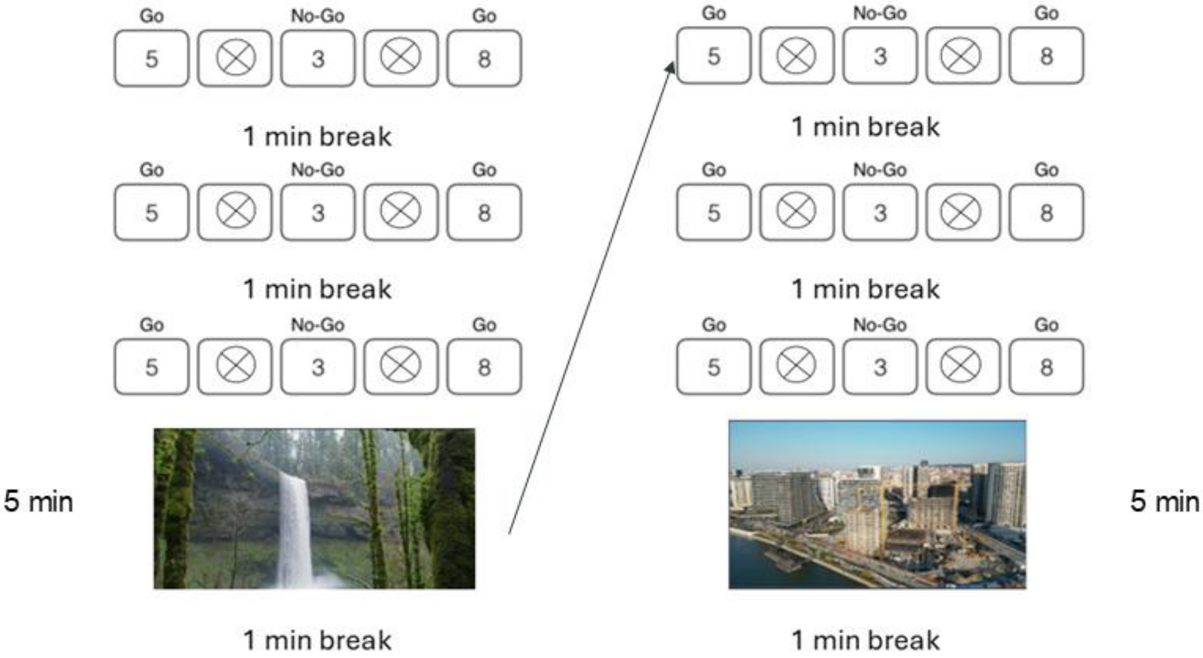

Figure 28. Experiment 4 study flow. Video order was counter-balanced between participants.

5.3.3 Stimuli

One natural and one urban video were created by splicing together 20- to 40-second natural and urban videos taken from Pexels, an online video and photo sharing platform. The natural video included clips of a mountain, the sky, forests, flowers, and bodies of water. The urban video included clips of highways, high-rise buildings in cities, and mid-rise buildings in cities. The natural and urban video were both 5 minutes long.

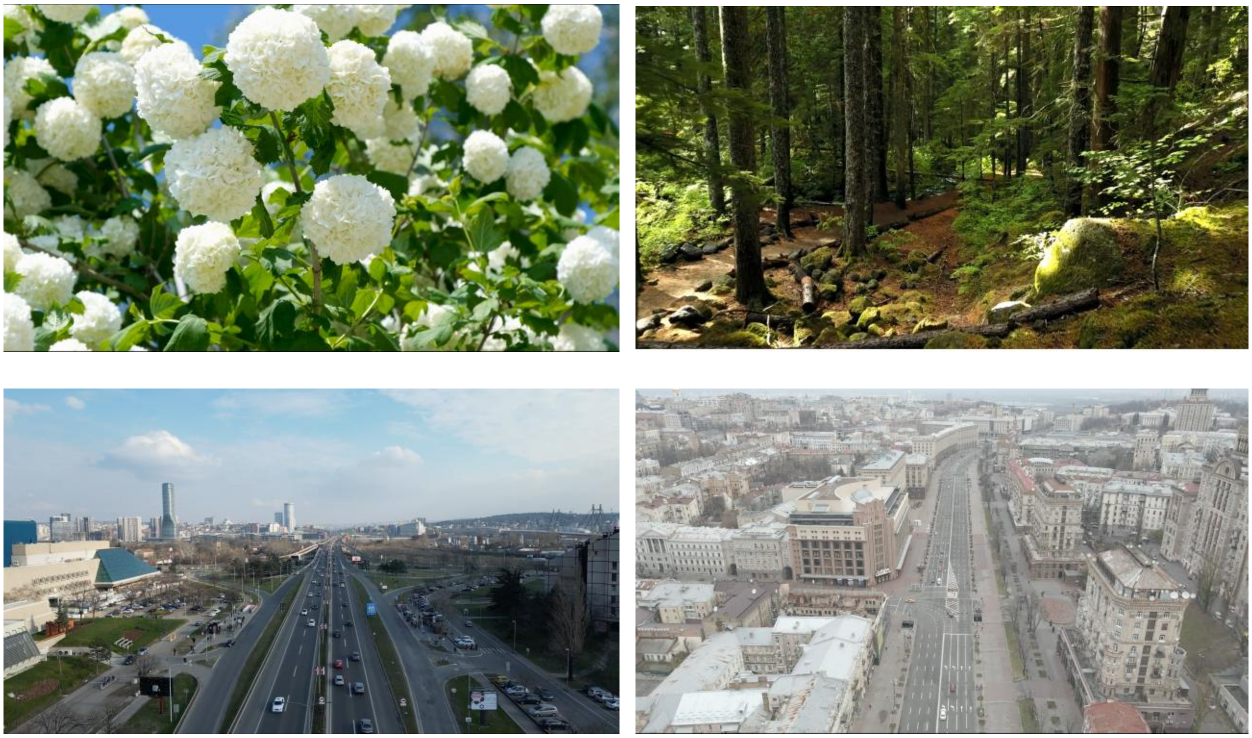

Figure 29. Stills from the Experiment 4 nature (top) and urban (bottom) videos.

5.3.4 Data analysis

As with experiments 1-3, blinks consisted of periods where there was no pupil information. Fixations, saccades, and microsaccades were discarded if they occurred within a 100 ms interval of a blink. In experiments 1-3, fixations shorter than 80 ms or longer than 1000 ms were removed. In this experiment, fixation durations were substantially longer on average during the SART conditions, necessitating a different approach. Fixations longer than 2500 ms or shorter than 80 ms were removed. Unlike experiments 2-3, where trials with a total blink time greater than 25% were excluded, experiment 4 explicitly aimed to induce fatigue in participants. Since fatigue should have been associated with an increased blink rate, the criteria for excluding participants was loosened. For both the SART and the video trials, trials with a total blink time greater than 50% were excluded. One note of the experiment design was that the second video presented was not followed by a subsequent SART block. Analyses of how natural or urban videos affect performance in subsequent SART blocks used between-subjects data (since only the first video was followed by a SART block), while all other analyses were within-subjects.

5.4 Results

Tables 7 and 8 summarize results contrasting natural vs. urban videos, and the first SART block (block 1) vs. the last SART block (block 6). Table 7 reports η^2_p values instead of *d* values since these tests are from two-way ANOVAs.

Measure	***M* (Natural)**	***M* (Urban)**	***p***	**η^2_p**
Fixation count	439.6	596.8	< .001	.62
Saccade count	461.9	583.1	< .001	.55
Fixation duration	385.6	333.5	< .001	.51
Saccade amplitude	6.1°	6.2°	.47	.01
Pleasantness	5.5	4.3	< .001	.31
Microsaccade slope	.88	1.01	.001	.22
Microsaccade rate	.54	.56	.48	.01
Blinks	128.8	104.5	< .001	.31

Table 7. Means, *p*-values, and effect size for natural and urban scenes in Experiment 4.

Measure	***M* (SART 1)**	***M* (SART 6)**	***p***	***d***
Microsaccade slope	1.24	1.21	.45	.12
Microsaccade rate	1.01	1.11	.18	.21
Blinks	71.9	120	< .001	.94

Table 8. Means, *p*-values, and effect size for the first SART block compared to the last SART block in Experiment 4.

