Illusory Motion and Design

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master thesis

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Abstract

Motion illusions can be created by repeating asymmetric patterns of contrasting colours. They have been extensively studied to reveal underlying features of visual perception, often difficult to tease out from veridical seeing. This thesis explored the potential applications of motion illusions in an architectural context, using the extensive scientific research on the effect to guide the design process. Three experimental prototypes were developed, each addressing uncertainties about the illusion to better understand its feasibility in design, how it could be implemented and in what contexts. The first study utilized biological computation to create novel illusory motion patterns visually represented by swarm agents. The following two studies explored the potentials of motion illusions on nonuniform, three-dimensional surfaces. This research suggests illusory motion offers opportunities for designers to manipulate the perception of material constructs to achieve compelling visual effects, but many challenges must be overcome for their successful execution.
Table of Contents

Chapter 1: Introduction
1.1 Background and motivation ........................................... 1
  1.1.1 Research question .................................................. 2
  1.1.2 Research approach .................................................. 2
1.2 Methodology ............................................................ 3
  1.2.1 Design process ....................................................... 3
  1.2.2 Design evaluation and analysis .................................... 3
1.3 Outline ................................................................. 3

Chapter 2: Background
2.1 Lessons from illusions .................................................. 5
  2.1.1 The neurophysiology of the visual system ...................... 5
  2.1.2 The inverse optics problem ....................................... 6
  2.1.3 Redefining illusion .................................................. 6
2.2 The Fraser-Wilcox illusion .............................................. 7
  2.2.1 A historical summary of Fraser-Wilcox type illusions ........ 7
  2.2.2 Understanding the illusion ....................................... 9
  2.2.3 Beyond pictures ..................................................... 9
2.3 Environmental Psychology, patterning and the ecological approach to perception ............................................. 10
  2.3.1 Gestalt psychology .................................................. 10
  2.3.2 Gibson and ecological approach to perception ............... 11
  2.3.3 Gombrich on art ..................................................... 11
2.4 Illusions in art, architecture and design ............................ 11
  2.4.1 Illusions in architecture ........................................... 12
  2.4.2 Illusions in paintings .............................................. 12
  2.4.3 Beyond scientific applications ................................... 14
2.5 Conclusion ............................................................. 14

Chapter 3: Illusionary swarm agents
3.1 Methods ................................................................. 16
  3.1.1 Swarms and their applications ................................... 16
  3.1.2 An illusionary swarm program ................................... 17
  3.1.3 Reynolds’ boid model and steering urges ...................... 18
  3.1.4 Setting up initial program conditions ......................... 18
### 3.1.5 Running the simulation

- Results...21
- Observations...21

### Chapter 4: Origami

- Methods...25
  - Why origami?...26
  - Choosing a RAP...26
  - Creating a folding pattern...27
- Results...28
  - Observations...28

### Chapter 5: 3D Rollers Illusion

- Methods...33
  - Choosing a model...34
  - Constructing a 3D model...34
  - Building two models...35
- Results...36
  - Observations...37

### Chapter 6: Summary of Results

- Illusionary swarm agents...38
- Origami...38
- 3d Rollers Illusion...38

### Chapter 7: Discussion

- Illusionary swarm study...39
  - Design considerations...39
- Origami study...41
  - Design considerations...42
- 3d Rollers study...44
  - Design considerations...44
- Limitations...46
  - Research limitations...47
  - Design limitations...47
- Future work...48
  - Background...48
7.5.2 Hypothesis ......................................................... 49
7.5.3 Design implications .......................................... 51

<table>
<thead>
<tr>
<th>Chapter 8:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Conclusion</td>
<td>52</td>
</tr>
</tbody>
</table>

| Chapter 9:                    |                  |
| References                    | 53              |
List of Figures

Figure 1  Examples of popular visual illusions.  ........................................... 2
Figure 2  Motion illusions. ................................................................. 3
Figure 3  Rotating Snakes Illusion. ......................................................... 4
Figure 4  Illusions in architecture. ......................................................... 5
Figure 5  Trompe l‘oeil in painting. ......................................................... 6
Figure 6  Illusions from the renaissance. .................................................... 7
Figure 7  Illusion on the sidewalk. .......................................................... 8
Figure 8  Distance and angle parameters determine the neighbourhood of a boid agent.  . 12
Figure 9  Initial swarm program conditions............................................. 13
Figure 10 Precedents for the origami chevron patterns and colours. ............... 14
Figure 11 Folding technique developed. ................................................... 15
Figure 12 Creating origami RAP forms. .................................................... 16
Figure 13 The 3D Rollers illusion. ........................................................... 17
Figure 14 Profile of 3D Rollers models. .................................................... 18
Figure 15 Illusionary patterns created by optimal swarm conditions. ............... 22
Figure 16 Illusionary patterns created by less optimal swarm conditions. .......... 23
Figure 17 Examples of RAP streamlines used in the origami study. ................. 24
Figure 18 Various origami folds created. ................................................... 25
Figure 19 Examples of patterns created in the origami study. ......................... 26
Figure 20 3D motion illusion folded every second chevron. .......................... 27
Figure 21 3D motion illusion folded every third chevron. ............................ 28
Figure 22 3D Rollers illusions. ............................................................... 29
Figure 23 Side view of 3D Rollers illusion. ............................................... 30
Figure 24 Gestural motion cues. .............................................................. 32
Figure 25 Example of RAP patterns as a facade. ....................................... 34
Figure 26 Approximately the section of the original Rollers illusion recreated as a 3D model. ............................................................... 36
Figure 27 Staircase illusion. ................................................................. 37
Figure 28 Illuminated spheres illusion. ..................................................... 40
Figure 29 RAPs as abstracted versions of 3D objects. .................................. 44
List of Tables

Table 1  Basic steering urges of swarms based on Reynolds’ boids model. . . . . . . . . . . 11
Table 2  Variables in the illusionary swarm program and their effect on swarm behaviour.. 22
Chapter 1: Introduction

This chapter begins by describing the background and motivation of this thesis, to arrive at the research question and research approach. Next, the methodology is described, followed by the final section which highlights the structure and chapters of the proceeding document.

1.1 Background and motivation

It can be difficult to appreciate the immense complexity which underlies the seemingly effortless act of seeing (Eagleman, 2001). Visual illusions have been extensively studied for this reason, they help reveal underlying features of visual perception, which are otherwise hidden or difficult to recognize in ordinary seeing (Epstein & Rogers, 1995). Yet, before modern science discovered their utility as study models, illusions had already been exploited for a variety of applications, especially by artists and architects, who found useful opportunities in their intrinsic ability to manipulate perception.

Fraser-Wilcox type illusions elicit percepts of motion from static images, by using repeated asymmetric patterns (RAPs) of contrasting colours. Despite being extensively studied and relatively simple to create heuristically, motion illusions, unlike other kinds of illusions, have yet to receive much attention from creative fields. Illusions of scale, form, and perspective, for instance, have been used by architects to enhance the experience of built spaces, in light of economic or spatial constraints (Spiliotis, 2008). Illusory motion could offer another opportunity for designers to manipulate the perception of material constructs for aesthetic and functional visual characteristics.

Perception of motion is useful for more that just perceiving the movement of objects. Attention guides what visual stimuli are perceived and which are ignored. Motion acts like a spotlight for attention, making it a powerful visual cue. Motion perception is also used by the visual system to differentiate between figure and ground, compute the shape of three-dimensional objects and determine the relative distance of objects from oneself (Heeger, 2006).

Design with implied motion could potentially serve many of the same functions as real motion; it could imply liveliness, capture attention, provide cues about form, distance and direction. It offers possibilities to control and enhance the experience of spaces and materials, by evoking genuine percepts of movement from their static forms. Patterning is already a well-established design tool used for various functions like aesthetics, wayfinding, symbolism and camouflage. The characteristic patterning of Fraser-Wilcox motion illusions, could be applied in many of the same ways as other patterns: as screens, facades, cladding, and ornamentation, for instance.

As a preliminary, qualitative design study, this thesis explored the potential for motion illusion in design and architecture, by developing experimental prototypes. These prototypes address basic
questions about the challenges and opportunities which could arise as new variables are introduced to these otherwise simple motion illusion graphics. Moving beyond images on a piece of paper, into applicable, contextual, performative design effects, motion illusions offer new ways to imaging the conception of space.

1.1.1 Research question

Does illusory motion have applications in architectural design and if so, why and how?

1.1.2 Research approach

“The scientist believes that problems can be solved with his intellectual equipment plus instruments. His answers are always quantifiable. The designer goes along with this to a great extent, but he also relies on the evidence of his senses and his intuition. So his work falls somewhere between art and science.”


