Exploring the Restorative Effects of Nature:

Testing A Proposed Visuospatial Theory

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.

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Abstract

In this thesis, the restorative effects of exposure to nature are examined through the lens of existing restoration theories. Limitations of existing theories, such as Attention Restoration Theory and Psycho-evolutionary Restoration Theory, are highlighted. To address the limitations of existing theories, an expanded theoretical framework is proposed: The expanded framework introduces a newly proposed neural mechanism and theory of restoration that build on existing theories by proposing a link to recently discovered reward systems in the ventral visual pathway. Results from six experiments provide consistent evidence to suggest that positive and negative responses to visual scenes are related to the low-level visuospatial properties of the scenes. Specifically, a discovery is made to suggest that the power of a limited visual spatial frequency range can consistently predict responses to natural, urban, and abstract scenes on measures of restoration (blink-rates, number of fixations, self-reported stress and pleasantness). This provides the first evidence to suggest that low-level visual properties of scenes may play an important role in affective and physiological responses to scenes. Furthermore, this newly discovered relationship provides a new way to objectively predict the relative restorative value of any given scene.

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Chapter 1: Introduction

In the environmental psychology literature, numerous studies have focused on exploring the beneficial properties of exposure to nature. These "restorative effects of nature" have been both widely studied and replicated in research labs across the world over the past thirty years. To date, there are over two hundred studies exploring the benefits of incorporating exposure to nature into daily life. This focus on the beneficial properties of nature is partially motivated by the belief that exposure to nature not only has beneficial effects on individuals and populations, but also that the decreased exposure to nature prompted by living in urban centers and large cities may result in increased mental illness, increased stress, and decreased health (Gullone, 2000; Grinde & Patil, 2009). Indeed, studies exploring workplace satisfaction and health have found that office spaces that afford views of nature (be they of plants or posters), result in improved job and life satisfaction, reduced stress and anger, and fewer sick-days taken off work compared to office spaces that do not (Kweon et al., 2008; Leather et al., 1998; Kaplan, Talbot, & Kaplan, 1988; Bringslimark, Hartig & Patil, 2007; Shibata & Suzuki, 2004). In a similar vein, some observational research has even suggested that crime rates and mental distress in cities are lower for areas that are closer to vegetation and green spaces (Kuo & Sullivan, 2001; White et al., 2013). Due to these patterns in pathology linked to the absence of nature, researchers in psychology have placed great importance on learning about the beneficial and restorative properties of being exposed to nature. In the literature, the restorative effects of nature have been categorized into the three broad categories of improved cognitive function, improved affect, and reduction of physiological and cognitive stress (Berman, Jonides & Kaplan, 2008; Gullone, 2000; Hartig, Mang & Evans, 1991).

1.1 Influences of Exposure to Nature on Cognitive Function

The positive effect of exposure to nature on cognitive function is a relatively new discovery. The cognitive benefits of exposure to nature were first proposed by Kaplan & Kaplan (1989), who stated that natural environments may promote the use of involuntary attention, allowing for directed attention resources to be restored. An initial field study by Tennessen & Cimprich (1995) exploring the relationship between window views of nature in dormitories and students' performance on measures of attention found a correlation between the amount of nature visible from students' dorm windows and their performance on directed attention tasks. However, it was not until much later that this improvement in direct attention was demonstrated in a controlled lab setting. Berman, Jonides & Kaplan (2008) used a controlled empirical paradigm, where measures of attention were taken before and after exposure to nature, to demonstrate that after participants viewed pictures of nature scenes, or went on a nature walk, they performed better on two measures of cognitive performance and executive function relative to participants who viewed urban scenes or went on a walk in a downtown area: The two measures of cognitive function included a backwards digit-span task, and the Attention Network Task (a task which measures alerting, orienting, and executive attention). Improvements in Attention Network Task performance were restricted to measures of executive attention, and not alerting or orienting (Berman et al., 2008). Similar findings were also found by Berto et al. (2010) who found that memory for viewed natural scenes was better than for urban scenes. Complementing this research, Raanaas et al. (2011) have also found evidence to suggest that studying in an office setting with potted plants and flowers increased memorization performance compared to studying in an office without plants. The improved performance persisted even after a short break (Ranaas et al., 2011). These general findings that exposure to nature can improve performance on various cognitive tasks have also been found in clinical research:

Research by Taylor et al. (2001; 2009) exploring the cognitive benefits of exposure to nature for children who were diagnosed with Attention Deficit Disorder (ADD), and Attention Deficit Hyperactivity Disorder (ADHD), found that when children went on nature walks (versus walks in an urban setting) or played in an area with nature, their symptoms were significantly reduced while their ability to concentrate was significantly improved. For this clinical population, the beneficial effects of going on a nature walk were comparable to those seen after administration of methylphenidate (Ritalin), a drug commonly prescribed to treat ADHD (Taylor et al., 2009).

It is important to note that while there has been evidence suggesting that exposure to nature may improve capacity for directed attention and ability to focus, there is also evidence that the cognitive benefits may not generalize to other tasks that measure ability to sustain attention. For example, Valtchanov & Ellard (2010) found both improvements in affect and reductions in physiological stress (i.e., restoration) after participants went on a virtual nature walk, but did not find improvements in performance on the Sustained Attention to Response Task (SART).[1] Given this, it is not fully clear if "restoration" resulting from exposure to nature always includes improvements in cognitive function and/or ability to sustain attention, or if improvements in cognitive function, affect, and stress levels may occur independently. In past literature only part of the three categories of restorative effects were measured in any given study, making it difficult to determine the level of co-occurrence.

[1] The SART requires participants to respond to repetitive stimuli (usually digits) which are individually presented on a computer screen by pressing a button, and to withhold their response when the target appears (usually the digit 3) (Berto et al. 2010).

1.2 Influences of Exposure to Nature on Affect and Stress

Unlike the effect of exposure to nature on cognitive function, the effects on emotional state (affect) and stress have been more widely and reliably replicated across many different paradigms and studies. Some of the early empirical evidence was described by Ulrich (1981), who found that viewing slides of nature scenes prompted more positively toned affective states than viewing urban scenes. The initial findings were greatly expanded upon by Ulrich et al. (1991) who demonstrated that viewing photographs of nature versus urban scenes significantly increased self-reported positive affect while decreasing feelings of anger, sadness and fear. Furthermore, Ulrich et al. (1991) found physiological evidence that was consistent with these effects, demonstrating that skin-conductance levels, muscle tension and heart-rate all decreased after viewing nature scenes. These self-reported and physiological effects have been replicated using videos of nature (de Kort et al., 2006; van den Berg et al., 2003) and even using immersive virtual nature walks (Valtchanov & Ellard, 2010; Valtchanov et al., 2010). The general effects of improved affective state and reduced physiological and perceived stress have been demonstrated in different scenarios across the world: Views of nature in the workplace have been shown to reduce work-related stress (Kweon et al., 2008; Leather et al., 1998). Nature exposure therapy has been found to be effective for clinical stress management (Villani & Riva, 2012) and stress and anxiety reduction for deployed military medics (Stetz et al., 2011). And, nature posters and plants in hospital waiting rooms have been shown to reduce patient stress (Beukeboom, Langeveld & Tanja-Dijkstra, 2012). Furthermore, there has been recent evidence to suggest that viewing nature scenes may also reduce pain perception after undergoing painful bone marrow aspiration and biopsy (Lechtzin et al., 2010). From these studies, it is evident that exposure to nature reliably produces improvements in affect and reductions in both perceived and physiological stress, with the minimum requirement for the effects being brief viewing of nature scenes.

Given that the beneficial effects of nature on stress and affect have been well documented and reliably replicated in the literature, the interest of researchers has begun to shift from documentation and replication to application. As described earlier, medical settings are now incorporating nature exposure into the hospital experience to alleviate stress and anxiety (Beukeboom et al., 2012; Lechtzin et al., 2010) while clinicians are attempting to help chronically and acutely stressed patients using relaxation therapies that incorporate exposure to nature scenery (Villani & Riva, 2012; Stetz et al., 2011). This shift has been a logical one given that exposure to nature is easy to deliver, inexpensive, and reliably beneficial. The use of nature to improve well-being is not limited to lab and hospital settings. Stress-relief through the use of self-exposure to nature also appears to be an intuitive (and perhaps self-preserving) behaviour in individuals in high-stress environments: Field experiments exploring where students prefer to take study breaks, and how teachers cope with stress, have found that both groups gravitate toward areas containing natural stimuli when they are feeling stressed (Felsten, 2009; Gulwadi, 2006). This line of research suggests that even though individuals may not be explicitly aware of the research surrounding the restorative effects of nature, they may have intrinsic motivation to seek out nature and its stress-reducing properties.

1.3 Theories on the Restorative Effects of Nature

Unfortunately, while there are hundreds of studies demonstrating the beneficial effects of nature, and more importantly, how they can be applied to improve quality of life and well-being, the mechanism behind restoration is still poorly understood. Presumably, if the mechanism behind the restorative properties of nature was better understood, it may be possible to better understand why humans have such a positive response to viewing nature scenes, and how this positive response could be better harnessed to improve performance and quality of life. Currently, there are three main theories that attempt to explain why nature has beneficial properties.

1.3.1 The Cognitive Perspective. The first theory is a logical argument that has previously remained unnamed. In this dissertation it is referred to as the *Cognitive Perspective.* The *Cognitive Perspective* has no formal citation, but is often brought up as an alternate explanation for the positive effects of nature by both scholars and non-scholars alike.[2] The argument made by the *Cognitive Perspective* states that individuals living in modern settings have vastly different associations with when it comes to natural environments (such as forests, parks) and urban environments (such as cities), that could be shaping their responses to nature versus urban scenes in a top-down fashion. Nature environments are experientially associated with going on vacation, escape from stress, spending time with family and friends, adventure, etc. Meanwhile, urban environments are experientially associated with work, chores, pollution, and stress.

van den Berg, Hartig, & Staats (2007) have argued that individuals living in compact urban centers desire to live in the greener suburbs due to a romanticised view of rural life: The romanticized view focuses on the disappearance of simplicity and pureness of rural life, and idealizes nature in a naive manner. They continue to argue that urban dwellers must struggle to deal with demands of work and family, and that seeking contact with nature (e.g. vacationing)

[2] Department faculty, scholars attending conferences, colleagues, and non-scholars at public talks have independently proposed the same consistent ideas which are encapsulated by the *Cognitive Perspective*. This alternate explanation has been proposed every time the present research has been shared with others.

could provide immediate relief from the demands of city life (van den Berg et al., 2007). Indeed, there appears to be some truth to these hypotheses. In a nationwide survey among inhabitants of The Netherlands, 95% of respondents indicated that visiting nature was a useful way of relieving stress (Frerichs, 2004). Furthermore, a survey of nine Swedish towns and cities indicated that residents would recommend a walking in the forest to a friend that was feeling stressed (Grahn & Stigsdotter, 2003). Mirroring these results, when students were asked where they prefer to take study breaks, and how teachers cope with stress, both groups gravitated toward areas containing nature (Felsten, 2009, Gulwadi, 2006). Interestingly, the survey of Swedish towns and cities also revealed that both those living in the suburbs and in the city cores were equally interested in spending more time immersed in nature than they currently did (Grahn & Stigsdotter, 2003).

Thus, it is evident that the general population appears to have a romanticized view of being around nature, and also believes that being around nature will relieve stress. It is logical that these associations may have some top-down effect on the way individuals respond to scenes in a lab setting. It is possible that viewing natural scenes reminds individuals of the positive experiences they previously had while on vacation or the positive experiences they may have if they were to go on vacation. Similarly, viewing urban scenes could prompt individuals to think about their next work deadline, having to pay their bills, or any of the numerous chores they deal with in daily life. It can thus be argued that the emotions prompted by these associations may then lead to changes in affective state. These associations may also lead to mind-wandering (e.g., worrying about a deadline) which could influence performance on cognitive measures and stress levels. Similarly, viewing nature may distract individuals from fixating on things that may otherwise cause them stress, causing stress levels to decrease.

Unfortunately, there is limited empirical research which explores top-down effects on restoration: Aside from the theoretical perspectives of van den Berg et al. (2007) arguing for rural romanticism, and survey results from Felsten (2009), Gulwadi (2006), and Grahn & Stigsdotter (2003), there is little (if any) controlled laboratory research exploring the subject. It is unclear if environmental psychology researchers have been unable to find support for the ideas presented by the *Cognitive Perspective*, or if it fell out of favour in the restorative effects literature due to the adoption of evolution and attention based restoration theories. Given that the *Cognitive Perspective* is an intuitive and plausible explanation for some of the positive effects of exposure to nature that has no published evidence directly refuting it, it is considered as a possible explanation of why nature might be restorative in this dissertation.

While the argument presented by the *Cognitive Perspective* is intuitive and easy to understand, it suffers from several faults: It is a theory that does not make direct predictions about what types of nature scenes are restorative, or if some nature scenes are more restorative than others. The same also applies to its failure to make predictions about urban scenes, and whether all urban scenes are stressful or just some of them. Furthermore, it does not describe an underlying biological or cognitive mechanism. It is possible for individuals to have many positive memories and associations with urban scenes (going to parties, clubs, watching movies, having dinner with friends) and negative associations with nature scenes (being stranded without food or shelter, being bitten by bugs, having to deal with rain, mud, and animals). In these cases, nature should be perceived as stressful and urban scenes should be perceived as calming and pleasant. Unfortunately, there is a staggering amount of literature (some of which has been presented in this dissertation) to suggest that exposure to nature scenes reliably has beneficial effects, while exposure to urban scenes does not. It is possible that because of these reasons, the *Cognitive Perspective* has been ignored in the literature on the restorative effects of nature.

1.3.2 *Attention Restoration Theory* (ART). In contrast to the *Cognitive Perspective*, Kaplan's *Attention Restoration Theory* (1995, 2001) has been widely cited and supported in the literature on the restorative effects of nature (Berto et al., 2010; Taylor et al., 2009, Berman et al., 2008). *Attention Restoration Theory* (ART) builds on the assumption that human cognitive capabilities evolved in natural environments (Hartig, Evans & Garling, 1997). Based on this assumption, it postulates that mechanisms for controlling attention and managing cognitive resources have difficulty navigating and coping with the stimuli present in urban city environments (because of the many differences between urban and natural environments), resulting in a depletion of cognitive resources (Kaplan 1995;2001). The depletion of resources is believed to create cognitive fatigue, which then increases stress and negative affect due to being unable to cope with the surrounding environment. The theory further argues that exposure to natural stimuli allows these depleted resources to recover, restoring capacity for executive function.

The mechanism proposed by ART is based on the separation of attention into the two components of directed attention and involuntary attention (Kaplan 1995; 2001). With directed attention, attention is shifted toward a specific stimulus in the surroundings using top-down control at the expense of cognitive resources (Kaplan, 1995; 2001). In order to successfully direct attention in highly stimulating environments, more cognitive resources are consumed to suppress distracting stimuli (Kaplan 1995; 2001). With involuntary attention, attention is captured in a bottom-up fashion by inherently intriguing or important stimuli. According to ART, interacting with inherently fascinating stimuli (e.g. waterfalls, sunsets) captures involuntary attention *modestly*, allowing it to wander freely while directed attention mechanisms replenish (Kaplan 1995; 2001). Kaplan (1995; 2001) calls this *modest* capture of involuntary attention by pleasant stimuli *soft fascination.* This is made distinct from *hard fascination* where stimuli capture attention *dramatically* and do not allow attention to wander, requiring top-down resources to disengage from the stimuli (Kaplan 1995; 2001).[3] Kaplan (1995, 2001)'s *Attention Restoration Theory* argues that natural environments contain *soft fascination* (trees gently swaying with the wind, waves in the water) allowing directed attention resources to replenish, while urban environments contain *hard fascination* (car horns, loud noises, flashing lights) that require use of directed attention resources to navigate and inhibit stimuli (Kaplan 1995; 2001).

A key point of interest that is often overlooked is that *Attention Restoration Theory* doesn't require the use of natural stimuli in order to create restoration, but rather it argues that any stimulus that satisfies the criteria for *soft fascination* may be sufficient. Unfortunately, Kaplan has been unable to explain what exactly constitutes *soft fascination* objectively. Despite its popularity, Kaplan (1995; 2001)'s *Attention Restoration Theory*, like the *Cognitive Perspective*, suffers from limitations. Given that the distinction between *soft fascination* and *hard fascination* is based mostly on immersive experiences (i.e., seeing trees gentle sway with the wind versus cars moving and/or their flashing lights), it is difficult to generalize the proposed mechanism of shifts between directed and involuntary attention when photographs of scenes are used instead of immersive experiences. Given that empirical studies have demonstrated improvements in stress, affect, and cognitive ability after viewing photographs of nature (Ulrich et al., 1991, Berman et al., 2008), it is puzzling why one would predict different cognitive loads

[3] Kaplan (2001, pp. 482) defines fascination as "containing patterns that hold one's attention effortlessly."

(and restoration of cognitive resources) when viewing nature versus urban scenes solely based on *Attention Restoration Theory*. The main problem lies in the vague definition of fascination used by Kaplan (2001, pp. 482), stating that fascination is anything that contains patterns that hold one's attention effortlessly. Due to this vague definition, it is unclear why photos of nature scenes may prompt different amounts of fascination than photos of urban scenes. With an objective definition of what makes a scene fascinating (such as its complexity, symmetry, contrast, self-similarity, or patterns in visual spatial frequency), it may be possible for ART to better explain empirical results.

1.3.3 *Psycho-evolutionary Restoration Theory*. A competing theory to Kaplan (1995, 2001)'s *Attention Restoration Theory* (ART) has been proposed by Ulrich et al. (1991). Similar to *Attention Restoration Theory*, Ulrich et al. (1991)'s *Psycho-evolutionary Restoration Theory* (PERT) is also based on the assumption that human physiology has evolved in a natural environment. Because of this, it also shares the assumption that brain and sensory systems are tuned to efficiently process natural content and are less efficient at processing urban or built environments, thus resulting in physiological and cognitive depletion when interacting with urban environments (Ulrich et al., 1991). Research by Mace, Thorpe, & Fabre-Thorpe (2005) using ERPs has found support for this assumption of "rapid processing of natural scenes" by providing evidence that individuals can accurately categorize natural scenes by content[4] with presentation times as low as 28 milliseconds.

However, unlike Kaplan (1995; 2001)'s *Attention Restoration Theory* where replenishment of directed attention is believed to be the source of restoration, Ulrich et al. (1991)'s Psycho-evolutionary Restoration Theory (PERT) proposes that there is an automatic

[4] Individuals could categorize scenes based on whether animals were present or absent.

affective response to environments driven by adaptive behaviour. PERT proposes that cognitive and physiological events experienced by an individual exposed to an environment are shaped by the "automatic affective response" to that environment (Ulrich et al., 1991). The theory makes a distinction between threatening and non-threatening natural environments, suggesting that environments which would facilitate survival or on-going well-being (such as savannah-like areas or settings with water) would prompt a positive affective response while those that threatened survival (such as environments with predators or dangerous cliffs) would prompt a negative response (Ulrich et al., 1991). It is argued by PERT that this "automatic affective response" to environments is the result of millions of years of evolution that have favored individuals who demonstrated two adaptive responses to nature: (1) restoration responses following stressful or taxing events; and (2) in the absence of stress, preferring content that favored well-being or survival (Ulrich et al., 1991). Furthermore, PERT explicitly makes the important prediction that involuntary attention should be a prominent component of both the restorative response to unthreatening natural stimuli and the stress response to natural settings containing risk or threat (Ulrich et al., 1991). This prediction is similar to what is proposed by *Attention Restoration Theory* with the concepts of *soft fascination* and *hard fascination*, suggesting that the interaction between the environment and involuntary attention plays a role in its restorative properties.

It is easy to see where *Attention Restoration Theory* (ART) and *Psycho-evolutionary Restoration Theory* (PERT) overlap. Both theories are based on assumptions of evolutionary psychology, and both theories propose a bottom-up mechanism for restoration. *Attention Restoration Theory* recruits the concept of *soft fascination,* referring to patterns of visual information that capture involuntary attention *modestly*, while Psycho-evolutionary Theory proposes that there is an automatic affective response to environments based on millions of years of evolution. Both theories agree that that attention, physiological response and affect change as a result of exposure to natural scenes, even if the order of events is a point of contention: While ART proposes that changes in attention lead to changes in affect and stress; PERT proposes that changes in affect lead to changes in attention and stress.

Given the similarity between the two theories, *Psycho-evolutionary Restoration Theory*, like *Attention Restoration Theory*, also suffers from several shortcomings. The bulk of the theory is based on adaptive survival behaviour, which is problematic when considering the function of urban environments and cities: Modern day cities afford significantly better odds of survival, resources and health compared to savannah-like areas. Obtaining medicine, food, water, and shelter is significantly easier in a city than it is in the wilderness (especially for individuals that have no wilderness survival training). If preference was truly driven by access to resources that facilitate survival, then urban cities should be preferred over most natural environments. However, the contrary has been demonstrated in empirical research. This point is partially combated by the evolutionary argument made in PERT, which suggests that since our sensory and cognitive systems evolved in natural settings, they are tuned to natural stimuli and have difficulty classifying urban-environments as "beneficial" to survival (Ulrich et al., 1991). Unfortunately, there is little mention of the specific (evolved) sensory and cognitive systems that may be responsible for the "automatic affective response" to environments (i.e. preference and restoration). This shortcoming of describing a mechanism for the "automatic affective response" is similar to *Attention Restoration Theory*'s shortcoming in defining the source of "soft fascination." It is here that one may pause and consider that the underlying mechanism of both the "automatic affective response" to scenes, and the "soft fascination" prompted by scenes, may be the same or similar.

If we consider the proposals made by ART and PERT, stating that sensory and cognitive systems evolved in natural settings, and that specific mechanisms may have evolved to favour survival, it stands to reason that the underlying mechanism may be a reward system tuned to specific information in the environment that has evolutionarily been linked to survival and well-being. Activation of these "evolved" reward systems could have motivated the pursuit of adaptive behaviour through endogenous rewards, manifesting itself as what Kaplan (1995; 2001) now calls "soft fascination" or what Ulrich et al. (1991) refer to as an "automatic affective response" given that things which are endogenously rewarding in the environment should both capture involuntary attention *modestly* and promote a positive affective response.

1.4 The Missing Piece of the Puzzle: Proposing Reward Restoration Theory

The logical implication of a reward mechanism as the missing piece in both Kaplan (1995; 2001)'s *Attention Restoration Theory* and Ulrich et al. (1991)'s Psycho-evolutionary Theory has been indirectly supported in research on scene preference. Research exploring scene preference using functional neuroimaging (fMRI) has found that scenes which are preferred (as measured by self-reported scores on a preference scale) prompted a greater blood-oxygen level dependent (BOLD) response (i.e., "activation") in the ventral striatum (involved in conventional reward systems) and parahippocampal cortex (a region with a high-density of μ-opioid receptors[5]) in the ventral visual pathway (Yue, Vessel & Biederman., 2007; Biederman & Vessel, 2006). These findings have been independently replicated by Taylor et al. (2011) using

[5] Pharmacological studies have shown that β-endorphin and enkephalin have the best affinities for μ-opioid receptors (Merrer et al., 2009)

abstract fractal art[6], where greater activation in these brain areas was found for fractals that were subjectively preferred by participants. Opioid reward systems such as these have been linked to natural reinforcement, and regulation of pain, stress, and emotion (Merrer et al., 2009). When reviewing the restorative effects of nature, there is a striking similarity between responses to nature scenes and activation of opioid reward systems: Similar to activation of opioid reward systems, viewing nature scenes has been shown to reduce perception of pain (Lechtzin et al., 2010), improve affect, and reduce physiological and perceived stress (Valtchanov & Ellard, 2010). From these studies, and a comprehensive review by Grinde & Patil (2009), it is evident that *visual* contact with nature is important in triggering the restorative response. Given that visual contact with nature has similar effects to activation of opioid reward systems (i.e., "restoration") and that opioid reward systems are present in the ventral visual stream (Yue, Vessel & Biederman., 2007), it can be hypothesized that there is a connection between the visual information processed by the ventral visual stream and the "restorative response."

In order to understand how viewing nature scenes might be activating the ventral visual pathway and implicated reward systems (Yue, Vessel & Biederman, 2007; Biederman & Vessel, 2006), we must consider how scenes are processed by the visual system. Olhausen & Field (1995, 1996) have argued that information in visual scenes is sparse coded by primary visual cortex (V1) based on spatial frequencies. Specifically, it is argued that groups of V1 neurons work as Gabor filters for incoming visual information (Olhausen & Field, 1995, 1996, 1997). It is argued that visual information is coded into component spatial frequencies (SF) because the human visual system has evolved in a natural setting, and sparse coding of SF is the most

[6] Fractals are patterns of self-similar shapes that repeat with variation in scale. Fractals are believed to have similar visual properties as nature, which consists of self-similar repeating shapes and objects (e.g., leaves on a tree look similar, trees in a forest look similar, etc) (Taylor et al., 2011).

efficient way to represent natural visual information (Simoncelli & Olhausen, 2001; Geisler, 2008). This notion of efficient coding of spatial frequencies has been supported in more recent research, which suggests that response properties of V1 cells can be explained by statistical regularities of natural images (Doi & Lewicki, 2005). Furthermore, research by Karklin & Lewicki (2008) using computational modeling of neurons has been able to demonstrate that complex cells in V1, and those in later visual areas, can code the input from oriented Gabor filters (i.e., spatial frequencies) and discriminate between scene content. In their distribution coding model, Karklin & Lewicki (2008) suggest that high-order visual processing occurs by discriminating between statistical distributions of SF. To summarize, primary visual cortex codes the spatial frequencies of visual scenes (Olhausen & Field, 1995, 1996, 1997), which are then aggregated into distributions by higher-level visual areas and compared, allowing the visual system to discriminate between scene content (Karklin & Lewicki, 2008). By understanding that visual scenes are perceived through neural coding of spatial frequencies, it becomes possible to understand the type of visual information that the ventral visual stream may respond to.

The classic understanding of how the human visual system suggests that there are two biologically and functionally distinct pathways: There's a dorsal visual pathway which computes spatial and volumetric properties of visual input in order to support eye-movements, locomotion, and grasping; and the ventral visual pathway which extracts object identity across orientation, size and distance (Mahon, Kumar & Almeida, 2013). Visual information for the dorsal visual pathway originates from parasol ganglion cells which are sensitive to low spatial frequencies and relay information through magnocellular nerve pathways (Mahon et al., 2013). Visual information in the ventral visual pathway originates from midget ganglion cells which are sensitive to mid-to-high spatial frequencies and project through parvocellular nerve pathways (Mahon et al., 2013).[7]

The notion that the ventral visual pathway is sensitive to mid-to-high spatial frequency information as well as identity of objects has been supported by recent research using functional magnetic resonance imaging (fMRI): Fintzi & Mahon (2013) decomposed visual images into their component spatial frequencies using Fourier transforms. Low spatial frequency (LSF) and mid-to-high spatial frequency versions of the images were then created by using a Gaussian bandpass filter on the Fourier transform and inverting it. This process muted all but the desired spatial frequencies, creating images that contained only specific spatial frequency information (Fintzi & Mahon, 2013). When participants were shown the images containing only specific spatial frequency information, the ventral visual stream showed a maximal BOLD response ("activation") to images containing spatial frequencies with 4.75 to 9.14 cycles per degree of visual angle (c/d) (i.e., "mid-to-high" SF) (Fintzi & Mahon, 2013), providing evidence that the ventral visual stream is tuned to this limited spatial frequency range. A muted, but significant BOLD response was also present for spatial frequencies with 2.09 to 4.73 c/d. Furthermore, in convergence with classical theory, the identity of the objects in the image was most easily recognized for images that contained spatial frequencies around 5 c/d ("mid-to-high" SF) (Fintzi & Mahon, 2013). Similar to these findings, research using neural-modeling has also predicted that the human visual system utilizes tuning to specific spatial frequency ranges that offer optimal discrimination between complex visual stimuli (such as faces) (Keil, 2008, 2009).

[7] There is asymmetrical mixing of parvocellular and magnocellular information in primary visual cortex, such that the dorsal visual pathway also receives some parvocellular input, and the ventral visual pathway receives some magnocellular input (Mahon, Kumar & Almeida, 2013).

Thus, knowing that the ventral visual pathway responds to mid-to-high spatial frequency information (specifically, spatial frequencies with 2.09 to 9.14 c/d) (Fintzi & Mahon, 2013), it is reasonable to surmise that the visual reward mechanisms in the ventral visual pathway discussed by Yue et al. (2007) may be tuned to some or all of these spatial frequencies as well. If such is the case, then there should be a relationship between the positive effects of viewing nature scenes and spatial frequencies between 2.09 and 9.14 c/d. Furthermore, it also stands to reason that activation of the ventral visual reward systems by these frequencies could be what prompt the "soft fascination" discussed by Kaplan (1995; 2001)'s *Attention Restoration Theory* and the "automatic affective response" discussed in Ulrich et al. (1991)'s *Psycho-evolutionary Restoration Theory*. Activation of such a visual reward mechanism in a bottom-up fashion by specific visual information would satisfy the criteria for both "soft fascination" (since visual information that is rewarding would capture attention *modestly*), and the "automatic affective response" (since endogenous rewards would promote changes in affect). For these reasons, a novel theory, hereto referred to as *Reward Restoration Theory* (RRT), is proposed in this dissertation as "the missing puzzle piece" of the existing theoretical framework on the restorative effects of nature.

The purpose of the proposed *Reward Restoration Theory* is simple: The current theoretical framework on the restorative effects of nature is arguably insufficient to fully explain why exposure to nature has the discussed beneficial effects. For this reason, it must be extended through a complementary, and empirically based, theoretical framework that provides testable predictions about which specific types (and subtypes) of visual scenes will promote restoration. For this reason, the scope of the proposed *Reward Restoration Theory* is limited to proposing a mechanism behind the "automatic affective response" proposed by Ulrich et al. (1991) and "soft fascination" proposed by Kaplan (1995; 2001). By better understanding the underlying mechanism of the existing theories through the proposed RRT, it may be possible to make better predictions about cognitive, affective, and physiological responses to scenes beyond the current categorical statements, which state that nature scenes are more restorative than urban scenes. Thus, the proposed *Reward Restoration Theory* makes the following claims:

> [1] *There are reward pathways in the visual system, potentially those already discussed by Yue, Vessel & Biederman (2007) and Taylor et al. (2011), which are activated as part of the restoration response when viewing restorative images and environments.*
>
> [2] *Similar to the proposal by Ulrich et al. (1991) and Kaplan (1995; 2001), the reward pathways evolved in a natural setting and are thus tuned to visual information that is predominantly found in non-threatening natural scenes which once facilitated survival and well-being.*
>
> [3] *Since reward systems in the ventral visual pathway*[8] *involving ventral striatum and parahippocampal cortex are implicated, the specific visual information that stimulates the reward pathway (and thus restoration) must be in the mid-to-high visual spatial frequency spectrum of natural scenes.*
>
> [4] *Similar to the proposal by Ulrich et al. (1991) and Kaplan (1995; 2001), the restoration response should be bottom-up (stimulus-driven) since it should be (partially) facilitated by bottom-up activation of visual reward pathways.*

[8] The ventral visual pathway is predominantly associated with processing mid-to-high spatial frequency information (Mahon, Kumar & Almeida, 2013)

[5] *Any scene (natural, urban, or abstract) that contains a similar amount of mid-to-high spatial frequencies to those found in non-threatening nature scenes*[9] *should activate the implicated reward pathways and promote restoration.*

[6] *Responses to scenes should be along a gradient relative to the amount of these "natural" spatial frequencies in the scene, in line with activation of neural reward pathways.*

1.5 The Main Question

The claims made by the proposed *Reward Restoration Theory* (RRT) are novel, logical, empirically based, and complementary to existing restoration theories by Kaplan (1995; 2001) and Ulrich et al. (1991). Since RRT has been largely based on existing empirical findings, and a plausible neural mechanism that has been directly linked to scene preference (Yue et al., 2007; Taylor et al., 2011), it is able to make bold predictions and expand the theoretical framework on the restorative effects of nature. The goal of this dissertation is to empirically explore the limitations in ability to predict responses to scenes using existing theories on restoration (including the *Cognitive Perspective*, *Attention Restoration Theory,* and *Psycho-evolutionary Restoration Theory*), and directly test the novel claims made by RRT, in order to determine if the theoretical framework on the restorative effects of nature can be expanded by considering the proposed neural mechanism. To accomplish this goal, the presented research deals with a simple main question and a series of related sub-questions:

[Main question]: *"Are responses to nature and urban scenes affected by changes in low-level visual properties?"*

[9] The definition of "non-threatening nature scene" is the same as that described in Ulrich et al. (1991), referring to areas with lush vegetation and water that do not contain predators or threats to survival or well-being.

[Sub-question #1]: *"If so, do responses change as a result of changes in visual-spatial frequency (as predicted by the proposed Reward Restoration Theory)?"*

[Sub-question #2]: "*If responses are affected by visual-spatial frequencies, which frequencies are implicated (and are these frequencies in the mid-to-high range as predicted by the proposed Reward Restoration Theory)?"*

The main question stems from the inability of existing theories to make direct predictions about what happens to individuals' (restoration) response to scenes when low-level visual properties (such as spatial frequency spectrum) are altered while scene content is kept constant. The answer to this simple question will illustrate the potential limitations of existing theories, the potential need for an expanded theoretical framework (such as RRT), and speak to validity of the claims made by RRT. Assuming an affirmative response to the main question, answers to the sub-questions will address the validity of the claims made by RRT, while also contributing novel findings about what visual properties of scenes may contribute to restoration.