5.4.1 Fixation count and saccade count

An ANOVA evaluated the relationship between fixation count and video type, including video presentation order as a variable. As with experiments 1-3, there was a significant effect of video type, with fixation count significantly higher for urban videos (*M* = 596.8) than nature videos (*M* = 439.6), *F*(1,42) = 69.19, $p < .001$, $\eta^2_p = .62$. There was no order effect (*F*(1,42) = 0.28, $p = .60$, $\eta^2_p = .01$) or any interaction between order and video type (*F*(1,42) = 0.19, $p = .66$, $\eta^2_p = .01$). There was a significant effect of video type on saccade count, with more saccades on urban videos (*M* = 583.1) than nature videos (*M* = 461.9), *F*(1,42) = 51.47, $p < .001$, $\eta^2_p = .55$. There was no order effect (*F*(1,42) = 0.31, $p = .58$, $\eta^2_p = .01$) or any interaction between order and video type (*F*(1,42) = 0.19, $p = .68$, $\eta^2_p = .00$).

5.4.2 Fixation durations and saccade amplitudes

Consistent with experiments 1-3, fixation durations were significantly longer for nature videos (*M* = 385.6 ms) than urban videos (*M* = 333.5 ms), *F*(1,42) = 44.41, $p < .001$, $\eta^2_p = .51$. There was no significant order effect (*F*(1,42) = 0.09, $p = .76$, $\eta^2_p = .00$). There was a significant interaction between order and video type (*F*(1,42) = 4.58, $p = .038$, $\eta^2_p = .10$). Examining the interaction, I found no significant effect of order on fixation durations for the nature video (*F*(1,42) = 0.95, $p = .34$, $\eta^2_p = .02$) or for the urban video (*F*(1,42) = 0.39, $p = .53$, $\eta^2_p = .01$).

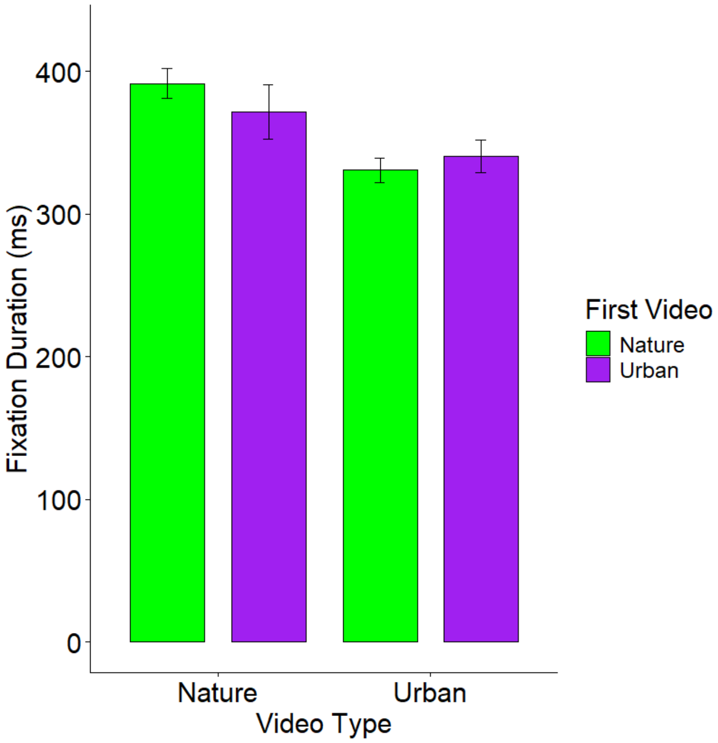

Figure 30. Mean fixation durations for nature and urban videos by viewing order. Green indicates values when the nature video was viewed first, while purple indicates when the urban video was viewed first.

Surprisingly, there were no significant differences in saccade amplitude for nature videos ($M = 6.1°$) when compared to urban videos ($M = 6.2°$), $F(1,42) = 0.54$, $p = .47$, $\eta^2_p = .01$. There was no effect of order ($F(1,42) = 0.02$, $p = .90$, $\eta^2_p = .00$) or interaction effect ($F(1,42) = 0.09$, $p = .77$, $\eta^2_p = .00$) on saccade amplitude.

5.4.3 Pleasantness

As predicted, natural videos (*M* = 5.5) were rated significantly higher on pleasantness (*M* = 4.3) than urban videos, *F*(1,42) = 18.67, $p < .001$, $\eta^2_p = .31$. There was no effect of order (*F*(1,42) = 1.41, $p = .24$, $\eta^2_p = .03$) or interaction effect (*F*(1,42) = 3.20, $p = .081$, $\eta^2_p = .07$) on pleasantness. Correlational analyses tested whether pleasantness ratings for the videos were significantly related to eye movement metrics. Unlike experiments 1-3, pleasantness was positively correlated with fixation duration ($r = .29$, $p = .006$). There were no significant relationships between pleasantness and saccade amplitude ($r = -.18$, $p = .093$), fixation count ($r = -.13$, $p = .23$), saccade count ($r = -.11$, $p = .30$), microsaccade rate ($r = -.07$, $p = .54$), or blink rate ($r = -.08$, $p = .46$). Exploratory analyses ($\alpha = .025$) found that correlations between eye movement metrics and pleasantness did not significantly vary between natural and urban scenes (all *p*s > .17).

5.4.4 Microsaccade slope

Consistent with experiment 3, microsaccade slopes were significantly smaller for nature videos (*M* = 0.88) compared to urban videos (*M* = 1.01), *F*(1,42) = 11.76, $p = .001$, $\eta^2_p = .22$. Order of presentation was not significant, *F*(1,42) = 0.00, $p = .96$, $\eta^2_p = .00$. There was no significant interaction between video type and presentation order, *F*(1,42) = 0.66, $p = .42$, $\eta^2_p = .02$. Figure 31 depicts microsaccade slopes by SART block. Planned contrasts tested differences between the first and third SART block (time-on-task for SART task 1), the fourth and sixth block (time-on-task for SART task 2), and between the first and sixth block for an overall SART time-on-task effect. Microsaccade slopes did not significantly change from block 1 (*M* = 1.24) to block 3 (*M* = 1.23), *t*(43) = 0.43, *p* = .67, *d* = .06. There was no significant change in microsaccade slopes between blocks 4 (*M* = 1.19) and 6 (*M* = 1.21), *t*(42) = 0.71, *p* = .48, *d* = .11. There was also no overall time-on-task effect, with microsaccade slopes not significantly changing from block 1 to block 6, *t*(42) = 0.76, *p* = .45, *d* = .12. Video type did not have a significant effect on microsaccade slopes on a subsequent SART block, *F*(1,42) = 0.03, *p* = .86, $\eta^2_p = .00$.

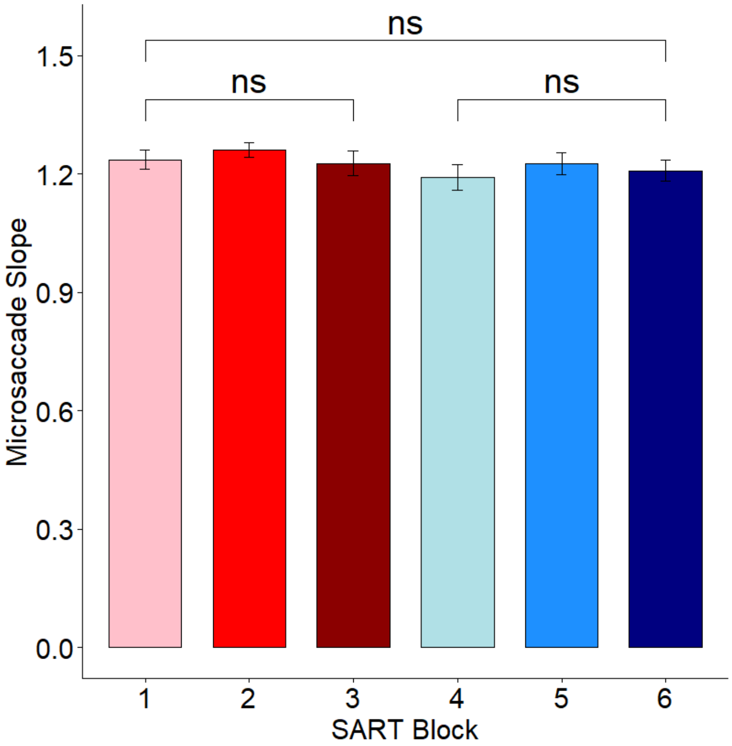

Figure 31. Microsaccade slope during SART blocks.

