

Differentiating Visual Search Efficiencies for Symmetry Type and Texture Regularity

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ABSTRACT

Symmetry is believed to be a fundamental gestalt that aides in our day-to-day ability to interact with the visual world. The goal of this thesis was to investigate the differential processing of types of symmetry when embedded in texture or when viewed as individual objects. Across four experiments, I used the behavioural paradigm of the visual search task to measure processing efficiency across types of symmetry and texture regularity. I used stimuli called “wallpaper groups” which allowed for manipulations of symmetry type while holding constant low and mid-level visual cues. My results indicated that reflection symmetry was processed more efficiently than rotation symmetry and when these symmetries are embedded in a regular texture, they are processed more efficiently than not. The results of this research extend previous findings across behavioural psychology and visual neuroscience.

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PREFACE

Chapter 2 is a manuscript which is being submitted to Journal of Vision, by Rachel Moreau, Nihan Alp, Alasdair DF Clarke, Erez Freud and Peter J. Kohler entitled “Visual search efficiency is modulated by symmetry type and texture regularity”. The author of the current thesis is the first author of this work whose contributions include the development of the experimental design, data collection and analysis, and drafting and editing of the manuscript. The second and third author contributed to development of experimental stimuli and editing of the manuscript. The last two authors developed the study concept, contributed to study designs, and edited the manuscript.

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Chapter 1:
GENERAL INTRODUCTION

1.1 Symmetry and Texture Perception

Every day our experience of the world is facilitated by our perception of wavelengths of radiation within the visible light spectrum. Our brains interpret these wavelengths to generate a rich experience of colour, shape, and meaning which we call vision. Our understanding of this process is always changing as scientists explore the mysteries of our visual experience through the fields of neuroscience, behavioural psychology, computer science, and biology. One sentiment which extends across all fields is that while the phenomenological experience of vision may seem effortless to the average person, the process by which the brain generates vision is very complex. This fact has been foundational to perception research and early research proposed that the task of vision must be simplified in some way. Seminal studies posited a set of fundamental gestalts which provide structural limitations on how visual stimuli are interpreted (Wertheimer, 1923). These gestalts help simplify vision by constraining the possible interpretations our visual system may have for incoming signals from the world. This helps to reduce the number of possibilities for stimuli which may otherwise be ambiguous. In this thesis, we will investigate how one of these fundamental gestalts; symmetry, influences the perception.

Gestalt theory suggests that due to the complexity of the world around us, the visual system must have some way of reducing the oncoming information into more manageable patterns for our brain to interpret. These patterns involve what is often referred to as “mid-level” perception; that is, the information in the brain which is more complex than the simple wavelengths of light picked up by the retina, but less complex than semantic object or scene perception. An example of a mid-level visual process could be how visually similar textures may combine to form the perception of a single shape differentiated from another texture, even if there’s no hard lines which may define the edges of said shape (Figure 1). Mid-level vision is not

believed to be semantic, in that it does not provide the viewer with the identity of objects or scenes such as “chair” or “island” or “face”. Instead, mid-level vision works to identify and feed-forward fundamental components or visual cues to higher-order visual areas. It is these high-order visual areas which complete the work of semantic identification.

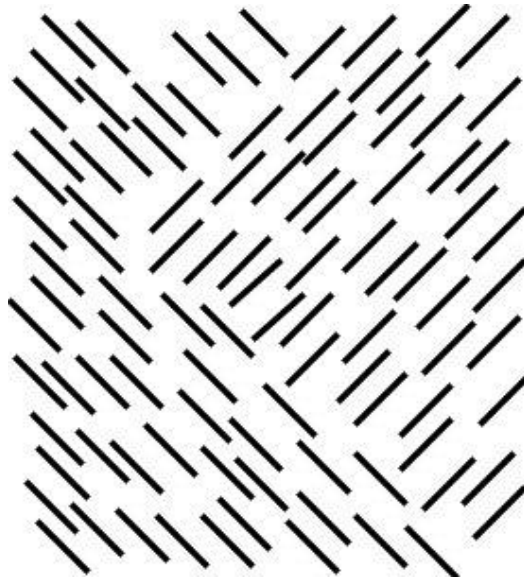


Figure 1: An example of mid-level visual processing from Rensink (2006). Both textures are similar from a low-level vision perspective, however, can be used to differentiate two distinct shapes. This is an example of texture segmentation, another fundamental gestalt.

In our research, we focus on one particular mid-level property which is symmetry. Symmetry can be defined as the property of an object in which it is invariant of under transformations. For example, if you were to rotate a cube by a multiple of 90 degrees around an axis that runs through the centers of two parallel faces, it would result in the same cube in the same position and orientation in 3D space. Similarly, if you were to reflect one half of said cube across the same axis, it would result in the same cube (Pizlo & Barros, 2021). These axes can be in any number of orientations given the shape of the object, and the similarity of components does not need to be completely identical for the emergence of visual symmetry to occur (Werheimer, 1923). Early work studying crystallography posited that there are four fundamental types of

symmetry which include *reflection*, *rotation*, *translation*, and *glide* (Fedorov, 1891; Polya, 1924) these types of symmetry have formed the nomenclature of how we define symmetry and formed a basis of how we may develop symmetrical stimuli (Lui, et al., 2010). Of importance to our research are reflection and rotation symmetry. Reflection symmetry can be defined by similar components being flipped across the axis and is commonly seen in nature through bilateral organisms and in man-made objects throughout history (Jablan, 2014). Rotation symmetry occurs when similar components are rotated around a central axis, rather than flipped. In nature, examples of rotation symmetry can be found in flower petals and snowflakes. One of the first behavioural studies to identify the perceptual distinction between rotation and reflection symmetry was by Royer (1981). This study sought to explore some of the details surrounding the detection of symmetry. Royer (1981) developed a series of reaction time experiments in which they asked participants to view displays with abstract patterns which contained horizontal-vertical symmetry (reflection symmetry), diagonal symmetry, centric symmetry (rotation symmetry), a combination of symmetry types, or no symmetry. The task of the first experiment was to identify if the displays had any form of symmetry. Royer (1981) found that reaction times were faster for displays with combinations of symmetry types. They also found that reflection symmetry elicited faster reaction times than rotation symmetry. Additionally, Royer (1981) conducted a secondary experiment which asked participants to only respond to particular types of symmetry. They found that participants had a much harder time rejecting reflection symmetry over rotation symmetry. These findings were particularly important in that they were some of the first to provide strong evidence that the perception of different types of symmetry can be measured through behavioural techniques such as reaction time and also indicated a potential

bias towards reflection symmetry and combinations of different symmetry types over rotation symmetry.

The fact that symmetry can be found throughout our daily visual experience in both the natural world and in man-made objects, is indicative of its importance to the visual system. For this reason, symmetry perception has been studied in psychology, neuroscience, computer science, and biology, as a fundamental gestalt. These multiple disciplines in vision research have identified a key role for symmetry in scene and object perception (Bertamini, Silvanto, Norcia, Makin & Wagemans, 2018), shape perception (Bahnsen, 1928; Machilsen et al., 2009) and judgments about facial attractiveness (Grammer and Thornhill; 1994). Although the importance of symmetry is broadly recognized, most symmetry perception research has focused primarily on reflection symmetry while neglecting other types such as rotation. This thesis seeks to explore this gap in the literature by examining the differential processing of reflection and rotation symmetry when embedded in a regular texture and as individual objects.

In order to investigate the processing of symmetry types and how textural regularity may have an impact, it is important to develop a strong foundation of how previous research has explored these topics in the past. In this introduction I will discuss what we know about the neuroanatomy behind symmetry and texture perception by first providing an overview of past behavioural and neuroimaging findings. After a review of past literature, I will then provide a brief explanation of the research methods and logic we used to explore the topic.

1.2 Symmetry as a Fundamental Gestalt

Bahnsen (1928) was one of the first behavioural scientists to explore symmetry perception. Bahnsen conducted a series of figure/ground experiments which asked participants to view an

ambiguous, abstract display and report what portion appeared to be the foreground and what portion appeared to be the background. This study found that when presented an ambiguous figure/ground display, participants tend to see displays that are symmetrical as the figure while displays which are asymmetrical as the background. This finding helped to provide some of the first behavioural evidence of a bias towards symmetry in the visual system, in that participants tend to attribute symmetry to objects in the foreground.

More contemporary behavioural research involving symmetry and object perception was conducted by Machilsen et al. (2009) which sought to explore a similar figure/ground distinction as Bahnsen (1928), however, using Gabor stimuli to introduce more ambiguity into the display. Participants were provided with two stimuli presented simultaneously, one of which contained a target item which was partially obscured by Gabor-generated noise, while the other did not contain the target but had similar visual noise. The participants were asked to identify which of the stimuli contained the target object as quickly as possible. The results indicated that symmetrical target items were easier to detect than asymmetrical target items. Both Bahnsen (1928) and Machilsen et al. (2009) provided strong evidence that symmetry may be used as a fundamental cue in object perception and disambiguation of ambiguous stimuli. Both these studies suggest that symmetry may have been evolutionarily advantageous for identifying other living creatures (predator or prey) and finding food in visually noisy environments (Bahnsen 1928 & Machilsen et al., 2009).