This research is a preliminary, exploratory, qualitative design study. The role of the researcher is not that of a psychologist, trying to explain or reveal new understandings of motion illusions through quantitative methods. Instead, the role is that of a designer, exploring the potential applications of motion illusions in an architectural context, using scientific precedents as guidance. Human subjects and statistical tests of significance which one would expect from a psychological study on visual illusions, are not used in this study. The goal is not to prove the effectiveness or characteristics of particular designs by comparing them among human subjects, but to explore the design possibilities of this effect. Conclusions drawn, are those of the researcher and largely guided by intuition and observation.

Design, though difficult to precisely define, can be loosely understood as starting with a problem and arriving at a contextual solution (Theil, 1981) – a purposeful intervention. This work begins with a problem, the research question and the work that follows does not unravel from a predictable, linear plan of action, but arrives at new insight through trial and error.

All Fraser-Wilcox illusions known to date are pictorial. The preliminary and exploratory nature of this research is largely due to the unpredictability of attempting motion illusions in a more complex, three-dimensional (3D), architectural context. Perception of pictures is not the same as perception of objects in the environment. The usual perceptual cues like shading, texture, motion and figure-ground relationships are not present in pictures except by representation (Gibson, 1978). What this means in regards to motion illusions, as one moves beyond picture illusions is unknown, and a main challenge of this research.
1.2 Methodology

This thesis consists of an analysis of related literature and precedents, followed by three design studies and their evaluation. It follows an interpretivist, qualitative approach to research, based on observation and normative assessments of the results. The preliminary, open-ended nature of the research question is addressed through exploratory, heuristic methods which develop and evaluate design prototypes, to suggest possible applications of motion illusions in architectural contexts.

1.2.1 Design process

First, an extensive literature review examines the theoretical and applied research on visual perception, motion perception, visual illusions, and Fraser-Wilcox motion illusions. A brief description of environmental psychology, as it pertains to visual perception, is then described to establish the relationship between the science and artistic components of this work. Related design precedents with an emphasis on illusions in art, architecture and design are then described. These provide insight to inform the conception and design of the experimental prototypes in each study of the three studies: Illusionary swarm agents, Origami and 3D Rollers. Each study addresses questions and perceived obstacles about the illusion’s feasibility in design, how it could be applied and in what kind of contexts.

The first study develops a biological computation program where swarm agents are visually represented as illusionary shapes and used to generate novel illusory motion patterns. This study reveals several variables which influence the effective strength of motion illusions. In the second study, motion illusion paper images are folded into 3D origami surfaces to explore illusory motion on non-uniform surfaces. This study brings awareness to several opportunities and challenges for the applications of the illusion within a 3D context. In the final study, a 3D version of a motion illusion image is constructed, comparing their illusionary effectiveness, and exploring how form and illusion can be designed concurrently.

1.2.2 Design evaluation and analysis

The design prototypes in this study are evaluated by observation and direct experience, whether or not they generate illusory motion and the characteristics of their effect on the researcher. The prototypes are normatively evaluated and the results provide new insight about the potential applications of illusory motion for design.

1.3 Outline

The proceeding Chapter 2 provides a background and literature review in four sections. First it
describes illusions from a scientific perspective, basic features of visual perception and the usefulness of illusions for research. The following section provides an overview and brief history of Fraser-Wilcox motion illusions. The third section describes the field of environmental psychology within the scope of visual perception, to demonstrate the relationship between the science that informs this thesis and the qualitative, design approach to the work. The final section highlights uses throughout history of illusion in art and architecture.

The three design studies are each assigned their own chapter, first describing the methods used for that prototype, followed by the results. Chapter 3 describes the Illusionary Swarm study. Chapter 4 consists of the Origami study, and Chapter 5 presents the 3D Roller Illusion. Chapter 6 provides a brief, overall summary of the results of all three studies, as a prelude to the discussion in Chapter 7.

The discussion is organized into three sections. The first discusses the results of each design study as they relate to the potential design applications for illusory motion. The second section discusses the limitations of this thesis and the limitations of illusory motion for design. The final section presents a new hypothesis to potentially explain motion illusions, and suggests future work which could address it. Chapter 8 is the conclusion, outlining the main outcomes of this thesis and the potentials for future work.
Chapter 2: Background

Scientists have systematically studied visual illusions to unravel the intricacies of the visual system, while artists have creatively explored them for aesthetics. Despite differing intentions, the underlying usefulness of illusions lays in their ability to bring awareness to the subjectivity of our own perception. The following discusses the diverse applications of illusions both in the sciences and the arts, and provides a brief overview of visual perception and environmental psychology research, to arrive at the relevance of illusions in this present thesis.

2.1 Lessons from illusions

While examples of visual illusions are familiar to most people, there is some difficulty in rigorously defining what they are, exactly. The following briefly describes some basic features of the visual system to help arrive at a definition of illusions, from a psychology standpoint, and an understanding of their usefulness as study models for scientific research.

2.1.1 The neurophysiology of the visual system

The simplest concept of an illusion is a visual experience or ‘percept’ that fails to agree with real world measurements (Purves, Wojtach & Howe, 2008). This definition, though not quite complete, provides a useful starting point, because it alludes to perception as being something other than an absolute representation of the world.

Visual stimuli are not simply received and mirrored back into a conscious experience. They must be sensed, processed and interpreted through a series of complex structures and pathways. Visual information is first received by receptors, rods and cones, located on the retina. Their input projects through the optic nerve to a subcortical region in the brain, the lateral geniculate nucleus (LGN), which serves as a major relaying and processing centre for visual information. Input from the LGN is sent to the primary visual cortex where it flows through a cortical hierarchy processing a variety of visual primitives specific to their cortical layer, such as edge detection, orientation, motion and colour. Information travels along two different pathways in the cortex, the ventral stream, concerned with determining the ‘what’ of a given scene and the dorsal stream determining the ‘where’ (Vitay, Rougier & Alexandre, 2005). These separate pieces are put back together to paint a cohesive interpretation of environmental stimuli for us to see and react to. The visual system is organized as a set of recurrent loops, not a simple linear chain of causation (Anderson, 2011) and vision is much more than a passive diffusion of sensory information.
2.1.2 The inverse optics problem

Not only are pieces of visual information processed independently then pieced back together, but the initial retinal information is inherently two-dimensional, out of which the brain must reconstruct a three-dimensional world. This is a central, underlying problem in vision research, the inverse optics problem (Howea, Lotto & Purves, 2006). Any 2D retinal image could result from an infinite number of real world pairings, yet the visual system somehow accounts for this ambiguity and generally interprets it successfully (Purves, et al., 2008). The sheer complexity of the visual system and its ability to interpret useful stimuli while filtering out a bombardment of unnecessary stimuli, has made it a difficult system to unravel.

Here lies the usefulness of perceptual illusions, the complex structure of the visual system can be exposed by them. Stimuli at the extremes of what our system has evolved to handle, illusions often stem from assumptions made by the visual system (Eagleman, 2001) and bring awareness to underlying processes otherwise hidden and difficult to recognize in ordinary, veridical seeing (Epstein, 1995).

2.1.3 Redefining illusion

In a sense all vision is illusionary, since perception pieces together a useful interpretation of the world which does not necessarily coincide with reality. We are unaware of our blind spot, the edges of

![Figure 1: Examples of popular visual illusions. a) Rubin’s vase, an ambiguous figure  b) Müller-Lyer illusion, both vertical lines are the same length but the one on the left appears longer  c) Zöllner illusion, the diagonal parallel lines appear non-parallel (created by author).](image)

our field of view, or the poor acuity of our peripheral vision (Eagleman, 2001). We enjoy the ‘illusion’ of a seamless, boundless visual field because our visual system constructs this for us. In light of this understanding, visual illusions, could be redefined as simply the more extreme instances in which the differences between what one sees and measured reality are especially obvious (Purves, Wojtach & Howe, 2008). It is this awareness which makes them so useful for research.
2.2 The Fraser-Wilcox illusion

Rubin’s vase, Müller-Lyer illusions and Zöllner illusions (Figure 1) are a few popular examples of illusions which have been brought awareness to some of the mechanics of visual perception and assumptions made during visual processing. For instance, Figure 1b shows two lines vertical of identical lengths. However, the adjacent lines joining them, makes one appear longer than the other, suggesting an underlying assumption is made by the visual system, on the basis of the context.