5.4.5 Microsaccade rate

Unlike experiments 2 and 3, microsaccade rates did not vary significantly between nature videos ($M = 0.54$) and urban videos ($M = 0.56$), $F(1,42) = 0.50$, $p = .48$, $\eta^2_p = .01$. Order of presentation did not have a significant effect, $F(1,42) = 0.02$, $p = .89$, $\eta^2_p = .00$. There was a significant interaction between video type and presentation order, $F(1,42) = 8.51$, $p = .006$, $\eta^2_p = .17$. There was no significant effect of order on microsaccade rate for either the nature video ($F(1,42) = 1.52$, $p = .22$, $\eta^2_p = .04$), or the urban video ($F(1,42) = 0.87$, $p = .36$, $\eta^2_p = .02$). Microsaccade rate was not significantly correlated with fixation durations ($r = -.02$, $p = .89$), saccade amplitudes ($r = .02$, $p = .83$), or fixation count ($r = -.10$, $p = .36$).

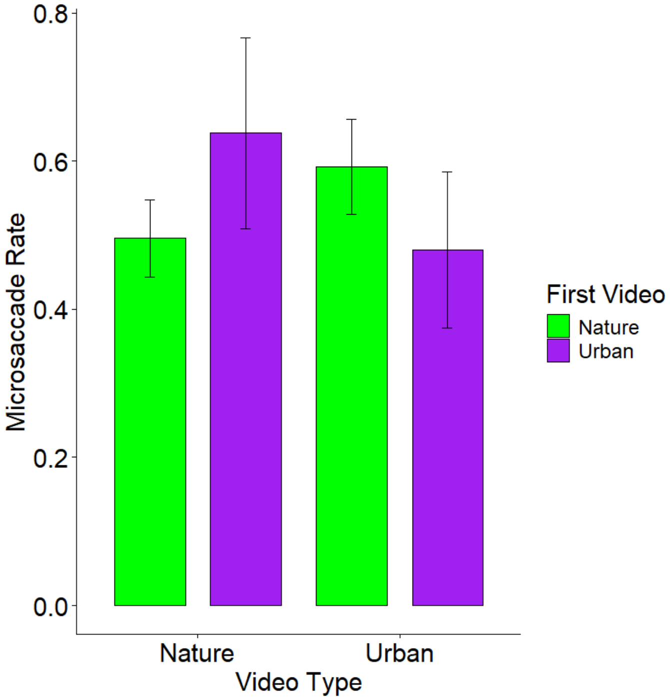

Figure 32. Microsaccade rate for nature and urban videos by viewing order. Green indicates when the nature video was viewed first, purple indicates when the urban video was viewed first.

Figure 33 depicts microsaccade rates by SART block. Planned contrasts tested differences between the first and third SART block, fourth and sixth block, and the first and sixth block. One participant was excluded from the analysis of the sixth block due to excessive blinking (>50%) during that block. Microsaccade rates did not significantly change from block 1 (*M* = 1.01) to block 3 (*M* = 0.96), *t*(43) = 1.07, *p* = .29, *d* = .16. There was a significant increase in microsaccade rate between blocks 4 (*M* = 0.95) and 6 (*M* = 1.11), *t*(42) = 0.20, *p* = .012, *d* = .40. There was no overall time-on-task effect, with microsaccade rates not significantly changing from block 1 to block 6, *t*(42) = 1.35, *p* = .18, *d* = .21.

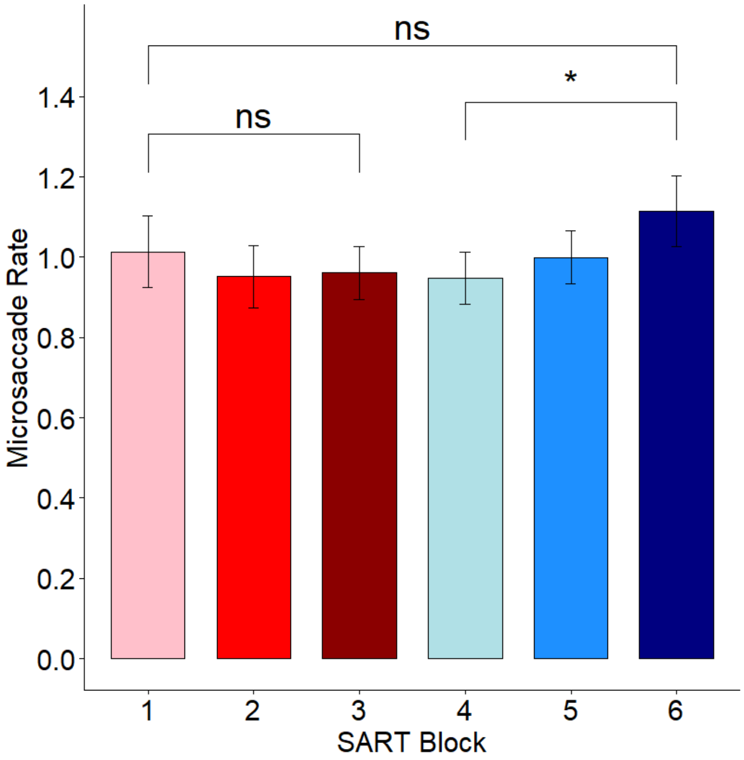

Figure 33. Microsaccade rate during SART blocks.

5.4.6 Blink rate

Consistent with experiments 1 and 3, blink rates were significantly higher when viewing nature videos (M = 128.8) than urban videos (M = 104.5), $F(1,42) = 18.73$, $p < .001$, $\eta^2_p = .31$. Order of presentation did not have a significant effect, $F(1,42) = 0.94$, $p = .34$, $\eta^2_p = .02$. There was a significant interaction between video type and presentation order, $F(1,42) = 11.16$, $p = .002$, $\eta^2_p = .21$. Examining the interaction, I found a significant effect of order on blink rate for the nature video ($F(1,42) = 4.44$, $p = .041$, $\eta^2_p = .10$), but not for the urban video ($F(1,42) = 0.04$, $p = .84$, $\eta^2_p = .00$).

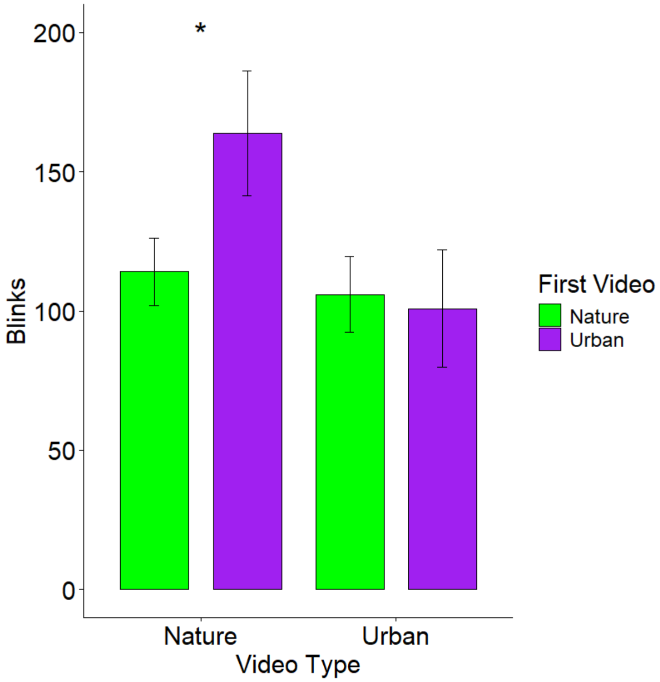

Figure 34. Mean blinks for nature and urban videos by viewing order. Green indicates when the nature video was viewed first, purple indicates when the urban video was viewed first.