Grammer and Thornhill (1994) also suggested that reflection symmetry may be an evolutionarily salient cue for sexual selection. In an applied behavioural study, they asked participants to rate the attractiveness of various face stimuli using a Likert-scale. These face stimuli were varied by minute shifts in facial proportions through software editing. One of these

proportions which was shifted was facial symmetry. Their results found that participants rated faces which were symmetrical as more attractive than faces which were not. These findings suggest that symmetry is not only important for identifying objects and differentiating stimuli from a background, but that it may also be an important evolutionary factor when creating more complex visual judgments such as finding a suitable sexual partner. In order to position symmetry as an evolutionarily salient cue, one would expect that there is a strong neural basis for symmetry perception, and our close evolutionary relatives may have similar neural responses to symmetry. These topics were explored in a study by Sasaki et al. (2005) in a comparative functional MRI (fMRI) study. In this study, participants were made to view symmetric versus random disk stimuli while in an MRI. They found significant neural activity in visual areas V3A, V4, V7, and LO while participants viewed the symmetrical stimuli. This was an important finding as it provided a neurological basis for symmetry as a distinct visual element, situated in mid-level visual areas. Furthermore, this study also compared the fMRI activity found in human brains to the macaque cortices. Similar to the human participants, macaque monkeys were also scanned while viewing symmetrical and random dot stimuli. Sasaki et al. (2005) found that activation in the previously defined “symmetry centres” appeared to be especially salient in human brains but were still present in our evolutionary cousins. These results provided vision researchers with insight into the neural mechanisms which may underlie symmetry perception and show evidence that these patterns of activation persist across species which diverged long ago. This is indicative that symmetry is fundamental to human and other primate vision as a mid-level visual cue.

This positioning of symmetry as an evolutionarily salient, fundamental, visual cue, led to a great number of brain-imaging studies which involved symmetry perception. Further exploration of the neural underpinnings of symmetry perception using brain-imaging techniques has

provided the fields of behavioural science, visual neuroscience, and computational modelling with a richer understanding of the underlying mechanisms of symmetry detection. Additionally, these studies have provided some insight into the significance of symmetry detection in the greater context of our visual experience as a whole. In the next section, I will review some of these significant brain-imaging studies and their impact in regards to our understanding of symmetry perception.

1.3 Neural Underpinnings of Symmetry Perception

There have been several brain-imaging studies on symmetry perception using a variety of methods including fMRI and electroencephalography (EEG) methods. These studies have provided a strong neural basis for the symmetry selective network found in Sasaki et al. (2005) while also providing additional insight into what cortical regions are especially active (or less active) when viewing symmetrical stimuli. One such study by Tyler et al. (2005) used fMRI techniques to discover a similar activation pattern to Sasaki et al. (2005) and also noted that the contrast between symmetric and random patterns produced no activation in primary visual area V1. This further solidifies the findings of a symmetry specific network which operates in V3A, V4, V7, and the LO.

Another brain-imaging approach to symmetry research makes use of sustained posterior negativity (SPN) methods. SPN research makes use of EEG techniques to measure visual event related potential (ERP) across a brief time period after a subject views a visual stimulus. This method allows for researchers to examine patterns of activation across neural regions with greater temporal resolution than fMRI techniques. Norcia et al. (2002) made use of this technique and presented participants with symmetric and random dot patterns. They found that

ERP for symmetric stimuli diverged from asymmetric stimuli about 220ms after onset. This is indicative that symmetry specific activation appears to occur only in the later components of visual processing. This corroborates the fMRI findings of Sasaki et al. (2005), and Tyler et al. (2005). Other SPN studies by Makin et al. (2012) and Jacobsen and Hofel (2003) also found similar latencies in symmetry specific ERP, however these precise timing varied around 250-300ms across these studies. Nevertheless, these SPN studies helped to further identify how the processing of symmetry appears to deviate from asymmetry in the brain.

Bertamini and Makin (2014) wanted to further clarify the neurological underpinnings of symmetry research and constructed a comprehensive review which compared the previously mentioned fMRI and SPN research above. They summarized the research by focusing on the automaticity of symmetry perception, what extrastriate regions were implicated, if specific types of symmetry seemed to be a special case compared to other forms of symmetry, view invariance, lateralization, and if symmetry prompted positive affect in the viewer. They found an automatic and sustained response to symmetry across an extensive network of extrastriate areas to higher-order cognitive regions. This suggests that the brain automatically and efficiently processes symmetry and has a strong symmetry-selective cortical architecture (Bertamini & Makin, 2014). This review provided visual neuroscientists with a deeply informative summarization of a neural basis for symmetry perception. However, this review also prompted a great number of questions regarding the specifics of symmetry perception in extrastriate areas, how various types of symmetry may affect the brain differentially, and how these neuroimaging findings might extend to behaviour.

To further explore the operation and interactions between the extrastriate regions identified in previous research, some studies worked to re-examine the network subserving symmetry

processing using other neuroimaging methods. Van Meel et al. (2019) used multi-voxel pattern analyses (MVPA) and functional connectivity analyses to study the representation of reflection symmetry in the brain. Their results indicated that neural representations gradually changed throughout the stream of visual cortical areas. The information started as very similar part-based representations for symmetrical and asymmetrical stimuli in V1 and V2, but increasingly differentiated in both V3 and V4 and finally led to a holistic representation for symmetrical compared to asymmetrical stimuli in high-level LOC (Van Meel, Baeck, Gillebert, Wagemans, Op de Beeck, 2019). This research provided further insight into how visual information transforms across the previously identified neural regions associated with symmetry perception. This created a deeper understanding of how the brain represents symmetry across mid-level visual areas and higher-level visual areas and gives more insight into the previous behavioural research which implicated symmetry as a salient cue for lower level perception (object recognition) along with more complex perception (facial attractiveness scores). However, these neural findings were not novel, this propagation across neural regions had previously been suggested by Sasaki et al. (2005) and further explored by Kohler et. al (2016) in a study using human participants using fMRI and high-density EEG.

Some brain-imaging research also combined neurological methods with behavioural manipulations. Keefe et al. (2018) sought to investigate the effects of attentional demands on symmetry perception. They examined fMRI responses to both fronto-parallel and slanted symmetry while manipulating visual attention. They found that symmetry-specific responses emerged in V3 and continued across higher-order visual areas, similar to previous work. The ventral occipital cortex (VO1) showed the strongest symmetry-selective response. What was especially interesting about their work, was that Keefe et al. (2018) also found neural and

behavioural evidence that symmetry viewed on the slanted plane (viewed at an angle which is not perpendicular to the viewer) elicited responses in V3 and follow a similar trajectory to fronto-parallel symmetry. These slanted plane responses continued through higher order visual cortices and were strongest in VO1 and LOB. Furthermore, both slanted plane and fronto-parallel symmetry evoked similar activity when participants performed a behavioural task however, people performed more poorly on the slanted symmetry task despite the neurological underpinnings appearing similar (Keefe et al. 2018). This provided some evidence that while the neural underpinnings for processing symmetry appear to be automatic, changes in symmetrical displays may elicit different behavioural responses. This begs the question; how do other aspects impact symmetry at the behavioural and neurological level. This very question led researchers to explore diverse types of symmetry and their respective neural underpinnings through a new set of stimuli called “wallpaper groups”.

1.4 Wallpaper Groups and the Hierarchical Frame

The wallpaper groups are a set of 17 unique combinations of the four fundamental symmetry types: reflection, rotation, glide and translation (Fedorov, 1891; Polya, 1924; Liu et al., 2010). The wallpaper name is apt as they are regular textures which resemble a Victorian wallpaper or rug. A growing literature has developed using these wallpaper groups as they allow for very controlled yet powerful comparisons between the various types of symmetry, their internal complexity, and an interaction with texture (Figure 2).

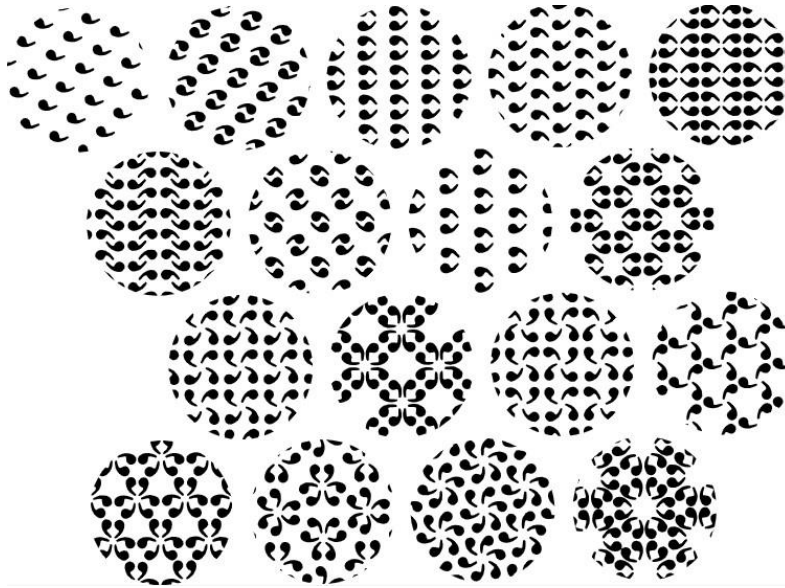


Figure 2: The 17 wallpapers rendered with a comma-like symbol as the repeating element. Illustration based on Wade (1993).