Motion illusions, characterized by the perception of movement in static imagery, have themselves a large body of research devoted to their understanding. There are several different types of motion illusions, for instance, motion aftereffects and stroboscopic images. This thesis focuses specifically on Fraser-Wilcox motion illusions, sometimes referred to as peripheral drift illusions (Faubert & Herbert, 1998), characterized by asymmetric patterns of repetitive colour sequences. A brief history of some of the research regarding Fraser-Wilcox illusions is described below.

2.2.1 A historical summary of Fraser-Wilcox type illusions

Figure 5a shows the original Fraser-Wilcox illusion, or ‘escalator’ illusion, consisting of repeated elements shaded dark to light, arranged in a step-like spiral staircase pattern. Though the observed motion is generally perceived as weak, it induces the percept of rotary illusory motion for most observers (Fraser & Wilcox, 1979). Several years later, Faubert and Herbert (1998) described their peripheral drift illusion as being of the same phenomenon as Fraser-Wilcox (Figure 5b), with both demonstrating the strongest effect in the peripheral visual field. Their illusion is visually quite similar to the original, but rather than a staircase-like pattern with elements tapering towards the centre, Faubert and

Figure 5: Motion illusions. a) Fraser-Wilcox Illusion also known as Escalator Illusion (Fraser & Wilcox, 1979). b) Peripheral Drift Illusion (Faubert & Herbert, 1998).
Herbert’s illusion consists of equally sized sawtooth luminance gradients shaped like pie pieces.

Kitaoka strengthened the motion effect by developing what he calls an optimized Fraser-Wilcox illusion (Kitaoka, 2006a). He assigned a basic rule for generating illusory motion using repeating asymmetric patterns (RAPs) of colour in the order: black, dark gray, white, light gray. His famous Rotating Snakes in Figure 2, is a later example of this rule, where he also demonstrated his discovery of particular colour pairs as successful replacements for achromatic RAPs (Kitaoka, 2006b).

Kitaoka’s rule can be satisfied by infinite configurations, but several authors since described particular properties which strengthen or lessen the effect in a composition. A detailed description of these is provided by Backus and Orec (2005). Chi, Lee, Qu and Wong (2008) most recently developed a computational approach to generating new, more complex, optimized Fraser-Wilcox illusions they call ‘self-animating images.’ Using an input image, their approach creates coloured streamlines of RAPs along vector fields implied by the different colours and shape boundaries within the image, and developed optimized ways to arrange these streamlines to generate a strong motion effect. The researchers’ own ‘Starry Night’ illusory image created using this method, based on the famous Van Gogh painting, is a compelling example of the strides which have been made to increase the strength and complexity of the original illusion (hyperlink).

![Rotating Snakes Illusion](image_url)
2.2.2 Understanding the illusion

The perceptual mechanism which underlies Fraser-Wilcox illusory motion is still a matter of debate. Some suggest it can be explained simply by the mechanics of the eye, while others suggest it results from higher cortical reasoning. The original authors did not propose an explanation, but shed light on the illusion’s polymorphic response (Fraser & Wilcox, 1979). They demonstrated that different subjects observed different directions and longevity of motion from one another. Faubert and Herbert (1998) suggested the illusion is generated by the interaction of three processes: (i) resetting produced by eye movements or blinks (ii) differing latencies in the processing of dark and light luminance, and (iii) the integration of these luminance signals across the periphery, which becomes misinterpreted as motion. Kitaoka explained the similarities between his own optimized Fraser-Wilcox illusions and several other illusion types, including phi movement and stereopsis, suggesting they share a common underlying neural mechanisms (Kitaoka, 2006). He proposed eye movements to be key for generating the effect (Murakami, Kitaoka & Ashida, 2005; Kuriki, Ashida, Murakami & Kitaoka, 2008) and luminance contrast to be a critical factor (Kitaoka & Ashida, 2003). Backus and Oreć (2005) proposed the illusion results primarily from fast and slow changes over time in the neuronal representation of contrast or luminance, and suggest people infer the presence of motion in static RAPs because they evoke a pattern of neural activity that normally occurs only when objects really are moving.

2.2.3 Beyond pictures

The preliminary nature of this thesis work is largely due to the uncertainty of attempting to create motion illusions in a context beyond 2D pictures, which represents all Fraser-Wilcox illusions known to date. Pictures are so familiar to us, it may be surprising that understanding the perception of pictures is a challenge in itself, that has plagued not only vision researchers, but artists and their critics, as well. J.J Gibson (1978), an seminal author in vision research writes:

“To see the environment is to extract information from the ambient array of light. What is it, then, to see a picture of something?...The kind of vision we get from pictures is harder to understand than the kind we get from ambient light, not easier... A picture is both a surface in its own right and a display of information about something else. The viewer cannot help but see both, yet this is a paradox, for the two kinds of awareness are discrepant. ”

He suggests theories of visual perception should end with explaining pictures not begin with them. Most researchers tend to use pictures in their studies, deeming them the simplest, most basic features from which to study perception. Gibson argues they are, in fact, the most difficult to understand and their perception should not be considered identical to objects.
2.3 Environmental Psychology, patterning and the ecological approach to perception

The field of environmental psychology is a comprehensive and multidisciplinary field concerned with the interrelationship between humans and the environment. Just as the term environment can be broadly defined, so to is the breadth of research in the field, encompassing ideas from psychology, planning, architecture, anthropology and biology, for instance (De Young, 1999). It reinforces a link between science and design, because of its emphasis on better managing and designing the built environment through a greater understandings of human-environment interactions.

Within this broad field of research, focusing more specifically on that which is pertinent to this thesis, several thinkers were largely influential in bringing awareness to the contextual nature of perception, and how visual perception influences and is influences by the environment. The following highlights some of the early theorists which lent themselves to the foundations of environmental psychology, with an emphasis on visual perception and patterning.

2.3.1 Gestalt psychology

Gestalt psychology emerged in Germany during the early part of the twentieth century (Theil, 1981). Critical of traditional reductionist approaches to psychology, their ‘gestalt’ or ‘whole form’ approach emphasized that external stimuli are perceived as a whole rather than the sum of their parts (Soegaard, 2010). They suggest the mind innately and automatically organizes stimuli into patterns, developing principles of organization and laws of grouping. For instance, their Law of Proximity refers to when visual stimuli are close to one another, they are automatically perceived as forming a group (Figure 3a). Likewise, their Law of Similarity refers to the tendency of element sharing commonalities

![Figure 3: Lessons from Gestalt. a) Elements of visual stimuli located in close proximity to one another have a tendency to be perceived as a group. b) Elements sharing similar colour attributes tend to be perceived as a group](image)

**Figure 3: Lessons from Gestalt.** a) Elements of visual stimuli located in close proximity to one another have a tendency to be perceived as a group. b) Elements sharing similar colour attributes tend to be perceived as a group.
in form, size, or color, for instance, as being perceived as a group (Figure 3b) (Theil, 1981).

2.3.2 Gibson and ecological approach to perception

Gibson credited the Gestalt psychologist for their influence on his ideas in his ‘Ecological Approach to Visual Perception’ (1979) though he was not without criticism of their ideas as well (Gibson, 1978). Nonetheless, Gibson was largely influential to the field of environmental psychology because of his emphasis on an ecological approach to perception, emphasizing the role of the interaction between oneself and the environment in the act of seeing. He was critical of traditional methods of vision research which used controlled, distilled, laboratory conditions for studying vision because they did not reflect the way in which we view the real world, which is reliant on context and pattern for meaning and interpretation. He explained in his earlier works, he considered vision to depend on the eye connected to the brain. Later, he approached vision as depending on ‘the eye in the head on a body supported by the ground’ reflecting an embodied approach to cognition and perception, heavily dependent on human-environmental interactions.

2.3.3 Gombrich on art

Gibson’s work also influenced that of Gombrich. His seminal book ‘Art and Illusion’ (1960), was an attempt by the art historian to explain pictorial representation, in the context of how we are able to understand and appreciate art. Like Gibson, he took an ecological stance, suggesting we use context and previous experience to interpret representational images. In another of his famous works, ‘A Sense of Order’ (1979), he suggests organisms seek out on patterns in the environment because they require a perceptual framework against which ‘to plot deviations from regularity’ (Kolarevic & Klinger, 2008). He suggests there exists an inherent bias in human perception for simple configurations, geometries and other simple orders (Popow, 2000). The ubiquitousness of visual simple patterning in architecture, art, and fashion, for instance, amongst all cultures, reflects this influential role of pattern in cognition and perception (Gombrich, 1979).