Figure 35 depicts blink rates by SART block. Planned contrasts tested differences between the first and third SART block (time-on-task for SART task 1), the fourth and sixth block (time-on-task for SART task 2), and between the first and sixth block for an overall SART time-on-task effect. The number of blinks significantly increased from block 1 ($M = 71.9$) to block 3 ($M = 103.5$), $t(43) = 6.02$, $p < .001$, $d = .91$. There were no significant differences in blink rate between blocks 4 ($M = 119.1$) and 6 ($M = 120.0$), $t(43) = 0.20$, $p = .84$, $d = .03$. There was an overall time-on-task effect, with blink rates significantly increasing from block 1 to block 6, $t(43) = 6.23$, $p < .001$, $d = .94$.

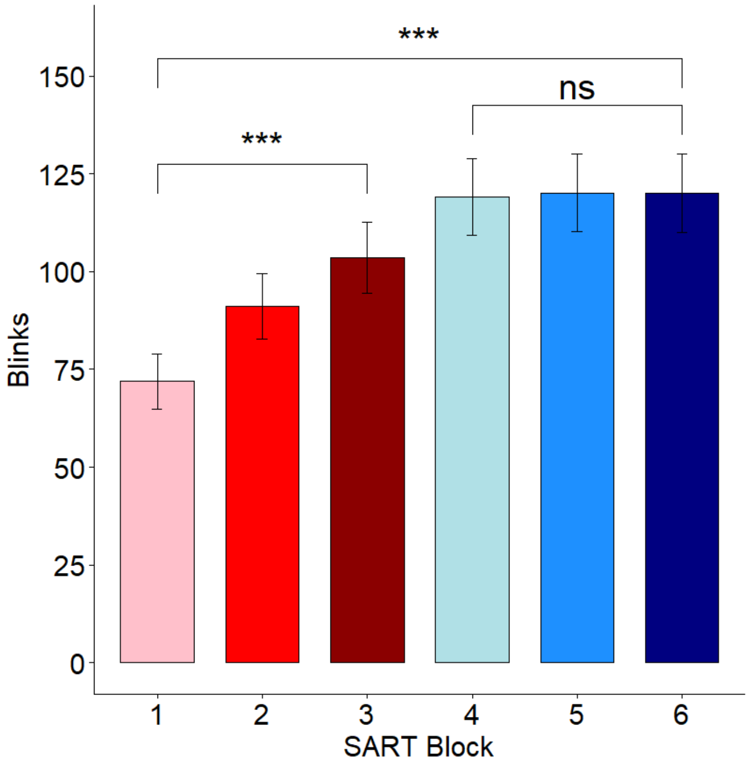

Figure 35. Mean number of blinks during SART blocks.

Video type did not have a significant effect on blink rate on a subsequent SART block, *F*(1,42) = 0.06, *p* = .81, η^2_p = .00.

5.4.7 SART performance

Planned contrasts tested differences during SART task 1, SART task 2, or from the first SART block to the last SART block. For GO trials, none of these tests showed any significant differences for reaction times (*p*s > .53, *d*s < .10).

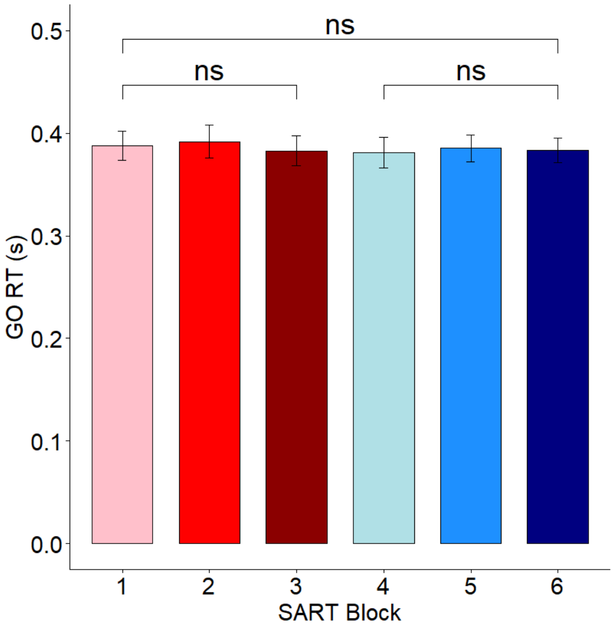

Figure 36. RTs on GO trials by SART block.

I tested whether viewing a nature video would improve GO RTs in a subsequent SART task compared to viewing an urban video. To be consistent with Berto (2005) and subsequent studies (Hicks et al., 2020; Neilson et al., 2021), I only used the fourth SART block for this analysis. This is the SART block immediately after viewing the nature or urban video, and it is a similar length (225 SART trials vs. 240 trials) as the SART trials used in other studies. An ANOVA did not find a significant effect of video type of GO RT in a subsequent SART task, $F(1,42) = 2.38$, $p = .13$, $\eta^2_p = .05$. RTs after viewing nature videos ($M = 395.8$ ms) were not significantly different from RTs after viewing urban videos ($M = 346.0$ ms).

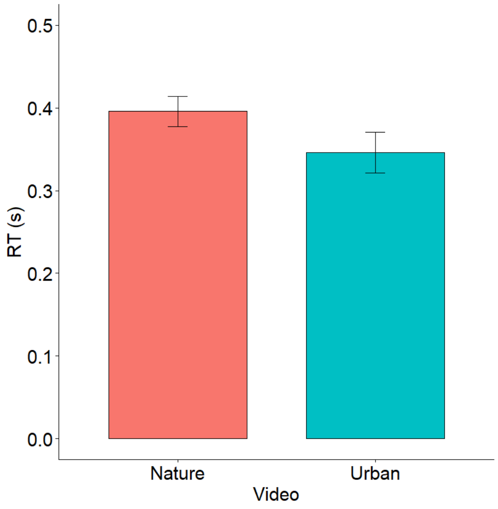

Figure 37. RTs on GO trials in the SART by preceding video type.

For GO trials, planned contrasts did not find any significant differences in accuracy during SART task 1, SART task 2, or from the first SART block to the last SART block (all *p*s > .39, *d*s < .14). Participants were virtually perfect on average at responding to GO trials, regardless of trial block.

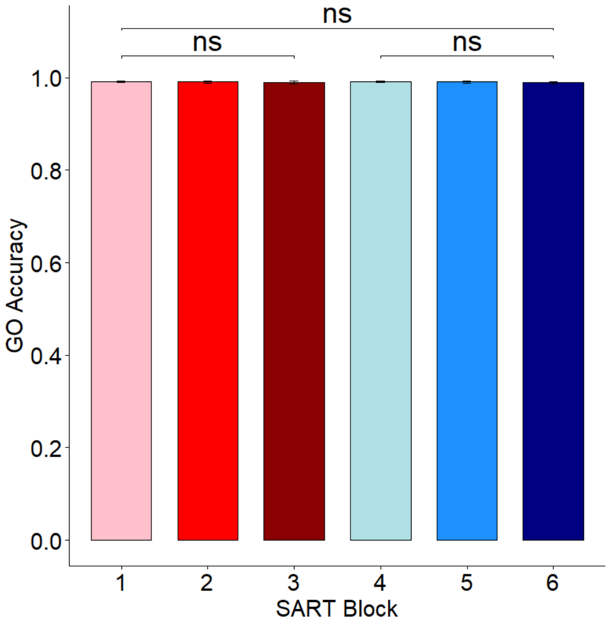

Figure 38. Accuracy on GO trials by SART block.

Accuracy on GO trials was not significantly affected by watching a nature video (*M* = 0.99) before compared to watching an urban video (*M* = 0.99), *F*(1,42) = 0.47, *p* = .50, η^2_p = .01.