1.6 Fourier Transforms of Scenes

In section 1.4, literature on the theoretical workings of the human visual system is reviewed: The reviewed literature suggests that the visual system derives identity of objects and scenes in the world using spatial frequencies and spatial frequency distributions (Olhausen & Field, 1995, 1996, 1997; Karklin & Lewicki, 2008; Geisler, 2008; Mahon, Kumar & Almeida, 2013, Fintzi & Mahon, 2013). In order to study the theoretical behaviour of the visual system and how it responds to visual spatial frequencies, computational models of visual cells (Karklin & Lewicki, 2008), functional imaging of visual pathways (Mahon, Kumar & Almeida, 2013, Fintzi & Mahon, 2013), and behavioural experiments (Fernandes & Wilkins, 2008; Joubert, Rousselet, Fabre-Thorpe, & Fize, 2009) have been combined with Fourier analysis. Fourier transforms of visual scenes allow for the scenes to be decomposed into their component visual spatial frequencies; something that is useful given that current theory suggests the visual system responds to visual spatial frequencies (Geisler, 2008; Fintzi & Mahon, 2013). Similar to these experiments, the research presented in this dissertation also uses Fourier transforms of visual scenes to explore the relationship between the component visual spatial frequencies present in the scenes, and responses across various measures of restoration to the scenes.

1.6.1 Computing Fourier transforms. As mentioned earlier, Fourier analysis is a method for expressing a function as a sum of complex sinusoidal components ("component frequencies"). When dealing with a discrete sample (such as an image), a discrete Fourier transform can be used to convert a finite list of equally spaced samples (e.g. pixel values of an image) into a list of coefficients for a finite combination of complex sinusoids (i.e., "component visual spatial frequencies"). The standard formula used in scientific computation packages such as SciPy (http://www.scipy.org/) (which is used in this thesis) to transform a sequence of N complex numbers $x_0, x_1, ..., x_{N-1}$ into an N-periodic sequence of complex numbers $X_0, X_1, ... X_{N-1}$ is as follows: $k = 0, ..., N-1$

$$X_k = \sum_{n=o}^{N-1} x_n \cdot e^{-2\pi ikn/N}$$

However, the above formula applies only to 1-dimensional discrete Fourier transforms. Since images are 2-dimensional, the above equation is expanded in SciPy in order to perform a 2-dimensional Fourier transform[10]: *k = 0, ..., N-1; l = 0, ..., M-1*

[10] Source: http://docs.scipy.org/doc/numpy/reference/routines.fft.html

$$X_{kl} = \sum_{m=o}^{M-1} \sum_{n=o}^{N-1} x_{mn} \cdot e^{-2\pi i (\frac{mk}{M} + \frac{nl}{N})}$$

The above equation yields an *N* x *M* array of complex periodic components (X_{kl}) representing the 2-dimensional component frequencies within the input (image). From the output X_{kl}, the amplitude and phase of each component frequency can be calculated from the real and imaginary portions of the complex number output as follows:

$$amplitud: |X_{kl}| = \sqrt{Re(X_{kl})^2 + Im(X_{kl})^2}$$

$$\varphi_{kl}: \arg(X_{kl}) = atan2(Re(X_{kl}), Im(X_{kl}))$$

The amplitude and phase (φ) components can be manipulated or examined independently, and can also be recombined into a complex periodic using the following relationship:

$$X_{kl} = |X_{kl}| \cdot (\cos \varphi_{kl} + i \sin \varphi_{kl})\ or\ X_{kl} = |X_{kl}| \cdot e^{i\varphi_{kl}}$$

For a more thorough explanation of how to use discrete Fourier transforms and Fourier theory, please consult chapters 12 and 13 in Press, Teukolsky, Vetterline, & Flannery (2007). Using the described formulas above (or simply their implementation in SciPy: http://www.scipy.org/), it is possible to transform an image into a 2-dimensional discrete Fourier series depicting the component visual spatial frequencies found within the image. These component frequencies can then be analyzed in terms of their amplitude and phase, trimmed, and can even be recombined after manipulation to create altered versions of the original image via inversion of the Fourier transform.

1.6.2 Fourier analysis in image statistics and perception research. In the field of image statistics, the spectral properties of images and how they change with respect to image content are sometimes analyzed by computing the 2-dimensional power spectrum of the Fourier transform, which is simply the squared amplitude of the component frequencies (i.e., $| X_{kl} |^2$), and looking for patterns in plots of power versus spatial frequency (Torralba & Oliva, 2003; Oliva & Torralba, 2006). By using this method and averaging over large databases of images, Torralba & Oliva (2003) have been able to demonstrate that specific scene properties and objects have distinct spectral signatures (i.e., scenes and objects can be identified by the strength [power] of specific visual spatial frequency combinations in the image). For example Torralba & Oliva (2003, 2006) have been able to demonstrate that it is possible to identify natural versus man-made objects, forests versus cities, and streets versus beaches based on their spectral signatures using a computational model tuned to these signatures. They further suggest that cells in the human visual system may also work in a similar way (Torralba & Oliva, 2003), and that the parahippocampal cortex may be able to perform the necessary computations of these spectral signatures to derive scene identity (Oliva & Torralba, 2006). Geisler (2008) has reinforced this idea that human perceptions of visual scenes can be described and studied using natural scene statistics, stating that the human visual system might be exploiting such statistical properties to identify, categorize and discriminate between objects. More recent research by Koch, Denzler, & Redies (2010) has shown that it is possible to categorize and differentiate between visual art, cartoons, comics and photographs using the power spectrum of images derived from their Fourier transform.

The use of Fourier analysis in image statistics and perception research is not limited to image categorization of scenes by computational models using 2-dimensional spectral signatures: A more common approach has been to radially average the 2-dimensional power (or amplitude) spectrum into a 1-dimensional power (or amplitude) spectrum and correlate the 1-dimensional spectrum to responses to scenes (Simoncelli & Olhausen, 2001; Fernandez & Wilkins, 2008; Juricevic et al, 2010; Wilkins & Webster, 2010; Melmer et al., 2013). For example, a recent study by Melmer et al. (2013) explored the Fourier statistics of images with low and high aesthetic appeal: Melmer et al. (2013) propose that since art and writing are created by humans for viewing by humans, the images may exhibit statistical properties that reflect sensory integration done by the human visual system. Their findings suggest that Fourier power spectra of text are *not* scale-invariant unlike the Fourier power spectra for aesthetic images (Melmer et al., 2013). They further note that the lack of scale invariance in the Fourier spectrum appears to be associated with a lack of visual aesthetics. Importantly, Melmer et al. (2013) also note that scale invariance in the Fourier power spectra (such as that found in natural scenes) does not necessarily mean that the image will be aesthetically pleasing, but rather that it is a consequence of some other unknown feature of aesthetics. Lastly, by analyzing cross-cultural artworks, Melmer et al. (2013) demonstrate similar spectral features (such as scale invariance in the Fourier domain) across all cultures, and suggest that the specific perceptual mechanisms for aesthetic judgement may be common amongst humans across different cultures.

The link between specific patterns in the power (i.e., amplitude squared) spectrum and visual aesthetics discussed by Melmer et al. (2013) is unsurprising when considering previous research by Fernandez & Wilkins (2008) and O'Hare & Hibbard (2012) exploring the relationship between the amplitude spectrum of images (such as natural scenes) and ratings of aversiveness. Research by Fernandez & Wilkins (2008) found that higher amplitudes of spatial frequencies with approximately 3 to 7 cycles per degree of visual angle (c/d) were correlated with self-reported aversion to images. Fernandez & Wilkins (2008) also correlated aversion to the amplitude of spatial frequencies in rural and urban scenes, and found that aversion to the scenes increased as amplitude of spatial frequencies between 3 and 7 c/d increased. They also found that the amplitude spectra of images influenced responses to the images more than the phase spectrum, despite the fact that the structural appearance of objects was better preserved in the phase spectra (Fernandez & Wilkins, 2008).

It should be noted that in Fernandez & Wilkins (2008) participants viewed booklets and projected images at non-controlled viewing distances: This means that images presented did not occupy similar visual angle across participants and the spatial frequency range may not be entirely accurate. In a more recent study, O'Hare & Hibbard (2012) created images from noise filtered to have a 1/f amplitude spectrum (a spectrum which is typical of natural images) and found that having a higher amplitude of spatial frequencies with 0.375 to 1.5 c/d was more aversive than peaks at higher spatial frequencies. Similar to findings by O'Hare & Hibbard (2012) and Fernandez & Wilkins (2008), which suggest that the amplitude of visual spatial frequencies (as derived from Fourier analysis) are important for visual perception, research by Joubert et al. (2009) also suggests a link between visual perception and the amplitude of visual spatial frequencies. Using a rapid scene categorization task, Joubert et al. (2009) found that equalization of the amplitude spectra of images (also known as "whitening") significantly reduced categorization accuracy for scenes (from 96% to 90%) while adding noise to the phase spectra had non-significant effects when up to 50% of the phase was replaced with noise. Beyond 50% noise in the phase spectra of images, categorization accuracy dropped off exponentially (Joubert et al., 2009).

1.6.3 Use of Fourier analysis in the current experiments. As reviewed in section 1.4, existing literature on the visual system suggests that the identity of objects and scenes in the world can be derived from their visual spatial frequencies and their spatial frequency distributions (Olhausen & Field, 1995, 1996, 1997; Karklin & Lewicki, 2008; Mahon, Kumar & Almeida, 2013, Fintzi & Mahon, 2013). Furthermore, as discussed in section 1.6 so far, literature on natural image statistics and human perception has validated the use Fourier transforms to decompose images into their component visual spatial frequencies so that responses and categorization of scenes may be explored in relation to their amplitude (power) and phase spectra (Torralba & Oliva, 2003; Fernandez & Wilkins, 2008; Joubert et al., 2009; O'Hare & Hibbard, 2012; Mahon, Kumar & Almeida, 2013,Melmer et al., 2013; Fintzi & Mahon, 2013). Given that the main goal of this dissertation is to explore how responses to nature and urban scenes may vary with respect to low-level visual properties, as suggested by the proposed *Reward Restoration Theory,* the work presented in this dissertation draws heavily on these previously established methodologies for exploring the relationships between amplitude and phase spectra of visual-spatial frequencies of scenes and responses to them.

Specifically, in Experiments 1 and 2, Fourier transforms of scenes are computed (as discussed in section 1.6.1) and the amplitude and phase components are altered using similar methods to those in Joubert et al. (2009) in order to create some of the experimental stimuli. For example, to create a "mid-to-high spatial frequency" version of scenes, the amplitude spectra of the experimental stimuli is equalized ("whitened"), eliminating contrast information. In the later experiments, Fourier transforms are used to compare the amplitude ("power") of component visual spatial frequencies to restoration responses prompted by the scenes in a similar fashion to how Fernandez & Wilkins (2008) and Melmer et al. (2013) explored the relationship between the amplitude spectra of images and self-reported aversiveness and visual aesthetics of images.

1.7 The Experiments

In order to investigate the main question and sub-questions posed in this dissertation, the present research used a series of modified “slide-show presentation” paradigms to expose individuals to a variety of different scenes, some of which were nature scenes, urban scenes, abstract fractals, and variations of these scenes that contained only low spatial frequency information, or mid-to-high spatial frequency information. These experimental paradigms were based on those used in previous experiments to demonstrate that photographs (and posters) of nature scenes can produce restoration (Berman et al., 2008; Kweon et al., 2008; Berto, 2005). Measures of restoration included self-report, and eye-tracking,[11] which have both been validated as reliable measures of restoration across different studies and have been found to correlate with measures of physiological stress (Valtchanov & Ellard, 2010; Berman et al., 2008, Berto et al., 2008, Ulrich et al., 1991; Cruz et al., 2011). In total, six experiments were conducted.

In Experiment 1, the effects of various different image alterations on responses to scenes are explored. Participants viewed a mixture of unaltered and altered photographs of nature and urban scenes to determine if low-level visual properties influenced responses to scenes. Altered versions included photographs with only low visual spatial frequency or mid-to-high visual spatial frequency information, and photographs where the phase or amplitude of the visual spatial frequencies had been scrambled. Results indicate that restoration responses are influenced by visual spatial frequencies, implicating mid-to-high visual spatial frequencies and overall amplitude (power) of visual spatial frequencies as potential factors in determining the restoration response. Results illustrate the limitations of existing theories of restorative effects in

[11] Eye-tracking was used in only two of the experiments due to constraints on availability.

predicting how responses to scenes may vary based on changes in low-level visual information, and provide support for claims made by the proposed *Reward Restoration Theory*.

Experiments 2 and 3 explore the effects of top-down influences (proposed by the *Cognitive Perspective*) versus bottom-up mechanisms (proposed by *Attention Restoration Theory*, Psycho-evolutionary Theory, and *Reward Restoration Theory*) on responses to scenes. Results indicate that responses to scenes are driven by bottom-up mechanisms. The results from Experiment 3 also suggest that self-reported ratings of pleasantness and stress are related to the proportion of an individual's visual field that is occupied by nature; this is consistent with predictions made by *Reward Restoration Theory.*[12]

Experiment 4 explores the finding in Experiment 3, suggesting that responses to scenes may be directly proportional to the amount of natural stimuli in the visual field, by using photographs of scenes that contained different proportions of natural to urban visual stimuli. Results reveal that responses to scenes were indeed proportional to the ratio of natural to urban content in the visual field, illustrating the limitations of *Psycho-evolutionary Restoration Theory* and *Attention Restoration Theory* in their ability to predict the effect, and validating the claim made by *Reward Restoration Theory*. Furthermore, analysis of how responses to scenes vary with respect to spatial frequencies in the scenes reveals that the power of a narrow range of visual spatial frequencies is predictive of restoration.[13] A meta-analysis of Experiments 1 to 4 reveals that the power of the discovered spatial-frequency range is predictive of all measures of restoration across the experiments, providing strong support for claims made by *Reward Restoration Theory*.

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[12] Reward Restoration Theory [6]: *Responses to scenes should be along a gradient relative to the amount of these "natural" spatial frequencies in the scene.*

[13] Amplitude of spatial frequencies and frequencies in the mid-to-high range were implicated in restoration in Experiment 1.

Experiments 5 and 6 directly test the predictive power of the visual spatial frequency range discovered in Experiment 4 in determining restoration under circumstances where restoration would not be predicted by *Attention Restoration Theory*, *Psycho-evolutionary Restoration Theory*, and the *Cognitive Perspective*. Experiment 5 employs the use of fully-urban scenes, while Experiment 6 employs the use of abstract fractal images. Both experiments use images that vary in power of the implicated visual spatial frequency range. In both cases, a strong predictive relationship is found between power of the "restorative" spatial frequency range and restoration, validating findings in the previous four experiments. Urban scenes and abstract fractals that are similar in visual spatial frequency to (non-threatening) nature scenes are found to be the most restorative. This finding provides further evidence to suggest that part of the restoration response is dependent on bottom-up processing of specific visual spatial frequency information, consistent with predictions made by the proposed *Reward Restoration Theory*. Based on the consistent support for *Reward Restoration Theory* and demonstrated limitations of predictive power of existing theories across all six experiments, it is suggested that theories on restoration can benefit from expanding the theoretical framework to include the visual-reward mechanism and claims proposed by *Reward Restoration Theory*.

In summary, it is suggested that the existing theoretical framework on the restorative effects of nature is insufficient to predict (or understand) the restorative response to viewing scenes and environments. To address this shortcoming, an empirically based theory on the mechanism behind the “automatic affective response” in *Psycho-evolutionary Restoration theory* (Ulrich et al., 1991) and "soft fascination" in *Attention Restoration Theory* (Kaplan, 1995; Kaplan, 2001) is proposed. Six experiments are used to outline the limitations of existing theories, and to demonstrate that prediction of the restorative response could be improved by considering *Reward Restoration Theory*. Beyond this demonstration, evidence is found that a specific visual spatial frequency range appears to be associated with the restoration response, suggesting that visual reward pathways implicated in scene preference (Yue et al., 2007) may be tuned to specific spatial frequencies. These conclusions and their implications for understanding the restorative effects of nature are expanded in the General Discussion.

Chapter 2 Experiment 1: Exploring How Preference, Recognition and Eye Movements Are Influenced By Low Level Visual Properties

2.1 Introduction

The first experiment in this dissertation had three main goals: The first goal was to replicate the supporting evidence for *Attention Restoration Theory* (ART), found by Berto, Massaccesi & Pasini (2008), using a novel paradigm and novel stimuli. In their research on ART, Berto et al. (2008) have demonstrated that eye-travel distance and number of fixations are greater when viewing urban scenes compared to nature scenes.

The second goal of this experiment was to build on these findings by including blink rates as a measure of cognitive processing and attention, since they have been previously found to be an acceptable measure of cognitive load: Blink rates have been found to increase when cognitive load increases (Stern, Walrath, Goldstein, 1984; Bentivoglio et al., 1997; Siegle, Ichikawa & Steinhauer, 2008; Cruz et al., 2011). Furthermore, self-report of pleasantness of the scenes was also included as a measure to determine if eye movements (i.e., measures of visual attention) could predict perceived pleasantness (i.e., "restoration"), as claimed by *Attention Restoration Theory*.

The third goal of this experiment was to explore the newly proposed notion by *Reward Restoration Theory* that the restorative effects of nature may be partially driven by low level visual properties of scenes. This new theory shares the main idea that there is a bottom-up response to scenes with *Attention Restoration Theory*, but differs in attributing the response to bottom-up activation of visual reward pathways by specific visual stimuli (which may create shifts in attention) rather than shifts in attention by themselves. In order to explore how individuals respond to different parts of visual information present in scenes, methods of image manipulation previously used in studies on the visual system were recruited (Doi & Lewicki, 2005; Mahon et al., 2013; Fintzi & Mahon, 2013).[14] Visual spatial frequency isolation (low versus mid-to-high) and image degradation (phase and amplitude scrambling) on measures of cognitive load, visual attention, and pleasantness were explored in order to develop a foundation for the theory.

Given these goals and previous literature, five main hypotheses were formed:

H1: A replication of Berto et al. (2008)'s findings was expected, such that the number of fixations and eye-travel distance would be greater when viewing urban scenes compared to nature scenes. Average fixations times were hypothesized to show the inverse relationship since a greater number of fixations should result in less time per fixation.

H2: Blink rates were hypothesized to be lower when viewing nature scenes compared to urban scenes, given that viewing nature scenes are believed to reduce stress and restore attention while viewing urban scenes is believed to be stressful and result in a higher cognitive load (Berman, Jonides & Kaplan, 2008; Valtchanov & Ellard, 2010).

H3: Nature scenes were hypothesized to be rated as more pleasant than urban scenes, replicating previous findings in the restorative effects of nature literature. Furthermore, it was predicted (based on *Attention Restoration Theory*) that pleasantness (a measure of “restoration”) would be predicted by measures of attention.

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[14] A review of spatial frequencies, how the visual system responds to them, and how previous studies have manipulated images to include only specific spatial frequencies were discussed in Chapter 1: Section 1.4

H4: Related to the previous hypothesis, it was hypothesized that individuals would spend more time fixating centrally and view the image holistically rather than looking at individual objects, (signalling global processing,) when viewing nature scenes versus urban scenes. This was hypothesized since viewing nature scenes has been previously found to improve affect and reduce stress (Valtchanov et al., 2010; Valtchanov & Ellard, 2010; de Kort et al., 2006; van den Berg et al., 2003), which should broaden the scope of attention and result in holistic processing of the scene (Fredrickson & Branigan, 2005). Previous research on the restorative effects of nature has indicated that individuals spend different amounts of time fixating centrally when viewing nature versus urban scenes, but has failed to explain the cause (Berto et al., 2008).

H5: If low level visual properties, such as visual spatial frequency, are differentially stimulating visual reward pathways, and thus partially driving the restorative effect, removing broad ranges (e.g., mid-to-high frequencies or low frequencies) should influence measures of attention, cognitive load, and affect (i.e., Eye-movement patterns, blink-rates and ratings of pleasantness.)

2.2 Method

2.2.1 Participants. Prior to recruitment, participants were pre-screened using a mass-testing questionnaire. Participants were required to speak and read English fluently (in order to understand instructions), and to have reported that they had normal 20/20 vision. A sample of twenty-six participants (13 male, 13 female) was recruited from the University of Waterloo SONA participant pool to participate in the study in exchange for course credit. Upon being recruited, participants were asked if they suffered from any visual disorders such as having a "lazy eye" or "crossed eyes" or "colour blindness." None of the participants reported having any visual disorder or problem. This was done to ensure that they did not suffer from visual disorders that might influence eye-tracking.

2.2.2 Materials. This experiment used a simple slide-show presentation of various types of images on an nVisor SX60 head-mounted display (HMD) that featured an Arrington monocular eye-tracker and 44 degrees of horizontal field of view (34 degrees vertical field of view).

Images used in this study were collected from a free Internet computer wallpaper gallery that featured both urban and nature photography. All eight images were photographs from cities or natural scenery around the world. All images were converted to grayscale and cropped to the dimensions of 900 x 900 pixels using Adobe Photoshop Elements 10 (occupying approximately 30 degrees field of view when presented on the HMD).[15] All images were saved in JPEG format, and had their brightness levels and contrast balanced using the “Auto Levels” and “Auto Contrast” options in Adobe Photoshop Elements 10. When displayed during the experiment, images were in their native resolution, such that pixels in the image matched pixels on the display in a 1:1 ratio. Sample of photographs used can be seen in Figure 2.1.

Four "altered" versions of each image were created from the original images, giving a total of five variations of each image. The first was a 1-dimensional phase scrambled version, created by scrambling the phase of the visual spatial frequencies in the image across one dimension, which eliminated all identifiable contours of objects and shapes while retaining the

[15] All scenes were presented in grayscale in order to control for colour information. This was done after pilot testing revealed that restorative effects were still present for grayscale images. Recent research by Codispoti, Cesarei & Ferrari (2011) has validated this approach by demonstrating that color information is not critical for processing of natural scenes using EEG/ERP techniques.

approximate contrast of the scene. The phase scrambled images were included as a baseline comparison for spontaneous blink rates and fixations.

The second altered image type was a 1-dimensional amplitude scrambled version of the images, which preserved some contours but greatly degraded image quality. This image type was included for exploratory purposes to see if eye-movements and blink rates change when visual information is greatly degraded. *Details and reasoning for using these types of phase and amplitude scrambling are described in Appendix A.*

The third altered image type was a low spatial frequency version of the image created by applying a Gaussian filter with a 15 pixel radius to the image, effectively eliminating middle and high spatial frequencies while maintaining overall contrast and shape of objects. This version of the image was included to explore the effects of removing middle and high spatial frequencies on responses to the image.

The fourth altered image type was a middle to high spatial frequency "whitened" version of the image created by flattening the amplitude of the visual spatial frequencies in a similar fashion to methods used by Joubert et al. (2009), eliminating the majority of the low spatial frequencies. The process created an image that contains edge and contour information carried by middle-high spatial frequencies and is sometimes referred to as "whitening" in the image statistics literature (Simoncelli & Olhausen, 2001). This image type was included in order to explore the effects of removing low spatial frequencies and contrast on responses to the scene.

2.2.3 Design. A completely within-subjects design was used in this experiment, where all images were seen by every participant. Images were presented in random order with the condition that the image currently presented to the participant had to be the least recognizable version of the scene that had not been already viewed. Figure 2.2 shows a sample of altered image versions from least recognizable (a) to most recognizable (d) of the bottom-right scene in Figure 2.1. Since the unaltered version was the most recognizable, it was seen after all of the previous versions. This was done to promote bottom-up processing of each image and prevent top-down order effects. To accomplish this, all 40 images (8 originals + 8 x 4 altered versions) were pilot tested using naive participants before this study was conducted. Participants in the pilot study were asked to rate how well they could identify the types of objects in the scenes (e.g. trees, mountains, water, plants, buildings, windows, cars, etc). This data was used to determine presentation order in the current study.

Figure 2.1. Experiment 1: Sample of nature (left) and urban (right) photographs used.

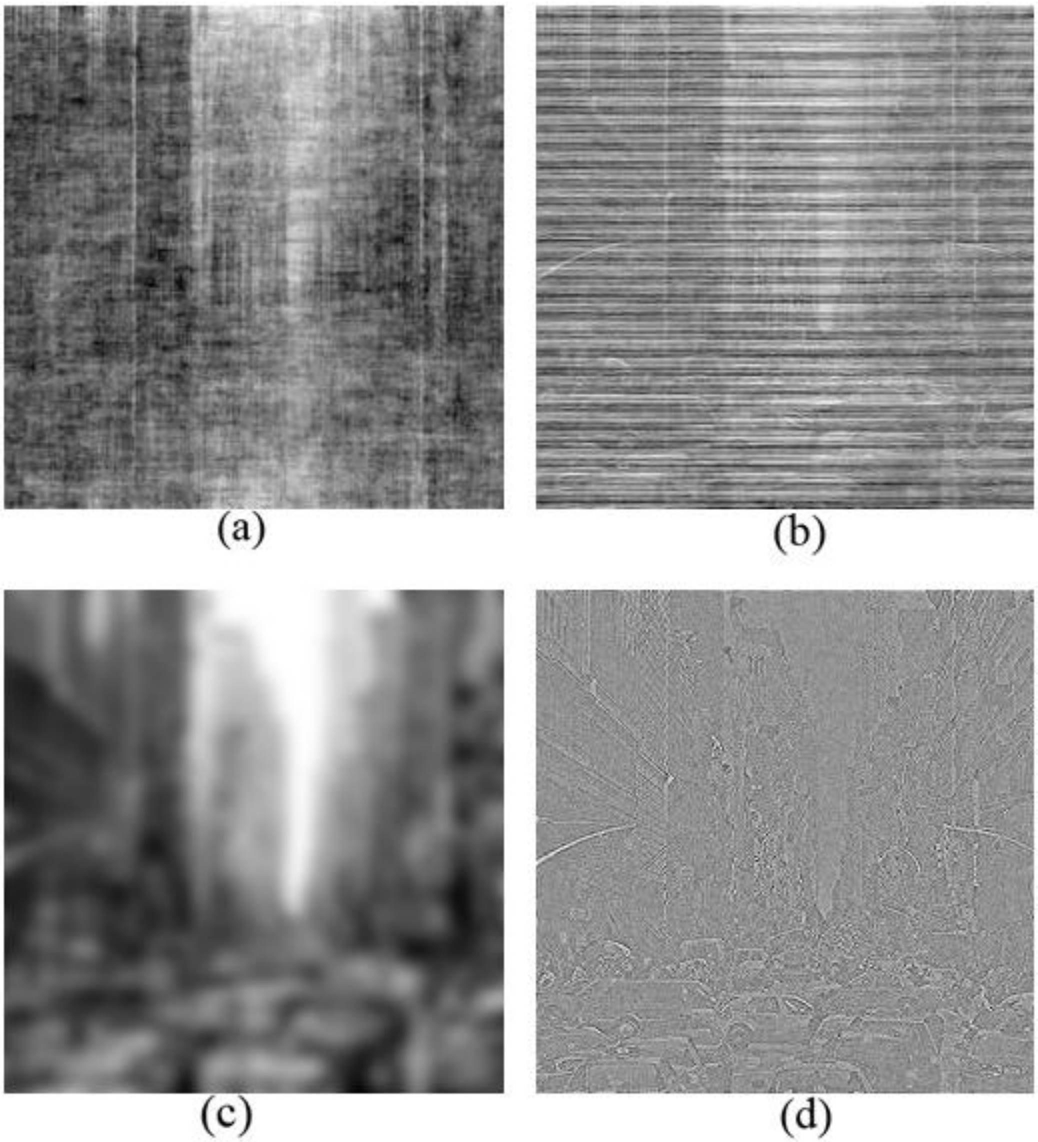

Figure 2.2 Experiment 1: Sample versions of images used: (a) phase scrambled in 1-dimension, (b) amplitude scrambled in 1-dimension, (c) low-spatial frequency, (d) “whitened” mid-to-high spatial frequency.[16]

[16] Please note that since these are smaller versions of stimuli, object details may be degraded and harder to see.

2.2.4 Procedure. Individual participants were scheduled to come to the lab using the University of Waterloo's SONA online system. Upon their arrival, participants were greeted by the researcher, briefed on the procedure of the experiment and given an information and consent form to read and sign. Upon agreeing to participate in the experiment, participants were fitted with the nVisor SX head-mounted-display and calibrated with the attached Arrington eye-tracker.[17] Participants were informed that they would see a variety of images that were urban, nature, or altered, each of which would be followed by two questions: The first asking how pleasant they found the image and the second asking how well they could recognize the types of objects in the image.

Every trial started with a central cross on a gray background, which functioned as a fixation trigger. Participants had to fixate on the fixation cross in the center of the screen for 150 milliseconds before the trial would start. This was done to force all participants to fixate in the same place at the start of the trial to ensure consistency across participants.[18] Once the fixation trigger was fixated for 150 ms, the fixation cross and grey background disappeared and the image was presented. Images were presented in the center of the screen (occupying 30 degrees field of view) on a black background, one at a time, for fifteen seconds each. After the fifteen seconds, the screen shifted to a series of grey screens with the questions written on them. Participants responded to the questions using the number pad on the keyboard on a scale from 1 (low) to 5 (high).

[17] An HMD was used because it was the only available display with eye-tracking in our lab, and eye-tracking was required for the experiment. It included the bonus of controlling for viewing distance/field of view across participants and blocking out external visual stimuli.
[18] The first fixation was not included in analyses since it was forced via fixation trigger.

2.3 Results and Discussion

2.3.1 Testing hypothesis 1: Replication of Berto et al. (2008). In order to examine if Berto et al. (2008)'s findings were replicated in this experiment, preliminary analysis was restricted to participants' responses to the unaltered versions of the images, since Berto et al. (2008) used unaltered images in their study. Data was collapsed across the images based on type (urban versus nature) and examined using a repeated-measures ANOVA. The first fixations of participants were not included in the analysis since the fixation trigger was in the center of the screen, causing all first fixations to be at that location. Hypothesis 1 was partially supported: As predicted, there were significantly more fixations on urban scenes (M = 2.4 fixations per second) than nature scenes (M = 2.2 fixations per second), $F(1,25) = 15.1$, $MSE = 0.034$, $\eta_p^2 = 0.376$, $p < 0.001$. Fixation times had the inverse relationship, with urban scenes having a significantly shorter time per fixation (M = 0.31 seconds) than nature scenes (M = 0.36 seconds), $F(1,25) = 13.3$, $MSE = 0.002$, $\eta_p^2 = 0.347$, $p < 0.001$. Surprisingly, eye-travel distance was not found to be different between viewings of nature and urban scenes, $F(1,25) = 0.9$, $p = 0.35$, n.s., suggesting that the eye-travel differences found by Berto et al. (2008) may be dependent on the stimuli or paradigm used, and is thus not a reliable measure. The replication of differences in fixation behaviour and strong effect sizes presented here support this notion. Overall, these results agree with Berto et al. (2008)’s previous findings that suggest there are changes in visual attention when looking at nature versus urban scenes.

Results such as these have been used in the past (Berto et al., 2008) to support *Attention Restoration Theory;* which suggests that nature scenes are more “fascinating”, allowing them to capture attention in a bottom-up way, so that the restoration of directed attention to can occur. While we can say that photographs that are high in “fascination” (as defined by high ratings of qualitative statements about the scene[19]) promote longer fixation times and fewer fixations (as in Berto et al. (2008)), we can also examine the results from the perspective of the proposed *Reward Restoration Theory*.

Here, *Reward Restoration Theory* predicts the same pattern of results, but for a different reason. If the visual system responds to specific visual characteristics of scenes with the release of biological rewards, then the observed visual behaviour was a logical outcome of reward-seeking behaviour. It is possible that individuals fixated longer on particular areas that offered visual reward (i.e., had longer fixations for nature scenes due to their rewarding/restorative properties). However, at this stage in the analysis it was unclear what visual information (if any) individuals could be responding to.

2.3.2 Testing hypothesis 2: Blink rates as a measure of cognitive load. Blink rates were hypothesized to be lower when viewing nature scenes compared to urban scenes, indicating a more relaxed state since exposure to nature was expected to 'restore' individuals and reduce stress and cognitive load (Berman, Jonides & Kaplan, 2008; Valtchanov, Barton & Ellard, 2010). Preliminary analysis was done on blink-rates for the unaltered images in order to see if there were indeed differences in cognitive load when viewing nature versus urban scenes. Hypothesis 2 was supported: A repeated-measures ANOVA was conducted and it was found that participants blinked significantly more when viewing urban scenes (M = 25.9 blinks per minute) compared to nature scenes (M = 24.4 blinks per minute), $F(1,25) = 6.4$, $MSE = 4.3$, $\eta_p^2 = 0.20$, $p < 0.05$.