2.4 Illusions in art, architecture and design

Not only have illusions played an important role in vision research, but artists have made use of them since classical antiquity to achieve desirable aesthetic effects. The following presents a brief overview of some of their more creative applications.
2.4.1 Illusions in architecture

One of the most famous and oldest known application of illusions in architecture is the Parthenon in Athens. The Greeks corrected for perspective distortion by using curved and tapered columns which appear perfectly straight and symmetric to the viewer (Spiliotis, 2008). A modern, perhaps more literal example in architecture, is the cafe wall illusion which was transposed directly onto the Port 1010 building in Melbourne, Australia (Figure 4). The illusion makes the high rise building appear as if its floors are sloped and uneven, despite their uniformity, creating a simple but compelling building facade.

2.4.2 Illusions in paintings

Following the discovery of perspective during the Renaissance, two well-known illusionary painting techniques developed, the trompe l’oeil and anamorphosis (Spiliotis, 2008). In the trompe l’oeil technique, artists used realistic imagery to create the illusion of their depicted objects existing outside of their paintings, like the curtain hanging in front of a vase of flowers in Figure 5 by Adriaen van der Spetl and Frans van Mieris. Often this technique has been intertwined with architecture, like the artist Paolo Veronese who worked in conjunction with architect Andrea Palladio to design frescoes for his Villa Barbaro. His vivid depictions include servants peaking their heads out of imaginary doors.

Figure 4: Illusions in architecture. Port 1010 in Melbourne Australia, an example of the Cafe Wall illusion (Bek, 2007).
and beautiful landscaped scenery made visible from imaginary windows (Figure 6a).

Anamorphosis is the creation of a distorted projection or representation of an image, which appears to be in proportion only when the viewer occupies a specific vantage point (Topper, 2000). A famous example is Holbein’s ‘The Ambassadors’, depicting a large skull only revealed by standing far right of the painting (Figure 6b). This technique would later influence thinking in psychology and the works of postmodern theorists who argued that it illustrated the ambiguous, relative nature of visual perception (Topper, 2000). Ames famous chair demonstration of a mishmash of sticks reconstituting the shape of chair, when viewed from only one specific vantage point, was another example used to support this assertion (Epstein, 1995) and the subjectivity of human experience (Topper, 2000).

20th century illusions like those of the Op Art movement, are perhaps more familiar examples. One of its pioneers, Bridget Riley, masterfully developed pictorial techniques to evoke genuine percepts of movement and three-dimensional form in her paintings. In Cataract #3 for instance, she creates the illusion of depth and movement using only line arrangements and a palette of four colours. What is so interesting about Riley’s work in the context of this thesis, is her constant use of patterning. Like RAPs, Riley’s patterns of dots, triangles, curved lines and circles, are so meticulously arranged, they evoke percepts of movement, through the subtle adjustments to multiple elements. Like Ames and
anamorphosis, Riley’s work has been used a psychological model for studying illusory motion (Zanker, Hermens & Walker, 2010; Wade, 2003).

2.4.3 Beyond scientific applications

McLuhah and Parker suggest ‘the effect of all arts under all conditions is to counteract the invisible character of the environment and thus heighten perception’ (Theil, 1981). Art brings awareness and consideration to that which is often overlooked and undervalued, much the same way that visual illusions are used by researchers for the same purpose.

Illusions have a history predating modern science, through various mediums and for a diverse range of applications. Illusions need not always serve a scientific purpose, they can simply create interesting, more visually engaging designs like the tourist drag of Las Ramblas in Barcelona, which has an illusion embedded in the tiles of its street (Figure 8). Its wavy pattern of gray and off-white tiles deconstructs the typical, flat floor plane, creating a sense of dimension to an otherwise typical, uninteresting surface.

2.5 Conclusion

While motion illusions have been extensively studied by scientists, other than a few examples such as Bridget Riley’s op art, they have not been explored with the same vigour as other illusions,
for aesthetic applications. While scientists study illusions to understand the mechanics of perception, the nature of their work, rarely moves beyond explanation to application, because this lies beyond the goals of their research. This thesis work makes the connection between research to design. The breadth of research on motion illusions provides a useful point of departure to guide the design process, while the many examples of other illusions created by artists offer useful design precedents.

Figure 8: Illusion on the sidewalk. Las Ramblas, a busy main street in Barcelona. The repetitive two-tone tiles create the illusion of a wavy 3D surface (image by author).
Chapter 3: Illusionary swarm agents

Chapter 3, 4 and 5 describe the three design studies undertaken: Illusionary swarm agents, Origami, and 3D Rollers, respectively. Each chapter is broken up into two sections, the first describes the methodology used, then the results of that study. Chapter 6 provides a concise summary of the results of all three studies as a prelude to the discussion in Chapter 7. The following describes the first of the three studies conducted, illusionary swarms.

3.1 Methods

Kitaoka’s rule of using repeated patterns of four sequential colours (see section 2.2.1) could be satisfied with an infinite number of forms and arrangements, yet at the same time, simply creating a composition abiding his rule does guarantee an illusory effect. There already existed many examples of motion illusion but the difficulty of attempting to create a new one, was unknown. The first, most preliminary study with swarm agents was foremost an attempt to produce a motion illusion. A computational program was developed to explore the emergence of illusory motion from arrangement of RAPs and observe how different RAP patterns influenced its effectiveness.

3.1.1 Swarms and their applications

In 1987, Reynolds presented a computational approach to animating the flocking behaviour of birds. Rather than scripting the path of each individual element, boids, as he coined them, were programmed as a group, with a relatively simple set of individual behaviours. Through local interactions with each other and their environment, they could achieve complex group dynamics, like flocking. The principles of his agent-based swarm model found applications in many other research fields (von Mammen, Wong & Jacob, 2008).

Real-life swarms are found throughout the animal kingdom, such as schools of fish and many social insects such as bees, wasps and termites (Hinchey, Sterritt & Rouff, 2007). In computer science, swarms consist of multiple simple entities, programmed with local interactions to respond to each other and their virtual environment (von Mammen, Jacob & Kokai, 2005). Each agent is implemented as an independent actor, navigating its environment according to its own perception, the physics of its motion, and a set of behaviours programmed by the ‘ animator’ (Reynolds, 1979). The usefulness of swarms lay in their ability to achieve complex group behaviour from a set of simple, ubiquitously applied parameters. They can generate intricate structures, provide data on their local environments, even find optimal solutions to assigned tasks (Hinchey et al., 2007). Swarms have recently become a useful tool for artists, architects and designers, who utilize the accessibility of their relatively simple
computing and lively organic qualities, to achieve complex visual effects (von Mammen, et al., 2008).

### 3.1.2 An illusionary swarm program

In the present thesis, swarm agents were used as a tool to explore RAP patterning and develop novel motion illusions, using their versatility and malleability as an exploratory design technique. Swarms, by their nature, are related parts in relative motion. This made them a useful tool for exploring the relationship between emergence and topology of the illusion.

![Figure 9: Kitaoka’s ‘Rollers’ illusion.](image)

The software development platform Processing® was used to create a program where swarm agents were visually represented as RAPs and their coordinated flight yielded illusionary patterns. Segments of illusion, or RAP forms, were programmed as ‘illusionary swarm agents’ where each individual shape was recreated as a free moving agent with flocking behaviour, based on Reynolds’ boids model (Reynolds, 1979). The RAP form was based on shapes in Kitaoka’s ‘Rollers’ illusion (2006), shown in Figure 9, because this illusion produced a relatively strong motion effect. Secondly, unlike other illusory compositions, such as his ‘Rotating Snakes’ (Figure 2), ‘Rollers’ is composed of individual RAP entities. Rather than large streamlines of patterns, these could be easily visually translated to individual agents. Thirdly, the RAP properties (colour, shape, size, etc.) had already been proven successful by
Kitaoka, so one could begin these experiments knowing that if a proper arrangement pattern is met, the forms should produce an illusory effect.

**Table 1: Basic steering urges of swarms based on Reynolds’ boids model** (created by author based on: Reynolds, 1979; Reynolds, 2001).

<table>
<thead>
<tr>
<th>Steering Urge</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Separation:</strong></td>
<td>Avoid collisions with nearby flockmates. Insures boids do not run into each other</td>
</tr>
<tr>
<td><strong>Alignment:</strong></td>
<td>Attempt to match velocity of nearby flockmates.</td>
</tr>
<tr>
<td><strong>Cohesion:</strong></td>
<td>Attempt to stay close to nearby flockmates. Boids are urged towards the mean centre of the flock</td>
</tr>
</tbody>
</table>

### 3.1.3 Reynolds’ boid model and steering urges

Following Reynolds’ boid model (1979), each illusionary agent was programmed with three interrelated variables: alignment, cohesion, and separation weights. A description of these flocking urges is provided in Table 1. The strength of their influence on swarm behaviour could be regulated by their respective weight values. Typically, boids only react to other flockmates within their neighbourhood. This region is defined by a distance (measured from the centre of the boid) and an angle, measured from the boid’s direction of flight (Figure 10). Flockmates found outside their neighbourhood perimeter are ignored by the individual (Reynolds, 1979).