Much of the findings involving wallpaper groups are framed in terms of a series of hierarchical relationships among the wallpaper groups that are based on mathematical group theory. Interestingly, brain imaging results appear to be remarkably consistent with group theory. Kohler and Clarke (2021) conducted an EEG and behavioural study which measured the neural activation across the symmetry selective network and reaction time and accuracy when identifying wallpaper stimuli. They found that wallpaper groups lower in the proposed hierarchy produce smaller neurological response amplitudes and required longer presentation time to be accurately detected (Kohler & Clarke, 2021). These results show that the visual cortex may have comprehensive representations of symmetries in regular textures and that individual symmetry types embedded in textures are coded with a very high degree of precision.

These findings demonstrate a relationship between the mathematically defined hierarchy among wallpaper groups, and brain responses. This allows for us to develop better models of symmetry and texture perception using these mathematical principles. These findings are also

especially exciting because they are some of the first instances in the literature which emphasize how texture and symmetry appear to be deeply interconnected. Up to this point in our literature review, we have only focused on symmetry, and before we continue with how behaviour is informative of symmetry and symmetry and texture appear to intertwine, I will briefly review some neurological literature on texture perception research.

1.5 Texture Perception

Textures form the patterns that make up the surfaces of objects and environments, they play an important role for vision in everyday life. Like symmetry, textures have been used to disambiguate stimuli in a visually noisy environment and been shown to aid in object perception (Adelson, 2001). Which similarly positions them as an important and fundamental visual component which allows us to make sense of the world around us.

An important step towards the understanding and analysing human texture perception was the development of a computational model that made it possible to represent and synthesize visual textures based on joint statistics of the image (Portilla and Simoncelli, 2000). The model has proven highly useful in capturing how texture representations change across the visual field (Balas, Nakano and Rosenholtz, 2009; Freeman and Simoncelli, 2011) and how natural textures are represented in different areas of visual cortex (Freeman et al., 2013; Okazawa et al., 2015).

The Portilla and Simoncelli (2000) synthesized textures were used in a comparative fMRI study by Freeman et al. (2013). In this study, Freeman et al. (2013) constructed two sets of synthetic stimuli; one which replicated higher-order statistical dependencies similar to those found in nature and another which lacked in this naturalistic structure. They then showed these images to macaque monkey and human participants and measured responses in V1 and V2. Their

findings implicated a greater activation in V2 for the stimuli which more closely resembled textures found in nature. Whereas there was no distinction in response patterns between the types of stimuli in V1. This research has two important implications; there appears to be an important functional role for V2 in viewing naturalistic textures, and that this pattern of activation is consistent across humans and our close evolutionary relatives. This parallels previous comparative studies in symmetry research and helps to position texture perception as an evolutionarily salient visual cue. Additionally, it parallels symmetry research by implicating that naturalistic texture processing occurs in higher brain regions than V1, similar to symmetry processing.

In a further neuroimaging studies which use the Portilla and Simoncelli (2000) synthetic textures, it was found that V4 neurons typically respond best to particular sparse combinations of these statistically irregular textures. Okazawa and Tajima (2014) conducted a single-cell recording study on macaque V4. They found that individual cells in macaque V4 had linear tuning to sparse combinations of texture types and generated a clear picture of texture representation in the brain at the mid-level area. Additionally, they found that the statistics of each image can be computed from responses in V4 but can be traced downstream to neurons originating visual area V1, this indicates a clear account of how the visual system processes local image features to create the global perception of texture in natural images (Okazawa & Tajima, 2014). This pathway from V1 to V4 follows a similar trajectory to our previously mentioned stream of information found across the visual system when observing symmetry. This may indicate the possibility that texture perception and symmetry perception are intertwined at the cortical level.

Importantly, however, the computational modeling framework from Portilla and Simoncelli (2000) is limited as it is unable to synthesize regular textures like the wallpaper groups used in this thesis. The inability to synthesize regular textures using Portilla and Simoncelli (2000) highlights the need for the development of models that can describe and synthesize regular textures such as ones which exist in the natural world. The healing grid illusion by Fukuda and Seno (2012) may also be relevant for this (Figure 3). The illusion shows that a regular grid which is disrupted in the periphery can undergo illusory completion such that the disruption is not detected. That is, the irregularity in the periphery is filled-in by the regular texture. One interpretation of the illusion is that the visual system has a bias towards perceiving textures as regular.

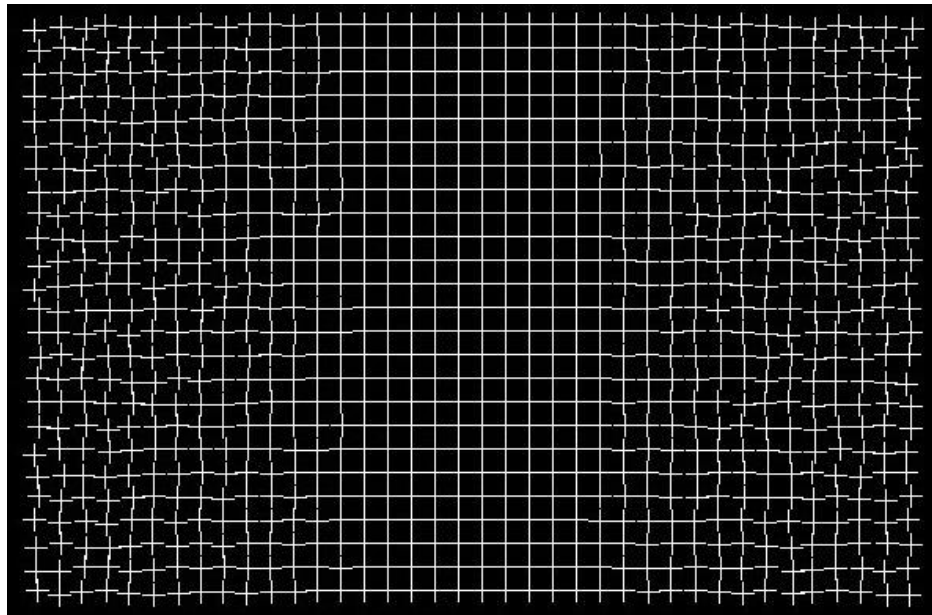


Figure 3: The healing grid illusion by Fukuda and Seno (2012)

1.6 The Visual Search Task

Thus far, have explored the importance of symmetry through behavioural and neuroimaging work, and we have developed a foundation of neural basis behind symmetry and

texture perception. The vast majority of the behavioural studies surrounding symmetry focused primarily on reflection symmetry, and the work which explored other types of symmetry through wallpaper groups provided only a neuroimaging account. The current thesis approaches the gap in the literature by using wallpapers to explore differential behavioural responses to reflection and rotation symmetry when embedded in a regular texture and as individual objects. To accomplish this, we used a visual search task.

The visual search task has been used to probe whether a given cognitive process is performed in a serial or parallel fashion. In this task, reaction time and accuracy are measured as participants search for a target among distractors. The basic assumption is that if the information is being processed serially, the greater the number of distractors, the longer and less accurate the participant would be as they must move throughout the array space and process each portion independently to find the target. Whereas if the information is being processed all in parallel, the target would “pop-out” of the set of distractors and result in shorter reaction times and higher accuracy which is invariable on the size of the array. Parallel processes generally require less conscious effort and attentional resources (Eriksen & Lappin, 1965). The visual search task has been used to dissociate parallel or serial processes by using visual properties such as colour and orientation in the past and found to be effective is distinguishing properties which require more cognitive resources (Bundesen, Kyllingsbæk, Larsen, 2003; Kyllingsbæk & Bundesen, 2007; Cavanagh, Arguin, Treisman, 1990). It is important to note that serial and parallel processing can sometimes be interpreted as isolated binaries. However, it is more effective to conceptualize them as endpoints along a spectrum (Wolfe, 1998, 2016). That is, cognitive processes may operate as strictly serial or parallel, but can also fall between these two styles of information

encoding to varying degrees. For this reason, it is more informative to compare conditions in terms of “more serial” or “more parallel” rather than assigning them to strict binary definitions.

Visual search has been used to study symmetry in two main variants: through inter-item symmetry and array symmetry. Inter-item studies compare items which have internal symmetry to items which do not have internal symmetry. Javadnia and Ruddock (1988) conducted an inter-item symmetry study in which they used objects which were either symmetrical or asymmetrical as targets versus distractors. Their results indicated that symmetrical targets elicited more parallel responses as opposed to asymmetrical targets.