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[19] Qualitative statements include: "*The setting has fascinating qualities,*" "*My attention is drawn to interesting things,*" "*I would like to spend more time looking at the surroundings*" (Hartig et al., 1997)

While there was clear support for the hypothesis that viewing urban scenes relative to viewing nature scenes would result in higher blink rates due to increased cognitive load, it was unclear whether viewing urban scenes *increased* blink rates or whether viewing nature scenes *decreased* blink rates relative to baseline. Thus, blink rates when viewing unaltered versions of urban and nature scenes had to be compared to blink patterns for the 1-dimensional phase-scrambled versions which were used as a baseline.

A baseline check was first conducted: Blink rates and self-reported ability to discern objects for phase-scrambled nature scenes and phase-scrambled urban scenes were compared using a repeated-measures ANOVA. No differences between the images were found for blink rates, $F(1,25) = 0.38$, n.s., or discernible objects within the scene $F(1,25) = 0.36$, n.s., confirming that the phase-scrambled images of nature and urban scenes were not significantly different from each other. This meant that blink-rates when viewing the phase-scrambled images could be used as a baseline for each participant as originally intended.

Difference scores were computed between baseline blink rates (i.e., blink rates per minute when viewing phase scrambled versions of scenes, $M = 25.5$) and blink rates for unaltered and nature and urban scenes for each participant. A paired samples t-test revealed that blink rates for nature scenes decreased significantly more relative to baseline ($M = 24.4$, $\overline{D} = -1.1$ blinks per minute) than did blink rates for urban scenes ($M = 25.9$, $\overline{D} = +0.4$ blinks per minute), $t(25) = 2.5$, $p < 0.05$, $SE = 0.57$. The results suggested that viewing nature scenes reduces blink rates, and thus reduces cognitive load, more than viewing urban scenes. Unfortunately, this result is potentially ambiguous in terms of directionality, since it is possible that phase-scrambled images were less interesting, causing participants to mind-wander. A different baseline and/or thought probes may be required to control for potential mind-wandering.

It should be noted that in this study, images were presented for only 15 seconds, in a random order, were sandwiched between questions and fixation triggers, and were novel, making it unlikely that participants were mind-wandering *only* when viewing the phase scrambled images. Instead, if mind wandering occurred, it is more likely that it simply added noise to the data since images were presented randomly. Overall, this is the first empirical evidence for differences in cognitive load, as measured by blink rates, when viewing urban scenes versus nature scenes. These results offer support for *Attention Restoration Theory* and *Psycho-evolutionary Restoration Theory*, which suggests that processing urban scenes is more cognitively taxing than nature scenes. These results also support *Reward Restoration Theory*, which suggests that blink rates would reduce when viewing nature scenes due to the stress-reducing effect of μ-opioid receptor activation (Cruz et al., 2011)

2.3.3 Testing hypothesis 3: Self-reported ratings of pleasantness. Based on the well documented effects of exposure to nature, viewing nature scenes was hypothesized to be significantly more pleasant than viewing urban scenes. Analysis focused on the unaltered images using a repeated-measures ANOVA. As expected, there was a robust main effect; nature scenes were rated as significantly more pleasant (M = 4.5 out of 5) than urban scenes (M = 3.7 out of 5), $F(1,25) = 14.2$, $MSE = 0.522$, $\eta_p^2 = 0.36$, $p < 0.001$. While this confirmed that the general findings in the literature on the restorative effects of nature were replicated, it did not offer any new information on the topic. Given this, and the rich dataset of the current experiment, it made sense to perform exploratory analyses testing *Attention Restoration Theory*. Surprisingly, few previous studies had explored both measures of attention and measures of affect in the same paradigm. Those that have measured both, have reported mixed results (Valtchanov et al., 2010; Berman et al., 2008).

2.3.4 Exploratory analysis testing the relationship between visual attention and changes in cognitive load and affect. *Attention Restoration Theory* states that as directed attention shifts to involuntary attention when viewing nature scenes, cognitive and affective restoration occurs (Kaplan, 1995, 2001). In the current study there were measures of visual attention (fixation patterns), cognitive load (blink rates), and affect (self-reported pleasantness), and thus an opportunity to test the direct predictions of *Attention Restoration Theory*. Exploratory analysis was conducted to test the predicted relationships using multiple regression. Since this study used a completely within subjects design, between subjects variability was removed from the data so a within-subjects multiple regression could be performed. Methods to remove between-subjects variability used were those described in Cousineau (2005).[20]

For the first set of analyses, self-reported pleasantness was entered as the dependent variable, and number of fixations and average fixation time as the predictors in separate regression models.[21] The first model revealed that number of fixations significantly predicted self-reported ratings of pleasantness, *standardized* β = -0.43, t(24) = 3.4, $p < 0.005$. Number of fixations also explained a significant portion of variance in self-reported pleasantness, $R^2 = 0.19$, $F(1,24) = 11.6$, $p < 0.005$. The second model revealed that fixation time also predicted self-reported pleasantness, *standardized* β = 0.344, t(24) = 2.6, $p < 0.05$. Fixation time also

[20] The method used retains within-subject variability while normalizing participant means to the grand mean. Thus, the reported effect size from the regression represents within-subjects effect and closely matches the effect size from repeated-measures ANOVA. Other methods using dummy coding for performing multiple-regression on within-subjects data were considered, but found to disagree with repeated-measures ANOVA regarding effect size.

[21] A mediation analysis was conducted to see if eye-movements mediated the effect of scene type on self-reported pleasantness. No evidence for a full or partial mediation was found.

explained a significant portion of variance in self-reported pleasantness, $R^2 = 0.12$, $F(1,24) = 6.7$, $p < 0.05$. A third regression model was then tested, with both fixation time and number of fixations as predictors of self-reported pleasantness in order to see the independent effect of each of the predictors. The model revealed that when both predictors were included, only number of fixations continued to predict self-reported pleasantness, *standardized* $\beta = -0.4$, $t(23) = 2.0$, $p < 0.05$, while fixation time did not, *standardized* $\beta = 0.003$, $t(23) = 0.01$, $p = 0.99$, n.s. This suggested fixation time was dependent on the number of fixations, so a final regression model was used to test if number of fixations predicted fixation time: Number of fixations were found to predict fixation time, *standardized* $\beta = -0.792$, $t(24) = 9.17$, $p < 0.001$, and a significant portion of the variance in fixation time, $R^2 = 0.63$, $F(1,24) = 84.1$, $p < 0.001$.

The second set of regression analyses aimed to examine predictions of *Attention Restoration Theory* that changes in attention would result in changes in cognitive load. Since the previous analysis revealed that number of fixations was the best predictor of self-reported pleasantness, it was used as the sole predictor for blink rates. The regression analyses revealed that number of fixations significantly predicted blink rates, *standardized* $\beta = 0.401$, $t(24) = 3.1$, $p < 0.05$ and a significant portion of variance in blink rates, $R^2 = 0.161$, $F(1,24) = 9.6$, $p < 0.05$.

The exploratory analyses provided novel and significant support for predictions made by *Attention Restoration Theory*. These results, combined with reported findings for eye-movements and self-reported pleasantness, contribute a significant pool of empirical evidence supporting predictions made by ART, which was previously absent. While noteworthy, these findings did not dissociate between *Attention Restoration Theory* and *Reward Restoration Theory*.

2.3.5 Testing hypothesis 4: Holistic processing of natural scenes. It was hypothesized that since exposure to nature scenes improves affect and reduces stress (Valtchanov et al., 2010; Valtchanov & Ellard, 2010; de Kort et al., 2006; van den Berg et al., 2003), participants would have a broadened scope of attention and therefore have longer central fixations, which would allow them to process the scene more holistically (Fredrickson & Branigan, 2005). Fixating on the center of the image would fit the entire scene within 15 degrees of eccentricity, optimizing visual input. To test this hypothesis, fixations across all unaltered nature scenes and all unaltered urban scenes were compared by computing pooled fixation maps for each type of image (nature versus urban) and calculating a difference map. To do this, each image was sectioned into 8100 sections with the size of 10x10 pixels, and fixations within the sections were averaged. The computed difference map was then separated into two sections: A central fixation area encompassing the 5 degrees of visual angle at the center of the image (i.e., 2.5 degrees of eccentricity), and an extra-central area encompassing the rest of the image.

A one-sampled t-test was used to determine if the differences in central fixation times between nature and urban scenes were significantly different from zero. The analysis revealed that participants had longer central fixations ($\overline{D}$ = 67 ms per fixation) when viewing nature scenes versus urban scenes, $t(168) = 3.8$, $p < 0.001$, SE = 17.5. A second one-sampled t-test was used to see if there were differences in the extra-central area of the image: The analysis revealed that participants had slightly shorter extra-central fixations ($\overline{D}$ = 3.9 ms per fixation) when viewing nature scenes versus urban scenes, $t(5624) = 6.1$, $p < 0.001$, SE = 0.64. These findings can be seen in Figure 2.3. These findings support the hypothesis that nature scenes may broaden the scope of attention due to restoration (Berman et al., 2008; van den Berg et al., 2003; Fredrickson & Branigan, 2005), and prompt longer central fixations as a result.

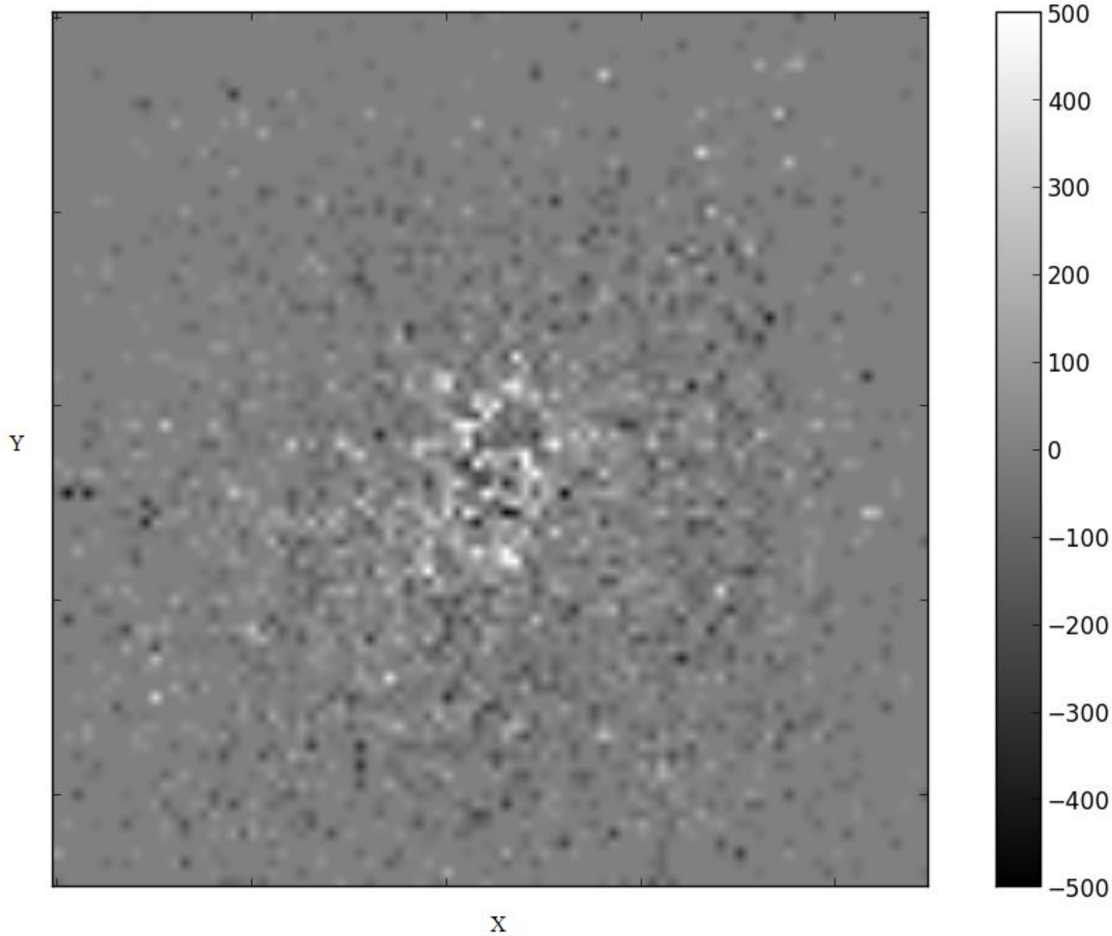

Figure 2.3 Experiment 1: Two dimensional difference map of fixation time (in milliseconds) for natural scenes minus fixation time for urban scenes for each 10 x 10 pixel section of the images; Participants fixated significantly longer in the centre of nature scenes (as shown by the lighter central area). Participants also fixated longer non-centrally when viewing urban scenes (as shown by darker pericentral area).

2.3.6 Testing hypothesis 5: Effects of low level visual properties on self-reported pleasantness. Given that the effects of low level visual properties on restoration had not been previously explored in the literature, and Kaplan's *Attention Restoration Theory* and Ulrich's *Psycho-evolutionary Restoration Theory* did not make predictions about the effects of degrading visual information, the following analyses focused on predictions made by the proposed *Reward Restoration Theory*. RRT predicts that the restorative response is dependent on incoming visual information, and thus degrading visual information would attenuate the response.

First, the effect of changes in low-level visual properties on self-reported pleasantness was explored using a repeated-measures ANOVA. The unaltered versions, middle-high spatial frequency (M-HSF) versions, and low-spatial frequency (LSF) versions of the photographs were included in the analysis. There was a significant main effect of image content (nature versus urban) on self-reported pleasantness, $F(1,25) = 22.7$, $MSE = 0.71$, $\eta_p^2 = 0.476$, $p < 0.001$. There was also a significant main effect of image version (original, M-HSF or LSF) on reported pleasantness, $F(2,50) = 70.3$, $MSE = 0.70$, $\eta_p^2 = 0.74$, $p < 0.001$. The content by image version interaction was not significant, $F(2,50) = 1.9$, $p = 0.16$, n.s. However, given the direction toward a “trending” content by image version interaction, it is possible that Experiment 1 did not have enough statistical power to show the interaction effect.

A polynomial linear contrast was used to determine if there was a linear relationship between removing spatial frequency ranges and self-reported pleasantness. The linear contrast revealed that as more spatial frequencies were removed (i.e., full SF range [unaltered version] versus M-HSF only versus LSF only), ratings of pleasantness decreased, $F(1,25) = 99.7$, $MSE = 0.98$, $\eta_p^2 = 0.80$, $p < 0.001$. Paired samples t-tests (with Bonferroni correction for multiple comparisons) revealed that viewing the unaltered images ($M = 4.1$ out of 5) was significantly more pleasant than viewing versions that contained middle-high spatial frequencies (M = 3.3), t(25) = 6.6, SE = 0.13, $p < 0.001$, which in turn was more pleasant than viewing those that contained only low-spatial frequencies (M = 2.2), t(25) = 6.5, SE = 0.16, $p < 0.001$. These results can be seen in Figure 2.4.

The overall findings supported the main prediction of *Reward Restoration Theory*: These findings suggested that viewing middle-high spatial frequency information is more pleasant than viewing low spatial frequency information. Finally, the linear relationship between removing spatial frequency ranges and the findings that nature scenes are rated as more pleasant across different spatial frequencies suggested that responses to scenes are based on more than just the range of spatial frequencies in the image.

The observed pattern of results suggested that the unexplored dimension, the amplitude of the spatial frequencies in the images, may also contribute to the observed differences in responses to nature and urban scenes. Given this, it was expected that scrambling the amplitude of spatial frequencies in nature and urban scenes would attenuate differences in self-reported pleasantness. To explore this potential relationship, a repeated-measures ANOVA was used to check if there was an interaction when including responses to the unaltered versions of the scenes, and responses to the amplitude scrambled versions of the scenes in the analysis. The analysis revealed a significant content (nature versus urban) by image version (unaltered versus amplitude scrambled) interaction on ratings of pleasantness, $F(1,25) = 13.2$, MSE = 0.24, $\eta_p^2 = 0.35$, $p < 0.001$.

Simple effects tests were conducted using paired-samples t-tests. A Bonferroni correction for multiple comparisons was used, reducing the required alpha level for significance to 0.016. The first comparison revealed that the unaltered versions of nature scenes (M = 4.5) were significantly more pleasant than their amplitude scrambled versions (M = 2.6), $t(25) = 10.9$, SE = 0.18 $p < 0.001$. The second comparison revealed the same pattern for urban scenes, where unaltered versions (M = 3.7) were rated as more pleasant than amplitude scrambled versions (M = 2.6), $t(25) = 5.8$, SE = 0.21, $p < 0.001$. The final comparison revealed that there was no difference between amplitude scrambled versions of urban (M = 2.6) and nature (M = 2.6) scenes, $t(25) = 0.5$, $p = 0.62$, n.s., indicating that once amplitudes of spatial frequencies within the images were scrambled in one dimension, images were similarly pleasant. These findings suggested that the amplitude of the spatial frequencies in the scenes was important for pleasantness responses since scrambling the amplitudes in one dimension both lowered self-reported pleasantness to the scene relative to the unaltered versions, and also removed differences between nature and urban scenes. [22] These findings are consistent with research by Fernandez & Wilkins (2008), O'Hare & Hibbard (2012) and Melmer at al. (2013) who have also found a link between the amplitude of spatial frequencies in scenes and self-reported aversiveness and visual aesthetics. This pattern of results can be seen in Figure 2.5.

[22] Participants reported being able to discern objects for amplitude scrambled scenes (where there was no nature versus urban effect) easier than for LSF versions (where there was a significant nature versus urban effect), $t(25) = 4.3$, $p < 0.05$, suggesting that the lack of nature versus urban effect in amplitude scrambled scenes was not due to visual ambiguity.

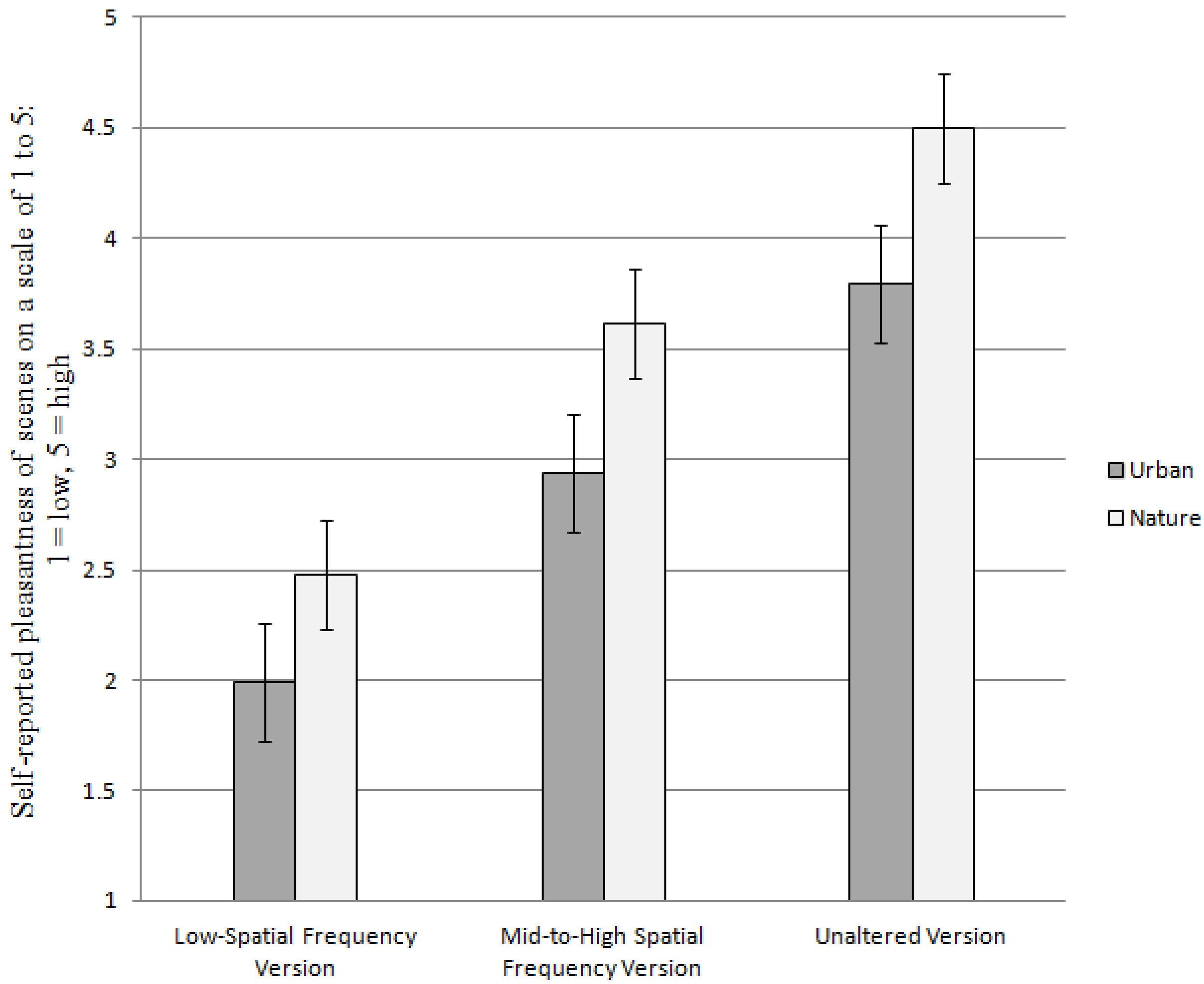

Figure 2.4. Experiment 1: Self-reported pleasantness of scenes with respect to image version on a scale of 1 (low) to 5 (high). Error bars on graph represent 95% confidence intervals.

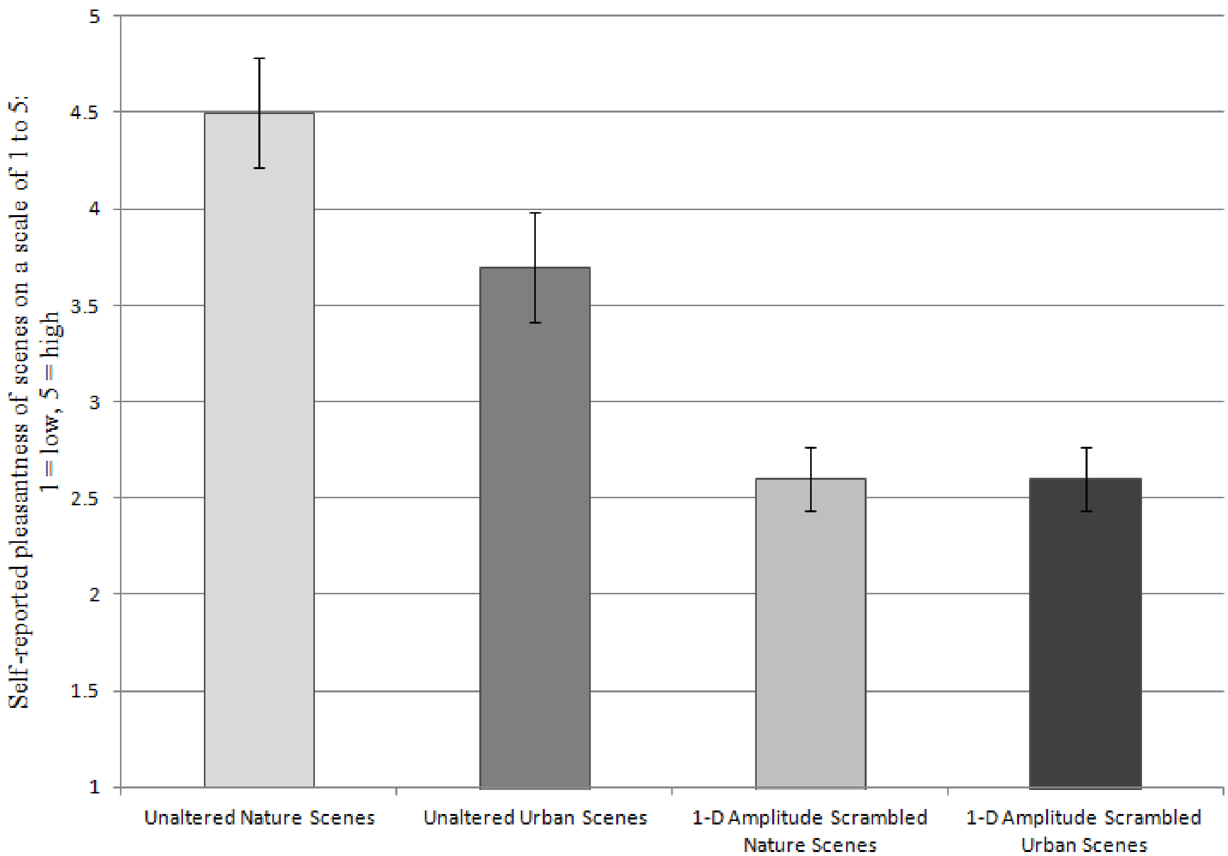

Figure 2.5. Experiment 1: Self-reported pleasantness of unaltered and 1-D amplitude scrambled scenes on a scale of 1 (low) to 5 (high). Here the significant difference in self-reported pleasantness of nature and urban scenes can be seen (on the left half of the graph). Also, the elimination of the difference between nature and urban scenes when amplitude is scrambled can also be seen (on the right half of the graph). Error bars on graph represent 95% confidence intervals.

2.3.7 Testing hypothesis 5: Effects of low level visual properties on number of fixations. Given that in a previous regression analysis, number of fixations was found to predict fixation time, blink rates, and self-reported pleasantness, the current analysis focused on the effects of low level visual properties on number of fixations. Number of fixations was analyzed in the same way as self-reported pleasantness in order to determine if the same pattern of results existed within the eye-tracking data. Similar to findings for self-reported pleasantness, there was a significant main effect of image content (nature versus urban) on number of fixations, $F(1,25) = 23.1$, $MSE = 0.027$, $\eta_p^2 = 0.48$, $p < 0.001$ and there was also a main effect of image version (unaltered, M-HSF, LSF) on number of fixations, $F(1,25) = 37.9$, $MSE = 0.052$, $\eta_p^2 = 0.60$, $p < 0.001$. However, unlike findings for self-reported pleasantness, a (weak) content by image version interaction on number of fixations was found, $F(2,50) = 3.3$, $MSE = 0.022$, $\eta_p^2 = 0.12$, $p < 0.05$, suggesting that the differences in number of fixations between nature and urban scenes changed with respect to the spatial frequencies in the images.

Paired samples t-tests, using a Bonferroni correction to an alpha of 0.008, were used to explore simple effects: The tests revealed that the number of fixations was not significantly different between the unaltered scenes and the M-HSF versions for nature scenes, $t(25) = 0.08$, $p = 0.93$, n.s., and urban scenes, $t(25) = 1.5$, $p = 0.15$, n.s. However, LSF versions had significantly fewer fixations than M-HSF versions for both nature scenes $t(25) = 5.4$, $SE = 0.05$, $p < 0.001$, and urban scenes, $t(25) = 6.8$, $SE = 0.05$ $p < 0.001$. No differences in number of fixations were found between LSF versions of nature and urban scenes, $t(25) = 1.6$, $p = 0.11$, n.s. This pattern of results suggested that the differences in number of fixations between nature and urban scenes were driven by medium to high spatial frequencies, since removing that range (i.e., looking at results for LSF versions) resulted in no significant difference between nature and urban scenes.

2.3.8 Testing hypothesis 5: Effects of visual ambiguity. A known effect of manipulating low-level visual properties of images was that it resulted in changes in ability to recognize the types of objects in the image, creating increased visual ambiguity as more spatial frequencies were removed. For this reason, participants were asked to rate their ability to recognize objects in each image on a scale from 1 to 5, with higher scores indicating ability to discern all objects. The presence of this effect was confirmed in the current study using a repeated-measures ANOVA, which revealed that ability to discern objects decreased for the altered versions of the scenes, $F(1,25) = 196.3$, $MSE = 0.175$, $\eta_p^2 = 0.89$, $p < 0.001$. No differences in ability to discern objects existed between nature and urban scenes within the same image versions.

Given the effect of image alteration on ability to discern objects, it was possible that the effects reported earlier were a result of visual ambiguity. A within subjects regression model that included ratings of ability to discern objects and image content (nature versus urban) as a co-predictors was used to analyse the reported relationships between image version and self-reported pleasantness, and image version and number of fixations. The regression analysis revealed that image version (unaltered, M-HSF, and LSF) was a significant predictor of self-reported pleasantness, even when self-reported ability to discern objects was included in the model, *standardized* $\beta = 0.84$, $t(25) = 4.6$, $p < 0.05$. This indicated that the different versions of the images prompted different self-reported pleasantness, even when controlling for participants' ability to discern objects, providing support for the notion that changes in low-level visual properties may influence affective responses to scenes.

However, such was not the case for number of fixations: When ratings of ability to discern objects were included in the regression model, image version was not a significant predictor of number of fixations. Ratings of ability to discern objects, however, were a significant predictor of number of fixations when controlling for image version, *standardized* $\beta = 0.61$, $t(25) = 2.6$, $p < 0.05$. This indicated that the change in number of fixations between different image versions was likely the result of changes in individuals' ability to discern objects, and not the changes in spatial frequency.

Table 2.1
Experiment 1: Means for measures used with respect to image version and image category. Standard deviations are in parentheses.

Measure	Image category	Image version	Mean (SD)
Self-reported pleasantness	Nature	LSF	2.5 (0.98)
		M-HSF	3.6 (0.90)
		Unaltered	4.5 (0.49)
	Urban	LSF	2.0 (0.73)
		M-HSF	2.9 (0.76)
		Unaltered	3.7 (1.06)
Average fixation length (in seconds)	Nature	LSF	0.42 (0.09)
		M-HSF	0.36 (0.09)
		Unaltered	0.36 (0.10)
	Urban	LSF	0.39 (0.07)
		M-HSF	0.35 (0.09)
		Unaltered	0.31 (0.08)
Fixation rate (# of fixations per second)	Nature	LSF	1.9 (0.28)
		M-HSF	2.2 (0.26)
		Unaltered	2.2 (0.32)
	Urban	LSF	2.0 (0.26)
		M-HSF	2.3 (0.32)
		Unaltered	2.4 (0.31)
Blink rate (blinks per minute)	Nature	LSF	24.6 (6.4)
		M-HSF	25.1 (6.0)
		Unaltered	24.4 (6.7)
	Urban	LSF	26.7 (4.4)
		M-HSF	25.2 (6.0)
		Unaltered	25.9 (5.7)

*LSF = low-spatial frequency, M-HSF = mid-to-high spatial frequency

2.4 General Discussion

Experiment 1 demonstrated a wide scope of novel findings, the majority of which supported hypotheses formed based on existing theories by Kaplan (1995;2001) and Ulrich et al. (1991), and the newly proposed *Reward Restoration Theory*. Specifically, blink-rates, believed to be an indicator of cognitive load and stress (Stern, Walrath, Goldstein, 1984; Bentivoglio et al., 1997; Siegle, Ichikawa & Steinhauer, 2008) were found to decrease significantly when participants viewed nature scenes, indicating that stress and cognitive load were being reduced as predicted by restoration theories. Furthermore, for the first time in the literature on restorative effects, evidence was found to suggest that changes in visual attention predicted self-reported affective responses to the viewed scene, supporting previously untested predictions made by *Attention Restoration Theory*. However, this was not the entire story, as further analysis of fixation patterns revealed that the affective response toward scenes may be altering the scope of attention and fixations, as Ulrich et al. (1991) have previously theorized. The current results provide support for both theories by Ulrich et al. (1991) and Kaplan (1995, 2001) and suggest that, instead of one theory being "correct" and the other "incorrect," both are partially correct. The pattern of results suggests that there may be a bottom-up affective response to the scenes as well as a shift in attention, which may then influence cognitive and top-down (i.e., self-reported) affective responses to the scene.

To add more caveats to the story on restorative effects, analyses of the effects of changes in low level visual properties on responses to the scenes revealed that the power-spectrum of the scenes may be important in shaping self-reported affect; a result that is consistent with previous findings by Fernandez & Wilkins (2008), O'Hare & Hibbard (2012) and Melmer et al. (2013) who have found links between the amplitude (power) spectra of images and responses of aversion and visual aesthetics. Furthermore, changes in spatial frequency were found to alter fixation patterns within the scenes, supporting the notion that there is a bottom-up response to scenes that is sensitive to low-level visual properties. Specifically, removing middle-to-high spatial frequencies, or scrambling the amplitude of spatial frequencies greatly reduced the restoration response (as measured by self-reported affect, blink-rates and number of fixations). It is this set of findings that differentiates *Reward Restoration Theory* (RRT) from existing theories, in suggesting that the theorized bottom-up affective and attention responses to scenes theorized by Ulrich et al. (1991) and Kaplan (1995, 2001) may be influenced by visual spatial frequencies of scenes and their amplitudes. Perhaps it is merely a coincidence that removing middle-to-high spatial frequencies significantly reduced restoration responses to scenes. However, since these findings are consistent with predictions made by the proposed RRT[23], it is also possible that this is the first behavioural evidence of a bottom-up visual-reward mechanism for restoration. It is important to note that all three of the discussed theories appear to be describing the same overall restoration effect, but at different levels of the restoration process, with RRT being the only theory that makes (some) predictions about the effects of low level visual properties on restoration.