### 3.1.4 Setting up initial program conditions

570 illusionary agents were programmed to instantiate at random locations across the screen
(Figure 11). The eyelid-shaped agents were 36 pixels long, with randomly assigned widths between the range of 12 and 20 pixels, in accordance with the varying sizes within Kitaoka’s image. A key press ran the simulation allowing agents to move and interact with one another. Another key press stopped the simulation, freezing the agents in position and the resultant, frozen composition could be observed for illusory effectiveness. Large gaps between RAP forms was suggested to weaken the effect (Backus & Orec, 2005). Thus, the number of agents was chosen based on the maximum amount that could fit on the screen (900 x 900 pixels), while still maintaining enough room for them to move freely as the simulation ran.

3.1.5 Running the simulation

Illusionary agents were programmed with flocking behaviours, maximum and minimum distances for recognizing neighbours and a top speed. The weights of all these variables could be adjusted to observe their influence on agent behaviour, and the arrangement patterns that resulted. Variations of these variables were tested in different combinations to arrive at different pattern characteristics which could be compared for illusory effectiveness. Dozens of iterations of different combinations of weight values were tested by repeatedly running the simulation. The simulation could run for a second or even minutes, to see how arrangements changed over time. In each case, a combination of variables would run, and following a key press, the resulting image would be observed for illusory motion. The goal in these simulations was not simply to specify the role of each programmed variable, but to generate effective illusory motion and explore how different arrangements contributed to stronger or weaker effect.
Figure 11: Initial swarm program conditions. Illusionary swarm agents instantiated at random locations across the screen. Following a key press, the agents moved and interact with one another. The simulation could be be frozen with another key press so the resulting arrangement could be observed for illusory motion.
3.2 Results

The computational program was successful at creating illusory motion images. Running multiple simulations with different combinations of agent behaviours also revealed important attributes of the illusion which contribute to its motion effectiveness.

3.2.1 Observations

Even random configurations of illusionary agents in the swarm simulation program generated illusory motion. However, particular RAP arrangements were observed to have a stronger motion effect than the random condition, while others produced weaker effects. Table 2 describes the main variables within the simulation and how their values affected swarm patterning. Midrange values for all these variables produced the most ideal conditions which generated the strongest motion illusions. Because these variables were interrelated, the range of values are relative estimates and reflect the influence of each variable considering a midrange value of all other variables.

Two main conditions appeared to have the greatest influence on the motion effect: distance between agents and the orientation of agents. Patterns resulting from agents spaced far apart or clumped together and overlapping, generated weaker motion illusions than more uniformly distributed ones. Patterns of agents aligned in similar directions also appeared to generate stronger motion than those randomly configured. This condition did not require all agents on the screen be aligned in the same direction, even multiple groups aligned in different directions could elicit a stronger motion effect than complete randomness. The ideal conditions, represented by the midrange values described in Table 2, consisted of agents grouped into clusters of similar orientations, spaced uniformly apart within the whole composition, without overlapping.

Figure 12 shows two examples of swarm patterns resulting from the ideal conditions described. Within these ideal conditions, as the simulation ran neighbouring agents rotated and aligned with one another to match the orientation of their neighbour as they encountered one another. Common alignments would develop between adjacent agents, until groups formed and moved in unison as large clusters. This pattern formation through alignment strengthened the motion effect when the simulation was frozen and the direction of movement of the swarm clusters was retained as illusory motion in the frozen image. The simulation only took 30 seconds or more for this behaviour to occur. Once clusters formed, agents would generally remain within clusters, though the direction of their overall group movement sometimes changed over time.

Figure 13 shows examples of patterns created by the extreme conditions outside the ideal midrange values which produced weaker motion illusions. With too much alignment weight, not enough separation weight, or too great of a perceptual range, agents would clump together and overlap, creat-
ing large gaps between neighbouring clusters. An opposite effect occurred by reversing these variables. Too little alignment weight, too much separation weight or too little of a perceptual range and agents would spread far apart or would not align with one another.

**Table 2: Variables in the illusionary swarm program and their effect on swarm behaviour.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value range of effectiveness</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>topSpeed:</strong></td>
<td>0.4 &lt; topSpeed &lt; 1.2</td>
<td>Low: agents move too slowly, alignment and patterning takes a long time to develop.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High: agents move too quickly to react to one another.</td>
</tr>
<tr>
<td><strong>minDist:</strong></td>
<td>30 &lt; minDist &lt; 50</td>
<td>Low: agents align and clump together.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High: agents become spaced too far apart from each other.</td>
</tr>
<tr>
<td><strong>maxDist:</strong></td>
<td>20 &lt; maxDist &lt; 80</td>
<td>Low: agents of similar alignment clump together, otherwise do not align with one another.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High: agents spread far apart.</td>
</tr>
<tr>
<td><strong>alignmentWeight:</strong></td>
<td>0.3 &lt; alignmentWeight &lt; 1.1</td>
<td>Low: agents never align.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High: agents clump together and overlap.</td>
</tr>
<tr>
<td><strong>cohesionWeight:</strong></td>
<td>0.0 &lt; cohesionWeight &lt; 5.0</td>
<td>This value weight did not seem to have a major effect on the swarm configuration in the presence of the other two flocking urges.</td>
</tr>
<tr>
<td><strong>separationWeight:</strong></td>
<td>0.6 &lt; separationWeight &lt; 2.0</td>
<td>Low: agents clump together and overlap.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High: agents to do not align with one another.</td>
</tr>
</tbody>
</table>
Figure 12: Illusionary patterns created by optimal swarm conditions. Without overlap, uniform spacing and clusters of swarms similarly aligned, produced the strongest illusionary motion in the swarm simulation.
Figure 13: Illusionary patterns created by less optimal swarm conditions. **Above:** Too much overlap between neighbouring agents weakened the observed motion in comparison to more uniformly distributed agents. **Bottom:** Large gaps between adjacent RAP agents produced weaker motion effects than more uniformly and closely aligned agents.
Chapter 4: Origami

The following work describes the second design prototype developed, Origami, which uses printed motion illusions and paper folding to attempt three-dimensional motion illusions. First the methods are described, followed by the results.

4.1 Methods

To date, all known Fraser-Wilcox illusions are flat, print or digital images. The origami study was undertaken to attempt motion illusions on nonuniform, 3D surfaces. The potential design applications of illusory motion would be limited if they could only persist as even surfaces such as print images, projections, or on a computer screen. Motion illusions could have a much greater impact combined

Figure 14: Precedents for the origami chevron patterns and colours. **a)** A chevron shaped motion illusion image (created by author). **b)** A previously constructed 3D model based on the above image. The model was constructed from painted pieces of foamcore held together by wires. The model is bent into a curved arc shape (created by author).
with architectural elements which generally are not uniformly smooth and flat. Even seemingly flat walls and facades tend to have materials with differing thickness, seam edges, window ledges and door frames which interrupt their continuity.

4.1.1 Why origami?

The simplicity of paper folding provided a useful way to convert illusionary images into 3D surfaces. RAP images were created based on origami fold patterns, then printed onto paper and folded. Different images were created based on feedback from previous ones, through an iterative process.

Origami provided a useful medium for several reasons. Firstly, multi-faceted 3D surfaces could be created quickly from simple techniques and materials, making it feasible to rapidly test numerous images and folding patterns. Secondly, origami allowed immediate feedback for observing the effectiveness of an illusory motion design in a real-world context, unlike digital renders.