Research which focuses on array symmetry may use targets and distractors which do not contain internal symmetry, but instead, symmetry is an emergent property by the way the items are arranged within an array. An example of symmetry across an array can be found in Wolfe and Friedman-Hill (1992) where they used lines of varying orientation to generate distractor arrays which had symmetry through their textural arrangement. Participants were asked to find a target which disrupted the regular symmetrical texture of the array and produced asymmetry. They found that when the distractor arrays were arranged in terms of vertical (reflection) symmetry, finding the target was more efficient than when distractor arrays were arranged in terms of oblique (rotation) symmetry (Wolfe & Friedman-Hill, 1992). Both of these studies provided us with a strong foundation in which to investigate the visual property of symmetry using a controlled design which combines both inter-item and array symmetry methods. We constructed a study which uses the highly controlled, wallpaper-group stimuli from neuroimaging studies and a combination of inter-item and array symmetry behavioural methods to explore the differential processing of symmetry types and their relationship to textural regularity.

1.7 The Current Study

This thesis addresses two research questions: First, how inter-item symmetry type (reflection vs. rotation) influences the visual processing efficiency; Second, how texture regularity influences the efficiency of processing array symmetry. To accomplish this, we contrasted two wallpaper groups: *PMM*, which contains reflection symmetry; and *P4* which contains rotation symmetry but no reflection. The exact composition of these wallpaper groups and how the stimuli were generated are explored in the next chapter. Both *PMM* and *P4* contain inter-item symmetries and their subsequent lattices form arrays which also have array symmetry which emerges from the regularity of their arrangement. Additionally, we developed another set of stimuli which disrupts the regularity of the array. We developed this set of stimuli to measure the effect of each type of visual search symmetry; inter-item and array symmetry had on the processing efficiency. Based on previous results indicating that reflection is processed more efficiently than other types of symmetry, our first hypothesis was that we would find greater parallel processing (i.e., more efficient processing) for reflection than rotation symmetry. Our second hypothesis was that regular textures (array symmetry) would be processed more efficiently than non-regular textures, as an apparent disruption regularity and lead to a more evident pop-out effect.

Chapter 2:

Visual search efficiency is modulated by
symmetry type and texture regularity

Rachel Moreau, Nihan Alp, Alasdair DF Clarke, Erez Freud, Peter J. Kohler

2.1 Abstract

Symmetry has been heavily studied in vision research as a fundamental cue, which aids the visual system in making inferences about objects and surfaces in natural scenes. Most studies have focused on one type of symmetry, reflection, presented at a single image location. However, the visual system responds strongly to other types of symmetries, and to symmetries that are repeated across the image plane to form textures. We use a visual search paradigm with arrays of repeating lattices that contained either reflection or rotation symmetries but were otherwise matched. Participants were asked to report the presence of a target lattice tile without symmetry. When lattice tiles fill the plane without gaps, they form regular textures. We manipulated texture regularity by introducing jittered gaps between lattices. This paradigm lets us investigate the effect of symmetry type and texture regularity on visual search efficiency. Based on previous findings suggesting an advantage for reflection in visual processing, we hypothesized that search would be more efficient for reflection than rotation. We further hypothesized that regular textures would be processed more efficiently. We found independent effects of symmetry type and regularity on search efficiency that confirmed both hypotheses: visual search was more efficient for textures with reflection symmetry and more efficient for regular textures. This provides additional support for the perceptual advantage of reflection in the context of visual search and adds important new evidence for visual mechanisms specialized for processing symmetries in regular textures.

2.2 Introduction

As we move through the world, the brain generates our visual experience by rapidly processing a constant stream of visual stimuli. Despite the apparent effortlessness of vision, this process is highly complex. Seminal perception research proposed that visual processing is simplified through a set of fundamental gestalts which provide structural limitations on the interpretation of visual stimuli (Wertheimer, 1923). In the current study, we investigate how one of these fundamental gestalts; symmetry, contributes to the perception of textures and how this impacts the efficiency of visual processing.

Symmetries are prevalent in the natural world and can be found in man-made objects throughout human history (Jablan, 2002). Multiple studies have identified a key role for symmetry in scene and object perception (Bertamini, Silvanto, Norcia, Makin & Wagemans, 2018), contributing to behaviors as fundamental as shape perception (Bahnsen, 1928; Machilsen et al., 2009) and as sophisticated as judgments about facial attractiveness (Grammer and Thornhill; 1994). Much of this literature has focused on *reflection* or mirror symmetry, but reflection is only one of four fundamental symmetry types, with the others being: *rotation*, *translation*, and *glide reflection*. While reflection can be seen in the bilateral bodies of many animals and is especially behaviorally relevant for human faces, there are examples of all of the symmetry types in nature, e.g., rotation symmetry in flower petals, honeycombs, butterfly wings, and snowflakes.

This begs the question: how does the visual system process these various symmetry types, and how do they differ from previous findings with reflection symmetry? Since the earliest days of symmetry, reflection has been considered unique among the symmetry types as the topic in vision research (Mach, 1897, eng. translation 1959). Psychophysical studies show

that reflection symmetry can be detected preattentively, requires less cognitive resources, and allows for faster reaction time than rotation and translation (Wagemans 1995, Wagemans 1997, Olivers & Helm, 1998; Treder, 2010; Bertamini & Makin, 2014). It has been suggested that the advantage of reflection might be a result of evolutionary pressures to optimize the encoding of behaviorally relevant stimuli that have reflection symmetry, such as faces (Grammer & Thornhill, 1994).

Most studies on the role of symmetry in visual behavior have considered one or two axes of symmetry centered on a single location in the image, consistent with the way symmetries would most likely occur over objects in the natural world (Bertamini, Silvano, Norcia, Makin & Wagemans, 2018). However, symmetries can also be found in regular textures known as *the wallpaper groups* – a set of 17 unique combinations of the four fundamental symmetry types (Fedorov, 1891; Polya, 1924; Liu et al., 2010). The wallpaper name is apt as the textures resemble a Victorian wallpaper or rug. Regular and near-regular textures are abundant in natural and man-made environments (Liu, Lin & Hayes, 2004), and symmetries in regular textures generate strong responses in the visual cortex of humans (Kohler et al., 2016; Kohler et al., 2018; Kohler & Clarke, 2021) and other primates (Audurier et al., 2021).

The growing literature on wallpaper groups shows that when embedded in regular textures, each of the different symmetry types can give rise to reliable responses in the visual cortex. The behavioral consequences of this have yet to be explored. The current study seeks to address that gap in the literature by investigating the efficiency of processing reflection and rotation symmetries when these symmetries are presented in regular textures and when they are not. This will provide valuable information about how the human visual system handles complex

representations of symmetry and regularity, and how these striking patterns may contribute to the perception of natural scenes.

We addressed these questions using a visual search task. Visual search has been used to probe the extent to which a given cognitive process takes place in a serial or parallel fashion. Reaction time and accuracy are measured as participants search for a target. Typically, the target is either presented among distractors or hidden in noise. If information is being processed serially, the observer has to scan through each individual array element until the target is found. Thus adding more distractors to the array will result in longer reaction times and/or lower accuracy. On the other hand, if information is processed in parallel, the target will “pop-out”, resulting in reaction times and accuracy that are constant across array sizes (Treisman & Gelade, 1980). Previous studies have utilized visual search to dissociate parallel or serial processing of visual properties such as colour and orientation. It has been found to be an effective way of differentiating visual properties based on the cognitive resources required for processing (Bundesen, Kyllingsbæk, Larsen, 2003; Kyllingsbæk & Bundesen, 2007; Cavanagh, Arguin, Treisman, 1990, Wolfe, 1998). Serial and parallel processing are often presented in binary fashion, as two qualitatively distinct types of cognitive processing. However, it is likely more realistic to conceptualize them as endpoints along a spectrum (Wolfe, 1998, 2016). That is, cognitive processes may operate as strictly serial or parallel, but can also fall anywhere between the two. In the current study, we therefore compare conditions in terms of “more serial” or “more parallel”.

Visual search has been used to study symmetry in two main ways: through inter-item symmetry and whole-array symmetry. In inter-item studies, individual items in the search array either do or do not have internal symmetry. An example is a study by Javadnia and Ruddock

(1988) which varied symmetry between targets and distractors, in addition to several other parameters. Their results indicated that targets could be discriminated from distractors if they differed in if they were symmetrical or not, and that symmetrical targets elicited more parallel responses as opposed to asymmetrical targets. Studies that use the whole-array approach to symmetry in visual search use targets and distractors which are not different in internal symmetry, but are arranged such that they either do or do not form symmetrical textures across multiple array items. The first to do this was Wolfe and Friedman-Hill (1992) who used oriented lines that were arranged to form symmetrical textures across the search array. Participants were asked to find a target which was oriented such that it disrupted the symmetry of the array. They found that when the distractor arrays were arranged in terms of vertical (mirror) symmetry, finding the target was more efficient than when distractor arrays were arranged in terms of oblique (rotation) symmetry (Wolfe & Friedman-Hill, 1992). This indicates that there may be a processing advantage for reflection symmetry over rotation symmetry at the array level. The current study takes inspiration from both approaches and uses a wallpaper stimuli design which allow us to manipulate both inter-item and whole-array symmetry in a highly controlled manner.