Experiment 1 was the first small step toward testing claims made by the proposed *Reward Restoration Theory,* while demonstrating that previously reported effects predicted by *Attention Restoration Theory* and *Psycho-evolutionary Restoration Theory* were present when using the current experimental paradigm and grayscale photographs. The results demonstrating the novelty and importance of claims made by *Reward Restoration Theory* were limited, but

[23] *Reward Restoration Theory* suggests that the ventral visual reward pathway discussed by Yue et al. (2007) is involved in the restoration response. The ventral visual pathway is predominantly associated with processing mid-to-high spatial frequency information (Mahon, Kumar & Almeida, 2013)

encouraging. This was the first time in the literature on the restorative effects of nature that visual spatial frequency information was explored as a potential predictor of restoration. Given that results suggested that restoration responses may be related to visual spatial frequencies, further experiments on the topic were pursued.

Chapter 3 Experiment 2: Examining Top-down Influences on Eye-tracking and Self-reported Responses to Stimuli from Experiment 1

3.1 Introduction

While Experiment 1 contributed novel and interesting findings, the paradigm that was used did not give any insight into a long-standing (and often ignored) criticism of restorative effects findings. A problem persisting in the restorative effects literature is that it does not address potential top-down influences on individuals' responses to scenes. As described in Chapter 1, research exploring how the general population feels about nature using large-scale surveys has found that individuals have positive associations with nature, and share a belief that being around nature will relieve stress (Felsten, 2009, van den Berg et al., 2007; Gulwadi, 2006, Frerichs, 2004; Grahn & Stigsdotter, 2003). Van den Berg et al. (2007) propose that this is potentially the case due to "rural romanticism," the idea that people in urban centers believe the simplicity and pureness of rural life is diminishing, causing them to idealize nature and its benefits. Since upwards of 95% of the population in urban centers may have these positive associations with nature (Frerichs, 2004), it is both plausible and logical that these positive associations could be biasing responses to scenes in lab studies. These potential top-down influences are summarized under the label of the *"Cognitive Perspective."*

The *Cognitive Perspective* states that individuals in the modern world have vastly different associations when it comes to nature and urban environments which could be shaping their responses to scenes in a top-down fashion: Nature environments are experientially associated with going on vacation, escape from stress, spending time with family and friends, adventure, etc. Meanwhile, urban environments are experientially associated with work, chores, pollution, stress, and the monotony of everyday life (Felsten, 2009, van den Berg et al., 2007; Gulwadi, 2006, Frerichs, 2004; Grahn & Stigsdotter, 2003). It is logical that these associations have some effect on responses to scenes in a lab setting, however the size of the effect is unclear. Furthermore, it is unclear if this explanation could account for all findings, or just some of them. In Experiment 1, an attempt was made to address this problem by encouraging participants to respond to images in a bottom-up fashion by presenting the least discernible version of the scenes prior to more discernible versions. Thus, it was unlikely that the observed patterns in the data and the systematic changes with respect to spatial frequency could be explained by top-down cognitive influences. However, it became apparent that the effects proposed by the *Cognitive Perspective* had to be explored before conclusions about potential bottom-up mechanisms and effects could be made.

The goals of the second experiment were simple: The first goal was to explore potential top-down effects predicted by the *Cognitive Perspective*. Such a simple starting point was important since there is a striking absence of research exploring the *Cognitive Perspective* in the literature on the restorative effects of nature.

The second goal of this experiment was to determine if the novel findings of the previous experiment, which supported bottom-up theories of restoration, could be replicated using a different group of participants and a modified experimental paradigm which promotes top-down (i.e., cognition driven) processing of scenes. While restoration theories (*Attention Restoration Theory*; Kaplan, 1995, 2001; *Psycho-evolutionary Restoration Theory*; Ulrich et al.,1991) do not discount contributions of top-down influences, both theories state that the main driving forces for restoration are bottom-up (i.e., stimulus driven). *Attention Restoration Theory* requires that the scene capture involuntary attention so that directed attention may be restored (Kaplan, 1995;2001) while Ulrich et al. (1991)'s theory requires that there be an "automatic affective response" to the scene. Similarly, the proposed *Reward Restoration Theory* also states that the low-level visual properties of the scene drive (visual) reward mechanisms in a bottom-up manner. Thus, it was expected that if top-down influences were found, their effect would be minimal, and that results from Experiment 1 would replicate even in a scenario where top-down processing is promoted via experimental paradigm. To explore the effects of top-down processing, Experiment 1 was repeated with a modified procedure: The most discernible version of the scene was always shown before less discernible versions. This meant that participants always saw the unaltered version of each scene before seeing the altered (degraded) versions.

The main hypothesis for Experiment 2 was that due to the strong theoretical focus of existing theories on bottom-up processes in explaining the restorative properties of nature, and the lack of empirical evidence for top-down influences in the literature, top-down influences would not significantly contribute to the restorative effects of exposure to nature.

3.2 Method

3.2.1 Participants. As in Experiment 1, prior to recruitment, participants were pre-screened using a mass-testing questionnaire. Participants were required to speak and read English fluently (in order to understand instructions), and to have reported that they had normal 20/20 vision. A sample of twenty-nine participants (14 male, 15 female) were recruited from the University of Waterloo SONA participant pool to participate in the study in exchange for course credit. No participants reported having any visual disorder or visual problems.

3.2.2 Materials. The same equipment, lab room, and stimuli used in Experiment 1 were also used in Experiment 2 to allow for cross-experiment comparisons.

3.2.3 Design and Procedure. An identical design and procedure to Experiment 1 was used, with the exception that when participants were presented scenes randomly, they were presented in the relative order of most discernible version to least discernible version (compared to Experiment 1, where stimuli were presented from least discernible to most discernible.)

3.3 Results

Analyses done for Experiment 1 were repeated for Experiment 2 in order to determine if previously reported effects replicated using the modified paradigm. Mixed repeated-measures ANOVAs were used to determine if the "bottom-up" and "top-down" presentations of stimuli across Experiments 1 and 2 interacted with observed effects.

3.3.1 Analysis of fixation behaviour for unaltered images. A repeated-measures ANOVA was used to analyse fixation time, number of fixations, and eye travel distance for Experiment 2. All results replicated those in Experiment 1: There were significantly more fixations for unaltered urban scenes (M = 2.2) than unaltered nature scenes (M = 2.0), $F(1,28) = 19.4$, MSE = 0.025, $\eta_p^2 = 0.41$, $p < 0.001$ and fixation times when viewing urban scenes (M = 0.34 seconds) were shorter than when viewing nature scenes (M = 0.40 seconds), $F(1,28) = 11.4$, MSE = 0.004, $\eta_p^2 = 0.29$, $p < 0.005$. Eye-travel distance was once-again found to be non-significant, $F(1,28) = 1.6$, $p = 0.22$, n.s. Finally, a mixed repeated-measures ANOVA was used to determine if effects changed across Experiments 1 and 2 as a result of the "bottom-up" versus "top-down" stimulus presentation. No content (nature versus urban) by stimulus presentation ("bottom-up" versus "top-down") interaction was found on fixation time, $F(1,53) = 0.47$, $p = 0.5$, n.s., number of fixations $F(1,53) = 0.06$, $p = 0.8$, n.s., or eye travel distance, $F(1,53) = 2.2$, p =

0.14, n.s., indicating that the observed differences in fixation behaviour for nature versus urban scenes were not influenced by changes in stimulus presentation.

3.3.2 Analysis of blink rates for unaltered images. As observed in Experiment 1, in Experiment 2 participants blinked significantly more when viewing urban scenes (M = 25.2 blinks per minute) compared to nature scenes (M = 23.6), $F(1,28) = 9.9$, MSE = 4.2, $\eta_p^2 = 0.26$, $p < 0.005$. Replicating results of Experiment 1, blink rates decreased significantly more when viewing nature scenes compared to urban scenes relative to baseline (i.e., viewing phase scrambled images), $t(28) = 3.1$, SE = 0.53, $p < 0.005$. Following the pattern of fixation behaviour, no content (nature versus urban) by stimulus presentation ("bottom-up" versus "top-down") interaction was found on blink rates, $F(1,53) = 0.1$, $p = 0.76$, n.s.

3.3.3 Analysis of self-reported ratings of pleasantness for unaltered images. Just as with findings on fixation behaviour and blink rates, there was a replication of self-reported pleasantness: Nature scenes (M = 4.5 out of 5) were found to be more pleasant than urban scenes (M = 3.8), $F(1,28) = 26.4$, MSE = 0.24, $\eta_p^2 = 0.49$, $p < 0.001$. No content (nature versus urban) by stimulus presentation ("bottom-up" versus "top-down") interaction was found, $F(1,53) = 0.2$, $p = 0.69$, n.s. Self-reported pleasantness was very consistent across both experiments for both nature and urban scenes, with an average overall difference of 0.05 on a 5-point scale. This indicated that, despite being a subjective measure, self-reported pleasantness responses to scenes appeared to be consistent across experiments.

3.3.4 Analysis of fixation patterns for unaltered scenes. Once again, as observed in Experiment 1, analyses of fixation patterns in nature versus urban scenes revealed that participants had longer central fixations when viewing nature scenes ($\overline{D}$ = 90 ms per fixation), t(168) = 4.5, p < 0.001 and longer extra-central fixations ($\overline{D}$ = 6 ms per fixation) when viewing urban scenes, t(5624) = 8.5, p < 0.001. A set of independent samples t-tests revealed that differences in fixation patterns between nature and urban scenes did not change across experiments for central fixations, t(336) = 0.9, p = 0.37, n.s. However, there was a significant change across experiments for differences in extra-central fixations, t(11248) = 2.4, p < 0.05, where extra-central fixations for urban scenes (compared to nature scenes) were longer in Experiment 2 ($\overline{D}$ = 6 ms per fixation) than in Experiment 1 ($\overline{D}$ = 4 ms). Given the small magnitude of this change (2 ms) it is difficult to attach any useful meaning to it. Overall, the fixation patterns of participants in Experiment 2 replicated fixation patterns of participants in Experiment 1, indicating that the order of stimulus presentation did not influence the observed effects.

3.3.5 Effects of low level visual properties on self-reported pleasantness. Similar analyses as those done in Experiment 1 were first used to explore the effects of image version (unaltered, medium-to-high spatial frequency, and low spatial frequency) and content (nature versus urban) on self-reported pleasantness: As in Experiment 1, there was a main effect of image content, F(1,28) = 33.9, MSE = 0.31, η_p^2 = 0.55, p < 0.001, and a main effect of image version, F(2,56) = 205.0, MSE = 0.41, η_p^2 = 0.88, p < 0.001 on self-reported pleasantness. However, unlike results from Experiment 1, there was a significant content by image version interaction on self-reported pleasantness, F(2,56) = 12.5, MSE = 0.08, η_p^2 = 0.31, p < 0.001, suggesting that removing spatial frequencies of the images also attenuated differences in self-reported pleasantness for nature versus urban scenes, consistent with predictions by RRT that low level visual properties may be involved in the restoration response. Since this interaction was not present in Experiment 1, it is possible that Experiment 1 did not have sufficient power to demonstrate the interaction. No content by image version by stimulus presentation interaction was found on self-reported pleasantness, $F(2,106) = 1.1$, $p = 0.35$, n.s., indicating that the effects of image version and content on self-reports were not significantly different across the two experiments, once again signifying that Experiment 1 may have lacked enough power to demonstrate the image content by image version interaction on self-reported pleasantness described here.

Furthermore, analyses exploring the effects of amplitude scrambling in one dimension on self-reported pleasantness replicated findings from Experiment 1, indicating that amplitude scrambling eliminates observed differences in self-reported pleasantness for nature and urban scenes $t(28) = 1.3$, $p = 0.2$, n.s., suggesting once again that self-reported pleasantness may be linked to the spatial frequency power spectrum of scenes.

To discount the possibility that the elimination of the effect was due to visual ambiguity caused by scrambling of spatial frequency amplitudes in one dimension, ratings on ability to discern objects in the scene were compared to those for the low-spatial frequency (LSF) versions. However, prior to doing this, a paired-samples t-test was used to confirm that nature scenes were preferred over urban scenes in the LSF versions of the images: As expected, nature scenes were rated as more pleasant than urban scenes for the LSF images, $t(28) = 2.72$, $p < 0.05$.

Next, a paired-samples t-test was used to explore self-reported ability to discern objects for the amplitude scrambled and LSF versions of the images. The test revealed that participants were able to discern objects more easily in the amplitude scrambled versions than the LSF versions, $t(28) = 2.74$, $p < 0.05$. No differences for self-reported ability to discern objects were found between nature and urban scenes within image versions. Therefore, since participants found it significantly easier to discern objects in the amplitude scrambled versions (where nature scenes were not perceived as more pleasant than urban scenes) than the LSF versions (where nature scenes were perceived as more pleasant), it is unlikely that visual ambiguity caused nature and urban scenes to be perceived as similarly pleasant within the amplitude-scrambled image version.[24]

3.3.6 Effects of low level visual properties on fixation patterns. Similar to the analyses conducted for Experiment 1, the effects of low level visual properties on number of fixations were analyzed using multiple regression. This analysis was performed since Experiment 1 revealed that ratings of ability to discern objects in the altered versions of the scenes seemed to predict number of fixations better than image version. Image versions included in the analyses were unaltered (i.e., "full spatial frequency"), medium-high spatial frequency, and low spatial frequency versions.

The analysis revealed that, unlike in Experiment 1, when self-reported ability to discern objects, and image content (nature versus urban) were included as a co-predictor variables of number of fixations, image version (i.e., spatial frequency) was still a significant predictor of number of fixations, *standardized* $\beta = 0.81$, $t(28) = 7.6$, $p < 0.001$. This indicated that changes in the available spatial frequencies for the scenes were resulting in unique variance in participants' number of fixations. Specifically, number of fixations increased as the available spatial frequency range in the scene increased.

Here, it is important to note that since this relationship was different from Experiment 1, it is likely that the number of fixations for altered versions of scenes were driven by top-down

[24] The described analysis was also performed for data in Experiment 1: Participants reported being able to discern objects for amplitude scrambled scenes significantly more than for LSF versions, $t(25) = 4.3$, $p < 0.05$

influences such as memory or expectation of content. In Experiment 2, the most discernible version was always presented first, thus it is logical (as predicted by the *Cognitive Perspective)* that the content seen should influence responses to more degraded versions of the scene that were presented later on. Furthermore, this difference from Experiment 1 indicated that unlike self-report, number of fixations was susceptible to differences in stimulus presentation.[25]

[25] Multiple regression analysis for Experiment 2 revealed that, as reported in Experiment 1, image version (i.e., spatial frequency) was a predictor of self-reported pleasantness even when controlling for image content, and discernibility of the scene, *standardized* $\beta = 0.61$, $t(28) = 7.7$, $p < 0.001$.

Table 3.1
Experiment 2: Means for measures used with respect to image version and image category. Standard deviations are in parentheses.

Measure	Image category	Image version	Mean (SD)
Self-reported pleasantness	Nature	LSF	1.8 (0.75)
		M-HSF	3.0 (0.70)
		Unaltered	4.5 (0.45)
	Urban	LSF	1.6 (0.60)
		M-HSF	2.4 (0.50)
		Unaltered	3.8 (0.60)
Average fixation length (in seconds)	Nature	LSF	0.59 (0.29)
		M-HSF	0.46 (0.22)
		Unaltered	0.40 (0.14)
	Urban	LSF	0.53 (0.21)
		M-HSF	0.42 (0.24)
		Unaltered	0.34 (0.10)
Fixation rate (# of fixations per second)	Nature	LSF	1.7 (0.48)
		M-HSF	2.0 (0.43)
		Unaltered	2.0 (0.40)
	Urban	LSF	1.8 (0.40)
		M-HSF	2.1 (0.43)
		Unaltered	2.2 (0.36)
Blink rate (blinks per minute)	Nature	LSF	23.4 (6.2)
		M-HSF	23.1 (7.1)
		Unaltered	23.6 (7.4)
	Urban	LSF	24.7 (6.1)
		M-HSF	23.4 (7.0)
		Unaltered	25.2 (6.7)

*LSF = low-spatial frequency, M-HSF = mid-to-high spatial frequency

3.4 General Discussion

The first experiment yielded many findings that supported hypotheses formulated from *Attention Restoration Theory* (ART), *Psycho-evolutionary Restoration Theory* (PERT) and the newly proposed *Reward Restoration Theory* (RRT). These findings were then replicated in the second experiment using a modified experimental paradigm, demonstrating that they were robust across groups and mostly uninfluenced by order of stimulus presentation. However, before discussing the novel findings, it is important to note that this was the second time that eye-tracking results by Berto et al. (2008) were replicated using different stimuli and a different experimental paradigm, suggesting that eye-movement behaviour (e.g., number of fixations and fixation time) seems to show a robust difference between viewing nature scenes and urban scenes. Specifically, nature scenes prompted fewer fixations overall, and longer viewing time per fixation, which was in line with predictions made based on both *Attention Restoration Theory* (ART), and the newly proposed *Reward Restoration Theory* (RRT). The successful replication of the (limited) previous literature on restorative effects using eye-tracking measures was encouraging, since it both confirmed previous findings and also meant that novel findings in the current paradigms could be related to existing literature.

Experiments 1 and 2 used a combination of different measures (number of fixations, blink rates, and self-reported pleasantness of the scenes) to explore predictions made by *Attention Restoration Theory* and *Reward Restoration Theory*. Overall, findings converged across most measures in both experiments, providing strong empirical support for the restorative effects of nature and allowing interactions between different processes to be explored.

First, changes in blink rates were used as a measure of "restoration" for the first time in the restorative effects literature. Previously, higher blink rates have been linked with higher cognitive load (Stern, Walrath, Goldstein, 1984; Bentivoglio et al., 1997; Siegle, Ichikawa & Steinhauer, 2008) and higher anxiety/stress (Cruz et al., 2011), both of which were expected when viewing urban scenes versus nature scenes. Experiments 1 and 2 found evidence that blink rates when viewing nature scenes decreased, indicating a reduction in cognitive load and or stress, supporting predictions made by restoration theories.

Second, when self-reported pleasantness of scenes was explored, findings confirmed the hypothesis that viewing natural scenes is more pleasant than viewing urban scenes. This was in agreement with previous literature on restorative effects, where exposure to nature has been reported to improve affect (Valtchanov & Ellard, 2010; Valtchanov et al., 2010; Kweon et al., 2008, Ulrich et al., 1991). These results, while unsurprising, served to confirm previous findings and allowed previously unexplored interactions to be tested. The current experiments provided a unique scenario where number of fixations, blink rates, and self-reported pleasantness of scenes were measured. By examining the relationship between these measures, novel findings emerged: It was found that number of fixations (i.e., a measure of visual processing/visual attention in scenes) predicted both blink rates (i.e., cognitive load) and ratings of pleasantness (i.e., affect). Specifically, as the number of fixations decreased, self-reported pleasantness increased and blink rates (cognitive load) decreased. These relationships were consistent with predictions made by *Attention Restoration Theory* since it appeared that changes in visual attention (as a result from viewing different scenes) were prompting changes in both blink rates and pleasantness.

While the described predictive relationships *appeared* to support ART, it became apparent that there was more to the story when overall fixation patterns were examined.

Previous literature has found links between changes in affect and changes in attention and stimulus processing: Fredrickson & Branigan (2005) found that, compared to a neutral state, positive emotions broadened the scope of attention and thought-action repertoires, while negative emotions did the opposite. The current study found results consistent with these previous findings: When viewing nature scenes (which improved affect) versus urban scenes, participants had longer fixations for the center of the image, suggesting that their scope of attention was broadened, allowing them to process more of the image from the central fixation point. In this case, it appeared that an early (and potentially "automatic affective”) response was driving attention, as suggested by Ulrich et al., (1991; 2003), rather than changes in attention driving changes in affect. Given that the results from Experiments 1 and 2 provide support for both the attention-driven mechanism for restoration as proposed by *Attention Restoration Theory* (Kaplan, 1995, 2001), and for the automatic affective restoration mechanism proposed by *Psycho-evolutionary Restoration Theory* (Ulrich et al., 1991), the causal order of the restoration response cannot be clearly delineated: During the restoration response, it is possible that both shifts in attention and in affect co-occur, or that shifts in attention cause rapid changes in affect, or that changes in affect cause rapid changes in attention.

When considering support for Ulrich et al. (1991)'s theory, it is important to note the potential mechanisms behind it. In Ulrich et al. (1991), there is mention of numerous principles stemming from evolutionary theory, some of which suggest that since the brain and sensory systems evolved in natural environments, they are tuned to efficiently process natural content and less efficient at processing urban or built environments. The implication of this theoretical perspective is that natural environments are more efficiently processed and thus less taxing on cognitive resources (Ulrich et al., 1991). This notion is indeed supported by more recent research using ERPs which has demonstrated that individuals can accurately categorize natural scenes in terms of content (whether animals are present) with presentation times as low as 28 milliseconds (Mace, Thorpe, & Fabre-Thorpe, 2005). Interestingly, research by Elder and Velisavljevic (2009) has suggested that the fastest underlying mechanisms for such categorizations use shape contours (i.e., mid-to-high spatial frequency information) as the principle discriminative cue. The implication of there being "optimized" sensory systems is that humans may also have specific physiological functions (internal motivations/rewards) which exist to facilitate beneficial interactions with their environments, prompting the "automatic affective response" to scenes that has been previously discussed (Ulrich et al., 1991). While no *specific* neural pathways or testable biological mechanisms are described, the parallels to the proposed *Reward Restoration Theory* are evident.

The proposed *Reward Restoration Theory* attempts to fill the missing gap in the existing theoretical framework for the restorative effects of nature. Both Ulrich et al. (1991)'s *Psycho-evolutionary Restoration Theory* and Kaplan (1995,2001)'s *Attention Restoration Theory* share a common 'source' of restoration. As previously discussed, both theories suggest that viewing scenes prompts a bottom-up response in individuals. In *Psycho-evolutionary Restoration Theory*, this bottom-up response is affective, while in ART the response is that of "soft-fascination." Kaplan (1995, pp. 174) defines soft fascination as something that "readily holds attention in an undramatic fashion," allowing attention to shift effortlessly. In both of these cases, it is plausible that things that are subconsciously pleasant and/or "fascinating" to look at are thus so because they are associated with (or prompt the release of) rewards. This proposal is in agreement with existing research exploring the neural correlates of scene preference, which has demonstrated that visual reward pathways show greater activation for preferred scenes (Yue, Vessel &

Biederman., 2007; Biederman & Vessel, 2006). By taking this visual-reward mechanism approach as the stepping stone to affective and attention based restoration theories, it becomes possible to understand the results from experiments 1 and 2 which demonstrate that changes in low-level image properties influence responses to the images.

Experiments 1 and 2 both presented similar findings, suggesting changes in available visual spatial frequency information, as well as changes in the amplitudes of those spatial frequencies, can alter responses to scenes. Specifically, removing low spatial frequencies was found to have a lesser effect than removing medium-high spatial frequencies on both fixation behaviour and self-reported pleasantness. Furthermore, evidence across both experiments was found which suggested that self-reported pleasantness was driven by the amplitudes of the spatial frequencies. Without considering the visual-reward pathway mechanism proposed in *Reward Restoration Theory*, it would be difficult to make sense of such a pattern of data given that the scene content was kept consistent across different image versions. It is here that the benefits of a mechanistic model of restoration can be seen: Neither Kaplan's (1995) *Attention Restoration Theory*, nor Ulrich et al.'s (1991) *Psycho-evolutionary Restoration Theory* predict that there would be differences in responses to scenes that featured the same content at different visual spatial frequencies.

The reliable change in responses resulting from the reduction of available spatial frequency information observed in Experiments 1 and 2 demonstrated that low-level visual properties likely play a role in restoration. Specifically, responses to scenes appeared to be mostly based on the middle-to-high spatial frequencies and the amplitude of visual spatial frequencies. Removing this spatial frequency range (or scrambling amplitude of spatial frequencies) greatly reduced the restoration response as measured by eye-tracking, blink rates, and self-reported affect. Provided that the proposed visual reward mechanism suggested by *Reward Restoration Theory* (RRT) is in the ventral visual pathway, which is predominantly associated with processing middle-to-high spatial frequency information (Mahon, Kumar & Almeida, 2013), these findings are unsurprising. These findings provide some of the initial support for claims made by the proposed RRT, suggesting that there may be merit to the proposed mechanism of restoration.

Given the overall consistency of results and effects across both experiments, despite the differences in stimulus presentation, Experiments 1 and 2 suggest that responses to scene are mainly influenced by bottom-up factors (and only mildly influenced by top-down expectations or memories), consistent the proposed bottom-up reward mechanism theorized by *Reward Restoration Theory*. An encouraging finding was that self-reported pleasantness for scenes was strongly consistent across both experiments, suggesting that the different participants groups were in agreement, almost as if they were all using the same criteria or underlying mechanism to determine the pleasantness of a scene. This pattern is indeed what one would predict if a completely bottom-up neural mechanism was assumed to be driving their responses. However, a simple and completely bottom-up mechanism is unlikely given that human affective responses are both complex and vary between individuals.

It is important to emphasize that the restorative effects of nature appear to be complex and cannot be explained by just one theory. Results from Experiments 1 and 2 supported *Psycho-evolutionary Restoration Theory*, *Attention Restoration Theory*, and the newly proposed *Reward Restoration Theory*. Very limited support was also found for the *Cognitive Perspective*, when considering the differences resulting from the bottom-up versus top-down stimulus presentation used in Experiments 1 and 2 respectively.

Chapter 4 Experiment 3: Effects of Direct Semantic Priming on Perception of Natural and Urban Scenes and Self-report Measures.

4.1 Introduction

In the literature on the restorative effects of nature, there has been little evidence against the *Cognitive Perspective* (Felsten, 2009, van den Berg et al., 2007; Gulwadi, 2006, Frerichs, 2004; Grahn & Stigsdotter, 2003). However, this logical argument is an alternate explanation of the restorative properties nature that must be addressed if bottom-up mechanisms of restoration are to be considered. The underlying premise of the argument is that (in urban centers) everyday life creates negative associations with urban scenes (e.g., work, pollution, noise, and stress) and positive associations with natural scenes (e.g., vacations, escape, relaxation). When one views either natural or urban scenes, these associations (theoretically) work in a top-down fashion to put individuals in a different state of mind. This colours their perceptions of, and interactions with, the world. In essence, the argument is that viewing nature scenes makes individuals think happy thoughts which cause them to respond in a way that reflects their positive affective state; with the reverse being true for exposure to urban scenes.

Despite the intuitiveness of this alternate explanation, limited evidence was found for the *Cognitive Perspective* in Experiments 1 and 2. These experiments provided evidence that was more consistent with bottom-up theories on restoration: Their proposed bottom-up mechanisms fit the data significantly better than the claims made by the *Cognitive Perspective.* However, the paradigm used in Experiments 1 and 2 did not specifically test the *Cognitive Perspective*. While the results did not support the theory, they did not discount it either. In order to better understand role of top-down influences on responses to scenes, a third experiment was conducted using a direct semantic priming paradigm which specifically targeted the proposals made by the *Cognitive Perspective.*

The main goal of the current experiment was to use a direct semantic priming paradigm to test the top-down influences proposed by the *Cognitive Perspective* against the bottom-up effects proposed by *Psycho-evolutionary Restoration Theory*, *Attention Restoration Theory* (ART), and *Reward Restoration Theory* (RRT). A second goal of the current experiment was to pilot a series of self-report measures about the visual characteristics of the scene in order to better determine what is driving affective responses to scenes. Some of these included measures of classic findings by Poffenberger & Barrows (1924) indicating that particular feelings are tied to such things as jaggedness/smoothness and fluidity of lines; properties which are ultimately tied to visual spatial frequencies. This was of particular interest since recent research by Amir, Biederman & Hayworth (2011) found that humans, including infants, have a general preference for curved shapes and lines. Given these goals, four main hypotheses were formed:

H1: The first hypothesis was that the well documented effects of exposure to nature reducing stress and improving affect would be replicated as they were in Experiments 1 and 2.

H2: The second hypothesis was that if the *Cognitive Perspective* is correct, then exposure to fully natural or urban scenes should differentially prime participant responses to scenes that are 50% nature and 50% urban (e.g., city surrounded by nature, or park surrounded by buildings). Priming with fully natural scenes should cause participants to rate the 50/50 scenes as more pleasant and less stressful compared to priming with fully urban scenes. This was hypothesized since the *Cognitive Perspective* predicts that viewing nature should activate positive memories and associations, which would then influence responses to the 50/50 scenes in a top-down fashion. Similarly, viewing urban scenes should activate negative memories and associations which would then influence responses to the 50/50 scenes.

H3: The third hypothesis was that if existing bottom-up theories of restoration are correct, viewing nature scenes should elevate affect/relax participants and viewing urban scenes should create negative emotions/stress participants. Viewing the 50/50 images should create a contrast to these states: Stressing participants out if presented after viewing nature scenes, and restoring participants if presented after viewing urban scenes.

H4: The final hypothesis was that nature scenes would be rated as being less jagged/more smooth relative to urban scenes since they contain fewer straight lines and more organic shapes, and are generally more preferred. This hypothesis was based on findings by Poffenberger & Barrows (1924) and Amir et al. (2011) stating that humans prefer smoother and more fluid shapes.

4.2 Method

4.2.1 Participants. Prior to recruitment, participants were pre-screened using a mass-testing questionnaire. Participants were required to speak and read English fluently (in order to understand instructions), and to have reported that they had normal 20/20 vision. A sample of fifty-two participants (26 male, 26 female) were recruited from the University of Waterloo SONA participant pool to participate in the study in exchange for course credit. No participants reported having any visual disorder or visual problems.

4.2.2 Materials. This experiment used a simple slide-show presentation of various images on a 17 inch LCD monitor with a resolution of 1280 x 1024 pixels. The monitor screen occupied approximately 29 degrees of horizontal field of view. All participants were seated at the same distance from the monitor on a chair that could not be moved. The screen was 26 inches from participants' eyes.

Images used in this study were collected from publically available photos on flickr (http://www.flickr.com) and Google image search. Photos used in Experiments 1 and 2 were also included as part of the image pool. All images were cropped to the dimensions of 900 x 900 pixels (occupying approximately 20 degrees field of view when presented) and converted to grayscale using Adobe Photoshop Elements 10. All images were saved in JPEG format, and had their brightness levels and contrast balanced using the "Auto Levels" and "Auto Contrast" options in Adobe Photoshop Elements 10. When displayed during the experiment, images were in their native resolution, such that pixels in the image matched pixels on the display in a 1:1 ratio. The images consisted of four types: Full nature scenes, full urban scenes (e.g. New York City, Toronto), half-urban/half-nature scenes with the urban section in foreground (e.g. town surrounded by mountains in the background), and half-urban/half-nature with nature in the foreground (e.g. Central Park in New York City surrounded by tall buildings in the background). There was a total of 32 scenes used in this experiment: There were 12 full nature scenes, 12 full urban scenes and 8 50/50 images. The 8 50/50 scenes consisted of 4 *with urban content in foreground*, and 4 *with nature in the foreground*. This counterbalance was included in order to make sure that both nature and urban content was equally represented in the foreground/background across the scenes, since it was a concern that participants may just focus on the foreground content. Sample scenes are shown in Figure 4.1.

An image characteristics questionnaire was also developed for use in this study. Questions were adapted from those used in Experiments 1 and 2, and previous research by Poffenberger & Barrows (1924). The questionnaire consisted of 10 questions about the scene, some of which were reverse-scored pairs: Questions assessed how pleasant, calming/stressful, positive/negative, smooth/jagged, visually interesting, and visually complex participants perceived the scene to be on a scale of 1 (low) to 7 (high).

Figure 4.1. Experiment 3: Sample of scenes used in the experiment showing nature (left), urban (middle), and half-nature/half-urban (right) scenes.

4.2.3 Design. A completely within-subjects design was used in this experiment, where all images were seen by every participant. Images were presented one at a time, in a semi-randomized, counterbalanced order to allow for direct semantic priming. Images were randomly chosen from the image pool with no repeats based on predefined criteria: Images were presented such that three fully natural or three fully urban/built scenes were presented in a row, followed by a scene that was 50% nature and 50% urban. Participants answered the 10 questions assessing various characteristics of each scene (co-presented with the image), forcing them to actively think about the content. This set the stage for direct semantic priming: Participants had to answer 30 questions (3 scenes x 10 questions) about either natural or urban scenes before viewing a 50/50 scene, priming them to think about things associated with nature or urban scenes respectively. Furthermore, questions about the scenes directed their focus to things such as pleasantness and stressfulness of the scene, which should have enhanced the priming effect.

4.2.3 Counterbalancing. Questions were presented one at a time, in random order, and in a random location in a column to the left of the image. This was done to reduce automatic responses due to repetition of questions across images, to provide some level of novelty to keep participants engaged, and to prompt participants to read each question (since they could not predict what question was next). With the inclusion of reverse-coded pairs, and measurement of reaction time (RT),), validity of responses could be assessed.

Furthermore, presentation of the 50/50 images was completely counterbalanced, such that every 50/50 image followed both nature and urban scenes an equal number of times across participants. Order of presentation of the sets (three nature scenes followed by 50/50, and three urban scenes followed by 50/50 scene) was also counterbalanced using classical ABBA design.

Half of the participants viewed scenes in one order (ABBAABBA) and the other viewed the reverse order (BAABBAAB).