4.1.2 Choosing a RAP

Black, yellow, white and blue chevron shapes arranged in streamlines were chosen as a repeating RAP pattern to use for motion illusion images. This pattern, colour and form were chosen based on two previous precedents. First, an initial motion illusion image had been created by the author using similar colours and chevron shapes, and produced a relatively strong motion effect (Figure 14a). Secondly, a 3D curved model based on the image, composed of the same chevron shapes and colours, had also successfully demonstrated illusory motion in previous work (Figure 14b). Because of their proven success in these two contexts, it was anticipated these RAP shapes would also produce an illusory effect when they were applied to origami. RAP streamlines rather than discrete RAP forms were also more visually suited to paper folding. Furthermore, the observed behavioural properties

![Miura fold pattern](image1.png)  ![chevron fold pattern](image2.png)  ![chevron folded paper](image3.png)

Figure 15: Folding technique developed. The chevron folding patterns were based on an established origami pattern called the Miura fold (left). A sharper angle was introduced to the Miura fold to more closely resemble chevron forms (centre) when folded into paper (right).
which emerged from the swarm study suggested a grid style of RAP to be more ideal than random distributions of shapes

4.1.3 Creating a folding pattern

To create a folding pattern that mimicked the chevron form, a variation of the Miura-Ori fold was developed. The Miura-Ori fold is an example of rigid origami, a useful fold which can be packed into a compact area and unpacked in one motion (Miura, 2010). This fold was chosen because it was relatively simple to construct and bore resemblance to chevron shapes as it compacted. By using a sharper folding angle along one plane, a fold that resembles the chevron V-shape more closely, could be created from its basic pattern (Figure 15).

![Figure 15: A folding pattern, RAP pattern, and folded paper.](image)

**Figure 15:** A folding pattern, RAP pattern, and folded paper.

**Figure 16: Creating origami RAP forms.** Folding patterns (left) were used to derive RAP images (centre) and folded into 3D RAP surfaces made out of paper (right).

Initial tests with plain white paper determined useful variations of the Miura-Ori fold to create slightly different patterns for different illusion images. Using Adobe Illustrator these fold patterns were translated to digital images where fold edges were represented as thin lines. Using these lines as guides, coloured chevron shapes were transposed over top, creating RAP images which coincided with their respective fold patterns (Figure 16). Edges of chevrons in the printed images were designed to coincide with fold edges, so the coloured chevrons became somewhat of discreet 3D forms themselves.
4.2 Results

Unlike the chevron image and 3D form which provided precedents for this study, approximately a dozen different RAP compositions and folding patterns were created based on these, and the majority were ineffective at generating illusory motion percepts. However, several images did generated weak illusory motion even in their folded form.

4.2.1 Observations

Various origami forms that were created are illustrated in Figure 18. The first attempts consisted of long RAP streamlines with continuous linear edges running the length of each side. Deconstructing their smooth, linear edge appeared to be critical for the effect (Figure 17). Only in patterns in which the chevron edges were altered, giving each 90° corner edges, was illusory motion observed. Early designs also did not contain any gaps between adjacent streamlines, just continuous RAPs. Placing a gap between each chevron row, in conjunction with altering the chevron shape as described above, improved the effect. However, the gap alone did not. While colour contrast is a crucial component of the illusion, as long as Kitaoka's colour rule (see 2.2.1) is met, illusory motion appeared to be dependent on arrangement and RAP shape. The same repeating sequence of colours arranged into slightly different patterns could produce entirely different observed results (Figure 19).

The origami forms did not appear obviously folded in front view, in the absence of other visual cues (shadows or when viewed from side angles). They appeared much like the images from which they were created. Unlike digital or printed images, the different viewing angles afforded by these surfaces produced different patterns depending on the viewing perspective. Only origami forms viewed in front view could produce an illusory effect, as the viewing angle shifted, different patterns emerged from

Figure 17: Examples of the RAP streamlines used in the origami study. Top: Streamlines composed of long, continuous, linear edges did not generate observations of illusory motion. Bottom: Breaking up the smooth edges of each RAPs resulted in patterns which elicited illusory motion.
different viewing angles and the illusion disappeared.

The direction and strength of motion was consistent from images to folded forms. If an image produced illusory motion, it also generated illusory motion once it was folded in these studies. However, folding did not create illusory motion from ineffective images or strengthen the effect in any of the examples.

The images and origami folds were observed to also produce stereopsis effects. Streamlines appeared to pop out or recede relative to their neighbours in several of these patterns. This phenomenon,
was also remarked by Kitaoka (2006) in his studies of motion illusions.

The most successful patterns are shown in Figure 20 and Figure 21, which used identical images but different folding techniques. Both images produced similar illusory motion characteristics, in terms of strength and direction of motion. While none of the origami forms produced a strong motion effect, this study suggested it was indeed possible to observe motion illusions on non-planar, multi-faceted surfaces.

Figure 19: Examples of patterns created in the origami study. Despite their similarity, slight variations in chevron shape and spacing resulted in different illusionary effects. The image on the right produced the strongest illusory motion of the three images, but its effect is still weak.
Figure 20: Origami motion illusion folded every second chevron. The same pattern was used for this form and the form in Figure 21. Here the paper was folded every second chevron shape. These two examples produce the strongest motion effects of all the patterns attempted.
Figure 21: Origami motion illusion folded every third chevron. The same pattern as Figure 20 was used in this origami form, but here the paper was folded every third rather than second chevron shape.
Chapter 5: 3D Rollers Illusion

The last of the three studies returns to the ‘Rollers’ illusion (Figure 9) which inspired the first swarm study. Here a 3D version of the motion illusion was constructed to further explore motion illusions in 3D on nonuniform surfaces. First the methods used in the study are described, followed by results.

5.1 Methods

The previous study with origami suggested illusory motion could be evoked on uneven, 3D surfaces. The final design experiment was undertaken to further expand on this potential and attempted to use the 3D shape of a model to enhance its motion, where the form contributed to the sense of movement implied by the illusion. In the origami prototype, the direction of motion was only

Figure 22: The 3D Rollers illusion. Based on Kitaoka's original 'Rollers' illusion (Figure 8). The model is constructed from foamcore and cardstock.
back and forth, while the 3D Roller model was created to attempt 3D motion in depth. If feasible, this could exponentially increase the possibilities of motion evoked by RAPs and set a precedence for design elements where form and motion are integrated to achieve maximum effectiveness.

5.1.1 Choosing a model

Kitaoka’s Rollers illusion which inspired the RAP shapes of the swarm study (Figure 8) was used again as precedence, as it had already produced a relatively strong effect in the illusionary swarm study and consisted of basic eyelid shapes which could be constructed as three-dimensional forms. Furthermore, its illusory motion was particularly interesting because as its name implies, the direction of motion is more than bidirectional. It implies a sense of depth, as if the eyelid shapes are rolling into each other. This became an interesting property to explore with a 3D physical model.

5.1.2 Constructing a 3D model

To generate the varying eyelid shapes of the original Rollers illusion, a model was first designed using Rhinoceros®. Truncated cones were created, and by slicing out the middle portion of each cone and rejoining the two surfaces, 3D eyelid shapes were created. The same eyelid form was used for each one, but to create the varying sized eyelid shapes in Rollers, the top of each was sliced off at varying depths. A wavy surface was made in Rhino, and used as a guide to cut the tips of each cone to a correct depth. The deeper the cut, the wider the resultant eyelid shape, creating a concave roller surface shown in.

Eyelid cones were made from black and white cardstock glued to a yellow background of foamcore. The foamcore was perforated with uniform eyelid shaped holes evenly spaced apart. The truncated cones were attached along the edges of these holes. A blue background was placed behind

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Figure 23: Profile of 3D Rollers models. Top: The original model constructed. Bottom: The second shallower model constructed.
the yellow foamcore, and was visible through holes in the 3D truncated cones.

5.1.3 Building two models

It was initially considered that the illusory effect might be inhibited by shadows cast on the model surface due to the depth of the cones, potentially interfering with its readability as an illusion. Thus, a second model was created using the same materials and forms, but decreasing the depth of the truncated cones as much as could be allowed, to avoid shadow interferences (Figure 23). In the second model, all the cones were shortened by approximately an inch. However, the model’s curved shape made it difficult to entirely avoid shadows, because it still required differentiation between the deep and shallow cones to produce the same curved surface as the previous model.
5.2 Results

Both the shallow and deep 3D Rollers models demonstrated similar illusory effects. Each produced a slight motion illusion, though extremely subtle, suggesting 3D motion in depth could

![3D Rollers illusions. Top: First model constructed with deeper cones. Bottom: Second model constructed with more shallow cones to mitigate shadows. Both models produce slight illusory effects, the first model was observed to be slightly more effective.](image)
potentially be achieved in more refined prototypes. The models also produced additional but subtle illusory effects.

5.2.1 Observations

The second model with shallow cones was not observed to produce a stronger illusory motion than the model with longer cones. In fact, the shallow model seemed to be slightly less effective (Figure 24). Illusory motion could be observed in both models, although the effect was so subtle, it was not always apparent. The direction of illusory motion was curved towards the centre of the model.