We used the visual search task to address two research questions: First, how inter-item symmetry type (reflection vs. rotation) influences efficiency of visual processing; Second, how texture regularity, a whole-array property, influences the efficiency of visual processing. To accomplish this, we contrasted two wallpaper groups: *PMM* (Figure 4B), which contains 4-fold (90°) reflection and 2-fold (180°) rotation centered at the intersection of the reflection axes; and *P4* (Figure 4A), which contains 4-fold (90°) and 2-fold rotation, but no reflection. Both groups (and in fact all wallpaper groups) are textures in which a square lattice tile is repeated without gaps in the image plane, and the groups differ only in terms of the symmetries within the lattice

tile. In all experiments presented here, the target stimuli was a random disk pattern which contains no internal symmetry and replaced one of the repeating lattice tiles when target was present. This means that this version of the visual search task is effectively a search for the absence of symmetry, which is a reversal of a typical visual search task. We chose to use this reverse visual search task because it allowed us to examine the effects of the textural regularity produced by tiling our PMM and P4 stimuli, whereas if we embedded a single lattice tile within noise (as per the traditional visual search task), we would not be able to measure the effects of regularity. The choice of using PMM and P4 as stimuli makes it possible to generate exemplars that belong to one group or the other through a very simple image-level operation (see Figure 5 and the *Stimuli* section of the Methods), and thus manipulate symmetry while controlling for every other image-level attribute (spatial frequency, contrast, etc.). Our manipulation of wallpaper group allows us to investigate the effect of inter-item symmetry. In order to investigate the effect of regularity across the arrays, we developed “jitter stimuli”, in which gaps were introduced between the repeating lattice tiles, and lattice tile positions were jittered, such that the regularity of the textures was disrupted (see Figure 4). While this is not a manipulation of symmetry across the array, per se, regularity is by definition a whole-array property, and therefore potentially related to previous studies manipulation whole-array symmetry. This means that our design makes it possible to separately measure effects of inter-item symmetry and whole-array regularity.

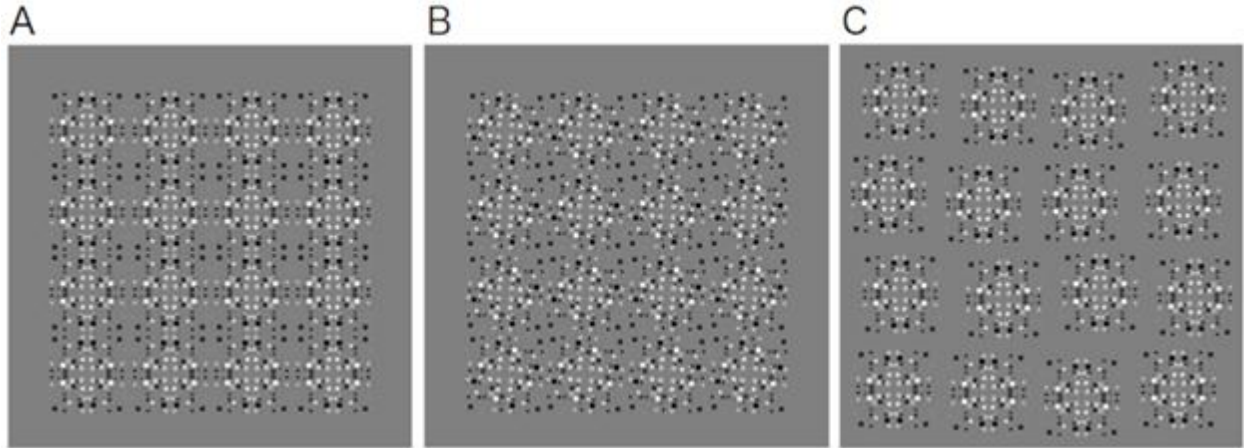


Figure 4: A. An example of a PMM wallpaper stimuli, B. An example of a P4 wallpaper stimuli. C. An example of a PMM “jitter stimuli”. Across all stimuli the individual lattice tiles were the same size and shown on a 50% grey background so the wallpaper would be seamless on the edge. In the jitter stimuli, the overall array is larger, but the lattice tile size is the same.

Our manipulations of the two dimensions of interest, symmetry type (PMM vs. P4) and texture regularity (no jitter vs. jitter between lattice tiles), giving rise to a 2×2 design across four visual search experiments, with four array sizes per experiment. We used the slope of the linear search function to describe how reaction time and sensitivity (d') change with larger search arrays as a measure of processing efficiency. Steeper search function slopes indicate that processing is more serial, while shallower slopes indicate more parallel processing, with perfectly flat search function indicating fully parallel processing.

Based on previous results indicating that reflection is processed more efficiently than other types of symmetry, our first hypothesis was that we would find more parallel processing for reflection than for rotation. Our second hypothesis was that regular textures would be processed more efficiently than non-regular textures, as the target would disrupt regularity and perhaps lead to a form of pop-out effect. Our results support the first hypothesis: Across both jittered and un-jittered conditions, reflection symmetries produced more parallel processing. We also confirmed our second hypothesis: search was *more* efficient for regular textures across both

types of symmetry. There were no interactions between symmetry type and regularity, suggesting that the effect of regularity was independent of the effect of symmetry type. These findings add new evidence to the literature on differential processing of reflection and other types of symmetry and demonstrate a novel processing advantage for regular textures.

2.3 Methods

Stimuli. The stimuli were square arrays of lattice tiles. Each lattice tile was created based on a random disk pattern called a fundamental region, repeated into a 2 x 2 array. Two different sets of transformations were applied to the fundamental region inside the lattice tile. In PMM lattices, the fundamental region is reflected along the vertical axis and then again reflected along the horizontal axis. This produces reflection symmetry along both axes. In P4 lattices, the fundamental region is rotated 90 degrees clockwise, starting with 0 degrees in the upper left quadrant, then 90 degrees to the upper right, 180 degrees in the lower right, and 270 degrees to the lower left. This produces a 4-fold rotation centered at the center of the lattice (see Figure 5). Importantly, all four experiments used the same random disk patterns as fundamental regions, meaning that image-level properties were matched across conditions. When lattices are used to tile the plane, they form regular textures known as wallpaper groups – PMM lattices produce wallpaper group PMM, and P4 lattices produce group P4. We used 10 different fundamental regions to create 10 exemplars of each wallpaper type.

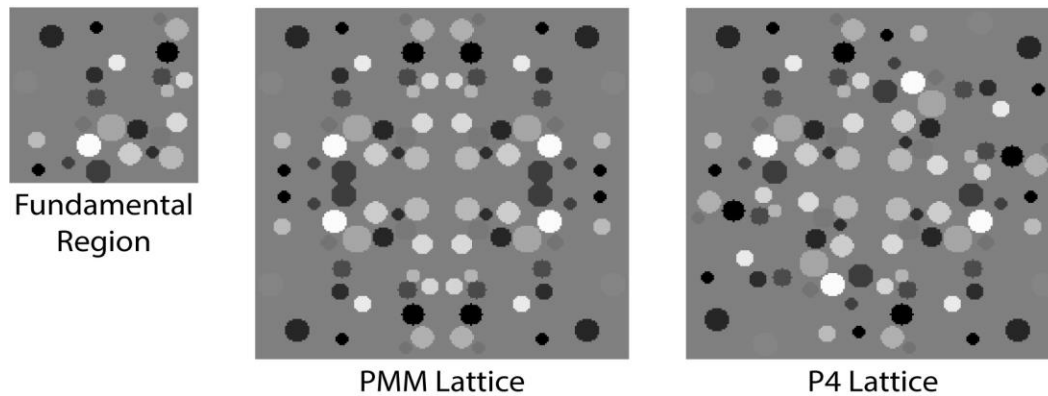


Figure 5: An example of a fundamental region and corresponding PMM and P4 lattice tiles. Here, you can see that the random disk pattern from the fundamental region is repeated 4 times to create a lattice tile but using different transformations. This allows for consistency between the two symmetry types regarding the amount of white, black, and shades of grey in each stimulus.

We also created a “random lattice tile” that contained no symmetry by using four distinct fundamental regions in each quadrant of the 2 x 2 array. These random lattice tiles can be embedded in the wallpaper group in place of any PMM or P4 lattice tiles and are matched to the symmetry lattices in terms of number of dots, contrast and spatial frequency. In our visual search task, the random lattice tile serves as the target and wallpaper group lattices serve as distractors (see Figure 6). As noted in the Introduction, this participants’ ability to identify the absence of symmetry in the search arrays is used as a measure of symmetry processing, across different conditions. We manipulated symmetry type by using PMM (“reflection”) and P4 (“rotation”) textures and further manipulated regularity by adding spacing around each lattice tile corresponding to 20% of the lattice tile width/height, and the position of each lattice tile was jittered randomly between $\pm 15\%$ in both the x and y direction. Across all experiments, these lattice tiles were arranged in 3x3, 4x4, 5x5, and 6x6 wallpapers to create different array sizes. In the regular PMM and P4 groups, the search arrays were presented with no gaps between the lattices, so that the distractors formed regular textures. The size of the lattice tiles was 100 by 100 pixels across all experiments.