4.2.5 Procedure. Individual participants were scheduled to come to the lab using the University of Waterloo's SONA online system. Upon their arrival, participants were greeted by the researcher, briefed on the procedure of the experiment, and given an information and consent form to read and sign.

Participants were then seated in front of the computer monitor and provided with a keyboard. They were asked not to adjust the monitor or chair, and to use the keyboard to input their responses to the questions on the screen. They were asked if they had any questions and told to inform the researcher once they had completed the study. The researcher then left the room and waited outside the door. Scenes were individually presented on the right side of the screen until all questions about the scene were answered. Questions were presented on the left side of the screen, as described in the counterbalancing section of this paper. Participants responded to questions by pressing the number on the keyboard corresponding to their response on a scale from 1 (low) to 7 (high). Participants were allowed to go through the experiment at their own pace. Upon completion, participants were debriefed and the purpose of the experiment was explained to them. No participants suspected deception or the true purpose of the experiment. As part of the debriefing, they were asked to provide their own definition of "jaggedness," and "visual complexity" in order to determine if there was a consistent definition across participants, since these variables were not explicitly defined by the researcher.

4.3 Results

For analysis purposes, self-reported scores on existing scales of 1 to 7 for measures depicting the same variable on opposite ends of a continuum (e.g., stressful & calming) were combined to create scales ranging from -6 to 6 with the midpoint [0] being neutral and the endpoints representing the max on each scale (e.g., highly calming [-6] and highly stressful [6]). This was done to better represent participant responses on the continuum of the measured variable, rather than analyzing responses for each tail individually.

4.3.1 Testing hypothesis 1: Exploring self-reported stress and affect for scenes. A repeated-measures ANOVA was used to compare self-reported stress and pleasantness responses to fully natural and fully urban scenes. As predicted, results replicated findings in the literature and in Experiments 1 and 2: Nature scenes were reported to be significantly more pleasant (M = 5.7 out of 7) than urban scenes (M = 4.0 out of 7), $F(1,51) = 119.9$, $MSE = 0.65$, $\eta_p^2 = 0.70$, $p < 0.001$. Nature scenes were also reported to be significantly less stressful and more calming (M = -3.7) than urban scenes (M = 0.4), $F(1,51) = 297.8$, $MSE = 1.51$, $\eta_p^2 = 0.85$, $p < 0.001$.

4.3.2 Testing hypotheses 2 and 3: Effects of priming on responses to 50/50 nature/urban scenes. Once again, a repeated-measures ANOVA was used to compare responses to 50/50 scenes that followed a block of either nature or urban scenes across the variables of interest; self-reported pleasantness and stress. Contrary to predictions made by the *Cognitive Perspective*, no significant difference was found between 50/50 scenes following blocks of nature scenes and those following blocks of urban scenes for self-reported pleasantness, $F(1,51) = 3.2$, $MSE = 1.1$, $\eta_p^2 = 0.06$, $p = 0.08$, n.s. In fact, the trend appeared to be going in the opposite direction of what the *Cognitive Perspective* predicted, with 50/50 scenes following blocks of nature being rated as less pleasant (M = 4.6 out of 7) than those following blocks of urban scenes (M = 5.0 out of 7). However, this trend should be taken lightly given its relatively tiny effect size despite the presence of a large sample size and within-subjects design.

Analysis of self-reported stress for the 50/50 scenes revealed that, unlike with self-reported pleasantness, there was a significant difference between those that followed blocks of nature scenes (M = -1.3) and those that followed blocks of urban scenes (M = -2.4), $F(1,51) = 10.9$, $MSE = 3.2$, $\eta_p^2 = 0.18$, $p < 0.005$. Half-nature/half-urban scenes were rated as significantly more calming when they followed blocks of fully urban scenes (as shown in Figure 4.2), which was contrary to predictions made by the *Cognitive Perspective* and consistent with predictions made by bottom-up theories on the restorative effects of nature. A secondary analysis was also done to explore how ratings changed from the scenes seen just before the 50/50 image to the 50/50 scene itself: The repeated measures ANOVA revealed a significant interaction of prime type (nature versus urban) and image (pre-50/50 versus 50/50) on stress ratings, $F(1,51) = 76.32$, $MSE = 5.90$, $\eta_p^2 = 0.60$, $p < 0.001$, confirming that the 50/50 scenes were rated as significantly more stressful than the preceding nature scene, and significantly less stressful than the preceding urban scene.

To verify that the observed results were not due to changes in perceived valence of the 50/50 scenes resulting from top-down influences (i.e., how positively/negatively scenes were perceived), a repeated-measures ANOVA was used to see if ratings of valence for the 50/50 scenes were consistent between those that followed blocks of nature scenes, and those that follow blocks of urban scenes. As expected, no differences in valence were found for the 50/50 scenes, $F(1,51) = 1.2$, $p = 0.28$, n.s., indicating that the 50/50 scenes were perceived to be similarly positive/negative regardless of the preceding scenes.

After the analyses, a pattern was noticed in the responses for the 50/50 images. It appeared as if participants were rating the 50/50 scenes mid-way between fully natural and fully urban scenes across measures, following a distinct linear relationship that would only be consistent with the bottom-up perspective of the proposed *Reward Restoration Theory*: *Reward Restoration Theory* states that if there is a reward mechanism that is tuned to specific visual information, presenting partial information should result in partial activation. A set of partial correlations controlling for participant variability were used to explore this apparent relationship post-hoc. The correlations revealed that the percentage of nature content in the scene was strongly correlated with self-reported pleasantness $r(153) = 0.59$, $p < 0.001$ and self-reported stress $r(153) = -0.75$, $p < 0.001$. This suggested that as percentage of nature content in the scene increased, perceived pleasantness of the scene increased and perceived stressfulness decreased. It should be noted that neither Kaplan's *Attention Restoration Theory* (1995, 2001) nor Ulrich et al.'s *Psycho-evolutionary Restoration Theory* (1991) could be used to make direct predictions about the presence of linear relationship between percent of nature content in the scene and response to the scene. The clear linear relationship can be seen in Figure 4.3.

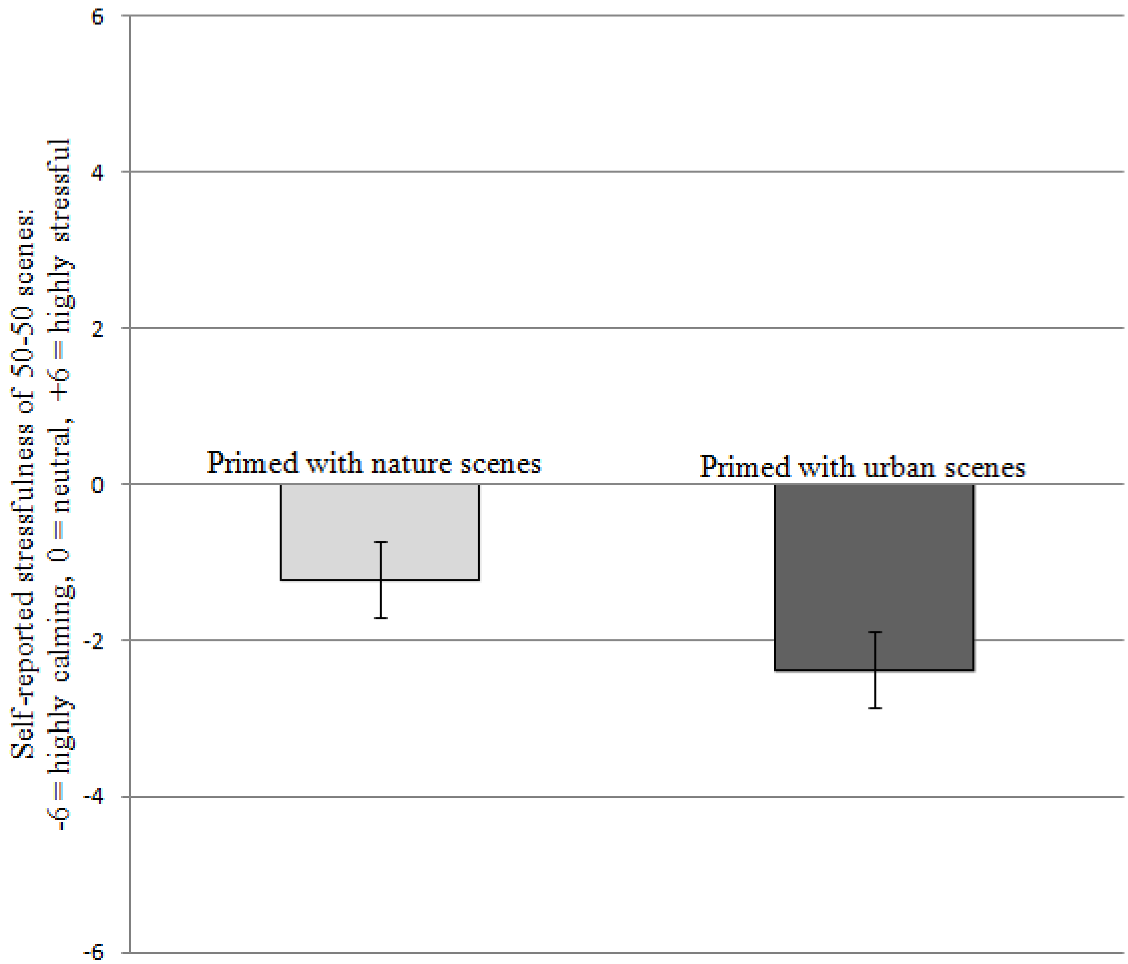

Figure 4.2. Experiment 3: Self-reported stressfulness of half urban/half nature scenes when primed with nature (left) and urban (right) scenes. Error bars represent 95% confidence intervals. Here it can be seen that 50-50 scenes are perceived as significantly more calming when primed with urban content versus nature content.

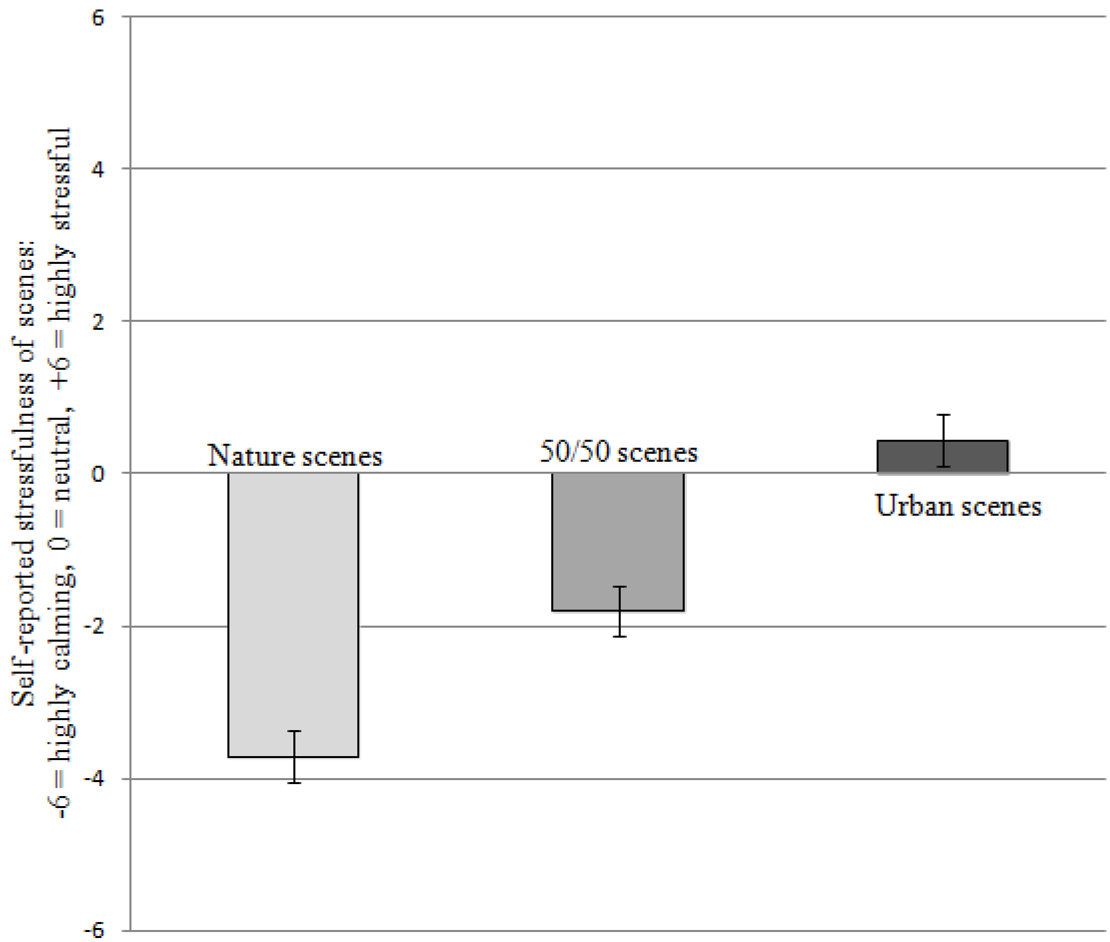

Figure 4.3. Experiment 3: Mean self-reported stressfulness of scenes. Error bars represent 95% confidence intervals. Graph demonstrates the clear linear relationship between proportion of nature to urban content in the scene (100% on the left, 50% in the middle, and 0% on the right) and perceived stressfulness of scenes.

4.3.3 Testing hypothesis 4: Relationships between smoothness/jaggedness and affective measures. Before proceeding with analyzing relationships between smoothness/jaggedness of scenes, it was important to verify that participants were using the same definition. From their independent debriefing statements, participants unanimously agreed that jaggedness was a measure of sharp edges and/or corners in the scenes. Scales for smoothness and jaggedness were combined to create a smooth-jagged continuum scale, with -6 representing very smooth and 6 representing very jagged. Full nature scenes were compared to full urban scenes on the smooth-jagged continuum using a repeated-measures ANOVA. The analysis revealed that urban scenes were perceived as significantly more jagged (M = 1.4) than nature scenes (M = -1.6), $F(1,51) = 95.1$, MSE = 2.4, $\eta_p^2 = 0.65$, $p < 0.001$, as hypothesized.

To explore the relationship between the smooth-jagged continuum and measures of self-reported affect predicted by previous research by Poffenberger & Barrows (1924) and Amir et al. (2011), partial correlations were used. For the first set of partial correlations, participant variability was controlled for since this was a within-subjects design. Jaggedness was correlated with self-reported pleasantness and stress. Strong correlations were found between perceived jaggedness and self-reported pleasantness, $r(153) = -0.55$, $p < 0.001$, and perceived jaggedness and self-reported stress $r(153) = 0.63$, $p < 0.001$, replicating previous findings suggesting that humans find smooth/fluid shapes and scenes to be more pleasant and less stressful.

Given the strong correlations, exploratory analysis using partial correlations was conducted to determine the specific relationship between jaggedness and self-reported affect. In the second set of correlations, participant, perceived complexity of the scene, and perceived interestingness of the scene were controlled for. The analysis revealed that there were still moderate correlations between perceived jaggedness and self-reported pleasantness, $r(151) = -0.39$, $p < 0.001$, and self-reported stress, $r(151) = 0.48$ $p < 0.001$

Finally, a set of partial correlations controlling for participant, perceived complexity of the scene, perceived interestingness of the scene and percent of natural content in the scene were used to determine if jaggedness was merely reflecting the differences between nature and urban scenes rather than a unique visual property. The analysis revealed that perceived jaggedness was still moderately correlated with self-reported pleasantness $r(150) = -0.27$ $p < 0.001$, and self-reported stress $r(150) = 0.33$, $p < 0.001$, when controlling for perceived interestingness, complexity, and percent of natural content in the scene. This suggested that the relationship between jaggedness and affect was independent of the controlled factors, suggesting that individuals prefer smoother and more fluid shapes even in complex visual scenes. This wasn't particularly surprising given that jaggedness (i.e., more edges, lines and corners) can be associated with increased power of middle to high spatial frequencies, which was linked to self-reported affect in Experiments 1 and 2.

Given this relationship between a visual-structural property of the scene and self-reported affect, and support for bottom-up theories in the results, it became evident that the pattern of results appeared to be in line with predictions that could be made from *Reward Restoration Theory*. Specifically, that visual patterns (and related visual-spatial frequencies) could be linked to (perceived) restoration.

4.4 Discussion

The current experiment tested predictions made by the *Cognitive Perspective* directly using a direct semantic priming paradigm for the first time in the literature on the restorative effects of nature. The *Cognitive Perspective* has been a logical alternative explanation for the restorative benefits of exposure to nature scenes. The main argument from the *Cognitive Perspective* has been that in modern urban centers (where most research is done), individuals have positive associations with nature (such as vacation, escape from work, relaxation, etc), and negative associations with urban scenes (such as work, pollution, stress, etc) which are activated when individuals view nature and urban scenes respectively. While this logical argument is intuitive, there has been little empirical evidence to support it. One reason for this is likely that there are other bottom-up mechanisms that overshadow the effects of top-down influences, such as those proposed by *Reward Restoration Theory*, *Attention Restoration Theory*, and *Psycho-evolutionary Restoration Theory*. Indeed, this certainly appears to be the case when considering the results from the current experiment.

Experiment 3 used a within-subjects design with a large number of participants to allow for greater statistical power, such that even small effects could be detected. Furthermore, the priming paradigm used was designed to specifically target top-down influences theorized by the *Cognitive Perspective*. Despite the effort made to detect top-down influences, no support for the *Cognitive Perspective* was found. Instead, results supported predictions made by bottom-up theories of restoration. Furthermore, emergent findings demonstrating that responses followed a strong linear pattern with respect to percentage of nature content in the scene provided the first distinct evidence that restoration is a function of the amount of nature occupying the visual field, rather than a top-down association. Neither Kaplan (1995,2001)'s *Attention Restoration Theory*, nor Ulrich et al. (1991)'s *Psycho-evolutionary Restoration Theory* predict that such a linear pattern exists. This exemplifies the need for a mechanistic model such as the proposed *Reward Restoration Theory* to fill the gap in predictive power of existing theories on restoration.

Furthermore, analyses of scenes along the smooth-jagged dimension, which has been previously linked to preference (Poffenberger & Barrows, 1924; Amir, Biederman & Hayworth 2011), demonstrated that participants' responses of stress and pleasantness were sensitive to specific visual properties within the scenes, even when percentage of nature content was statistically controlled for. This relationship between the amount of the jaggedness of the scene and affect/stress provided further evidence that visual reward mechanisms may be partly responsible for the restorative effects of nature. This relationship further demonstrated that nature scenes may be more pleasant and restorative than urban scenes because they happen to contain visual information and/or patterns that the humans (and even infants) prefer to view. Here it could be argued that it may not be nature itself that is restorative, but rather that the restoration may come from the patterns and visual information present in nature scenes. This would certainly help explain the difficulty of detecting top-down effects proposed by the *Cognitive Perspective*. If certain visual properties or patterns within nature scenes are restorative, rather than nature itself, it may be possible to promote restoration using scenes that are not conceptually natural but contain similar visual properties to nature scenes.

Unfortunately, while Experiment 3 offered novel insights and perspectives on the restorative effects of nature, it must be noted that the experiment was not initially intended to test predictions made by *Reward Restoration Theory*. The results that supported RRT were partly from post-hoc analyses and merely correlational. Furthermore, the current experiment also lacked enough data points to determine if the observed relationship between percentage of nature in the scene and ratings of pleasantness and stress was truly linear or an artifact of the stimuli used. With the half-urban/half-nature scenes it was possible that participants may have simply rated them relative to the fully natural and fully urban scenes by estimating the amount of nature and urban content in the scene (a relatively easy task given the foreground/background separation). However, if this was truly occurring, at least some of them should have mentioned their process during the post-experiment debriefing. Also, visual estimation of nature content in the scene could not explain the relationship between the jaggedness of the scene and pleasantness/stress that continued to exist even when controlling for amount of nature in the scene, perceived visual complexity, and perceived interestingness of the scene.

Chapter 5 Experiment 4: Exploring the Relationship Between the Proportion of Nature to Urban Content in Scenes and Self-reported Responses

5.1 Introduction

Experiment 3 offered novel insights into the relationship between the visual properties of scenes and self-reported responses of stress and pleasantness. Specifically, Experiment 3 demonstrated, for the first time, that there might be a linear relationship between the amount of nature content in the scene and the responses to the scene, a finding that existing theories on restoration could not directly address. Additionally, Experiment 3 demonstrated that that there may also be a linear relationship (even when controlling for image content and other factors) between visual properties such as jaggedness of the scene and self-reported responses to the scenes. Both of these findings were consistent with what the proposed *Reward Restoration Theory* predicts based on (proposed) tuning of reward systems in the ventral visual pathway that have been previously linked to scene preference by Yue, Vessel & Biederman (2007).

Unfortunately, since Experiment 3 was not specifically designed to explore these relationships, it was difficult to tell if the observed patterns of data were spurious or true evidence for bottom-up responses to specific visual information (i.e., prevalence [power] of specific visual spatial frequencies) and/or visual patterns (e.g., curves versus straight lines). In order to address these shortcomings of Experiment 3, the current experiment was designed to specifically explore the apparent relationships found in the previous experiment while addressing some of the limitations.

To address the problem of limited scene variability in the previous experiment, where only fully natural, half-urban/half-nature and fully urban scenes were used, scenes with more varied proportions of nature to urban content were introduced. Furthermore, instead of limiting scenes to foreground nature/background urban content, and foreground urban/background nature content, scenes with scattered nature and urban content were used to hinder participants' ability to estimate the proportion of nature to urban content in the scene. Lastly, since measures of affect/stress and jaggedness were self-reported, it was possible that participants' responses on these measures co-varied as a result of bias or top-down influences. To address this potential problem, the relationship between visual-spatial frequencies and their power (i.e., an objective measure of jaggedness), and responses to scenes was explored. This was also done to link results of the current experiment with results from Experiments 1 and 2 implicating middle-high visual-spatial frequencies, and power of visual-spatial frequencies, in influencing participants' responses to scenes.

Hypotheses for the current experiment were formed based on results from Experiments 1 to 3 and predictions made by the proposed *Reward Restoration Theory*.

H1: Based on the results from Experiment 3, it was predicted that there would be a linear relationship between proportion of nature to urban content in the viewed scene and self-reported affect.

H2: Based on results from Experiments 1 and 2, and general predictions made by the proposed *Reward Restoration Theory* stating that the visual reward pathways discovered by Yue, Vessel & Biederman (2007) should be tuned to specific visual information, it was predicted that the power of middle-to-high spatial frequencies would be able predict participants' affective responses to scenes. These frequencies were also expected to correlate with self-reported jaggedness.

Null Hypothesis: *Attention Restoration Theory* (Kaplan, 1995; Kaplan, 2001) and *Psycho-evolutionary Restoration Theory* (Ulrich et al., 1991) did not directly predict the observed linear relationships between visual content and participants' responses in Experiment 3, nor a mechanism that could explain the pattern of data. Based on these theories, there was reason to believe that the pattern of data observed in Experiment 3 was spurious and would not be replicated.

5.2 Method

5.2.1 Participants. Prior to recruitment, participants were pre-screened using a mass-testing questionnaire. Participants were required to speak and read English fluently (in order to understand instructions), and to have reported that they had normal 20/20 vision. A sample of twenty-nine participants (14 male, 15 female) were recruited from the University of Waterloo SONA participant pool to participate in the study in exchange for course credit. No participants reported having any visual disorder or visual problems.

5.2.2 Materials. As in the previous experiment, this experiment used a simple slide-show presentation of various images on a 17 inch LCD monitor with a resolution of 1280 x 1024 pixels. The monitor screen occupied approximately 29 degrees of horizontal field of view. All participants were seated at the same distance from the monitor on a chair that could not be moved. The screen was approximately 26 inches from participants' eyes.

Images used in this study were collected from publically available photos on flickr (http://www.flickr.com) and Google image search. Photos used in the current experiment were all new and did not include any stimuli from previous experiments. All images were cropped to the dimensions of 900 x 900 pixels (occupying approximately 20 degrees field of view on the monitor) and converted to grayscale using Adobe Photoshop Elements 10. All images were saved in JPEG format, and had their brightness levels and contrast balanced using the "Auto Levels" and "Auto Contrast" options in Adobe Photoshop Elements 10. When displayed during the experiment, images were in their native resolution, such that pixels in the image matched pixels on the display in a 1:1 ratio. The images consisted of six image sets: Images within the same set had a specific ratio of nature to urban content. The six image sets contained the following proportions of nature to urban content: {100:0}, {80:20}, {60:40}, {40:60}, {20:80} and {0:100}. Ratios for the images were calculated using pixel counting. The criterion used to identify natural versus urban content was as follows: Anything man-made was considered urban (streets, buildings, cars, sidewalks, etc), while everything else was considered natural (sky, clouds, lakes, rivers, vegetation, mountains, rocks). Due to the limitations of cropping photographs, there was minor variation in the ratio (+ or - 2%) between images within a set. Each set contained six scenes, for a total of thirty-six scenes. Sample scenes can be seen in Figure 5.1.

5.2.3 Design. A completely within-subjects design was used in this experiment, where all images were seen by every participant. The same presentation method used in Experiment 3 was also used in the current experiment. Images were presented one at a time in a randomized counterbalanced order. Counterbalancing and randomization was used to deal with potential contrast and order effects. Images were randomly chosen from each set and presented in the sequences A[26] and B[27] using the order of ABBAAB, or BAABBA. Participants were randomly assigned such that half viewed scenes on one order, and the other half viewed the other order.

[26] Sequence A: 100:0 Nature:Urban → 80:20 → 60:40 → 40:60 → 20:80 → 0:100
[27] Sequence B: 0:100 Nature:Urban → 20:80 → 40:60 → 60:40 → 80:20 → 100:0

This form of counterbalancing was used in order to counterbalance the contrast effects observed in the previous experiment.

Also, as in Experiment 3, 10 questions assessing various characteristics of each scene were co-presented with the scenes. Questions were presented one at a time, in random order, and in a random location in a column to the left of the image. This was done to reduce automatic responses due to repetition of questions across images, to provide some level of novelty to keep participants engaged, and to prompt participants to read each question (since they could not predict what question was next). With the inclusion of reverse-coded pairs, and measurement of RT, validity of responses could be assessed.

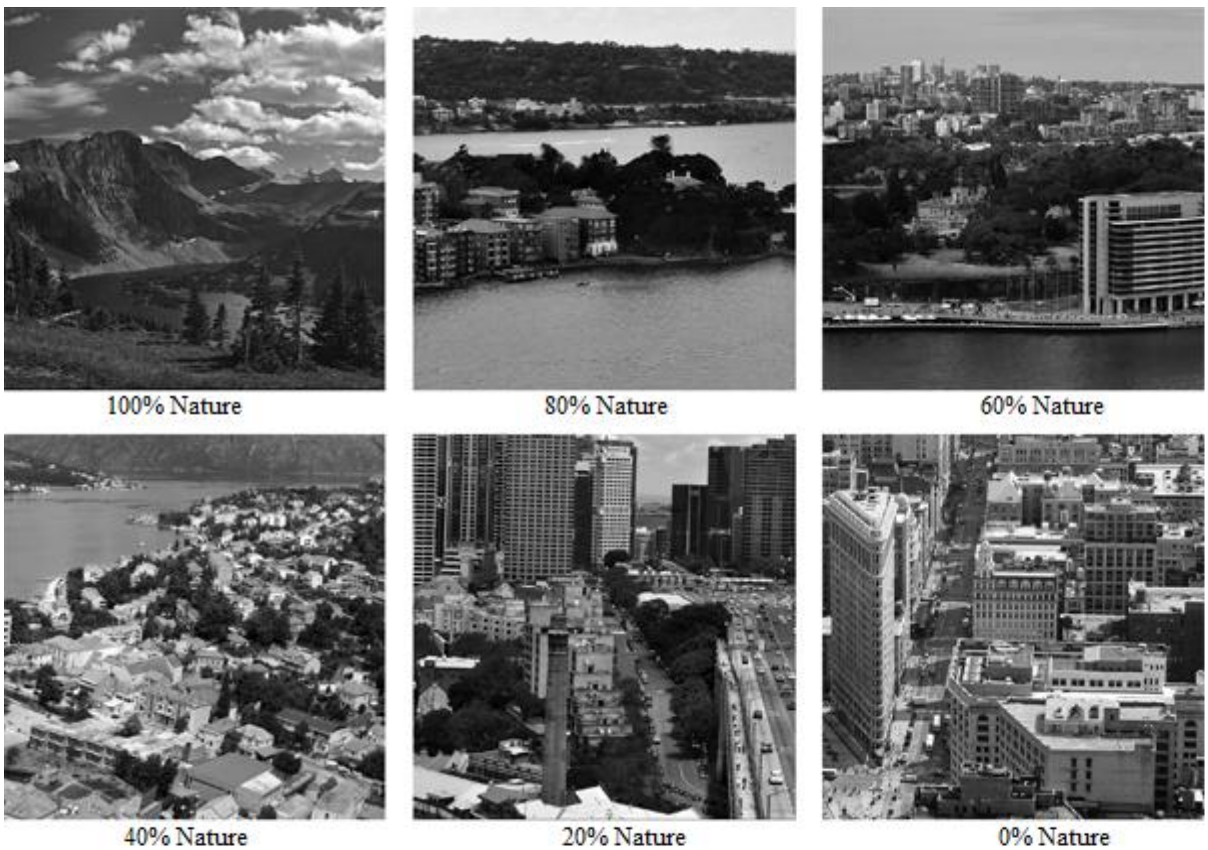

Figure 5.1 Experiment 4: Sample of scenes demonstrating the different proportions of nature to urban content used. Here it can be seen how nature and urban content was inter-mixed within the scenes.

5.2.4 Procedure. A similar procedure to that used in Experiment 3 was also used in Experiment 4: Individual participants were scheduled to come to the lab using the University of Waterloo's SONA online system. Upon their arrival, participants were greeted by the researcher, briefed on the procedure of the experiment and given an information and consent form to read and sign.

Participants were then seated in front of the computer monitor and provided with a keyboard. They were asked not to adjust the monitor or chair, and to use the keyboard to input their responses to the questions on the screen. They were asked if they had any questions and told to inform the researcher once they had completed the study. The researcher then left the room and waited outside the door. Scenes were individually presented on the right side of the screen until all questions about the scene were answered. Questions were presented on the left side of the screen, using the randomization procedure described earlier. Participants responded to questions by pressing the number on the keyboard corresponding to their response on a scale from 1 (low) to 7 (high). Participants were given the definitions of jaggedness and complexity that were reported by participants in the previous experiment, to ensure consistency across experiments.

Participants were allowed to go through the experiment at their own pace. Upon completion, participants were debriefed and the purpose of the experiment was explained to them. No participants suspected deception or the true purpose of the experiment.

5.3 Results

For analysis purposes, self-reported scores on existing scales of 1 to 7 for measures depicting the same variable on opposite ends of a continuum (e.g., stressful & calming) were combined to create scales ranging from -6 to 6 with the midpoint [0] being neutral and the endpoints representing the max on each scale (e.g., highly calming [-6] and highly stressful [6]). This was done to better represent participant responses on the continuum of the measured variable, rather than analyzing responses for each tail individually.

5.3.1 Testing hypothesis 1: Exploring the effect of different proportions of nature to urban content on responses. Based on the results from Experiment 3, it was hypothesized that there would be a linear relationship between the proportion of nature to urban content in a scene and participants responses for self-reported pleasantness and stress. To test if there was an effect of different proportions of nature to urban content in the scenes, a repeated-measures ANOVA was conducted:

The repeated-measures ANOVA revealed that there was a main effect of the proportion of nature to urban content in the scene on participants' self-reported pleasantness of the scene, $F(5,140) = 76.2$, $MSE = 0.36$, $\eta_p^2 = 0.73$, $p < 0.001$. Given the significant main effect, a polynomial linear contrast was conducted in order to determine if the data followed a linear pattern. As predicted, ratings of pleasantness decreased in a linear fashion as the proportion of nature to urban content in the scene decreased, $F(1,28) = 130.5$, $MSE = 0.56$, $\eta_p^2 = 0.82$, $p < 0.001$.[28]

The repeated-measures ANOVA also revealed that there was a main effect of the proportion of nature to urban content in the scene on the self-reported stressfulness of the scene, $F(5,140) = 97.0$, $MSE = 1.3$, $\eta_p^2 = 0.78$, $p < 0.001$. A polynomial linear contrast was conducted in order to examine if the data followed a linear trend. As predicted, ratings of stress increased as

[28] Ratings of valence (on a positive-negative continuum) mirrored this linear trend, $F(1,28) = 138.1$, $MSE = 1.43$, $\eta_p^2 = 0.83$, $p < 0.001$.

the proportion of nature content to urban content decreased in a linear fashion, $F(1,28) = 175.2$, $MSE = 2.7$, $\eta_p^2 = 0.86$, $p < 0.001$.