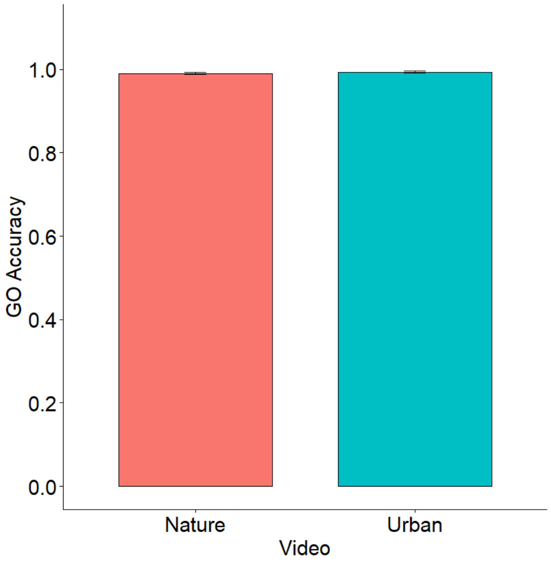

Figure 39. **Accuracy on GO trials in the SART by preceding video type.**

For NOGO trials, planned contrasts did not find any differences in accuracy between SART block 1 (*M* = 0.63) and SART block 3 (*M* = 0.59), *t*(43) = 1.57, *p* = .12, *d* = .24. There was a significant decrease in NOGO accuracy between block 4 (*M* = 0.61) and block 6 (*M* = 0.56), *t*(43) = 2.23, *p* = .030, *d* = .34. There was also a significant decrease between block 1 and block 6, indicating an overall time-on-task effect (*t*(43) = 2.49, *p* = .017, *d* = .38).

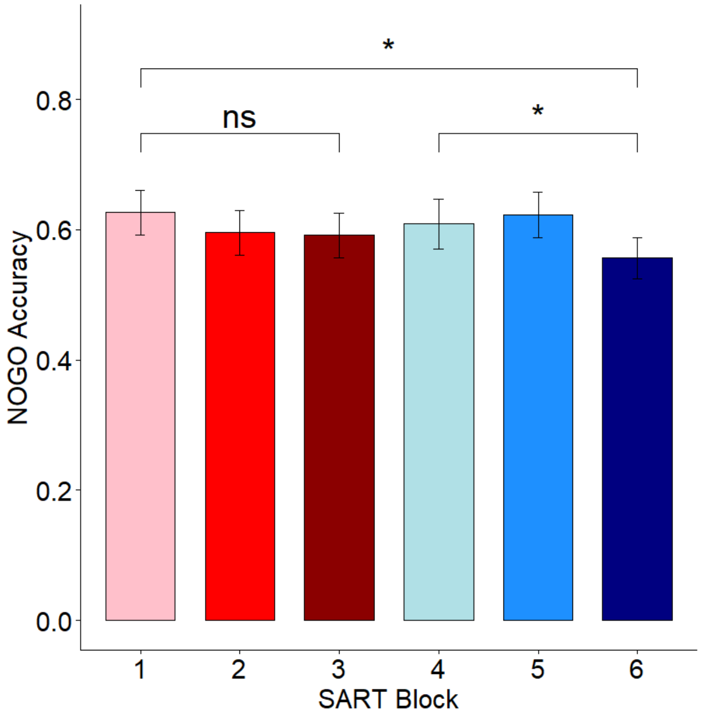

Figure 40. Accuracy on NOGO trials by SART block. * indicates *p* < .05.

Accuracy on NOGO trials was not significantly affected by watching a nature video (*M* = 0.64) before compared to watching an urban video (*M* = 0.52), *F*(1,42) = 2.31, *p* = .14, η^2_p = .05.

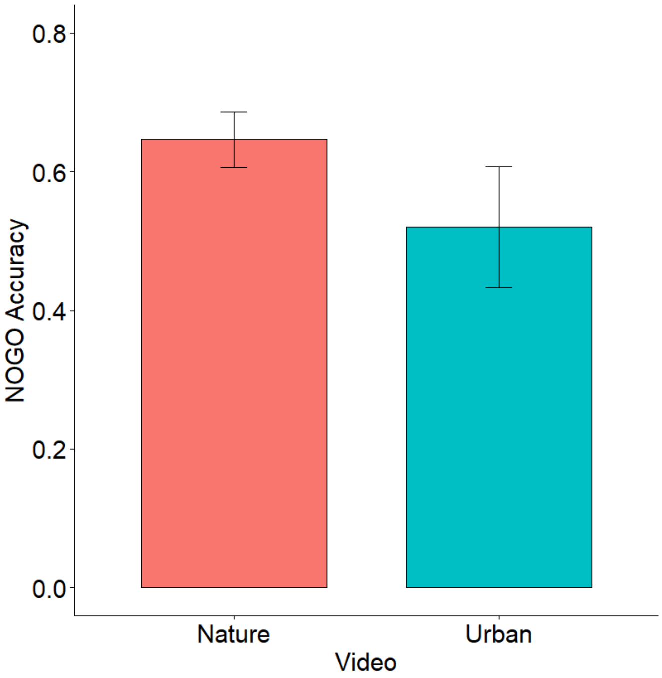

Figure 41. Accuracy on NOGO trials in the SART by preceding video.

5.5 Discussion

In experiment 4, performance on the SART decreased by time-on-task, with lower accuracy on no-go trials for the last SART block compared to the first SART block. The SART induced higher blink rates over time. This increase in blink rates indicates an increase in fatigue, reflecting a decrease in sustained attention capacity. A similar increase in blink rate caused by time-on-task was found in experiments 1 and 2, caused by a task consisting of free-viewing scenes. However, there was no difference in microsaccade slopes between the first and last SART block, unlike the time-on-task effect found in experiments 2 and 3. Performance on the SART did not improve after exposure to either natural or urban videos. Blink rates and microsaccade slopes when performing the SART after viewing a nature or urban video did not differ. The data in this experiment suggests that changes in fatigue or arousal measured by eye movements were localized to the moments when people were viewing the nature or urban videos, rather than impacting subsequent performance.

Experiment 4 differed from the previous experiments by using 5-minute videos of nature or urban places instead of static images viewed for only 20 seconds. As in experiments 1-3, natural videos induced a reduced fixation count, a reduced saccade count, and longer mean fixation durations compared to urban videos. One difference between this experiment and experiments 1-3 is that mean saccade amplitudes did not vary between the two videos. Despite the change to longer presentation times and the use of a video format, visual exploration was consistently different for nature compared to urban scene content. Consistent with the previous experiments, this study found that viewing natural videos involved a higher blink rate and reduced microsaccade slopes compared to viewing urban videos. Across different formats – black and white scenes, colour scenes, longer videos in colour – differences between viewing nature and urban content in blink rate and microsaccade slopes remained consistent. This was likely because viewing nature was associated with reductions in physiological arousal. The relaxing quality of viewing nature, by reducing arousal, induced eye movements similar to those induced by experiences of fatigue.

Experiment 4 tested Berto et al.'s (2008) claim that eye movement parameters such as fixation count or fixation duration changes with different types of fascination. In this experiment, pleasantness was positively correlated with fixation duration, but pleasantness was not correlated with fixation count. This contrasted with experiments 1-3, none of which found a significant correlation between pleasantness and fixation duration. However, in experiment 3, the relationship between pleasantness and fixation duration significantly varied by scene type. For urban scenes, pleasantness was inversely related to fixation duration, with an opposite (though not significant) effect for natural scenes. Importantly, experiment 4 differed from the previous experiments in several ways. Natural and urban scenes were presented in a video format, each stimulus was viewed for longer (5 min vs. 20 s), and people were fatigued through a sustained attention task before viewing the stimulus. More work is required to test how being fatigued changes the relationship between visual exploration and affective preference. One important result is that in three of the four experiments, relationships between eye movement metrics such as fixation counts, saccade amplitudes and fixation durations with pleasantness were similar for both natural and urban scenes. There was not enough evidence to support the idea that patterns of visual exploration relate differently to aesthetic preference based on the content being viewed.