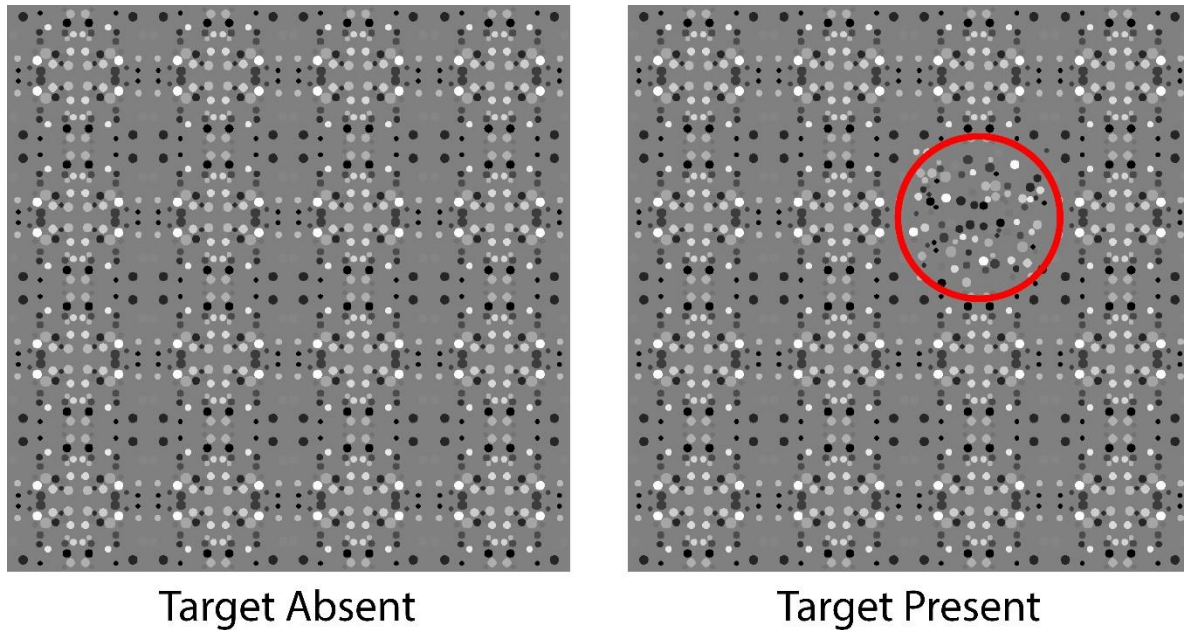


Figure 6: Example images from experiment 1; PMM target absent vs. present example. Circled in red is the target: random lattice tile.

Participants. Participants were gathered through the online participant pool, Prolific. They were compensated £8.50/hr for their participation, and the experiment lasted about 20mins. For each experiment, we collected data from 50 participants totaling 200 (Males = 115, Females = 85), and the average age of all participants was 22.46 ± 3.21 . Across experiments, we removed participants who had sensitivity (d') lower than 1 in all conditions, indicating that they were unable or unwilling to do the task (Experiment 1 (PMM) = 6; Experiment 2 (P4) = 10, Experiment 3 (PMM jitter) = 6, Experiment 4 (P4 jitter) = 12). Informed consent was obtained before the experiment under a protocol approved by the Office of Research Ethics at York University.

Procedure. All four experiments were written using JsPsych (de Leeuw, 2015), hosted online on Pavlovia.org, and followed the same general procedure. Participants were presented with one block of 24 practice trials, followed by 240 experimental trials broken into 10 blocks. The

wallpaper array contained a target lattice tile on 75% of trials. Fundamental region exemplars were pseudo-randomly assigned to target-present and target-absent trials so that each of the 10 exemplars was repeated an approximately equal number of times for target-absent and target-present trials, across all array sizes. Trials were shown in random order across exemplars, trial types, and array sizes. When targets were present, their location in the search array was chosen randomly on each trial.

Participants were asked to use their keyboard to indicate if a target lattice tile was present or not, pressing the “L” key to indicate that the target was present, and the “D” key to indicate that it was not. Trials only progressed after a selection had been made. After both practice and experiment trials, feedback was provided in the form of the word “Correct!” in green text or “Incorrect!” in red text, presented with a statement indicating how many trials the participant remained in the experiment. Feedback remained on the screen for 1000 ms before the next trial was presented. After each of the 10 blocks, the participants were given the opportunity to take a break before pressing any key to continue. At the end of the experiment, participants were thanked for their participation and redirected to a page where credit and/or payment could be assigned.

Data analysis. We followed the procedure for calculating d' outlined in Macmillian and Kaplan (1985). When individual participants had hit and/or false alarm rates that were 1 or 0, we corrected by adding or subtracting half a trial:

$$0 = \frac{0.5}{T} \qquad 1 = 1 - \left(\frac{0.5}{T}\right)$$

where T is the total number of target-present (if correcting hit rates) or target-absent (if correcting false alarm rates), this allowed us to use the standard z-score distribution.

2.4 Results

We computed the median reaction time and d' for each array size, for each participant in each of the four experiments. To test our two hypotheses, we ran a linear mixed models analysis (LMM) separately on the reaction time and d' data. Symmetry type (wallpaper group) and jitter were between-subject fixed effects, array size, treated as a continuous variable, was a within-participant fixed effect, and the participant was a random effect. For illustration purposes, we also computed the slope of the search function for reaction time and d' individually for each participant (averages across participants are shown in Figures 7B and 8B). Greater slope values are indicative of more serial processing.

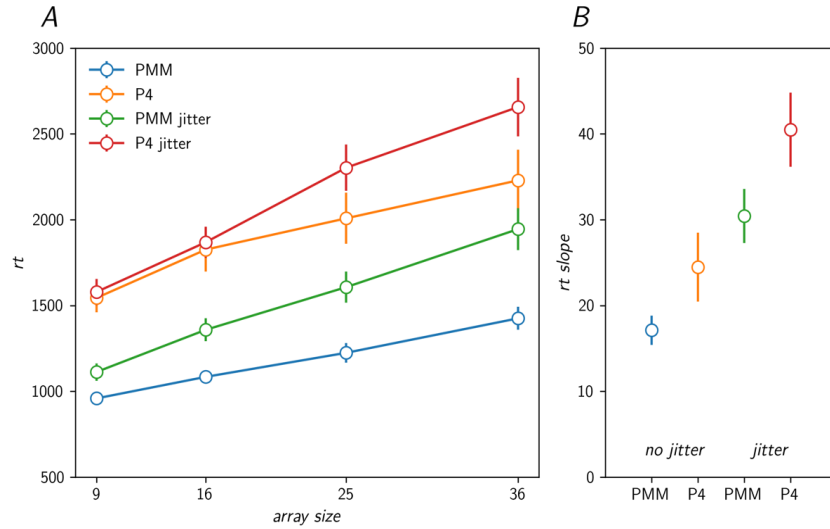


Figure 7: A. Reaction time data across the four experiments. Error bars reflect standard error of the mean. B. Slopes of the visual search function, averaged across participants, for each of the four experiments. Error bars reflect standard error of the mean. It is evident that slope values are smaller (more parallel) for PMM than for P4, and for non-jittered compared to jittered conditions.

For reaction time, we found a significant main effect of symmetry type ($F(1,152) = 83.736, p < 0.001$), indicating that participants were faster for reflection symmetry (PMM) than for rotation symmetry (P4) across all array sizes. There was also a significant main effect of array size ($F(1,152) = 283.198, p < 0.001$), indicating that reaction time increased with larger array sizes across conditions. Importantly, the significant main effects were modified by two significant interactions that elucidate the efficiency of the visual search: The first interaction was between symmetry type and array size ($F(1,152) = 6.776, p = 0.010$) such that rotation symmetry (P4) produced steeper search functions and thus less efficient search than reflection (PMM). The second interaction was between jitter and array size ($F(1,152) = 19.258, p < 0.001$), such that jittered conditions produced steeper search functions and thus less efficient search thanunjittered conditions. There was no main effect of jitter ($p = 0.345$) but the interaction between symmetry type and jitter approached significance ($F(1,152) = 8.403, p = 0.068$). Importantly, we did not find a three-way interaction (symmetry type \times jitter \times array size) ($F(1, 152) = 0.165, p = 0.685$), suggesting that symmetry type and jitter have separate and independent effects on processing efficiency.

We ran the same analysis with d' values as the dependent variable to determine if sensitivity was influenced by symmetry type and jitter, and to check for potential speed accuracy trade-offs. In agreement with the RT analysis, we found significant main effects of symmetry type ($F(1,152) = 14.554, p < 0.001$), jitter ($F(1,152) = 5.470, p = 0.021$), and array size ($F(1,152) = 55.029, p < 0.001$). The significant main effects were modified by a significant interaction between symmetry type and jitter ($F(1,152) = 4.317, p = 0.039$), but there were no other main effects or interactions (smallest $p = 0.258$).