5.3.2 Testing hypothesis 2: Exploring relationships between visual spatial frequency and self-report measures. To explore the second hypothesis, advanced visual spatial frequency analysis had to be conducted using Fourier transforms (see section 1.6 for review of Fourier transforms). In order to do this, a python script using SciPy was written for current (and future) analyses (sample code can be found in Appendix B). The procedure for the analyses was a follows: Images were first decomposed into two-dimensional arrays of complex numbers using fast Fourier transforms. The array of each image (900 x 900 pixels) was represented by 810,000 complex number entries. Each complex number contained information about the phase and amplitude of a specific visual-spatial frequency in 2-dimensions. The power (i.e., amplitude squared) of the 2-dimensional transform was calculated and radially averaged to create a 1-D power spectrum. This method has been commonly used in previous research looking at spatial frequencies in images (Simoncelli & Olshausen, 2001; Fernandez & Wilkins, 2008; Melmer et al., 2013). The 1-dimensional power spectrum yielded the radial power of visual spatial frequencies in cycles per image. The visual spatial frequencies were converted from their units of cycles per image into cycles per degree of visual angle for analysis purposes.

The power of each visual-spatial frequency bin ranging from 1 cycle per degree of visual angle ("c/d" for short) to 20 c/d (the near-maximum possible based on the image resolution) was correlated with an aggregate score of affective response (composed of self-reported pleasantness, stress, valence, etc)[29] while correcting for multiple comparisons. Since 20 comparisons were

[29] The aggregate score was used since the goal was to see if there's a relationship between restoration as measured by all affective measures, rather than by any individual measure.

made, an alpha of 0.0025 was used.[30] The exploratory analyses revealed that only the power of a narrow spatial frequency range of 5 to 7 c/d was significantly correlated with the aggregate measure of self-reported affective response. Since these correlations were co-linear, and the frequencies were adjacent, the power was averaged to create a single measure of power for spatial frequencies in the 5 to 7 c/d range. The correlogram for all spatial frequencies analyzed can be seen in Figure 5.2.

A linear-fit model was used to check if there was a linear relationship between transforms of the power of spatial frequency and the aggregate self-reported affective response measure, so that linear regression analysis could be performed. It was found that the quarter root of the power of the visual spatial frequencies, $(\text{power of 5-7 c/d SF})^{1/4}$, had the best natural fit. The quarter-root transform of the power of the 5-7 c/d SF range was used for all future analyses.

[30] Visual spatial frequencies that were lower than 1 cycle per degree of visual angle were not analyzed since results from Experiments 1 and 2 suggested that middle-high visual spatial frequencies are more important for determining participants' responses to scenes. Furthermore, the reward pathway implicated by Reward Restoration Theory was in the ventral visual system, suggesting that affective responses should be governed by middle-to-high spatial frequencies.

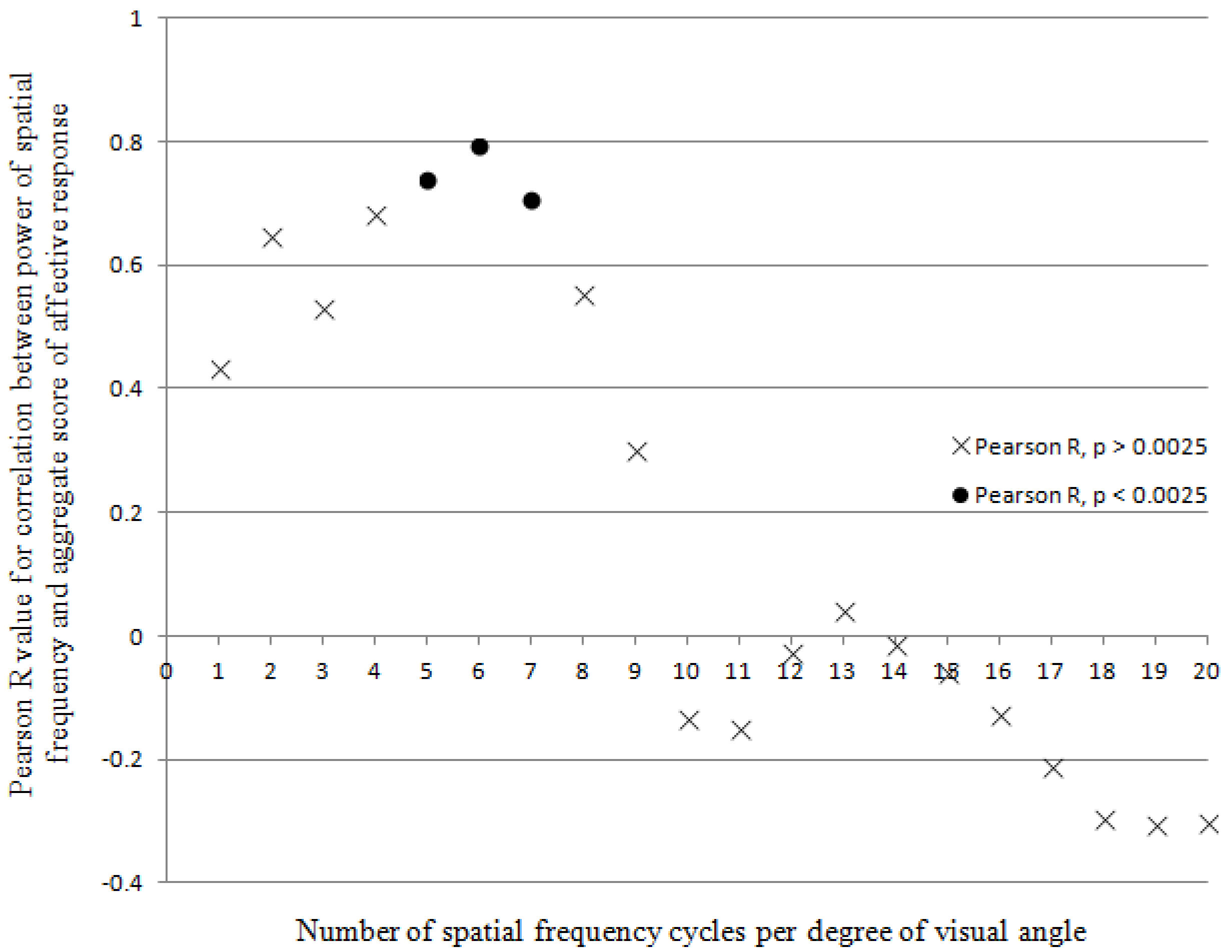

Figure 5.2 Experiment 4: Correlogram of Pearson R values for correlations exploring the relationship between power of visual spatial frequencies and (mean) aggregate affective response to scenes. Here it can be seen that there is a clear relationship between power of spatial frequencies with 5 to 7 cycles per degree of visual angle and the aggregate affective response (solid dots). The pattern of correlations (the inverted U shape) also suggests that affective responses may be “tuned” to these spatial frequencies.

In order to explore how well (power of 5-7 c/d SF)$^{1/4}$ could predict responses to specific scenes, the measure was calculated for the 36 scenes used in this study and used as the predictor variable in a linear regression. Responses for self-reported measures were averaged per scene and used as the dependent variables. As hypothesized, (power of 5-7 c/d SF)$^{1/4}$ was a significant predictor of both mean self-reported pleasantness scenes, *standardized* $\beta = -0.69$, $t(34) = -5.5$, $p < 0.001$, and mean self-reported stressfulness of scenes, *standardized* $\beta = 0.78$, $t(34) = 7.2$, $p < 0.001$. The relationship for self-reported stressfulness of scenes can be seen in Figure 5.3. The quarter root of the power of the 5-7 c/d SF range also explained a significant amount of variance in both mean self-reported pleasantness of scenes, $R^2 = 0.48$, $F(1,34) = 30.7$, $p < 0.001$, and mean stressfulness of scenes, $R^2 = 0.61$, $F(1,34) = 52.2$, $p < 0.001$.

A Pearson's correlation was used to check if self-reported jaggedness was correlated with (power of 5-7 c/d SF)$^{1/4}$ of scenes in order to determine if self-reported jaggedness of scenes was related to spatial frequencies in the scene. As hypothesized, there was a strong correlation between (power of 5-7 c/d SF)$^{1/4}$ and mean self-reported jaggedness of scenes, $r(34) = 0.76$, $p < 0.001$, indicating that ratings of jaggedness were related to these spatial frequencies.

Finally, a second set of regression analyses was conducted to determine if (power of 5-7 c/d SF)$^{1/4}$ could independently predict responses to scenes when (statistically) controlling for the proportion of nature to urban content in the scene. The proportion of nature to urban content in the scene was entered as a co-predictor of mean self-reported pleasantness and stressfulness of the scenes. When controlling for the proportion of nature to urban content in the scenes, (power of 5-7 c/d SF)$^{1/4}$ remained a significant predictor of both mean self-reported pleasantness, *standardized* $\beta = -0.48$, $t(33) = -3.0$, $p < 0.01$, and mean reported stressfulness of the scene, *standardized* $\beta = 0.51$, $t(33) = 3.8$, $p < 0.001$. This result was consistent with participants' debriefing reports that they were unanimously unaware of sequential images changing in proportion of nature to urban content in a graded fashion (e.g., 80:20 N:U → 60:40 N:U). Given that participants were both unaware of the scenes gradually changing from nature to urban (and vice versa), and that (power of 5-7 c/d SF)$^{1/4}$ remained a significant predictor of self-reported affect when statistically controlling for the proportion of nature to urban content in the scenes, it is unlikely that participants were explicitly responding to, or calculating, the amount of natural versus urban content in the scenes.

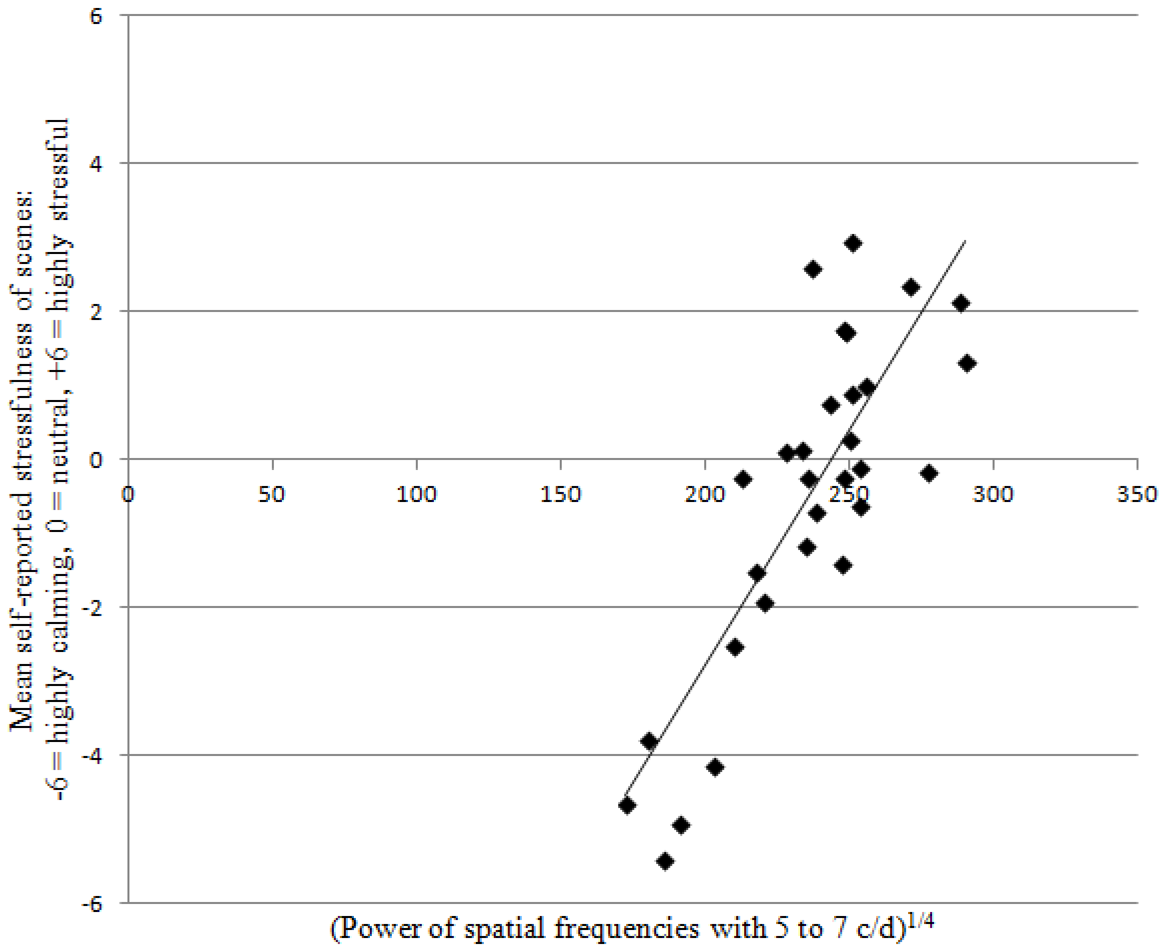

Figure 5.3 Experiment 4: Mean self-reported stressfulness of scenes with respect to quarter root of the power of spatial frequencies with 5 to 7 cycles per degree of visual angle. Graph demonstrates the linear relationship between power$^{1/4}$ and the self-reported stress/calming response to scenes.

5.3.3 Meta-analysis of experiments 1, 2, and 3 with respect to (power of 5-7 c/d SF)$^{1/4}$

The results from Experiment 4 were encouraging, however, the method for extracting the visual spatial frequency range created a self-referencing bias, since the range was both extracted and used to predict the same data. If the findings were to be trusted, the discovered relationship between (power of 5-7 c/d SF)$^{1/4}$ and responses to scenes had to be able to predict responses across different paradigms, stimuli, and participant groups. For this reason, results from experiments 1 to 3 were re-analyzed using (power of 5-7 c/d SF)$^{1/4}$ as a predictor of dependent variables in order to determine if it was a reliable predictor of responses to scenes.

Given that the effect of exposure to nature and urban scenes on self-reported pleasantness, blink rates, and number of fixations was consistent across Experiments 1 and 2, participant data across the experiments was collapsed to simplify analyses. Since these analyses were done post-hoc, a Bonferroni correction for multiple comparisons was used. The adjusted alpha for statistical significance was 0.01 (versus the standard 0.05). Linear regression was used to determine if (power of 5-7 c/d SF)$^{1/4}$ was a significant predictor of the dependent variables. The linear regression analyses revealed that the power of the spatial frequency range of interest was a significant predictor of self-reported pleasantness of scenes in Experiments 1 and 2, *standardized* $\beta = -0.41$, $t(53) = -6.8$, $p < 0.001$. It was also a significant predictor of number of fixations, *standardized* $\beta = 0.26$, $t(53) = 4.1$, $p < 0.001$, and blink rates, *standardized* $\beta = 0.30$, $t(53) = 4.9$ $p < 0.001$, demonstrating the pattern that as the power increased, pleasantness decreased while number of fixations and blink rates increased.

Linear regression analysis for Experiment 3 also revealed the same pattern, where (power of 5-7 c/d SF)$^{1/4}$ was a significant predictor of both self-reported pleasantness of scenes, *standardized* $\beta = -0.55$, $t(50) = -13.5$, $p < 0.001$, and perceived stressfulness of scenes, *standardized* β = 0.61, t(50) = 15.7, p < 0.001. This pattern was consistent with results from Experiments 1,2 and 4, suggesting that restoration occurs when the power of visual spatial frequencies in the 5 to 7 c/d range is low. If this is true, then it is possible that the hypothesized visual reward systems may be tuned to low power of these spatial frequencies.

5.4 Discussion

The main goal of Experiment 4 was to expand the novel findings from Experiment 3, by directly testing the relationship between responses to scenes and the proportion of nature content in the scenes. Also, a secondary goal was to build upon the novel findings from Experiment 3 suggesting that responses to scenes were linked to specific visual properties of scenes, such as jaggedness, by determining if this was related to the previously discussed effects of visual spatial frequencies in Experiments 1 and 2. The results from the current experiment addressed both of these goals.

Evidence was found for a significant linear relationship between the proportion of nature content in the scenes, and both the self-reported pleasantness and perceived stressfulness of the scenes. The large effect sizes combined with the careful counterbalancing and use of randomization suggested that strong linear relationship was not accidental. This, combined with the similar pattern of results in the previous experiment, indicated that participants were responding to the proportion of nature content in the scene in a highly predictable fashion. These results were surprising on both theoretical and intuitive levels:

Kaplan's *Attention Restoration Theory* (1995,2001) does not predict that such a linear relationship between restorative response and proportion of nature content should exist. Instead, based on ART, the response was expected to be either restorative or non-restorative rather than being proportional to the amount of nature content in the scene. Also, Ulrich et al. (1991)'s *Psycho-evolutionary Restoration Theory* does not make direct predictions about such a linear relationship. However, if we were to infer one, then predictions would be tied to an evolved preference for nature scenes based on evolved biological mechanisms that exist to facilitate survival. Even with such an inference, it is difficult to directly predict the observed linear relationship between perceived pleasantness/stressfulness of the scenes and the proportion of natural to urban content. Furthermore, if we were to consider the *Cognitive Perspective*, and potential top-down influences, it is difficult to make a logical argument that could explain the strong linear relationship between proportion of natural to urban content in the scene and responses for the scene. It could be argued, once again, that participants may have been somehow counting or intuitively estimating the amount of nature content in the scene and basing their responses on that. However, this was unlikely since measures were taken to make such a task difficult. This was done by randomizing the presentation of images within the sets as well as using images with inter-mixed natural and urban content. Instead, the scenario where participants simply had bottom-up response to the scenes proportional to activation of the visual reward pathways discussed by Yue, Vessel & Biederman (2007) seems more likely.

The proposed explanation based on *Reward Restoration Theory* and bottom-up activation of visual reward pathways becomes more plausible when considering the meta-analysis of results from Experiments 1 to 4 which explored the relationship between responses to scenes, and the power of visual spatial frequencies in the 5 to7 cycles per degree of visual angle (5-7 c/d SF). The analysis revealed a striking consistency in ability to predict responses to different scenes across different experimental paradigms, across different participant groups, and across different measures of restoration using only the power of the 5-7 c/d SF. It was possible to predict blink rates, number of fixations, perceived pleasantness, and perceived stressfulness, all of which have been previously linked to restoration (Valtchanov & Ellard, 2010, Berto et al., 2008, Ulrich et al., 1991). If they are all measures of restoration, then the ability to predict them using the power of the 5-7 c/d visual spatial frequencies suggests that restoration may be linked to bottom-up responses to spatial frequencies, possibly due to activation of reward pathways in the ventral visual system as predicted by the proposed *Reward Restoration Theory*. Furthermore, the limited range of spatial frequencies that has been linked to measures of restoration is consistent with the notion put forward by RRT, which suggests ventral visual reward pathways discussed by Yue, Vessel & Biederman (2007) may be tuned to specific visual spatial frequencies. Recent neuroimagine (fMRI) findings by Fintzi & Mahon (2013), which demonstrate that the ventral visual pathway shows maximal activation when presented with spatial frequencies with 4.75 to 9.14 c/d converge with the findings of Experiment 4. When considering that the ventral visual pathway is tuned to SF with 4.75 to 9.14 c/d (Fintzi & Mahon, 2013), it is not a far stretch to predict that reward mechanism within the ventral visual pathway (Yue et al., 2007) may be tuned to a subset of these spatial frequencies; Specifically, these systems may be tuned to the SF with 5 to 7 c/d that predict restoration responses in Experiments 1 to 4.

Overall, the results of Experiment 4, combined with the meta-analysis of Experiments 1 to 3 with respect to visual spatial frequencies and recent findings by Fintzi & Mahon (2013), provide consistent and robust evidence for the proposed bottom-up visual mechanism for the restorative effects of nature. Furthermore, not only was the evidence consistent across the different types of measures (self-report, fixations, and blink rates) and different experimental paradigms, but it also singled-out a narrow range of visual-spatial frequencies linked to measures of restoration that is consistent with the spatial frequency range that maximally activates the ventral visual pathway (Fintzi & Mahon, 2013). This is the first report in the literature on the restorative effects of nature describing the specific visual spatial frequencies that are linked to restoration.[31] Based on this finding, it is also possible to hypothesize that the visual reward pathways discussed by Yue, Vessel & Biederman (2007) may be tuned to these "restorative" frequencies. Such might be the case since both power of the 5-7 c/d visual spatial frequencies and activation of the visual reward pathways appear to predict affective responses to scenes (Yue et al., 2007).

[31] As noted in section 1.6.2, there has been previous literature in the computer vision and human perception literature linking the power (amplitude) spectrum of images to ratings of aversiveness and visual aesthetics (Fernandez & Wilkins, 2008; O'Hare & Hibbard, 2012; Melmer et al., 2013), but no literature on the restorative effects of nature and their link to the power/amplitude spectrum of images.

Chapter 6 Experiment 5: Exploring the Relationship Between Power of Spatial Frequencies and Responses to Urban Scenes

6.1 Introduction

The previous experiments lead to an encouraging discovery about the relationship between specific visual spatial frequencies and restorative responses to scenes. However, it was important to note a limitation of the methodology: While the meta-analysis revealed a significant and robust relationship between power of visual spatial frequencies with 5 to 7 cycles per degree of visual angle (the "restorative frequencies") and all measures of restoration, a significant limitation was that all four experiments used stimuli that contained nature. If responses to scenes were indeed driven by changes in the power of these "restorative frequencies", then it should not be the content in the image (i.e., nature) that drives restoration, but rather the visual spatial frequencies of the scene. Some support for this idea was found in Experiment 4, where spatial frequency could be used to predict responses to scenes even when statistically controlling for the proportion of natural to urban content. However, it was evident that to truly test this relationship, nature content had to be controlled for (or removed) empirically rather than statistically since it was possible that the amount of the "restorative frequencies" covaried with the amount of nature in the scene.

Reward Restoration Theory predicts that it should be possible to have restorative environments that are not necessarily natural, as long as they contain similar power of visual spatial frequencies with 5 to 7 c/d (i.e., restorative frequencies) to those found in nature scenes. Following this theoretical prediction, the logical experiment to conduct was one that would both test this proposal while also differentiating predictions made by existing theories from those made by *Reward Restoration Theory*. In order to do this, fully urban/built scenes were used as the stimuli in Experiment 5. Experiments 1 to 4 demonstrated consistent evidence that natural scenes were more pleasant and less stressful than urban scenes, consistent with the literature on restorative effects of nature (Valtchanov & Ellard, 2010; Berto et al., 2008; de Kort et al., 2006; van den Berg et al., 2002). Also, there was little to no evidence in the literature suggesting that urban scenes could be restorative (Berto et al., 2010). Furthermore, existing theories on restoration (and the *Cognitive Perspective)* suggested that urban scenes are inherently stressful (Kaplan, 1995, Ulrich et al., 1991). Thus, using fully urban scenes varying in power of the restorative spatial frequencies as the stimuli effectively stacked the odds against predictions made by *Reward Restoration Theory*, since (based on the literature on restorative effects) it was unlikely that urban scenes could be perceived as calming or pleasant.

H1: Based on the consistent support for the relationship between the power of specific visual spatial frequencies and self-report measures of stress and affect across Experiments 1 to 4, and the theorized tuning to these frequencies of the reward systems in the ventral visual pathway found by Yue et al. (2007), it was hypothesized that urban scenes that were similar to nature scenes in power of visual spatial frequencies with 5 to 7 c/d would prompt less self-reported stress and greater self-reported pleasantness than those that were different.

H2: Furthermore, it was hypothesized that if the perceived stressfulness and pleasantness of scenes was truly linked to the described spatial frequencies in a linear fashion as described in the previous four experiments, that same linear relationship should also exist when using only urban scenes.

6.2 Method

6.2.1 Participants. Prior to recruitment, participants were pre-screened using a mass-testing questionnaire. Participants were required to speak and read English fluently (in order to understand instructions), and to have reported that they had normal 20/20 vision. A sample of twenty-four participants (12 male, 12 female) were recruited from the University of Waterloo SONA participant pool to participate in the study in exchange for course credit. No participants reported having any visual disorder or visual problems.

6.2.2 Materials. As in the previous experiment, this experiment used a simple slide-show presentation of various images on a 17 inch LCD monitor with a resolution of 1280 x 1024 pixels. The monitor screen occupied approximately 29 degrees of horizontal field of view. All participants were seated at the same distance from the monitor on a chair that could not be moved. The screen was approximately 26 inches from participants' eyes.

Images used in this study were collected from publically available photos on flickr (http://www.flickr.com) and Google image search. Urban scenes were collected from these sources and manually filtered to exclude images with large amounts of nature (i.e., those where nature covered greater than 5% of the visual area). Urban scenes with little-to-no nature in them were cropped to the dimensions of 900 x 900 pixels (occupying approximately 20 degrees field of view on the monitor) and converted to grayscale using Adobe Photoshop Elements 10. All images were saved in JPEG format, and had their brightness levels and contrast balanced using the "Auto Levels" and "Auto Contrast" options in Adobe Photoshop Elements 10. When displayed during the experiment, images were in their native resolution, such that pixels in the image matched pixels on the display in a 1:1 ratio. The power of visual spatial frequencies with 5 to 7 cycles per degree of visual angle was extracted from the scenes using the same method as in the previous experiments. The extracted power was then used to blindly select a sample of thirty scenes for use in the current experiment. Scenes were selected based on power such that they covered a wide range in the continuum starting from low (similar to nature) to high (the highest found in the sample of scenes collected). Sample scenes can be seen in Figure 6.1.

6.2.3 Design. Similar to the previous experiment, a within-subjects design was used where all images were viewed by every participant. A similar presentation method to that which was used in Experiment 4 was also used in the current experiment. Images were presented one at a time in a randomized order. Image presentation order was randomized for every participant in order to randomize any potential order effects.

Also, as in the previous experiment, 10 questions assessing various characteristics of each scene were co-presented with the scenes. Questions were presented one at a time, in random order, and in a random location in a column to the left of the image. This was done to reduce automatic responses due to repetition of questions across images, to provide some level of novelty to keep participants engaged, and to prompt participants to read each question (since they could not predict what question was next). With the inclusion of reverse-coded pairs, and measurement of RT, validity of responses could be assessed.

6.2.4 Procedure. A similar procedure to that used in experiments 3 and 4 was also used in Experiment 5: Individual participants were scheduled to come to the lab using the University of Waterloo's SONA online system. Upon their arrival, participants were greeted by the researcher, briefed on the procedure of the experiment and given an information and consent form to read and sign.

Participants were then seated in front of the computer monitor and provided with a keyboard. They were asked not to adjust the monitor or chair, and to use the keyboard to input their responses to the questions on the screen. They were asked if they had any questions and told to inform the researcher once they had completed the study. The researcher then left the room and waited outside the door. Scenes were individually presented on the right side of the monitor until all questions about the scene were answered. Questions were presented on the left side of the screen, using the randomization procedure described earlier. Participants responded to questions by pressing the number on the keyboard corresponding to their response on a scale from 1 (low) to 7 (high). Participants were given the definitions of jaggedness and complexity that were used in the previous experiment to ensure consistency across experiments.

Participants were allowed to go through the experiment at their own pace. Upon completion, participants were debriefed and the purpose of the experiment was explained to them. No participants suspected deception or the true purpose of the experiment.

Figure 6.1 Experiment 5: Sample of urban scenes used, ranging from scenes with low power of spatial frequencies with 5 to 7 c/d (left) to medium power (middle) to high power (right).

6.3 Results

For analysis purposes, self-reported scores on existing scales of 1 to 7 for measures depicting the same variable on opposite ends of a continuum (e.g., stressful & calming) were combined to create scales ranging from -6 to 6 with the midpoint [0] being neutral and the endpoints representing the max on each scale (e.g., highly calming [-6] and highly stressful [6]). This was done to better represent participant responses on the continuum of the measured variable, rather than analyzing responses for each tail individually.

For the initial analysis, scenes were ordered based on their power of the 5-7 c/d spatial frequency range. Scenes were then grouped into five bins of equal size that represented sequential ranges of power of the 5-7 c/d spatial frequencies. Responses for scenes in each bin were averaged per participant. A repeated-measures ANOVA was used to determine if there were any differences in self-reported pleasantness and stress resulting from changes in the power of the 5-7 c/d spatial frequency range across bins. The analysis revealed a main effect of changes in power of the 5-7 c/d spatial frequency range on both self-reported pleasantness, $F(4,92) = 37.9$, $MSE = 0.40$, $\eta_p^2 = 0.62$, $p < 0.001$, and self-reported stress, $F(4,92) = 78.7$, $MSE = 1.13$, $\eta_p^2 = 0.77$, $p < 0.001$.

A set of polynomial contrasts were used to determine if the data followed the predicted linear relationship. The contrasts revealed that self-reported pleasantness followed a significant linear trend, $F(1,23) = 71.68$, $MSE = 0.70$, $\eta_p^2 = 0.76$, $p < 0.001$, decreasing as power of the 5-7 c/d spatial frequency range increased. Furthermore, the contrasts revealed that self-reported stress also followed a significant linear trend, $F(1,23) = 123.5$, $MSE = 2.26$, $\eta_p^2 = 0.84$, $p < 0.001$, increasing as power of the 5-7 c/d spatial frequency range increased. These results replicated the previous findings of Experiments 1 to 4 using only urban scenes, providing significant support for the proposed notion that part of the perceived pleasantness and stressfulness of scenes may be driven by specific visual spatial frequencies.

Linear regression analysis was conducted to determine if the quarter root of power of 5-7 c/d spatial frequencies was predictive of mean self-reported pleasantness and stressfulness per scene as it was in Experiment 4. The analysis revealed that (power of 5-7 c/d SF)$^{1/4}$ was indeed a significant predictor of both mean self-reported pleasantness, *standardized* $\beta = -0.86$, $t(28) = -8.9$, $p < 0.001$, and mean self-reported stressfulness, *standardized* $\beta = 0.83$, $t(28) = 7.8$, $p < 0.001$. The (power of 5-7 c/d SF)$^{1/4}$ measure also explained a significant portion of variance in mean self-reported pleasantness of scenes, $R^2 = 0.74$, $F(1,28) = 78.9$, $p < 0.001$, and mean self-reported stressfulness of scenes, $R^2 = 0.69$, $F(1,28) = 61.1$, $p < 0.001$. The pattern of data for self-reported stressfulness can be seen in Figure 6.2.

Next, since nature scenes have a low power of SF with 5 to 7 c/d and are perceived to be calming, it was important to determine if urban scenes that contained low power of the 5-7 c/d spatial frequency range (like nature scenes) were also being perceived as calming (i.e., restorative). Self-reported scores for these scenes on the highly calming (-6) to highly stressful (+6) continuum were compared to 0 (neutral) using a one-sampled t-test. The analysis revealed that urban scenes which had a similar power of the 5-7 c/d spatial frequency range to nature scenes were being perceived as slightly to moderately calming (M = -1.9), $t(23) = -7.3$, SE = 0.26, 95% CI [-2.4, -1.3], $p < 0.001$, confirming the prediction that even urban scenes can be perceived as calming if they contain similar power of the "restorative" visual spatial frequencies to nature scenes.

Given these findings, a new question arose as to whether urban scenes that were similar in power of their 5-7 c/d spatial frequency range to nature scenes were still perceived as significantly less calming than nature scenes. To explore this question, an independent samples t-test was used to compare self-reported stress responses toward full nature scenes in Experiment 4 to responses toward full urban scenes with similar power of the 5-7 c/d SF range in Experiment 5. The analysis revealed that nature scenes ($M = -4.1$) were significantly more calming than urban scenes ($M = -1.8$) when controlling for power of the 5-7 c/d spatial frequency range, $t(51) = 5.8$, $SE = 0.39$, $p < 0.001$. This indicated that while power of the 5-7 c/d SF range can account for a large portion of variance in participant responses to scenes,[32] it was clearly not able to fully explain the restorative effects of nature by itself. Part of the reason for this could be that there are multiple mechanisms working in parallel, and/or that the rough measure of spatial frequency derived from these experiments is simply not precise. There may even be top-down influences due to positive/negative associations with scene content that may be responsible for the remaining variance in participant responses.

[32] Refer to reported effect sizes of analyses concerning power of the 5-7 c/d SF range from experiments 1 to 5. Depending on the experimental paradigm, changes in power of the 5-7 c/d SF range accounted for approximately 40 to 80% of the variance in participant responses to scenes.