Berto's (2005) influential paper argued that viewing images of nature after having attention depleted would result in improvements in subsequent performance on a sustained attention task. Subsequent efforts by other researchers have been mixed, with some finding similar effects (Lee et al., 2015), and others failing to replicate (Cassarino et al., 2019; Hicks et al., 2020; Neilson et al., 2021). Experiment 4 expanded on previous work using this paradigm by measuring changes in arousal and fatigue. Rather than evaluating changes in attentional resources by measuring sustained attention performance after viewing nature, this experiment measures fatigue continually through eye movement measures. I measured changes in arousal and fatigue during the depletion task (SART trials), while viewing a nature or urban video, and during a subsequent attention task (more SART trials). Experiment 4 demonstrated that the SART increased fatigue not just through worse SART performance over time, but by increasing blink rates. Blink rates and microsaccade slopes did not vary on SART blocks that followed viewing a natural or urban scene. Importantly, there were significant changes in arousal when viewing nature videos compared to urban videos. Nature was associated with significantly reduced arousal, with smaller microsaccade slopes, and greater blink rates than urban videos. This is consistent with the findings in experiments 1 and 3, which found similar effects using images. However, there were no effects of viewing a natural or urban video on subsequent performance or eye movement patterns on a sustained attention task. This experiment significantly expands on the literature on attention restoration, demonstrating that visual exploration of nature varies from urban content when using videos, and that the effect on nature stimuli on arousal may be short-lived.

Chapter 6: General Discussion

People have an innate interest in nature. Our species has evolved in natural settings, and is inherently attuned to its features (Kaplan, 1995; Ulrich, 1983). Many studies have demonstrated that exposure to nature can improve people's affective and cognitive states, reducing stress. People prefer views of nature to urban settings. Yet in our day-to-day lives, we spend most of our time in cities and other urban areas. What kind of impact does casually viewing nature have? Several studies (Berto et al., 2008; Valtchanov & Ellard, 2015; Franek et al., 2018) find that visual exploration of natural scenes varies from urban scenes. In the attention restoration literature, merely looking at natural scenes on a computer is associated with reduced fatigue and improved attention (Berto, 2005). Using eye-tracking, my dissertation examined visual exploration of a variety of natural and urban scenes. My dissertation relates visual exploration to affective processing, along with physiological measures of fatigue. How do differences in visual exploration relate to our preferences for scenes?

5.6 Summary of findings

In experiment 1, I measured people's eye movements when they viewed natural and urban scenes on a computer screen for 20 s at a time. I replicated major results in the literature, that viewing nature involves longer fixation durations and a shorter fixation count than viewing urban scenes. I expanded on the literature by showing that mean saccade amplitudes were larger for natural scenes when compared to urban scenes. One major finding was that blink rates – an indicator of fatigue - were higher for natural scenes than urban scenes, in contrast to previous research (Valtchanov & Ellard, 2015). Blink rates increase as arousal levels decrease. Many studies have shown an increase in blink rates as people become deprived of sleep (Abe et al., 2011; Barbato et al., 2000; Barbato et al., 2007; Crevits et al., 2003; Shiferaw et al., 2018; Slama et al., 2018), or due to fatigue from performing a task over a long time (Luckiesh & Moss, 1937; Stern, 1994). Experiment 1 also found a similar time-on-task effect for blink rates. The effect of experiencing nature on reducing arousal has been validated using physiological measures such as heart rate or skin conductance (Gaekwad et al., 2022; Valtchanov et al., 2010). In the eye movement context, this was a first. The increase in blink rates supported the idea that viewing nature reduces arousal. This finding is important because a reduction in arousal is not always positive. In a work setting, interventions that make people more likely to fall asleep would not be helpful. In experiments 2-4, I attempted to replicate this novel finding about the relationship between viewing nature scenes and blink rates.

One major goal of experiment 2 was to incorporate microsaccadic rate and the slope of the microsaccade peak-velocity relationship as measures while people viewed scenes. These measures had been used in studies involving air traffic control tasks (Di Stasi et al., 2013), simulated driving (Di Stasi et al., 2015), and mental arithmetic (Siegenthaler et al., 2014). Microsaccade slope was used as a measure of fatigue and is reactive to time-on-task effects. Experiment 2 was the first study to apply microsaccade measures to the experience of nature, with the goal of providing converging evidence for effects related to fatigue. Experiment 2 also varies natural and urban scenes by levels of fractal complexity, testing if complexity influences differences in visual exploration. Experiment 2 did not replicate the finding that blink rates were different between natural and urban scenes, though the effect was in the same direction. Experiment 2 found a time-on-task effect, where blink rates and microsaccade slopes decreased over time between the first trials in the experiment to the last trials. Merely viewing natural or urban scenes on a screen was sufficient to make participants feel fatigued. Fractal complexity did not affect fixation duration or fixation count, but higher complexity scenes involved shorter saccades and were rated higher on pleasantness than lower complexity scenes.

Experiment 3 used the same method as experiment 2, but with the goal of identifying how scene content influences visual exploration and affective preference. It contrasted water scenes with greenery, and scenes of historic architecture with modern architecture. Historic architecture was preferred to modern architecture and involved a more exploratory pattern of visual exploration, with more fixations with shorter average durations. Experiment 3 found higher blink rates and shorter microsaccade slopes for natural scenes compared to urban scenes, reflecting lower arousal.

Finally, experiment 4 expanded on the previous three experiments by measuring visual exploration and changes in fatigue using video stimuli. In this experiment, participants completed a sustained attention task (the SART) before viewing natural or urban videos. This experiment again found that natural videos involved higher blink rates and shorter microsaccade slopes for natural scenes. There was a time-on-task effect, with increased blink rates over time while people were completing the SART.

In all four experiments, natural scenes involved longer fixations and fewer fixations than urban scenes, while three of four showed that natural scenes involved larger saccades. Natural scenes were consistently preferred to urban scenes. However, the interpretation that longer fixation durations and less frequent fixations are associated with preference (Berto, 2008) is unjustified. In each experiment, I correlated ratings of preference with eye movement metrics. Only one out of the four studies found a positive correlation between fixation durations and preference. Two out of the four scene-viewing studies found a positive correlation between fixation count and pleasantness, with the other two finding a null effect. People did not make less fixations on scenes that they like. Overall, differences between natural and urban scenes in fixation count, fixation duration, and saccade amplitude reflected differences in visual exploration, not affective processing.

5.7 Importance

Eye-tracking has exploded in popularity. Many studies have started to apply eye-tracking methods in architecture, tourism, and urban planning. My dissertation provides important evidence to validate the relationship between commonly used eye-tracking metrics and affective preference. I demonstrated that there are consistent differences in visual exploration – fixations and saccades – between natural and urban scenes. However, I also showed that those differences do not explain why natural scenes are preferred to urban scenes. I expanded on previous research by incorporating microsaccadic measures to help measure fatigue when people explore nature and urban scenes. One major goal of eye-tracking research is to be able to evaluate people's cognitive states throughout a particular task. By using measures such as blink rates and microsaccade slopes in the context of evaluating nature and urban scenes, this project provided important insights about their impact on fatigue. For example, I showed that not only was historical architecture visually explored differently compared to modern architecture, historic architecture was also associated with reduced fatigue and higher aesthetic preference. I showed that complexity was associated with preference for urban scenes, and that complexity changes patterns of visual exploration.

The studies in my dissertation repeatedly found time-on-task effects related to visual fatigue, indexed by blink rates and microsaccade slopes. A task as innocuous as having people free-view scenes was sufficient for arousal levels to decrease. I also expanded on this finding to identify changes in fatigue using blink rate during the SART. More work, however, is required to clarify whether viewing nature or urban videos can restore attention after it is depleted. My work suggests that any effects of viewing nature or urban videos is limited to the period of viewing those videos.

5.8 Limitations

One limitation of this work is that all four studies involved presentation of stimuli on a computer. More work is required to generalize findings from computer-based studies in the laboratory to real-world natural and urban environments. While I found in all four studies that natural stimuli were preferred to urban stimuli, consistent with research in real-world settings (Gaekwad et al., 2022), the magnitude of this difference might be smaller in the laboratory.

There are several possible effects this might have. One of the goals of this study was to examine the relationship between visual exploration and affective preferences. It may be the case that in real-world environments, visual preference relates differently to eye movement metrics than when viewing images on a screen. The intensity of stimuli may play a role here, with real-world settings being more immersive than a scene on a computer. A related limitation is that the claim about the relationship between viewing nature, experiencing relaxation, and changes in blink rates may be influenced by the task itself. It might be the case that blink rates only increase in natural stimuli because this was a task carried out in the laboratory, rather than in the real world. In the real world, natural scenes are filled with different objects and features to look at. The magnitude of the experience of being in nature does not entirely come through when viewing images on a screen. Thus, an important step for future research is to show that these eye movement effects exist using field research. Of course, the challenge for field research is that many of the measures used in my dissertation require very precise eye movement recording. Microsaccadic measures, for example, would be highly challenging to gather in field research, due to the accuracy required.