While the models themselves were already three-dimensional, they also produced stereopsis and additional illusory effects. For instance, the blue background sometimes appeared to be situated on the outmost surface edges of the cones rather than underneath them. The yellow flat surface also appeared curved or wavy, especially from a side angle view. Illusory motion, though not always apparent, seemed more pronounced from a side angle than perpendicular. Though the effects were very subtle, the model generated ambiguity in regards to perception of its form. Like the origami folds, these three-dimensional models created different RAP patterns depending on one’s vantage point (Figure 25). At an extreme side angle (close to 0°), no illusionary effects were observed.
Chapter 6: Summary of Results

The following summarizes the results of Chapters 3, 4 and 5, highlighting the key observations from each of the three design prototypes.

6.1 Illusionary swarm agents

In the swarm study, motion illusion images were created based on Kitaoka’s (2006b) original ‘Rollers’ using a biological computation program. The results of this study suggested RAP arrangement played a key role in generating effective illusions and a grid-like, evenly spaced pattern of RAPs was the most ideal composition within the possibilities of the program. Overlapping RAPs and large gaps between RAPs were observed to produce weaker illusory motion, than more closely aligned and uniformly distributed arrangements.

6.2 Origami

3D Motion illusions were created in the origami study, although the folded forms only produced weak motion effects. Due to the strong colour contrast within the images, the folded surfaces did not appear folded in natural light, unless viewed from the side to reveal their multi-faceted shape. Furthermore, the repetitive folding technique produced different patterns of colours and forms when each paper was viewed from different angles. The results of this study suggested motion illusions are possible on uneven surfaces.

6.3 3d Rollers Illusion

Two 3D Roller illusions were created, one with slightly shallower cone than the other. Both models demonstrated similar illusory effects. Each produced a slight motion effect, though extremely subtle. The results suggested 3D motion in depth could potentially be achieved in more refined prototypes. The models also produced additional illusory effects, including the misinterpretation of their form and stereopsis.
Chapter 7: Discussion

The following discusses the three studies, relating the results of each to their implications and insight for design. Next, a brief description of the limitations of this study and the constraints of motion illusions for design are described. The final section presents the potential for future work based on a new hypothesis which emerged from observations in this thesis. This hypothesis suggests a possible explanation for Fraser-Wilcox motion illusions.

7.1 Illusionary swarm study

In the swarms study of this thesis, the same number of illusionary agents were present at the beginning of the simulation and the end. Their size and colour remained constant, only their spatial arrangement changed over the course of the simulation. This suggests the difference in illusory strength of different swarm compositions resulted solely from their different RAP arrangements. While illusory motion may indeed be driven by differential processing of luminance contrasts, as suggested by others, contextual attributes like orientation and spacing, were shown in this study to be of critical importance for the effect. Backus and Orec (2005) remarked that “the illusion is most compelling when repeated elements are configured such that individual local motions, as might be generated by each element, contribute to the same motion within a larger image region.” Similarly, the tendency of swarm agents to align and move cohesively, contributed to a larger motion and stronger effect, suggesting context plays an important role in the effect.

7.1.1 Design considerations

This simulation demonstrated how swarm agents can be guided to create novel illusory motion patterns. While patterning is essential to create illusory motion it also performs many functions in design. Patterning can create more visually engaging building, contribute to a sense of place, provide visual cues for wayfinding, embody cultural significance and accentuate material qualities of surfaces and materials, through its application. Fundamentally, it can affect the experience of forms and spaces, embodying meaning and evoking feelings (Kolarevic & Klinger, 2008). The patterns created by illusionary swarm agents, could be but an extension of already well-established performative features of patterning in design and applied in much the same way, on building facades, as wallpaper, or thoughtful arrangement of construction materials, for instance.

An advantage of the swarm program created in this study, is its open-endedness and flexibility. New more complex simulations could be built up from this initial basic program to design site specific illusory motion effects. In the program, agents populated a rectangle on a computer screen, but they
could be applied to any virtual environment. More than ever, architectural designs are conceived or at least finalized in digital renders. These digital models could be used as virtual environment from which illusionary swarm agents could populate and react to, developing aesthetic and functional site-specific patterns. Agents could respond to physical constraints, like walls and windows and functional intentions, like space delineation.

In the swarm simulation, the direction of motion in the moving swarm clusters was retained as the direction of motion in the frozen image. By controlling the velocity parameters of the agents, swarms could be used to generate very specific motion intentions, while at the same time creating organic, seemingly random, organic organizations of RAPs.

Layers of more complex swarm behaviour could be added onto the agents, to create informative illusory patterns. For instance, running swarms through a virtual environment could determine the most optimal pathways through a building, and their trajectories could be translated onto the walls to guide the flow of pedestrian traffic. In this context the effect could be used as subtle gestural cues, integrated as a surface effect into the whole of a building’s design. In another application, strong, bright, conflicting, busy illusory patterns could be used to prevent loitering in a particular space, by creating an unresting, dizzying, overwhelming effect. By turning off a light, or by the setting of the

![Figure 26: Gestural motion cues. Patterns created by illusionary swarm agents can be used to guide users through a space using subtle motion cues.](image)

most optimal pathways through a building, and their trajectories could be translated onto the walls to guide the flow of pedestrian traffic. In this context the effect could be used as subtle gestural cues, integrated as a surface effect into the whole of a building’s design. In another application, strong, bright, conflicting, busy illusory patterns could be used to prevent loitering in a particular space, by creating an unresting, dizzying, overwhelming effect. By turning off a light, or by the setting of the
sun, the illusory patterns would no longer be visible, controlling the effect temporally as well.

Figure 26 provides an example of a potential design application using swarm patterns created in this study to suggestively guide users through a space. Illusory swarm patterns could beckon shoppers into a store, suggest an upwardly gaze at a church alter, or create a dynamic building facade. Illusory motion could help create contextually responsive sensory experiences through their integration with already well-established patterning techniques in architecture. This study demonstrated some of the patterning characteristics to consider to create successful motion effects, and the unavoidable trial and error process still required for any new context in which the effect is to be applied.

7.2 Origami study

Unlike the individual RAP eyelid shapes used in the previous swarm study, the origami study utilized long, continuous chevron-shaped streamlines. Despite their different geometries, both studies brought attention to more detailed characteristics of RAPs, beyond their colour sequence, which contribute to illusory motion. RAP geometry and spatial arrangement were key variables in this study and several iterations of different patterns and shapes were made before successfully achieving illusory motion forms.

For any new motion illusion, relying on repetitive colour sequences alone does not guarantee a

Figure 29: Kitaoka’s ‘Red snake’ illusion (Kitaoka, 2011). This illusion shares a similar RAP streamline as the unsuccessful chevron RAPs used in early origami models but unlike the origami images, produces illusory motion in its curved form.
successful illusion. In this case, introducing a gap between RAP streamlines generated illusory motion from images which otherwise did not. Similarly, fragmenting the continuous linear edge along each RAP line, improved illusory motion, coinciding with observations by Kitaoka and Ashida (2003), who found the illusion is enhanced by fragmented or curved edges while long edges produce weaker illusions. Figure 29 shows a motion illusion created by a similar RAP streamline as the unsuccessfully one used in the origami study (Kitaoka, 2011). Perhaps it is not only the continuous edge which prevented illusory effect with this streamline, but the linearity of the form. However, why this is the case, remains unknown, but perhaps edge detection plays a role in the readability of the illusion or fundamental differences in the perception of curved vs. straight lines. This study also revealed illusory motion could be evoked on 3D surfaces, which opens the door for new possibilities in RAP patterning and illusion forms.

7.2.1 Design considerations

Part of the difficulty of bringing motion illusions into 3D, was the unknown effects of the variables it introduced, like shading and surface deformation. By viewing any of the origami folds in front view (e.g Figure 18), their 3d shape might not be readily apparent, not only in photographs, but even with direct observation. This could explain the phenomenological similarities between 2D and 3D, as printed images generated relatively the same observed effects as their respective 3D origami forms after folding.

Initial concerns regarding the shadows cast by variable surfaces could contribute to weakening the effect. However, the high colour contrast seems to perceptually overpowers the lighting variation caused by the faceted surface, resulting in a weakened, but still present observation of motion. Similarly, surface deformation from folding did not noticeably interfere with the readability of the illusion. The folding technique may have contributed to this, as it affected the whole composition in a consistent way. Each individual chevron was still consistently visible at the same time, in front view.

These results are optimistic for the feasibility of illusory motion in real-life design applications. Since shadows and shape deformation did not eliminate the effect, there is likely some degree of liberty for using the illusion on variable surfaces while still maintaining its strength. If the illusion were only possible on smooth, unblemished materials, its design capacity and effectiveness would be much more limited. Even a flat, vertical building facade consists of ledges, windows, doors and variable construction materials, all with varying depth and material qualities.