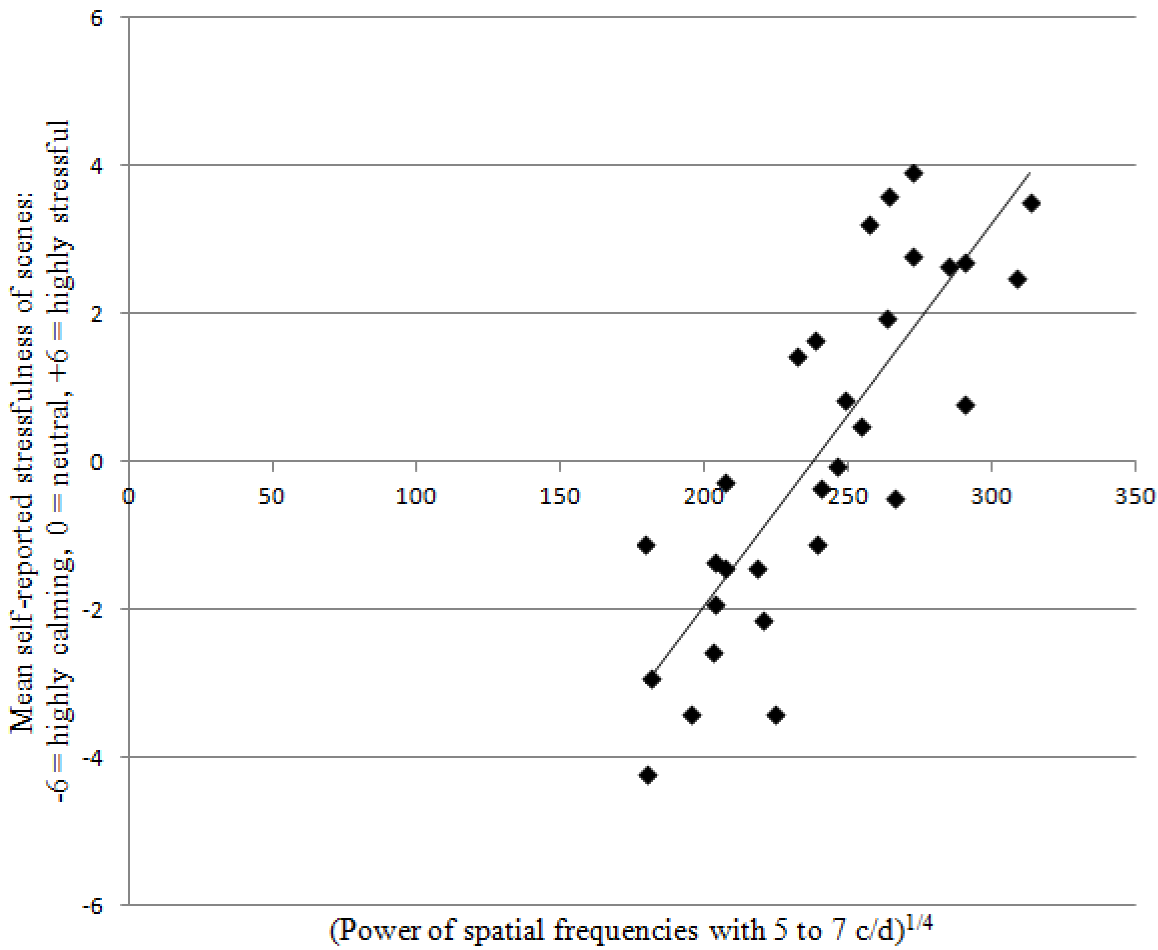

Figure 6.2. Experiment 5: Mean self-reported stressfulness of urban scenes with respect to quarter root of the power of spatial frequencies with 5 to 7 cycles per degree of visual angle. Graph demonstrates the linear relationship between power$^{1/4}$ and the self-reported stress/calming response to scenes.

6.4 Discussion

The current experiment aimed to explore predictions made by *Reward Restoration Theory* and build upon findings in the previous four experiments by empirically testing if scenes can be predictably perceived as calming and pleasant, even when they are not nature scenes. *Reward Restoration Theory* predicts that it is possible to have restorative environments that are not necessarily natural, as long as they contain the appropriate visual information that would stimulate visual reward pathways. Given that evidence was found in the previous four experiments for responses to scenes (eye-movements, blink rates, self-reported pleasantness and stress) being relative to the power of visual spatial frequencies with 5-7 cycles per degree of visual angle ("restorative" spatial frequencies), this visual information was theorized to stimulate visual reward pathways previously associated with scene preference (Yue, Vessel & Biederman., 2007; Biederman & Vessel, 2006). Thus, the current study aimed to test if even urban scenes, previously associated with stress and cognitive degradation (Ulrich et al., 1991; Kaplan, 1995;2001), could be perceived as calming and pleasant when they had similar power of restorative spatial frequencies to nature scenes.

As predicted by the proposed *Reward Restoration Theory* (RRT), not only were scenes with the similar power of SF with 5-7 c/d to nature scenes perceived as more calming and pleasant than other urban scenes, the relationship between responses and power of these visual spatial frequencies was linear as in the previous studies; as the power increased restoration decreased predictably. This finding not only supported the predictions made by the proposed RRT, but also demonstrated that restoration (as measured in this experiment) can occur when viewing urban scenes, where it would not be expected based on existing theories on the restorative effects of nature (Ulrich et al., 1991; Kaplan, 1995;2001). These results provided evidence suggesting that the reward mechanisms in question may not necessarily be tuned to categorical content (i.e., nature versus urban), but rather the power of a limited spatial frequency range that is present in many different types of scenes.

The evidence for bottom-up processing and a mechanism that appears to be linked to visual spatial frequencies is both consistent and strong across the five experiments presented, and is thus difficult to ignore when considering the direction of future research on the restorative effects of nature. However, as striking and consistent as the findings presented thus far have been, it is important to note that power of the 5-7 c/d visual spatial frequency range is not able to predict all of the variance in participants' responses to scenes. It is logical that scene preference and restoration in general would recruit a multi-faceted collection of mechanisms that work together to ultimately determine individuals' responses to scenes.

Evidence has been presented in the current experiment to suggest that even when empirically controlling for the power of the "restorative" spatial frequency range, nature scenes are still perceived as more pleasant and more calming than urban scenes. This suggests that the proposed visual reward mechanism is only a part of the bigger picture. It is possible that the top-down associations theorized by the *Cognitive Perspective*, the evolutionary preference proposed by Ulrich et al. (1991)'s *Psycho-evolutionary Restoration Theory*, and the attention mechanisms proposed by Kaplan (1995;2001)'s *Attention Restoration Theory*, are also contributing to the overall restorative effect of nature scenes. However, despite the complex and extremely difficult problem of disambiguating the unique contributions of each proposed mechanism, the ability to predict responses to scenes (with some error) solely based on an objective measure of power of a limited spatial frequency range is a step forward in understanding both the restorative effects of nature and scene preference in general.

Chapter 7 Experiment 6: Exploring the Relationship Between Power of Spatial Frequencies and Responses to Abstract (Fractal) Images

7.1 Introduction

The five previous experiments presented consistent evidence for a link between the power of specific visual spatial frequencies in scenes and responses of self-reported stress and pleasantness. The evidence presented in the previous experiments has suggested that this relationship appears to predict responses to scenes whether they be natural, urban, or a mixture of both. This recurrence of a strong relationship between the power of visual spatial frequencies with 5 to 7 cycles per degree of visual angle ("restorative" spatial frequencies) across different stimulus types and experimental paradigms has suggested that responses to scenes may be partially driven by a bottom-up visual mechanism that's responding to low-level visual information. After discovering that the power of these "restorative" spatial frequencies could be used to consistently predict responses to different scenes across experiments, a new question arose:

While the previous experiments provided consistent evidence for a link between specific spatial frequencies and self-reported responses to scenes, it was still unclear whether the observed relationship would persist if participants were presented with abstract scenes. This was an important question, since it was unknown if the proposed mechanism was tuned to real-world scenes, or if it was a general bottom-up mechanism that would influence restoration measures regardless of the stimuli. The importance of this distinction for understanding the restorative effects of nature could be argued to be minimal since, if the mechanism is one that evolved as Ulrich et al. (1991)'s *Psycho-evolutionary Restoration Theory* may suggest, it would be logical that reward pathways were specifically tuned to natural/real-world scenes. However, if there was evidence to suggest that the implicated visual spatial frequencies could also predict responses to abstract visual stimuli, it would indicate that similar approaches to those described in this dissertation could be used to also explore general image preference. Exploring the relationship using abstract (i.e., non-nature and non-urban) stimuli would also provide an opportunity to examine the relationship between power of visual-spatial frequency and responses to scenes while controlling for the potential top-down effects of nature and urban scenes. For these reasons, another experiment was conducted in order to determine if the previously observed relationship between power of SF with 5-7 c/d and self-reported pleasantness and stress was also present when participants viewed abstract scenes that were neither natural nor urban.

To accomplish the proposed goals, the current study employed the use of abstract fractal scenes in place of previously used urban and natural scenes. This was done because mathematicians have proposed that fractals share underlying visual properties, such as self-similarity and repetition, with natural and urban scenes (Taylor et al., 2005) and that because of these shared properties, it may be possible to have restorative fractals (Taylor & Sprott, 2008; Taylor et al., 2011). These shared visual properties also meant that the underlying spatial frequencies present in fractals would be similar to those present in natural and urban scenes, without having the categorical label of being natural or urban; making them ideal stimuli for use in this experiment.

H1: The main hypothesis for the current experiment was based on predictions made by the proposed *Reward Restoration Theory* (RRT). In the previous five experiments, it has been argued that the visual reward pathways implicated in RRT are working in a bottom-up fashion, and that their response is tuned to a limited range of spatial frequencies. Furthermore, the evidence for a consistent relationship between responses to scenes and power of SF with 5-7 c/d, regardless of types of scenes used, suggested that the relationship was not content or scene specific. Thus it was hypothesized that abstract fractal scenes that were similar to nature scenes in power of visual spatial frequencies with 5 to 7 c/d would prompt less self-reported stress and greater self-reported pleasantness than those that were different.

H2: It was also hypothesized that if the perceived stressfulness and pleasantness of scenes were truly linked to the described spatial frequencies in a linear fashion as described in the previous experiments, that same linear relationship should also exist for abstract fractal scenes that do not contain nature or urban content.

7.2 Method

7.2.1 Participants. Prior to recruitment, participants were pre-screened using a mass-testing questionnaire. Participants were required to speak and read English fluently (in order to understand instructions), and to have reported that they had normal 20/20 vision. A sample of twenty-four participants (12 male, 12 female) were recruited from the University of Waterloo SONA participant pool to participate in the study in exchange for course credit. No participants reported having any visual disorder or visual problems.

7.2.2 Materials. As in the previous experiment, this experiment used a simple slide-show presentation of various images on a 17 inch LCD monitor with a resolution of 1280 x 1024 pixels. The monitor screen occupied approximately 29 degrees of horizontal field of view. All participants were seated at the same distance from the monitor on a chair that could not be moved. The monitor was approximately 26 inches from participants' eyes.

Images used in this study were collected from publically available photos on flickr (http://www.flickr.com) and Google image search. Images tagged as "3D fractal" by these databases were mass-downloaded, providing a random sample of fractal images that contained depth information. "3D fractals" (i.e., ones made from 3-dimensional shapes such as cubes instead of 2-dimensional shapes such as squares) were used in order to ensure that the abstract images contained depth information similar to photos of real-world objects. This was done to attempt to control for depth information between fractal images and real-world scenes. The images collected were cropped to the dimensions of 900 x 900 pixels (occupying approximately 20 degrees field of view on the monitor) and converted to grayscale using Adobe Photoshop Elements 10. All images were saved in JPEG format, and had their brightness levels and contrast balanced using the "Auto Levels" and "Auto Contrast" options in Adobe Photoshop Elements 10. When displayed during the experiment, images were in their native resolution, such that pixels in the image matched pixels on the display in a 1:1 ratio. The power of visual spatial frequencies with 5 to 7 cycles per degree of visual angle was extracted from the scenes using the same method as in the previous experiments. The power was then used to blindly select a sample of thirty scenes for use in the current experiment. Scenes were selected based on power of spatial frequency such that they covered a wide range in the continuum starting from low (similar to nature) to high (the highest found in the sample of scenes collected). Sample images can be seen in Figure 7.1.

7.2.3 Design. Similar to the previous experiment, a within-subjects design was used where all images were viewed by every participant. A similar presentation method to that which was used in Experiments 4 and 5 was used in the current experiment. Images were presented one at a time in a randomized order. Image presentation order was randomized for every participant in order to randomize any potential order effects.

Also, as in the previous experiment, 10 questions assessing various characteristics of each scene were co-presented with the scenes. Questions were presented one at a time, in random order, and in a random location in a column to the left of the image. This was done to reduce automatic responses due to repetition of questions across images, to provide some level of novelty to keep participants engaged, and to prompt participants to read each question (since they could not predict what question was next). With the inclusion of reverse-coded pairs, and measurement of RT, validity of responses could be assessed.

7.2.4 Procedure. A similar procedure to that used in Experiment 5 was also used in Experiment 6: Individual participants were scheduled to come to the lab using the University of Waterloo's SONA online system. Upon their arrival, participants were greeted by the researcher, briefed on the procedure of the experiment and given an information and consent form to read and sign.

Participants were then seated in front of the computer monitor and provided with a keyboard. They were asked not to adjust the monitor or chair, and to use the keyboard to input their responses to the questions on the screen. Participants were instructed to respond based on their “gut-reaction” and/or the emotion they felt when viewing the abstract fractal scenes.[33]

Participants were then asked if they had any questions and told to inform the researcher once they had completed the study. The researcher then left the room and waited outside the

[33] This instruction was added after the debriefing of pilot participants revealed that the fractal images were so abstract to participants, that they did not know how to interpret them, and thus did not know how they could rate them on pleasantness and stressfulness. The added instruction, telling them to respond using the emotion they felt when looking at the images, allowed participants to subjectively respond to the scenes.

door. Scenes were individually presented on the right side of the monitor until all questions about the scene were answered. Questions were presented on the left side of the screen, using the randomization procedure described earlier. Participants responded to questions by pressing the number on the keyboard corresponding to their response on a scale from 1 (low) to 7 (high). Participants were given the definitions of jaggedness and complexity that were used in the previous experiment to ensure consistency across experiments.

Participants were allowed to go through the experiment at their own pace. Upon completion, participants were debriefed and the purpose of the experiment was explained to them. No participants suspected deception or the true purpose of the experiment.

Figure 7.1 Experiment 6: Sample of fractal images used, ranging from images with low power of SF with 5 to 7 c/d (left) to medium power (middle) to high power (right).

7.3 Results

For analysis purposes, self-reported scores on existing scales of 1 to 7 for measures depicting the same variable on opposite ends of a continuum (e.g., stressful & calming) were combined to create scales ranging from -6 to 6 with the midpoint [0] being neutral and the endpoints representing the max on each scale (e.g., highly calming [-6] and highly stressful [6]). This was done to better represent participant responses on the continuum of the measured variable, rather than analyzing responses for each tail individually.

For the initial analysis, scenes were ordered based on their power of the 5-7 c/d spatial frequency range. Scenes were then grouped into five bins of equal size that represented sequential ranges of power of the 5-7 c/d spatial frequency range. Responses for scenes in each bin were averaged per participant. A repeated-measures ANOVA was used to determine if there were any differences in self-reported pleasantness and stress resulting from changes in the power of the 5-7 c/d spatial frequency range across bins. The analysis revealed a main effect of changes in power of the 5-7 c/d spatial frequency range on both self-reported pleasantness, $F(4,92) = 3.95$, $MSE = 0.44$, $\eta_p^2 = 0.15$, $p < 0.005$ and self-reported stressfulness of scenes, $F(4,92) = 15.9$, $MSE = 0.90$, $\eta_p^2 = 0.40$, $p < 0.001$.

A set of polynomial contrasts was used to determine if the data followed the predicted linear relationship. The analysis revealed that there was a significant linear trend for both self-reported pleasantness, $F(1,23) = 7.9$, $MSE = 0.78$, $\eta_p^2 = 0.26$, $p < 0.05$, and self-reported stressfulness of abstract fractal scenes, $F(1,23) = 29.13$, $MSE = 1.48$, $\eta_p^2 = 0.56$, $p < 0.001$, where self-reported pleasantness decreased and self-reported stressfulness increased as power of the 5-7 c/d spatial frequency range increased. These results replicated the previous findings of

Experiments 1 to 5 using abstract fractal scenes, providing further evidence that perceived pleasantness and stressfulness of scenes may be related to the "restorative" spatial frequency range.

Linear regression analysis was conducted to determine if the quarter root of power of 5-7 c/d spatial frequencies was predictive of mean self-reported pleasantness and stressfulness per scene as it was in the previous experiments. Replicating the pattern of findings in previous experiments, the analysis revealed that (power of 5-7 c/d SF)$^{1/4}$ was a significant predictor of both mean self-reported pleasantness per scene, *standardized* β = -0.57, t(28) = -3.6, $p < 0.001$, and mean self-reported stressfulness per scene, *standardized* β = 0.71, t(28) = 5.4, $p < 0.001$. The (power of 5-7 c/d SF)$^{1/4}$ also explained a significant portion of variance in mean self-reported pleasantness of scenes, R^2 = 0.32, F(1,28) = 13.2, $p < 0.001$, and mean self-reported stressfulness of scenes, R^2 = 0.51, F(1,28) = 29.0, $p < 0.001$. The linear relationship between self-reported stressfulness of scenes and their power of the 5 to 7 c/d spatial frequencies can be seen in Figure 7.2.

Next, as in the previous experiment, it was important to determine if abstract fractal scenes that contained low power of the 5-7 c/d spatial frequency range (like nature scenes) were being perceived calming (i.e., restorative). Self-reported scores for these scenes on the highly calming (-6) to highly stressful (+6) continuum were compared to 0 (neutral) using a one-sampled t-test. The analysis revealed that abstract fractal scenes that had a similar power of the described spatial frequency range to nature scenes were perceived as slightly calming, M= (-1.2), t(23) = -5.3, SE = 0.24, 95% CI [-1.78, -0.78], $p < 0.001$, confirming the prediction that abstract fractal scenes can be perceived as calming if they contain similar visual spatial frequencies as nature scenes.

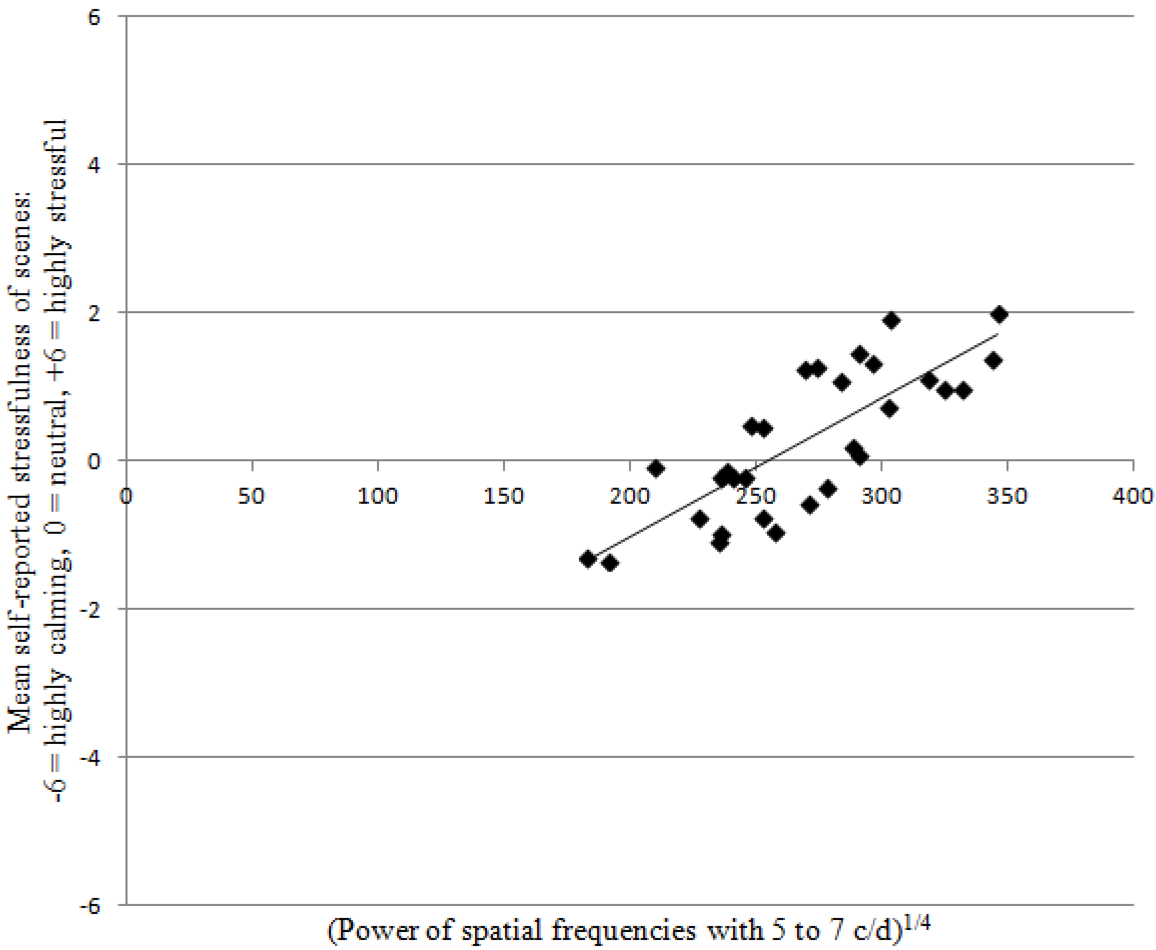

Figure 7.2 Experiment 6: Mean self-reported stressfulness of fractal images with respect to quarter root of the power of spatial frequencies with 5 to 7 cycles per degree of visual angle. Graph demonstrates the linear relationship between power$^{1/4}$ and the self-reported stress/calming response to abstract fractals**.**

7.4 Discussion

The final experiment presented in this dissertation was able to replicate effects found in the previous five experiments using abstract fractal scenes. Evidence was found to suggest that even when individuals are viewing abstract fractal shapes, their feelings of pleasantness and stressfulness appear to be related to the power of spatial frequencies with 5 to 7 cycles per degree of visual angle; a spatial frequency range that that has been shown to predict a myriad of responses to scenes across the five previous studies. Since this relationship was found across all six studies, it is plausible that it plays an important role in determining responses to images and scenes, regardless of the other visual content. It is these findings that suggest that there is a consistent underlying mechanism for all scene and image preference, and potentially restoration responses.[34]

Reward Restoration Theory, and the associated bottom-up reward mechanism previously described by Yue et al. (2007), have been proposed in an attempt to explain a *part* of the underlying mechanism responsible for the restoration response. The proposed underlying mechanism for restoration, which is theorized to include activation of previously discovered reward pathways by Yue et al. (2007), contributed to making accurate hypotheses about how individuals respond to viewing images for the current and previous experiments. This provided consistent support for the notion that such a mechanism may be involved in restoration responses, as proposed by *Reward Restoration Theory*. With this final experiment, it becomes possible to relate the proposed mechanism to parallel research conducted by Taylor et al. (2011) on the restorative properties of fractals. In their work, Taylor et al. (2011) have proposed that it

[34] It is important to note that there was a compression of response range for fractal scenes in Experiment 6 (shown in Figure 7.2) relative to responses to real-world scenes used in previous experiments (Figures 6.2 and 5.2). This is potentially the result of the abstractness of fractals, and participants not knowing how to attribute a valence to such abstract images. This issue was present in pilot testing as noted in the previous footnote within the Methods section

may be possible to have restorative fractals. Their preliminary research using fMRI techniques has implicated greater BOLD response in the same reward systems in the ventral visual pathway described by Yue et al. (2007) when viewing fractals that are perceived as calming and pleasant. When considering this research, the findings of the current experiment become both less surprising and more convincing: If a generalized reward mechanism is partly responsible for restoration, as described in the proposed *Reward Restoration Theory*, then it is understandable that activation of this mechanism should result in (at least small amounts of) restoration, even if it is done via presentation of abstract visual forms such as fractals. The strong linear relationship between power of spatial frequencies with 5 to 7 c/d and responses to fractal scenes suggests that the discussed reward pathways may indeed be tuned to the power of this narrow spatial frequency range, regardless of the visual content (natural, urban, mixed nature/urban, or abstract).

Provided that the relationship between responses and visual spatial frequencies observed in the previous studies remained strong in the current experiment, the results suggest that it may be possible to predict general image preference (and restoration) using the described visual spatial frequency range, rather than just being able to (roughly) predict the restorative response to natural and urban scenes. This finding broadens the scope of all of the results described in this dissertation, given that they are all linked to the underlying predictor (power of spatial frequencies with 5 to 7 degrees of visual angle). Future research exploring the restorative effects of nature, image preference, and even aesthetics of art and photography may benefit from considering the visual reward pathways and visual spatial frequencies that have been discussed.

Given that the results of the current experiment agree with Taylor et al. (2011)'s findings, which suggest that it is possible to have restorative fractals, it is also important to discuss the methods and criteria they used to determine what makes fractals “restorative.” In previous research looking at the potential restorative properties of fractals, Taylor has suggested that nature scenes are restorative because they have a high degree of self-similarity (Taylor, 2006). He further suggests that fractals with a similar amount of self-similarity should also be restorative (Taylor, 2006). To measure this “self-similarity” Taylor et al. (2006, 2008, 2011) suggest calculating the fractal dimension of a scene. Fractal dimension (D) is a parameter that quantifies the scaling relationship between patterns observed at different magnifications: A fractal dimension of 1.0 categorizes a straight line, while a fractal dimension of 2.0 categorizes a filled square (e.g. an image that’s solid black). Images containing solid black lines on a white background have a fractal dimension between 1.0 and 2.0.[35] Taylor et al. (2006, 2008, 2011) claim that the “restorative” fractal dimension which is shared by most natural scenes and “restorative” fractals is 1.3. Fractal dimension is generally calculated using a “box-counting” method, where an image is separated into a grid of square sections and the contents of each section are compared to neighbouring sections using pixel matching techniques (Taylor, 2006).

One of the major limitations to calculating fractal dimension using this method is that is only accurate for two-tone images (i.e., black & white) and gives inaccurate and variable fractal dimensions for grayscale images (such as those used in this experiment) (Li, Du & Sun, 2009). A close inspection of Taylor et al. (2006, 2008, 2011)’s research and sample images indicates that they are aware of this limitation and have used only two-tone images. Further inspection indicates that their calculation of the “restorative” fractal dimension (D = 1.3) of natural scenes is based on traced contours of objects (mainly skylines and tree lines), rather than the content of the scenes.

[35] See Taylor (2006) for a more elaborate explanation of fractal dimension.

Given the significant restriction to two-tone images and contours, it is unclear how well fractal dimension actually categorizes visual information. Unlike spatial frequencies, which are believed to be the building blocks of visual percepts and have been shown to prompt predictable responses in visual pathways (Fintzi & Mahon, 2013; Mahon et al., 2013; Keil, 2008, 2009; Hansen et al., 2012; Tetsuya et al., 2004; Collins, & McMullen, 2005; Karklin & Lewicki, 2008), fractal dimension is both a limited descriptor of visual information, and an unlikely candidate for neural representation. This brings forth the question of why Taylor et al. (2011) found that fractals with a fractal dimension of 1.3 prompted activation of similar visual reward pathways to those associated with scene preference by Yue et al. (2007). To understand this, we must consider the overlap between what is measured by fractal dimension and what is measured by the spatial frequency analyses employed in the present study. Due to the way fractal dimension is calculated via box-counting method, it indirectly represents spatial frequency patterns in images. For example, if we were to imagine three sequential squares with a black circle of equal size in the center. In this example, the white areas represent peaks of the same sinusoidal wave (i.e, spatial frequency) in the image, while the black circles represent the valleys. The box counting method would yield a fractal dimension between 1.0 and 2.0. As in this example, every repetitive structure is inherently tied to an underlying visual spatial frequency, which means that fractal dimension is merely a measure of spatial frequency distributions within images. Knowing this, we can consider the distribution coding model of vision presented in Karklin & Lewicki (2008):

In their model, Karklin & Lewicki (2008) make the claim that higher-order visual areas respond to statistical distributions of spatial frequencies. If we take the distribution coding model into consideration and consider that fractal dimension is linked to distributions of spatial frequencies in the image, it is easier to understand why we may see activation in ventral reward pathways when viewing fractal images with a fractal dimension of 1.3 as Taylor et al. (2011) have shown. Provided that the fractal dimension of 1.3 was extracted from natural images and then fractals were created to have a similar fractal dimension, it is likely that these artificially created images also had very similar spatial frequency distributions to natural scenes. Given the results of the six experiments presented in this thesis implicating spatial frequency in the restoration response to scenes, it is unsurprising that similar spatial frequency distributions to those in nature scenes would prompt a restorative response. That being said, even though fractal dimension appears to also predict which images may promote restoration, it is important to note the benefits of looking at visual spatial frequency information instead of fractal dimension.

While Taylor et al. (2006, 2008, 2011) have been able to demonstrate that fractal images with a fractal dimension of 1.3 may be restorative, they have not been able to demonstrate that such is the case for any other type of image. Furthermore, since only a fractal dimension of 1.3 is believed to be restorative (Taylor et al., 2011), it is unclear if dimension just happens to categorize "nature" perceptually, and thus prompt "nature-like" responses from participants, or if it is activating visual reward mechanisms such as those proposed by *Reward Restoration Theory*. Also, due to the limitations of measuring fractal dimension, where only two-tone images and contours can be used, fractal dimension is not suited for analysis of complex visual scenes with grayscale information such as those used in the present experiment. Unlike fractal dimension, the present experiment demonstrates that the quarter root of the power of spatial frequencies with 5-7 c/d can linearly predict responses to complex grayscale fractal scenes, while the previous five experiments demonstrated that this spatial frequency range can also predict responses to both natural and urban scenes across a variety of restoration measures. These findings, and previous research supporting the notion that the visual system responds to spatial frequencies (Fintzi & Mahon, 2013; Mahon et al., 2013; Keil, 2009), suggest that spatial frequency is a much better predictor of restoration than fractal dimension.[36] Thus, it is recommended that future research exploring the restorative properties of fractal images use spatial frequency analysis rather than fractal dimension.

[36] Some of the benefits of using spatial frequency over fractal dimension are even echoed in Taylor et al.(2011, pp 8)

Chapter 8 General Discussion

The restorative effects of nature have been of great interest to psychologists over the last decade. Research has reliably shown that simply viewing photographs, posters, videos, or even virtual nature, can have a wide variety of beneficial effects on an individual. Some of these effects include improvement in emotional state, reduction in both perceived and physiological stress (Valtchanov & Ellard, 2010), improved cognitive performance (Berman et al., 2008), and even reduced perceptions of pain (Lechtzin et al., 2010). The effects have been demonstrated with such strength and reliability in the literature that they have been recently accepted and incorporated into healthcare facilities (Beukeboom et al., 2012; Lechtzin et al., 2010). At the current time, it could be argued that the restorative effects of exposure to nature have been replicated in so many different settings by different labs around the world that simply demonstrating the effect in an empirical paradigm is no longer novel. For this reason, the current six experiments focused on exploring the mechanism and theory behind the restorative response to nature, so that we may better understand how and why restoration occurs when individuals view natural scenery. During this endeavour, predictions of existing theories on restoration, including the *Cognitive Perspective*, *Attention Restoration Theory* (Kaplan, 1995; 2001) and *Psycho-evolutionary Restoration Theory* (Ulrich et al., 1991), were tested and their shortcomings in ability to predict the restorative response was illustrated. An underlying mechanism and theoretical expansion to existing theories is proposed, in the form of *Reward Restoration Theory* (RRT), to improve upon previously inadequate definitions of the "automatic affective response" in *Psycho-evolutionary Restoration Theory*, and "soft fascination" in *Attention Restoration Theory*. Most of the predictions made by the expanded framework were tested and validated throughout the six experiments. Unfortunately, not all of the predictions made by RRT could be directly tested due to limited time, resources, and lack of access to neuroimaging equipment.

8.1 Limitations of Existing Theories on Restoration

As described in Chapter 1, the *Cognitive Perspective*, *Attention Restoration Theory*, and *Psycho-evolutionary Restoration Theory* attempt to explain why natural environments are restorative. The *Cognitive Perspective* argues a top-down approach to restoration, suggesting that it is the result of conditioning: The *Cognitive Perspective* encompasses the idea that in urban cities individuals have positive associations with nature (e.g., vacationing, relaxation, break from work, etc) and negative associations with urban settings (e.g., stress, pollution, work, etc) (Felsten, 2009, van den Berg et al., 2007; Gulwadi, 2006, Frerichs, 2004; Grahn & Stigsdotter, 2003).. However, with no direct experimental support to validate these claims, the *Cognitive Perspective* has remained (mostly) ignored in the literature relative to *Attention Restoration Theory* and *Psycho-evolutionary Restoration Theory*.

Unlike the *Cognitive Perspective*, which suggests that restoration is a result of conditioned positive associations with nature, *Attention Restoration Theory* (ART) proposes that one of the main requirements for restoration is “fascination.”[37] In his work, Kaplan has defined “fascination” as a scene “containing patterns that hold one’s attention effortlessly” (Kaplan, 2001, pp. 482). With respect to the restorative properties of nature, Kaplan (1995, 2001) refers to what he calls “soft fascination,” where involuntary attention is captured *modestly* by the environment in a pleasant way; allowing directed-attention resources to recover. Many examples

[37] Kaplan (2001, pp 482) also states that for restoration to occur, the environment should be physically or conceptually distinct from everyday surroundings, be coherent, and be compatible with what one wants to do. Any novel urban or natural environment that does not depict disorder or threat satisfies these criteria for restoration. However, abstract fractal images do not (since they are not coherent, nor are they compatible with going on vacation or relaxing).

are given as to what may be “fascinating” in natural scenes, including allusions to trees and grass gently swaying with the wind, animal life, sunsets, and other events in nature that individuals could intuitively identify as being “intriguing,” “interesting,” or “pleasant” to witness (Kaplan 1995, 2001). However, the broad definition of what constitutes “soft fascination,” and the lack of objectivity of it, has made it difficult to use *Attention Restoration Theory* to predict the level of restoration that would be promoted by any given environment a priori.