The slopes were relatively flat and similar across conditions. The only exception is un-jittered reflection symmetries (PMM), which had a flatter slope than the other conditions (see Figure 8). This is consistent with the reaction time analysis, which shows that out of all the conditions, un-jittered reflection symmetries (PMM) led to the most efficient processing.

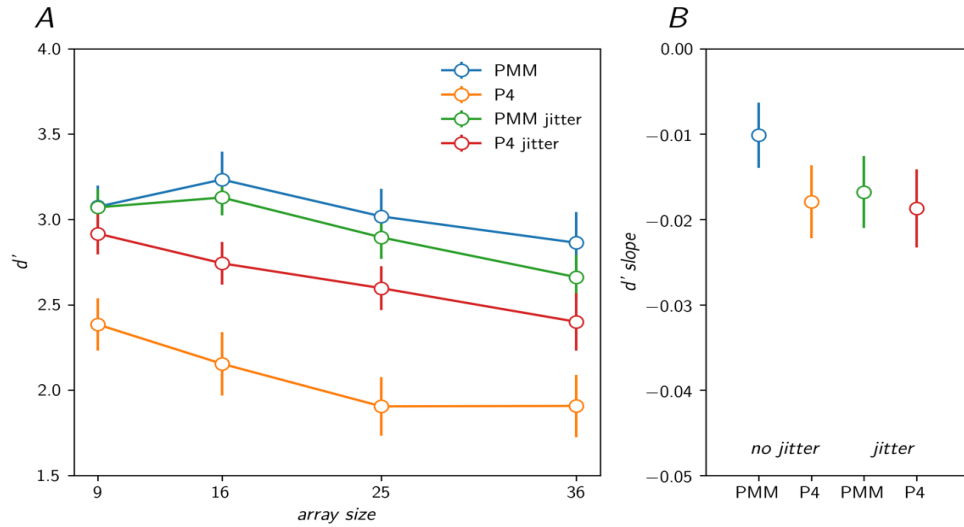


Figure 8: d' plotted in the same way as reaction time. Slopes across array sizes are relatively flat, and similar across conditions. The only exception is unjittered PMM, where the slope is flatter than the others. This implies that this condition was the easiest overall, which is consistent with the reaction time results.

2.5 Discussion

Our results identify independent effects of symmetry type and texture regularity on visual search efficiency. This is captured by the interactions between symmetry type and array size, and between jitter and array size, that we observe for reaction time. The interactions show that symmetry type and jitter both influence the slope of the search function, with reflection leading to shallower slopes than rotation, and un-jittered displays leading to shallower slopes than jittered displays. These results can be observed in Figure 5, where the shallowest slope is observed for un-jittered reflection symmetry (PMM) and the steepest for jittered rotation (P4).

The absence of a three-way interaction indicates that symmetry type and jitter have separate and independent effects on processing efficiency. The pattern of results for d' allows us to rule out speed-accuracy trade-off as an explanation for our reaction results.

Behavioral literature on symmetry, reflection vs rotation

Previous research generally used symmetry detection tasks when comparing reflection versus rotation symmetries and found that reflection was more perceptually salient than rotation (Mach, 1959; Royer, 1981; Palmer, 1991; Ogden et al., 2016; Hamada and Ishihara, 1988).

There may be evolutionary pressures toward more efficient encoding of reflection because reflection contributes to the identification of members of the same species, predators, and prey throughout evolution. Rotation symmetry on the other hand, while still prevalent in nature, may provide less salient information about objects or animals. For instance, much of the rotation symmetry which exists in nature can be seen in plants, however the distinction between plants which have rotation symmetry versus not, does not provide us with any insight if the plant is edible, or indicative of environmental danger. The presence of reflection symmetry, however, helps to quickly differentiate between animals and objects, a distinction which if made efficiently would be advantageous to an animal. Our findings are consistent with these prior works, and we thus extend these previous findings by showing an advantage for reflection in the context of visual search.

Our texture regularity manipulation reveals a novel processing advantage for symmetries when presented in regular textures. This finding is similar to previous demonstrations of whole-array effects of symmetry in visual search, but in our case, we are manipulating regularity rather than symmetry. The ecological relevance of this effect may be related to evolutionary pressures towards detecting disruptions in regular and near-regular textures in the environment, in the

context of detecting edible plants, predators or prey, that are embedded in the background vegetation.

Visual Search and Symmetry

Studies of symmetry using visual search has identified effects of both inter-item symmetry (Javadnia and Ruddock, 1988) and symmetry over the whole array (Wolfe and Friedman-Hill, 1992). Our experiment design is related to both: Symmetry type is an inter-item manipulation, while regularity is, by definition, a whole-array manipulation. Most previous work using both types of manipulation found evidence of pop-out indicating parallel processing of reflection symmetry. In our study, we do not see pop-out for any of our conditions, but rather were able to place each of our conditions along the spectrum of parallel and serial processing. However, our study is novel in that we are using the visual search task to explore the difference between types of symmetry, previous visual search work has focused only on reflection symmetry in both inter-item and whole-array manipulations. In addition to the fact our research is investigating different aspects of symmetry, we believe there may be a few reasons our results differ from previous symmetry and visual search research.

First, while our regularity manipulation is in the same general class of whole-array manipulations as those for which Wolfe and Friedman-Hill demonstrated parallel processing (Wolfe and Friedman-Hill, 1992), they are not the same: While they manipulated reflection symmetry across the array, we manipulated regularity. It is possible that there is a perceptual distinction between textural regularity and array symmetry, where pop-out is observed more in disruptions of array symmetry. We would not necessarily expect the same degree of parallel processing for these two manipulations.

But what about our inter-item manipulation of symmetry, which, especially in the jittered conditions seems generally similar to the types of displays used in previous work (REF) – why did we not observe parallel processing when inter-item reflection or rotation symmetry differed between the target and the distractor? One possibility is that parallel processing only occurs when symmetry is the target. Our design deliberately used an asymmetrical lattice as the target, while symmetrical lattices served as distractors, because this approach makes it possible to arrange the search arrays into wallpaper groups PMM and P4. We cannot rule out that using a symmetrical target among asymmetrical distractors would have led to pop-out with our stimuli, but from casual observations we consider it highly unlikely. Previous visual search work by Javadnia and Ruddock (1988) used both symmetrical and asymmetrical targets, and found evidence of parallel processing with both, and took that as parallel processing *of symmetry*. Another study which used both symmetrical and asymmetrical targets was Niimi and Yokosawa (2006) looked at processing differences between horizontal and vertical axis in reflection symmetry. In this study, they ran an analysis between conditions where the target was symmetrical versus asymmetrical and found a significant main effect in which search was more efficient when there was an asymmetrical target amongst symmetrical distractors. Despite this main effect, in both versions of their visual search task Niiki and Yokosawa (2006) also only found varying degrees of serial search patterns in all their conditions, similar to our findings where no true “pop-out” effects were observed. Niiki and Yokosawa (2006) also had very controlled symmetrical and asymmetrical stimuli which could not be discerned by lower-level visual attributes such as contrast, changes in overall scale, and shape complexity. This indicates to us that the presence of a pop-out may be more effected by the control of stimulus rather than what version of the visual search task was used.

It seems more likely that our manipulation of symmetry at the inter-item level was more carefully controlled than those used in previous work. A unique advantage of our stimuli is that we can control for low-level visual effects such as contrast and spatial frequency while still manipulating symmetry type. Previous research may have had more low-level visual differences between their symmetrical and asymmetrical stimuli which may have helped drive the pop-out effect observed there. A study which found evidence of pop-out effects was Roggeveen, Kinstone, and Enns (2003) who used similar stimuli to that found in Javadnia and Ruddock (1988), and also used letters and modified letters as stimuli. It is not unsurprising that Roggeveen, Kinstone, and Enns (2003) would find similar results when using stimuli which resembled that of Javadina and Ruddock (1998), however, it is important to note that there may have been perceptual interference by using stimuli which resembled letters. A study which highlights the impact differences between stimuli may have on visual search findings is Olivers and Van Der Helm (1998). In their study, they used four different sets of symmetrical stimuli and found varying results across experiments. Their results varied across the spectrum of parallel and serial processing, with the most similar to ours being their most well-controlled stimuli; dot patterns. These dot patterns were better controlled for low-level attributes than their other experimental stimuli which found more evidence of pop-out effects. An important goal for future research will be to determine under which conditions, if any, inter-item symmetry alone can give rise to pop-out.

Neuroimaging literature on symmetry, reflection vs rotation

The neuroimaging literature shows that both reflection and rotation produce strong responses in the visual cortex, even when participants are doing an orthogonal task and not paying attention to the symmetry (Kohler et al., 2016), but activity measured using EEG was

weaker for rotation than for reflection symmetry (Kohler & Clarke, 2021). A recent direct comparison of responses to different wallpaper groups in the visual cortex of macaque monkeys showed that activation in visual areas (V3 and V4) was approximately 1/3 larger for reflection (PMM) than for rotation (P4) (Audurier et al., 2021). Studies using non-texture stimuli with a single symmetry axis have also consistently found weaker responses for rotation than reflection (Makin et al., 2012, 2013, 2014; Wright et al., 2015). This neural advantage for reflection over rotation is consistent with the behavioral advantage observed in the current study and prior studies discussed above. An important goal for further neuroimaging research will be to directly compare symmetries when presented independently or embedded in regular textures to understand how the behavioral advantage for symmetries in regular textures arises in the brain.