Another limitation of this work is that experiment 4 did not allow us to reliably test if the attention restoration effect found in Berto's (2005) study can be replicated, due to it being underpowered for that particular test. Moreover, participants did not complete the SART after viewing the second video, meaning that there was only data on the impact on future SART performance for one of the two videos. Another challenge with experiment 4 is participants' responding strategies. Participants were virtually perfect on GO trials. One possibility is that they were using a strategy that involves pressing spacebar for every trial and would only have to pay attention if the target number appeared. Another limitation for this study, and arguably any future study using this paradigm is the participant pool involved. My research exclusively recruited undergraduates from a university. As Neilson et al. (2021) point out, cohort effects are a consideration in sustained attention tasks. Smartphone usage has dramatically increased over the last two decades and is associated with increased inattentiveness (Marty-Dugas et al., 2017; Poujol et al., 2022). Asking participants to be attentive in fatiguing laboratory studies may be a struggle with cohorts where people are used to constantly being engaged with smartphones. This may intensify the effects of a task like the SART, making interventions such as viewing nature or urban stimuli, less effective. Yet another advantage of the immersiveness of settings during field research is that this may counter-act the reduced attentional capacity that people have, allowing for more nuanced experiences. Tests like the SART or other sustained attention tasks may be more revealing in the real world, where it might not be as easy for attention to be completely depleted, unlike laboratory settings, which are more sterile.

5.9 Conclusion

Across all studies, I showed that visual exploration varies between natural and urban scenes, with natural scenes involving larger and less frequent fixations. I demonstrated that these differences are not consistent with affective preferences, with people preferring scenes where they make more fixations. For the first time in this field, I applied microsaccadic measures to comparisons of natural and urban scenes. Eye movement patterns related to fatigue and arousal –

blink rates and microsaccade slopes – indicated that people have lower arousal while viewing nature. I contrasted visual exploration and fatigue when viewing scenes that vary in complexity or in architectural style, providing evidence using eye movements for how people may explore historic vs. modern architecture. With the proliferation of interest in neuroarchitecture and the use of eye-tracking in the built environment, I hope my dissertation will be a useful resource for practitioners and researchers. It is my hope that research can help inform policymakers about how to design environments that are more pleasant and hospitable, and I believe eye-tracking is an important tool to accomplish this goal.

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Appendix A – Visual Field

Experiment 1

Central

Measure	*M* (Natural)	*M* (Urban)	*p*	*d*
Fixation count	54.2 (1.9)	54.4 (1.7)	.77	.01
Saccade count	59.8 (1.8)	60.3 (1.6)	.32	.05
Fixation duration	261.8 ms (6.5)	259.2 ms (5.4)	.21	.07
Saccade amplitude	3.8° (0.1)	3.6° (0.1)	.002	.26
Pleasantness	4.8 (0.1)	4.5 (0.1)	< .001	.50
Blinks	3.9 (0.5)	3.9 (0.5)	.77	.01

Peripheral

Measure	*M* (Natural)	*M* (Urban)	*p*	*d*
Fixation count	44.6 (1.6)	44.9 (1.7)	.62	.03
Saccade count	51.7 (1.5)	51.9 (1.5)	.68	.02
Fixation duration	284.4 ms (7.3)	279.7 ms (5.5)	.096	.10
Saccade amplitude	8.6° (0.2)	8.6° (0.2)	.96	.00
Pleasantness	3.9 (0.1)	3.6 (0.1)	.004	.25
Blinks	4.3 (0.5)	4.5 (0.5)	.56	.04

In the central vision condition, participants rated natural scenes ($M = 4.8$) more pleasant than urban scenes ($M = 4.5$), $t(41) = 3.79$, $p < .001$. Saccades were larger for natural scenes ($t(41) = 3.29$, $p = .002$). However, there were no differences for any other eye movement measures (*p*s > .21). In the peripheral vision condition, natural scenes were more pleasant than urban scenes (*t*(41) = 3.79, *p* < .001), but there were no significant differences for any eye movement measures (*p*s > .09).

Comparing ratings of pleasantness, a repeated-measures ANOVA revealed significant differences by scene type (*F*(1,41 = 21.7, *p* < .001) and visual condition (*F*(2,82 = 28.4, *p* < .001), without a significant interaction (*F*(2,82 = 3.1, *p* = .051). Bonferroni-corrected (α = 0.017) comparisons did not find a significant difference between control (*M* = 4.8) and central (*M* = 4.6) scenes, *t*(41) = 2.32, *p* = .025. Both control (*t*(41) = 5.45, *p* < .001) and central (*t*(41) = 5.62, *p* < .001) scenes were more pleasant than scenes in the peripheral vision (*M* = 3.7) condition.

Experiment 2

Central

Measure	***M* (Natural)**	***M* (Urban)**	***p***	***d***
Fixation count	49.6 (1.4)	50.3 (1.4)	.16	.07
Saccade count	51.1 (1.3)	50.5 (1.3)	.22	.06
Fixation duration	288.5 ms (5.2)	284.1 ms (5.2)	.034	.12
Saccade amplitude	3.5° (0.1)	3.4° (0.1)	.018	.12
Pleasantness	4.5 (0.1)	3.9 (0.1)	< .001	.77
Microsaccade slope	0.74 (0.04)	0.83 (0.04)	.032	.33
Microsaccade rate	0.54 (0.07)	0.59 (0.06)	.052	.10
Blinks	3.9 (0.4)	3.8 (0.4)	.50	.03

Peripheral

Measure	***M* (Natural)**	***M* (Urban)**	***p***	***d***
Fixation count	47.8 (1.3)	49.8 (1.2)	< .001	.22
Saccade count	52.3 (1.3)	53.8 (1.1)	.002	.18
Fixation duration	273.7 ms (5.6)	269.4 ms (5.0)	.049	.11
Saccade amplitude	8.1° (0.2)	8.0° (0.2)	.16	.08
Pleasantness	4.4 (0.2)	3.9 (0.1)	< .001	.53
Microsaccade slope	0.66 (0.03)	0.70 (0.04)	.19	.17
Microsaccade rate	0.55 (0.07)	0.59 (0.07)	.15	.08
Blinks	4.3 (0.4)	4.1 (0.4)	.22	.07

As in experiment 1, participants rated natural scenes ($M = 4.5$) more pleasant than urban scenes ($M = 3.9$) in the central vision condition ($t(49) = 5.61$, $p < .001$). There was again a significant effect for saccade amplitudes, with larger saccades on natural scenes ($t(49) = 2.46$, $p < .018$). Unlike experiment 1, there were significant differences on fixation duration, with longer fixations on natural scenes, consistent with the control condition ($t(49) = 2.18$, $p = .034$). Microsaccade slopes were also smaller for natural than urban scenes, consistent with the control condition ($t(49) = 2.20$, $p = .032$). Microsaccade rate was not significantly different ($t(49) = 1.99$, $p = .052$), but the direction was consistent with the control condition, with larger microsaccades when viewing urban scenes ($M = 0.59$) than natural scenes ($M = 0.55$). Fixation count, saccade count, and blink rate did not vary by stimulus type in the central vision condition (all *p*s > .16).

In the peripheral vision condition, participants again found natural scenes (*M* = 4.4) more pleasant than urban scenes (*M* = 3.9). Unlike experiment 1, there were significant effects on fixation count (*t*(49) = 3.69, *p* < .001), saccade count (*t*(49) = 3.21, *p* = .002) and fixation duration (*t*(49) = 2.02, *p* = .049). People made less frequent fixations and saccades, and longer fixations on natural scenes than urban scenes, consistent with the control condition. Saccade amplitude, microsaccade slope, microsaccade rate, and blink rate did not vary by stimulus type in the peripheral vision condition (all *p*s > .15).