Ulrich et al. (1991)’s *Psycho-evolutionary Restoration Theory* (PERT) shares a similar limitation to *Attention Restoration Theory* in terms of predictive power. *Psycho-evolutionary Restoration Theory* claims that individuals experience an “automatic affective response” to environments, based on evolved preferences for environments that facilitate survival, which triggers a cascade of physiological and cognitive changes (Ulrich et al., 1991). It is argued that non-threatening natural environments that would facilitate survival (by being rich in resources such as water and vegetation) would promote restoration while scenes that contained threats (such as predators, scarcity of resources, or other dangers) would not (Ulrich et al., 1991). Unfortunately, the mechanism responsible for the described “automatic affective response” is not described. Only a basic mechanism is mentioned, stating that evolution favored individuals who preferred content that promoted well-being and/or survival (Ulrich et al., 1991), suggesting that we may have sensory (or neural) systems that are tuned to information in our environments that would allow us to assess the capacity of an environment for promoting survival. However, without an elaborated description of this mechanism, PERT is also unable to predict the level of restoration that would be promoted by any given environment a priori.

The limitations of all three theories were first exemplified in Experiment 1. Unlike the proposed *Reward Restoration Theory* (RRT), none of the three existing theories directly predicted that restoration would be a function of the amount of visual spatial frequencies in the images. Meanwhile, Experiments 2 and 3 showed that top-down influences proposed by the *Cognitive Perspective* did not appear to play a major role in the restorative response to scenes, while also demonstrating a pattern of data that could not be predicted by either ART or PERT. Continuing this trend, Experiment 4 demonstrated a linear relationship between the ratio of natural to urban content in the visual field and the restorative response; a finding that could not be predicted using the existing theories on restoration (while still being congruent with claims made by RRT). Finally, Experiments 5 and 6 demonstrated that restoration could be promoted by both urban and abstract fractal scenes; this was consistent with RRT but contrary to what one may predict based on existing theories of restoration.

Across the six experiments presented in this dissertation, there were many results that were consistent with existing theories on restoration. These results were presented alongside results that were not directly predicted by these theories, illustrating the need for an expanded theoretical framework such as the proposed *Reward Restoration Theory*. It is important to note that the results presented in the six experiments could be viewed as "consistent" with *Attention Restoration Theory* and Psycho-evolutionary Theory,[38] if the mechanism behind "soft fascination" and the "automatic affective response" is defined to be the same or similar to the one proposed by RRT.

8.2 Contributions of Reward Restoration Theory

Reward Restoration Theory (RRT) is proposed as an expansion to both *Attention Restoration Theory* (ART) and *Psycho-evolutionary Restoration Theory* (PERT), which suggests

[38] This only applies to Experiments 1 to 5. Experiment 6 would only be consistent with PERT since ART requires the extra criteria of "coherency" (extent) and "compatibility" for restoration to occur (Kaplan, 2001).

a plausible biological mechanism for "soft fascination" in ART and the "automatic affective response" in PERT. As outlined in Chapter 1, the underlying biological mechanism proposed by RRT is based on existing neuroimaging research by Yue et al. (2007) and Taylor et al. (2011) implicating greater activation in the ventral visual reward pathways when preferred scenes are viewed. In this dissertation it is argued that this is a logical candidate for an underlying mechanism given that both ART and PERT propose similar bottom-up responses and share similar grounding in evolutionary theory, sharing the assumption that sensory and cognitive systems evolved in natural environments (and are thus specialized at processing them) (Ulrich et al., 1991; Kaplan 1995, 2001). If the evolutionary background of existing theories is considered, it is logical that there would be a reward pathway which offered greater reward to motivate preference for environments that would promote well-being and survival (Ulrich et al., 1991).

However, the potential evolutionary origin of this reward pathway is perhaps less important than its function in guiding (and/or potentially motivating) general preference for images and environments. Opioid reward systems, such as those in the ventral visual pathway, have been linked to regulation of pain, stress, and emotion (Merrer et al., 2009). Given that all of these are also affected by viewing natural scenes (Valtchanov et al., 2010; Lechtzin et al., 2010), the visual reward pathway is also a functional candidate for the underlying biological mechanism for the restoration response.

Based on the empirical research surrounding the ventral visual reward pathway (Yue et al., 2007), and the evolutionary links of such a mechanism inferred from Ulrich et al., (1991) and Kaplan (1995, 2001), *Reward Restoration Theory* was formulated. During its inception, the empirical and theoretical basis for RRT was used to formulate its six major postulates (described in Chapter 1). Five of these six claims were explored and supported in the presented research:

In *Reward Restoration Theory*, it was postulated that the restoration response was a result of bottom-up (stimulus driven) activation of visual reward pathways. While direct activation of visual reward pathways could not be measured in the absence of neuroimaging, consistent behavioural evidence was found in all six experiments to suggest that participants' responses to scenes were indeed stimulus-driven. The bottom-up nature of participants' responses was especially evident in Experiment 3, which employed direct semantic priming methods to attempt to force top-down effects.

Reward Restoration Theory also proposed that since the implicated visual reward pathway was in the ventral visual stream, which shows preference for processing mid-to-high visual spatial frequencies (Fintzi & Mahon, 2013; Mahon, Kumar & Almeida, 2013), there should be a finite number of spatial frequencies in that range that are associated with scene preference and the restoration response (i.e., demonstrating tuning). The first evidence for this was provided in Experiment 4, where a distinct relationship was found between the power of spatial frequencies with 5 to 7 cycles per degree of visual angle (c/d), and responses to scenes. A meta-analysis of the previous three experiments, and conception of two new experiments, confirmed that the observed relationship was highly reliable.[39]

Continuing this trend, the relationship between power of SF with 5 to 7 c/d and restoration responses followed a shape congruent with neural tuning in this pathway (i.e., an

[39] Cross-experiment analysis revealed that restoration responses were relative to the power of spatial frequencies with 5 to 7 cycles per degree of visual angle, and not the content in those frequencies: Images in Experiments 1 and 2 occupied a different amount of visual angle than images presented in Experiments 3 to 6. The relationship was present for power of SF per visual angle rather than power of SF per image. The importance of power versus content in that SF range was confirmed by demonstrating that the relationship occurred across different stimuli types (nature, urban, mixed nature/urban, fractal).

“inverted U” shape as shown in Figure 5.2)[40] It was expected that the reward pathway would be tuned to a spatial frequency range that would help it identify environments beneficial to survival and well-being. Recent functional neuroimaging findings by Fintzi & Mahon (2013), which have demonstrated that the ventral visual pathway shows maximal response (i.e., “tuning”) to spatial frequencies with 4.76 to 9.14 c/d, help validate that the “restorative” (5 to 7 c/d) spatial frequency range is indeed being processed by the ventral visual pathway. Provided that this relationship was present in all six experiments, it also served to support the prediction made by RRT that restoration responses to scenes should be along a gradient relative to the amount of "rewarding" spatial frequencies.

Experiments 5 and 6 expanded on the previous point by demonstrating that even images of urban scenes and abstract fractals could be perceived as restorative (i.e., calming and pleasant) when they contained similar power of spatial frequencies with 5 to 7 c/d as non-threatening nature scenes. This positive response to "natural" visual spatial frequency patterns presented in non-natural environments (urban and fractal scenes) suggested that RRT's proposal (similar to that made by ART and PERT) that the (evolved) reward pathway is tuned to visual information found in non-threatening natural scenes was also supported.

Furthermore, the finding that even urban and abstract fractal images could be perceived as restorative also supported the claim by RRT stating that stimulation of the proposed reward pathway (via presence of the desired power of the implicated spatial frequency range) was sufficient to promote (partial) restoration. Based on the consistent support for the mechanism of restoration proposed by *Reward Restoration Theory*, it is possible to see that attributing the

[40] Since the relationship was quartic, the quarter-root transform of power of SF with 5-7 c/d was used during data analysis to allow for linear trends, regression and ANOVA to be performed.

"automatic affective response" (*Psycho-evolutionary Restoration Theory*, Ulrich et al., 1991) and "soft fascination" (*Attention Restoration Theory*, Kaplan, 1995, 2001) to such a mechanism would help expand the existing theoretical framework on restoration. By attributing the mechanism behind "soft fascination," in Kaplan (1995, 2001)'s *Attention Restoration Theory* to a predictable response to the described spatial frequency range, it becomes possible to predict which scenes, images, and/or environments should promote improvements in attention and cognitive performance. This potential benefit is highlighted by the meta-analysis of Experiments 1 and 2 which demonstrated that the power of the 5-7 c/d spatial frequency range was predictive of previously used measures of attention (eye-movement patterns and blink rates) (Berto et al., 2008; Siegle, Ichikawa & Steinhauer, 2008). The benefits of considering the proposed mechanism to *Psycho-evolutionary Restoration Theory* are also similar to those for ART. Where PERT could be previously criticized for being unable to predict which environments within the same conceptual label (e.g. urban, nature, abstract) would promote a greater positive/pleasant automatic affective response, such criticisms could be addressed (and predictive power increased) by simply considering the proposed mechanism and the visual spatial frequencies in the scene.

It is here that it should be clarified that *Reward Restoration Theory* is meant to augment and expand existing theories on restoration. By themselves, the proposed mechanism and theory are not able to fully explain cognitive and physiological changes resulting from exposure to restorative scenes. However, when combined with *Attention Restoration Theory*, and *Psycho-evolutionary Restoration Theory*, it becomes possible to better predict and understand the restorative effects of nature than was possible previously. For this reason, it is argued that the expanded theoretical framework is more valuable for understanding how and why restoration occurs than either *Attention Restoration Theory* or *Psycho-evolutionary Restoration Theory* alone.

8.3 Limitations of the Current Research and Proposed Future Directions

The research presented in this dissertation attempts to expand the existing theoretical framework on the restorative effects of nature, and arguably does so, but it also suffers from limitations imposed by both the limited scope and resources allotted for a dissertation. Existing theories on the restorative effects of nature have been both tested and refined over decades of collaborative empirical exploration across the globe, while the proposed *Reward Restoration Theory* is mentioned and tested for the first time in the research presented here: *Reward Restoration Theory* is in its infancy and has significant room left to grow and be refined.

Firstly, the research described in this dissertation has used photographs and images of many different scenes, and it has been demonstrated that responses to these images follow a predictable pattern based on the power of a small visual spatial frequency range. However, while the findings are highly relevant to how individuals respond to viewing photographs of scenes (and maybe even art), they do not fully speak to how individuals respond to immersive experiences such as real or virtual walks in the park (or even videos of nature). In these cases, the visual information provided to the proposed reward pathways is constantly changing with the individual's perspective. It is likely (possible) that "affective responses" to constantly changing visual information from immersive environments may be based on spatiotemporal averaging of visual spatial frequencies. It is also possible that in such cases there would be other mechanisms involved in restoration, including those proposed by Kaplan (1995, 2001)'s *Attention Restoration Theory* suggesting that being physically away from stressors may help restoration. Whether or not such is the case is something that must be explored in future experiments. Without such experiments, the generalizability of the described findings is limited to explaining responses to still images and photographs.

Secondly, *Reward Restoration Theory* is proposed as being only part of the overall restoration mechanism, which attempts to explain the mechanism behind the "automatic affective response" of Psycho-evolutionary Theory and "soft fascination" of *Attention Restoration Theory*. The overall restoration response to environments, photographs, and videos appears to be complex and difficult to predict. The presented research has pioneered findings relating visual spatial frequency to restoration responses, allowing for significantly better predictions of restoration, but these findings cannot explain the entirety of the response. The restoration response is complex and multi-faceted. There are possibly top-down influences as well as bottom-up mechanisms involved, and while we are one step further in understanding the source of the restorative response, there is still much that is unknown. In order to better understand the interplay between top-down and bottom-up mechanisms in the restoration response, future research needs to include the use of thought probes in order to explore the associations and top-down cognitive events that may be contributing to participants' overall affective responses to scenes. Without the use of thought probes in the current research, it is difficult to determine how top-down cognitive events may have been contributing to the measured restoration response.

Thirdly, while the proposed *Reward Restoration Theory* draws heavily on the existing theoretical framework of *Psycho-evolutionary Restoration Theory*, and *Attention Restoration Theory*, the research described in this dissertation does not explicitly test one of the major predictions made by this framework; the present research does not test whether changes in the power of the spatial frequency range implicated in restoration can differentiate between natural environments that would be beneficial to survival and well-being (e.g., those containing water, lush vegetation, etc) and natural environments that would not (e.g., deserts, rocky terrain, winter scenes). If restoration is indeed tied to rewarding an evolutionary preference for natural environments that facilitate survival, then it should be possible to distinguish such scenes solely based on the power of implicated spatial frequency range. This question is one of great importance in determining the validity of an evolutionary theoretical framework, and should be explored in future research.

Fourthly, the research presented in this dissertation explored the relationship between responses to scenes and their power spectra, but it did not explore how responses to scenes may change (or may be predicted by) the phase spectra of images. It is possible that the restoration response to visual scenes may also be sensitive to low level visual information contained in their phase spectra. While the research in this dissertation presents empirical evidence implicating the power spectra of visual scenes in the restoration response, it does not offer insights into the role of the phase spectra (if any) in restoration. Future research that explores how responses to scenes change with respect to patterns in the phase spectrum is required in order to fully understand the effects of low-level visual properties of scenes on restoration: For example, an experiment which uses nature scenes that have had their phase spectra swapped with those of urban scenes (and vice versa) could help disambiguate the contribution of the spatial frequency power spectrum versus its phase spectrum to restorative effects of nature.

Lastly, the present research experiments tested only five of six postulates of *Reward Restoration Theory*. Perhaps one of the most important questions left, in light of the consistent behavioural results, is whether or not the proposed neural reward pathway[41] in the ventral visual system is tuned to the "restorative" spatial frequency range[42] as proposed by *Reward Restoration Theory* (RRT). Given that preferred scenes (and fractals), which have also been linked to the "restorative" spatial frequency range in the present research, have been previously shown to prompt greater activation in the proposed pathway (Yue et al., 2007, Taylor et al., 2011), it seems likely that the activation gradient of the pathway would be related to the power of the "restorative" spatial frequency range. In light of recent research by Fintzi & Mahon (2013), which has demonstrated tuning of the ventral visual pathway to spatial frequencies with 4.76 to 9.14 c/d, it is possible to infer that the ventral visual pathway would also be tuned to the sub-range of spatial frequencies with 5 to 7 c/d discussed in this thesis. Given this complete overlap of spatial frequency ranges between functional neuroimaging research on the ventral visual pathway (Fintzi & Mahon, 2013) and behavioural research presented in this thesis, it can be predicted that reward systems in the ventral visual pathway would show differential response to power of spatial frequencies of 5 to 7 c/d as suggested by RRT.

8.4 Why spatial frequencies with 5 to 7 c/d?

One question that comes to mind upon reading this dissertation is "what's so special about spatial frequencies with 5 to 7 c/d?" Unfortunately, there is no simple answer to this question. In this dissertation, six experiments have reliably demonstrated that restoration response to scenes (as measured by blink-rates, eye-movements, and self-reported affect) appears to be somehow linked to spatial frequencies with 5 to 7 c/d, a range of spatial frequencies that

[41] The reward pathway, as described in Chapter 1, includes preferential activation of μ-opioid rich areas in the parahippocampal cortex and conventional reward systems involving ventral striatum when preferred scenes are viewed.

[42] I.e., spatial frequencies with 5 to 7 cycles per degree of visual angle linked to the restorative response in the current research.

prompts maximal response by the ventral visual pathway (Fintzi & Mahon, 2013). In this dissertation, it has been predicted that reward systems in the ventral visual pathway (Yue et al., 2007) may be responding to these spatial frequencies, which would be consistent with the observed restoration response. If we consider research by Collin & McMullen (2005), Mahon et al. (2013), and Fintzi & Mahon (2013), it becomes possible to hypothesize why this may be the case.

Previous research on how mid-to-high spatial frequencies are processed by the visual system suggests that such spatial frequencies are important for object categorization and determining identity of objects (Collin & McMullen, 2005; Mahon et al., 2013; Fintzi & Mahon, 2013). Specifically, Fintzi & Mahon (2013) found that images composed of spatial frequencies around 5 c/d were most accurately categorized[43], indicating that spatial frequencies around 5 c/d carry important object identity information. Knowing this, it is possible to hypothesize as to why spatial frequencies with 5 to 7 c/d may predict the restoration response:

First we must consider the proposition made by *Psycho-evolutionary Restoration Theory* (Ulrich et al., 1991) (and the newly proposed *Reward Restoration Theory*), stating that since humans evolved in a natural setting, they have neural/biological mechanisms for determining which environments are beneficial to survival and well being. If such is the case, then it is logical that the spatial frequency range associated with restoration would carry visual information required for accurate scene categorization. If there was an evolved neural mechanism tuned to this information, it would be possible to categorize scenes as being beneficial to survival and well being. The question of why low power of this spatial frequency range is preferred, as demonstrated by the current research, can also be understood using this logic: It is possible that

[43] Proportion categorized correctly was approximately 95% (Fintzi & Mahon, 2013).

natural scenes that were evolutionarily beneficial to well-being and survival can be readily categorized by low power of spatial frequencies with 5 to 7 c/d. Categorization based on the power of spatial frequencies is a definite possibility given that research by Torralba & Oliva (2003,2006) has suggested that it is possible to categorize streets versus beaches and forests versus cities solely based on the power spectrum. Research by Koch et al. (2010) has also shown similar findings which suggest that it is possible to differentiate between visual art, comics, and photographs using the power spectrum of images. Lastly, research by Joubert et al. (2009) has also shown that the power of spectrum of images is important for accurate image categorization by humans. Given that such a categorization technique would be relatively simple on a neural level (Karklin & Lewicki, 2008), and that research has implicated the power spectrum in scene categorization (Torralba & Oliva, 2003; Joubert et al., 2009) it is a possible explanation. Furthermore, due to the simplicity of such a categorization criteria (i.e., low versus high power of 5-7 c/d), it is also logical that such a mechanism would be readily fooled by urban scenes and fractal images that featured no resources (such as vegetation or water) but still fit within the categorical power of spatial frequencies with 5 to 7 c/d. This is a possibility that should be explored in future research.

8.5 Concluding Comments

The present research has extended the existing theoretical framework and our understanding of the restorative effects of nature by demonstrating limitations of existing theories and providing empirical results to support the newly proposed *Reward Restoration Theory*. In doing so, a new and objective method for predicting restoration responses (i.e., those of pleasantness and stress) to visual scenes has also been provided. It has been demonstrated that it is possible to predict (with some error) perceived pleasantness and stressfulness of images which vary greatly in content, simply by considering their visual spatial frequencies. This finding has provided encouraging support for hypotheses made by the newly proposed *Reward Restoration Theory* suggesting that a neural mechanism previously associated with scene preference by Yue et al. (2007) could play a significant role in the previously documented restorative effects of nature (Valtchanov & Ellard, 2010; Berman et al., 2008; Ulrich et al., 1991). Thus, the present research has suggested a plausible core mechanism behind the proposed "automatic affective response" in *Psycho-evolutionary Restoration Theory* (Ulrich et al., 1991) and "soft fascination" in *Attention Restoration Theory* (Kaplan, 1995, 2001). Previously, the concepts of the "automatic affective response" and "soft fascination" to scenes were both vaguely defined and difficult to validate empirically. However, when the common neural mechanism proposed by *Reward Restoration Theory* is considered to be behind these responses, it becomes possible to make strong empirical predictions about how individuals should respond to viewing a variety of scenes and images.

Appendix A: Experiment 1 & 2 Image Scrambling Techniques

In order to partially scramble low-level visual information in the images used in Experiments 1 and 2, the Fourier transform of each image was computed. The Fourier transform provided a 2-dimensional array of complex numbers encapsulating the vertical and horizontal spatial frequencies present in the image. From the Fourier transform, the phase and amplitude of each (horizontal and vertical) spatial frequency were computed.

To create the "1-dimensional phase scrambled" versions of the images used in Experiments 1 and 2, the phase of the vertical spatial frequencies was scrambled and the Fourier transform was then inverted to recreate the partially scrambled image. This particular scrambling technique was chosen because it eliminated all visual information regarding content while keeping the relative luminance of the scene intact. This was important since the phase scrambled images were used as a baseline for eye-tracking data, and fixations have been previously shown to be influenced by luminance (Loftus, 1985; Henderson, 2013). In Figure A below showing examples of a 2-D phase scrambled version versus a 1-D horizontal phase scrambled version, it can be clearly seen that the 1-D vertical phase scrambled version preserved more of the scene luminance while the others did not.

Similar to how the "1-D phase scrambled" versions were created, the "1-D amplitude scrambled" versions of the images were created by computing the Fourier transform of the images, scrambling the amplitude of the vertical spatial frequencies in the scene, and inverting the Fourier transform. All three versions of amplitude scrambling shown in Figure A were considered (2D horizontal and vertical, 1D horizontal only, 1D vertical only). The purpose of including an "amplitude scrambled" scene was to see how image partial image degradation of the amplitude (power) spectrum would influences responses to scenes. The 1-D vertical amplitude scrambled versions were used over the other two, since (as seen in Figure A) the 2D amplitude scrambled versions looked like random noise and contained no content or luminance information, making responses to them uninformative. Similarly, the 1-D horizontal amplitude versions greatly degraded content and luminance information beyond recognition, also making responses them uninformative. Only the 1-D vertical amplitude scrambled versions contained some recognizable components of the original visual information. This can be clearly seen in Figure A below.

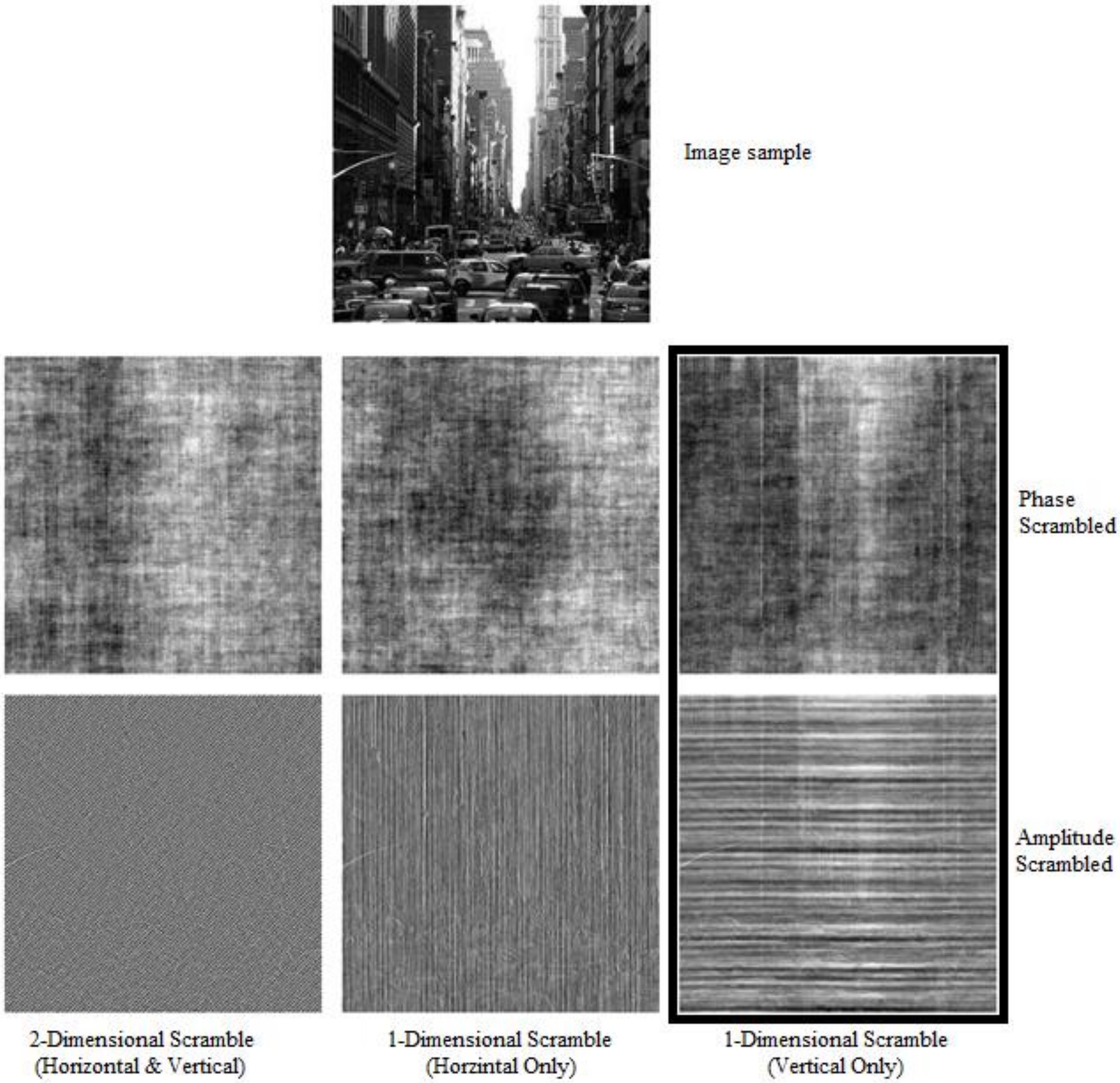

Figure A: Samples of different forms of image scrambling considered in Experiments 1 and 2. 1-D scrambling of the phase of vertical spatial frequencies was used to preserve image luminance while removing image content. Similarly, 1-D scrambling of the amplitude of vertical spatial frequencies was used to preserve some recognizable image content while degrading the image.

Appendix B: Sample python code

Sample python code for creating altered versions images in Experiments 1 and 2

```
"""This is a simple script to create altered versions of a 900x900 grayscale image (i.e., "orig.jpg")
such as those seen in Experiments 1 and 2.
This source code is not to be replicated without explicit permission from the author, Deltcho
Valtchanov. Copyright 2013"""

#download python 2.7 from http://www.python.org/
import numpy as np #download numpy and scipy from http://www.scipy.org/
import scipy, scipy.ndimage
import Image # requires python image library from: http://www.pythonware.com/products/pil/
import random

#import grayscale images and convert to array for processing.
image = Image.open('orig.jpg') #any 900x900 grayscale image can be used; place image in the
same folder as the script and name it to orig.jpg
x = image.convert('L') #takes pixel values of grayscale image

image2 = Image.open('orig.jpg')
xrnd = image2.convert('L') #a clone array is created for later randomization.

fftx = np.fft.fft2(x) #computes 2D fourier transform of original image.
fftx2 = np.fft.fft2(xrnd) #computes 2D fourier transform of clone

absx = np.abs(fftx) #computes amplitude of component frequencies
phase = np.angle(fftx) #computes phase
phase_complex = np.cos(phase) + 1J*np.sin(phase) #converts phase into complex number
which can be recombined with amplitude (See section 1.6.1 in thesis for more info)

Scrambling_Method = 'vertical' #specify how to shuffle Fourier array for altered images:
'vertical' or 'horizontal' or 'full'

if Scrambling_Method == 'horizontal' or Scrambling_Method == 'full':
   for i in range(900):
      random.shuffle(fftx2[i]) #shuffles horizontally
if Scrambling_Method == 'vertical' or Scrambling_Method == 'full':
   random.shuffle(fftx2) #1d shuffle of Fourier transform vertically

#compute amplitude and phase of shuffled array
absx2 = np.abs(fftx2)
phase2 = np.angle(fftx2)
```

```
phase_complex2 = np.cos(phase2) + 1J*np.sin(phase2)

#recombine amplitude with phase complex to create the fourier transform
y = absx*phase_complex #recreates original Fourier transform from components
y2 = np.average(absx)*phase_complex #whitens image/flattens amplitude spectrum
y3 = absx*phase_complex2 #creates phase scrambled image by combining phase of
unscrambled image + phase of scrambled array
y4 = absx2*phase_complex #creates amplitude scrambled image by combining phase of
unscrambled image + amplitude of scrambled array

#invert FFT to get back pixel values
xp = np.fft.ifft2(y)
xp2 = np.fft.ifft2(y2)
xp3 = np.fft.ifft2(y3)
xp4 = np.fft.ifft2(y4)

#take only real numbers of iFFT since pixels are real data points.
xp = np.real(xp) #original image
xp2 = np.real(xp2) #whitened
xp3 = np.real(xp3) #phase scrambled
xp4 = np.real(xp4) #amplitude scrambled

#save pixel data into a jpg image
scipy.misc.imsave('original_recreated.jpg', xp)
scipy.misc.imsave('whitened.jpg', xp2)
scipy.misc.imsave('phase_scrambled.jpg', xp3)
scipy.misc.imsave('amplitude_scrambled.jpg', xp4)
```

Sample code for calculating Fourier transform of images for analysis purposes:

```
""" This source code is not to be replicated without explicit permission from the author, Deltcho
Valtchanov. Copyright 2013.

This program takes the input image and outputs a tab-separated file containing the power of all
the frequencies in the image:

The image must be 900x900 pixels in size and grayscale for accurate calculations!

Output per line is: image name, power, spatial frequency in # of cycles per image (c/i).
The number of cycles per image must be converted manually to cycles per degree of visual
angle.

For the purposes of the dissertation research, 81-140 c/i = 5-7 c/d:
The bins used are 0-20 c/i = 1 c/d; 21-40 c/i = 2 c/d; 41-60 c/i = 3 c/d; 61-80 c/i = 4 c/d; 81-100
c/i = 5 c/d; 101-120 c/i = 6 c/d; 121 - 140 c/i = 7 c/d

This script can go through a large list of images if specified: Use pivot tables in excel to sort
output by image name"""

#download python 2.7 from http://www.python.org/
import numpy as np #download numpy and scipy from http://www.scipy.org/
import scipy, scipy.stats, scipy.ndimage
import Image #requires python image library from: http://www.pythonware.com/products/pil/
import random
from scipy import fftpack


def getAveragePower(shiftedFFT = [0,0], radius_max = 450, radius_min = 1, binsize = 1, centerx
= 450, centery = 450, Given2DPower = False):
  """Helper function: Takes in a centered 2D FFT and returns a 1D power spectrum density
array by radially averaging power"""

  power_1D = []
  power_1D_bin1 = []
  scratch_values = {}
  index = []

  for r in range(radius_max):#make a dictionary for each radius entry that has an empty list
    scratch_values[r+radius_min] = []
    index.append(r+radius_min)
```

```
    if Given2DPower == True: #loops through centered array (has 0,0 at center of array), and
adds each power to a dictionary based on radial distance from center.
        for row in range(len(shiftedFFT)):
            for column in range(len(shiftedFFT[0])):
                radius = np.sqrt(float(column-centerx)**2.0 + float(row-centery)**2.0)
                if int(radius) in scratch_values:
                    scratch_values[int(radius)].append(shiftedFFT[row][column])
    else:
        for row in range(len(shiftedFFT)):
            for column in range(len(shiftedFFT[0])):
                radius = np.sqrt(float(column-centerx)**2.0 + float(row-centery)**2.0)
                if int(radius) in scratch_values:
                    scratch_values[int(radius)].append((np.abs(shiftedFFT[row][column]))**2.0)#group
all items of similar radius into same dictionary.

    for item in index:
        power_1D_bin1.append(np.average(scratch_values[item]))

    if binsize > 1: #if binsize > 1, bin data according to size of bins. E.g.
        b = 0
        for i in range(len(power_1D_bin1)):
            if b <= 0:
                power_1D.append(np.average(power_1D_bin1[i:(i+binsize)]))
                b = binsize
            b -= 1
    else:
        power_1D = power_1D_bin1
    return power_1D

images = ['orig.jpg'] #specify list of images to be analyzed here.

image_data = []
print 'Creating power spectrum for each image, this may take a while...'

image_names = []
image_transforms = []

for i in range(len(images)): #loops through list of images specified
    if images[i] not in image_names: #if image has not been already analyzed...
        image_names.append(images[i])
        image = Image.open(images[i])
        image = image.convert('L')
        img = np.asarray(image)
```

```
        F1 = fftpack.fft2(img) #calculates 2 dimensional Fourier transform of current image:
http://docs.scipy.org/doc/numpy/reference/generated/numpy.fft.fft2.html
        F2 = fftpack.fftshift( F1 ) #centers Fourier transform:
http://docs.scipy.org/doc/numpy/reference/generated/numpy.fft.fftshift.html
        psd1D = getAveragePower(shiftedFFT = F2, Given2DPower = False) #Calculates radial
averaged power spectrum from FFT. See function code above to see how it works. It is as
described in the dissertation.
        psd2D = (np.abs(F2))**2.0 #calculate 2D power spectrum
        image_transforms.append(psd1D) #stores the 1D power spectrums in an array.
        print 'done', images[i]


for i in range(len(images)):
    if images[i] in image_names:
        index = image_names.index(images[i])
        image_data.append([images[i],image_transforms[index][0:450]])#outputs frequencies up
to Nyquist frequency

power_per_freq = file('freqs_per_image.xls','w') #output file
for x in range(len(image_data[0][1])):
    sf = []
    for img in range(len(images)):
        sf.append(image_data[img][1][x])
        power_info = ('%s\t%f\t%f\n') % (image_data[img][0],image_data[img][1][x],(x+1)) #output
per line is: image name, power, spatial freq in # of cycles per image
        power_per_freq.write(power_info)

power_per_freq.flush()
power_per_freq.close()

print 'Done analysis, check data file.'
```

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