Work on texture perception

Textures form the patterns that make up the surfaces of objects and environments; they play an essential role in vision in everyday life (Adelson, 2001). An important step toward understanding and analyzing human texture perception was the development of a computational model that made it possible to represent and synthesize visual textures based on joint statistics of the image (Portilla and Simoncelli, 2000). The model has proven highly useful in capturing how texture representations change across the visual field (Balas, Nakano, and Rosenholtz, 2009; Freeman & Simoncelli, 2011) and how natural textures are represented in different areas of the visual cortex (Freeman et al., 2013; Okazawa et al., 2015). Importantly, however, this modeling framework is unable to synthesize regular textures like the wallpaper groups used in our experiment (unpublished data) and therefore unlikely to contribute to our understanding of the regularity effect found in the current data or the brain imaging data mentioned above. The current data offer another piece of evidence suggesting that regular and near-regular textures

may play an important role in perception. Our findings highlight the need for the development of models that can describe and synthesize regular textures.

The healing grid illusion by Fukuda and Seno (2012) may also be relevant to our results. The illusion shows that a regular grid, disrupted in the periphery, can undergo illusory completion such that the disruption is not detected. That is, the irregularity in the periphery is filled-in by the regular texture. One interpretation of the illusion is that the visual system has a bias towards perceiving textures as regular. This may explain the finding that when the search array forms a regular texture, participants are more efficient in identifying a break in the regularity embodied in regular texture as the visual system may “default” towards regularity. While a mechanistic understanding of the relation between the results of the current study and the healing grid illusion is still lacking, the healing grid illusion nonetheless provides further evidence for the importance of regular textures in human vision.

Potential confounds and limitations

A possible limitation of this study is that while the stimuli were well controlled within participant, the data were collected online on participants own devices, which has the potential for introducing differences between participants. Participants were required to use a laptop or desktop computer for the experiment (no phones or tablets were allowed), but we made no attempts to control viewing distance or monitor resolution, which likely lead to differences in the size of the stimuli in degrees of visual angle between participants. In addition, the contrast and luminance of the stimuli may also have varied because of differences in the monitors’ used by different participants. It is important to note, however, that our effects of interest were measured within participant, and thus unlikely to be driven by these differences between participants. Furthermore, any noise added to our measurements by the lack of control is likely compensated

for by our ability to get data from a relatively large number of participants, compared to a standard psychophysical experiment.

A possible concern regarding our regularity manipulation is that the regular arrangement of the lattice in the wallpaper stimuli may have produced a mid-level visual effect where individuals dots in the lattices are perceptually grouped to form a grid-like pattern. It is possible that this grid helps guide the visual search task, because the target (a disruption of the grid) becomes easier to spot. It is important to note that such patterns across the whole texture are in a sense inherent to regular textures, and thus difficult to disambiguate from regularity itself. Furthermore, if the grid pattern was driving our regularity effect, we would expect there to stronger effect of regularity on PMM, where straight lines are more likely to form. This should produce a 3-way interaction between symmetry type, jitter, and array size. However, we did not find any such interaction, so we believe the grid effect is unlikely to impact our results.

Conclusion

Our results show that fewer cognitive resources are required to perceive reflection symmetry, than rotation symmetry. We also found that texture regularity has a significant effect on the processing of symmetries independent of symmetry type, such that when symmetries are embedded within a regular texture, they are more efficiently processed. Notably, these effects were additive to each other, and suggest symmetry and texture perception are different, presumably independent, perceptual mechanisms. These results reveal novel insights about the cognitive and neurological architecture underlying symmetry perception and provide the foundation for further research on how symmetries and textures interact in natural vision. Future work in behavioural symmetry research may seek to investigate more types of symmetry, such as translation and glide reflection, using wallpaper groups.

Chapter 3:
GENERAL DISCUSSION

3.1 Summary

The results of this thesis provide new insight into the independent effects of symmetry type and texture regularity on visual search efficiency. The results of the study show that symmetry type and textural regularity both influence the slope of the search function, with reflection leading to shallower slopes than rotation, andunjittered displays leading to shallower slopes than jittered displays. This is indicative that reflection is processed more efficiently than rotation and regular textures are processed more efficiently than isolated search items. The results provide a behavioural account which may accompany previous neuroimaging research using wallpaper groups. These results also provide insightful evidence how symmetry and texture affect behavioural responses.

3.2 Ecological Validity

While our results indicate that there is bias towards processing reflection symmetry, it begs the question, why might our brains organize symmetry information this way? The clearest explanation for this relates back to the original logic behind Gestalt theory, and the concept that fundamental gestalts may be evolutionarily advantageous. The world is an infinitely complex place, and the constant stream of visual input we receive daily could be overwhelming to the brain. To provide us with structure and direction, it is possible the visual system not only developed a prioritization of gestalts, but also more specifically, biases towards more ecologically salient versions of these gestalts. Previous behavioural research which used symmetry detection tasks when comparing reflection versus rotation symmetries and found that reflection was more perceptually salient than rotation (Mach, 1959; Royer, 1981; Palmer, 1991; Ogden et al., 2016; Hamada and Ishihara, 1988). The underlying assumption is that there may be

evolutionary pressures toward more efficient encoding of reflection because reflection contributes to the identification of members of the same species, predators, and prey throughout evolution. The findings of this thesis are consistent with this assumption. However, how does an ecological explanation extend to our findings on textural regularity?

In this study, texture regularity boasts a processing advantage for symmetries. While it is easy to infer the bias towards reflection symmetry may extend to the identification of bilateral organisms, the inference to an ecologically valid explanation of textural regularity is slightly less clear. It is possible that our brains are hard-wired towards symmetry in general, and therefore array symmetry found in textural regularities benefit from this by extension. Alternatively, since most animals exist in environments which are made up of near regular textures, for example, tall grasses, tree bark, thick brush - it would be advantageous for an animal to quickly be able to identify objects which disrupt the regular texture, such as a fruit in a tree, or a predator hiding. This may provide some insight into why our behaviour appears to have a bias towards textural regularity. However, most natural textures are not perfectly regular and as this is the case, we might expect that humans and other animals perform more efficiently on near regular textures than perfectly regular ones.

In order to tease apart the two possible explanations for a bias towards textural regularity, future research could explore if near regularity has an impact on the effects we found; are near regular textures processed more efficiently than perfectly regular, and vice versa? One such way may be to revisit the computational or neural differences found in the processing of symmetry versus texture, or to explore other examples of texture such as those which were generated by Portilla and Simoncelli (2000). Since the textures developed by Portilla and Simoncelli (2000) are near regular and do not have array symmetry, it may be easier to isolate texture processing

from internal symmetry processing. This would be a valuable next step in broadening our understanding of how these components of our visual experience interact with one another.

3.3 Visual Search as a Tool to Explore Vision

Our work differs from previous visual search studies in two ways: we made use of very controlled wallpaper group stimuli, and we were able to combine array symmetry methodology and inter-item symmetry methodology. These methods work to insight into the various methodology implementations of visual search.

While our results differ from previous visual search findings in that we did not find a strong pop-out effect for symmetry, our results provide evidence of a variance in serial and parallel processing which aligns with previous neuroimaging research on wallpaper groups. At the most basic understanding for the types of visual search, we have a dichotomy of serial versus parallel. Our findings do not align perfectly with this dichotomy and instead reflect a much more graduated spectrum between parallel and serial processing. Despite this, our findings provide behavioural evidence which bares resemblance to our understanding of how of visual cortices processes symmetries.

A study by Audurier et al. (2021) continued wallpaper work done by Kohler et al. (2016) in macaque monkeys and compared activation in the visual cortex when viewing reflection and rotation symmetries. They found that reflection symmetry elicited greater activation than rotation symmetry in V3, V4, and LOC and found little difference between symmetry type in V1 and V2. This implies that differences in processing types of symmetry can not only been seen at a neurological level but also occur in higher visual areas where more and feeds forward into higher order regions before making cognitive judgements. Based on these findings, we know that

differences between symmetry type are not distinguished in a low-level visual area, and therefore we should not expect processing them to be perfectly serial. Our results provide complementary behavioural data which support the differentiation between reflection and rotation symmetries found in Audurier et al. (2021) and that the mid-stage cortical processing of symmetrical displays matches that of non-perfect seriality in cognitive processing.

3.4 Conclusion

The current thesis provides strong evidence that reflection symmetry is processed more efficiently than rotation. The results not only provide insight into the independent processes of symmetry and texture perception but may indicate that a relationship between the two at a behavioural level. To further our understanding of the visual system, symmetry, and texture, future research should continue to investigate various types of symmetry and make use of a combination of behavioural and neurological methodology.

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