Consistent with experiment 1, a repeated-measures ANOVA revealed significant differences by scene type (*F*(1,49 = 44.9, *p* < .001) and visual condition (*F*(2,98 = 25.4, *p* < .001). Unlike experiment 1, the interaction was significant (*F*(2,98 = 4.28, *p* = .017). Unlike experiment 1, control scenes (*M* = 4.9) were more pleasant than central vision (4.2) scenes, *t*(49) = 7.13, *p* < .001. Control scenes (*t*(49) = 5.17, *p* < .001) were also more pleasant than scenes in peripheral vision(*M* = 4.2). However, central and peripheral vision scenes did not significantly vary in pleasantness (*t*(49) = 0.69, *p* = .49).

Experiment 3

Central

Measure	***M* (Natural)**	***M* (Urban)**	***p***	***d***
Fixation count	53.9 (1.2)	53.6 (1.3)	.49	.03
Saccade count	56.1 (1.1)	55.4 (1.2)	.20	.08
Fixation duration	274.7 ms (4.4)	273.6 ms (4.4)	.53	.03
Saccade amplitude	4.0° (0.1)	4.1° (0.1)	.16	.08

Pleasantness	4.8 (0.1)	4.1 (0.1)	< .001	.96
Microsaccade slope	0.78 (0.04)	0.91 (0.03)	< .001	.51
Microsaccade rate	0.42 (0.05)	0.44 (0.06)	.28	.06
Blinks	4.4 (0.5)	4.7 (0.5)	.035	.10

Peripheral

Measure	***M* (Natural)**	***M* (Urban)**	***p***	***d***
Fixation count	47.4 (1.1)	47.9 (1.2)	.33	.05
Saccade count	51.8 (1.0)	52.3 (1.2)	.27	.07
Fixation duration	284.6 ms (3.8)	281.1 ms (4.3)	.080	.12
Saccade amplitude	8.7° (0.2)	8.8° (0.2)	.21	.06
Pleasantness	4.5 (0.1)	3.9 (0.1)	< .001	.81
Microsaccade slope	0.69 (0.03)	0.69 (0.03)	.87	.03
Microsaccade rate	0.40 (0.04)	0.39 (0.04)	.44	.04
Blinks	5.0 (0.5)	5.0 (0.5)	.85	.01

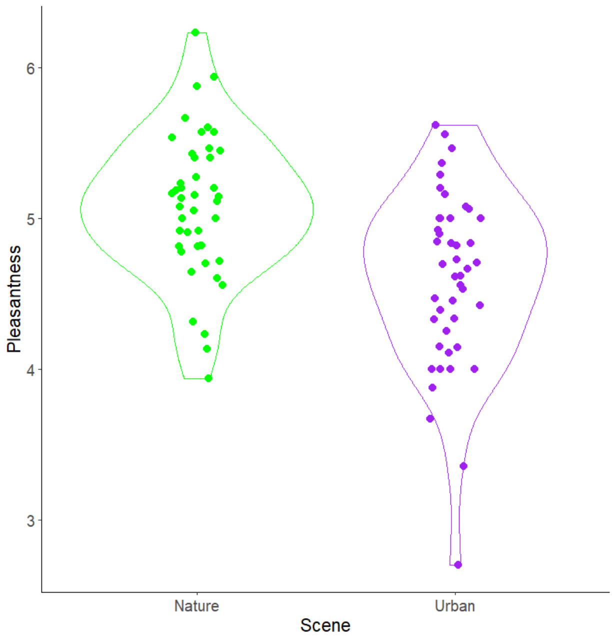
As in experiment 1, participants rated natural scenes ($M = 4.8$) more pleasant than urban scenes ($M = 4.1$) in the central vision condition ($t(50) = 6.91, p < .001$). Unlike experiment 2, there was a significant effect for microsaccade slopes, with smaller slopes for natural ($M = 0.78$) scenes than urban scenes ($M = 0.91$), consistent with the control condition, $t(50) = 4.15, p < .001$. There were also fewer blinks when viewing natural scenes ($M = 4.4$) compared to urban scenes ($M = 4.7$), an effect in the opposite direction as that found in the control condition, $t(50) = 2.16$, $p = .035$. This also varies from experiments 1 and 2, neither of which found any effect on blink rate in the central vision condition. There were no significant effects for any other measures (all *p*s > .16).

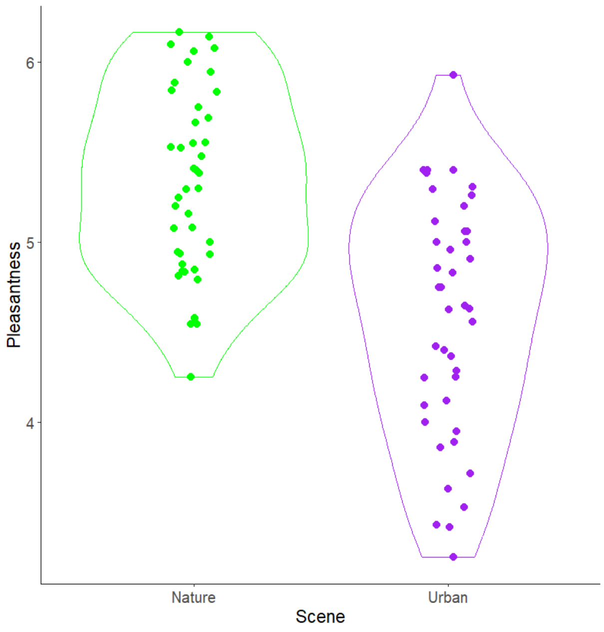
Other than the expected difference in pleasantness between natural and urban scenes ($t(50) = 7.03$, $p < .001$), there were no significant differences on any measures in the peripheral vision condition.

Consistent with experiment 1 and 2, a repeated-measures ANOVA revealed significant differences by scene type ($F(1,50 = 61.3$, $p < .001$) and visual condition ($F(2,100 = 32.2$, $p < .001$), without a significant interaction ($F(2,100 = 0.2$, $p = .82$). Unlike experiment 1, control scenes ($M = 5.0$) were more pleasant than central vision (4.4) scenes, $t(50) = 5.67$, $p < .001$. Both control ($t(50) = 6.33$, $p < .001$) and central ($t(50) = 2.97$, $p = .005$) scenes were more pleasant than scenes in peripheral vision ($M = 4.2$).

Appendix B – Pleasantness by Stimulus Type

The following scatterplots depict the range in pleasantness ratings for stimuli in the control condition for experiments 1-3. In all three experiments, natural scenes were rated as being significantly more pleasant than urban scenes (all *p*s < .001).





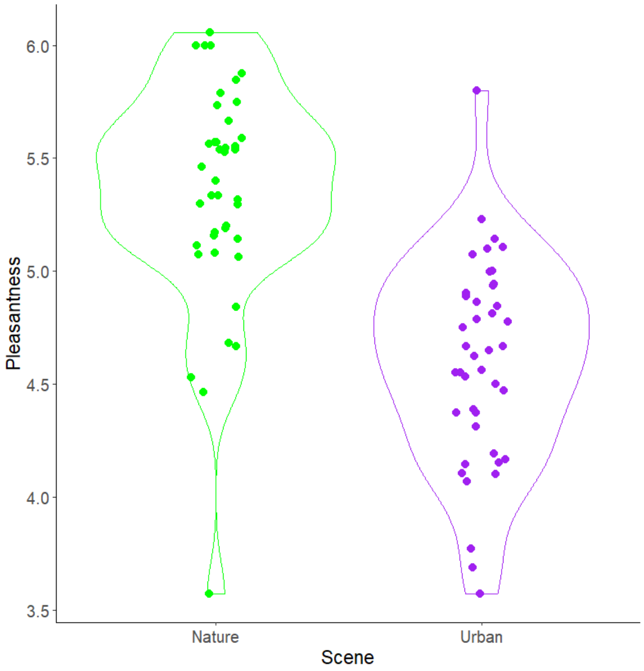


Figure A1. Pleasantness by stimulus type and experiment. Experiment 1 (top left), experiment 2 (top right), experiment 3 (bottom). Green indicates ratings on nature items, purple for urban items.