Figure 30 shows an example of how RAP patterns could be transferred to a building facade. A real building designed by Bernard Tschumi Architects in central France, is superimposed with RAPs on its existing uniformly coloured, wood facade. Despite the relative complexity of the image compared
to most motion illusions and the facade’s varied patterning, it still produces subtle illusory motion, as an image. However, one of the major drawbacks of this thesis work, which is elaborated on further in section 7.4.2, is that while successful as a motion illusion image, it is unknown if it could still be effective on a large scale building.

Perhaps the most telling design consideration which emerged from the origami study, was the realization of how different viewing angles of the same origami form, created completely different

Figure 30: Example of RAP patterns applied as a facade. A typical four colour RAP sequence was superimposed on an image of an already existing building, demonstrating a potential application for the effect in design (http://www.archdaily.com/254235/alesia-museum-bernard-tschumi-architects/).
patterns of shapes and colours depending on the position of the viewer. In this regard, the illusion could be used much like the painting technique anamorphosis, which has been previously described using Holbein's 'The Ambassadors' as an example (Figure 7).

One of the limitations of this illusion for design, is the strong colour contrast and patterning needed for the effect, which can be busy, overwhelming and distracting. Using anamorphosis, or controlled perspective, motion illusions could draw attention to a space, with subtle motion cues beckoning users inside. From an outsider’s perspective the illusion is present, and motion directs them into the space. Once inside, the chaos of motion might otherwise be too overwhelming for them to linger, so the effect could be eliminated in this new observer perspective, due to the positioning and 3D form of the illusion. The added complexity of 3D form allows a degree of control over its application. However, to apply it contextually would require an understanding of the space in which it will be applied and its spatial relationship to the users who would interact with it.

An interesting characteristic of the folding technique used in this study, a variation of the Miu-Miu-Ori fold, is its deployability. The form can be scrunched together or pulled apart over and over, in a single motion, without losing its integrity. A motion illusion from this kind of medium could be used as a collapsible screen, delineated adjacent spaces or providing window shading, for instance. The motion illusion would arise only if the screen is pulled open, otherwise the effect remains essentially dormant. This emphasizes the motion effect could also be temporal, offering another way of controlling its use.

7.3 3d Rollers study

In the final design study, a 3D version of Kitaoka’s ‘Rollers’ illusion was constructed. This illusion was chosen, in part, to see if the rolling motion in Kitaoka’s image could be recreated as three-dimensional illusory motion using the shape of a 3d model. Though subtle, the 3D Rollers creates curved illusory movement towards the centre of the model. These results suggest motion could be evoked not only on 3D surfaces but the direction of motion can be three-dimensional as well.

7.3.1 Design considerations

A large visual field has been described by Backus and Orec (2005) to enhance the strength of motion. In this study, the model’s weak motion could partially be attributed to its lack of RAPs, as only approximately a third of the original Rollers illusion was constructed. By cropping the original image down to the amount constructed as a physical model (Figure 27) this becomes apparent. Illusory motion is still present, but less compelling in the image with fewer eyelid shapes. Had the model been designed with more eyelid shapes, it may have been a more effective illusion, which is important to consider when developing an illusion for contextual effect.
The size of the whole illusion composition does not appear to be critical, but rather the number of RAPs in the composition. While these studies did not test illusory motion on a large scale model, like the size of whole buildings, the work in this thesis and by others (Backus & Orec, 2005) suggests the scale of the composition is unimportant, as long as the forms and colours are intelligible. The same motion illusion can be applied to a piece of paper or an entire wall and be equally effective, but it requires a critical number of RAPs to initiate a perceptual response. What this critical number is, remains to be understood.

Exploring the illusion in 3D made apparent its potential to create movement in depth, three-dimensionally. This exponentially increases the motion possibilities which can be evoked by this illusion. This effect could be incorporated into three-dimensional constructs to enhance their intention, integrating implied motion and form, for a synergistic effect. It could enhance the fluidity and restlessness of a wavy surface or the curviness of a wall. By utilizing both form and colour, this illusion offers much greater opportunities for spatial applications beyond the confines of flat illusion images. Figure 28 demonstrates an application of the effect in 3D, using a spiral motion illusion on a spiral staircase. The RAPs create not only a subtle motion illusion in the shape of a spiral but also implies a sense of depth, where the illusion is spiralling vertically up the stairs. Like the origami study, this 3D Rollers

Figure 27: Approximately the section of the original ‘Rollers’ illusion constructed as a 3D model. Illusory motion, while still present, becomes less pronounced in the cropped section of the image, as compared to the original by Kitaoka (2006).
study also reinforces the potentials of 3D motion illusion for anamorphosis applications. In the spiral staircase example, the motion illusion is most effective from a particular vantage point, at the bottom centre of the staircase, but is absent in other views.

Based on observations from these two studies it appears the main constraint for 3D surfaces is that all the colours of a RAP must be visible simultaneously. The effect drops off as one views it from a side angle, as distinct colours and their particular sequence are no longer simultaneously present. The same rule applies to the size of an illusion. The effect can be applied as a large or small composition, as long as each form and colour can be distinctly perceived at the same time. In a design context, this requires consideration of the distance from which observers will be able to view the effect, so the size of RAPs can be designed accordingly. If they are too small, the colours become blurred and undifferentiated, and the effect disappears.

![Figure 28: Staircase illusion](image)

**Figure 28: Staircase illusion.** An example of how RAPs could be applied to 3D forms to evoke illusory motion in depth.

### 7.4 Limitations

This thesis revealed several important considerations and potential applications for illusory motion in design. However, it remains a preliminary step which only provides ideas and guidelines for design and has yet to create strong motion effects in 3D. The contextual requirements of motion illusions make it difficult to describe universal rules for their potential applications, especially within a larger framework of design intention. Any application of illusory motion would need as much awareness about the context in which it is to be applied as the properties of motion illusions. The creation of
these illusions still require fine-tuning to develop strong and intentional illusory motion effects.

7.4.1 Research limitations

One of the major limitations of this study was the lack of subjects from which the results are based on. The observations reflect solely those of the author, which is a relatively small pool from which to draw conclusions from. However, the goal was not to prove the effectiveness or characteristics of a novel illusion by comparing them among test subjects, but rather the goal is to explore potential applications of the effect. Nonetheless, the subtle nature of the motion illusions makes it even more difficult to draw conclusions from when the researcher is the only observer, and may be biased in that regard. The Origami and 3D Rollers studies both produced very weak motion illusions, yet the design applications presented were premised on them being effective.

In these studies, only unreflective, uniform, opaque materials were used as RAP materials, images on a screen, printed paper, cardstock, foamcore and spray paint. However, the construction world is filled with variable materials. No reflective, porous, transparent or textured materials were attempted, so the potential impact of these variables on illusory motion is unknown. Furthermore, this discussion offers possible applications for the effect at different scales, suggesting it can be used for both large and small-scale designs. None of the studies tested a large scale illusion, like that of a building facade. It is unknown if such large applications would create additional variables, or perceptual conditions which could interfere with the effect.

7.4.2 Design limitations

A major limitation of this illusion for design is its contextual, unpredictable nature. Creating a successful motion illusion takes practice and even with a great deal of knowledge on the subject, designing a novel illusion still requires fine-tuning to be successful at generating observed motion in a given context. The subtleties and numerous variables which affect the illusion, makes it difficult to predict, even with the best renders, what will be observed when an illusion is transferred to a real-world environment. For instance, the illusions presented in this thesis are functional on a computer screen. However, once printed, or even on a different monitor, variation in colour of different monitors and printers can result in ineffective illusions, as the RAP colours are particularly calibrated to one medium.

An aesthetic constraints of this illusion, is the necessary colour contrast required to produce it. This limits the colour palette to work with, because the most crucial elements for illusory motion are suggested to arise from contrasting luminance profiles. This thesis work, and work by others (Chi, et al., 2008) suggests the more saturated the colours for RAPs, the more effective they are at creating illusory motion. Fluorescent, bright colours are not always the most desirable colour palettes of an
architect or designer and saturated colours can be difficult to reproduce depending on the type of medium. These colours can be loud and overpowering, especially in a large scale design. However, by using a more subdued palette, like gray scale RAPs, the illusion may lose effectiveness because gray-scale colours are likely to be more affected by real-world lighting conditions than bright colours.

Motion illusions do not have universal effects on all observers. Some cannot experience them entirely. Fraser and Wilcox (1979) described the polymorphic capability of experiencing their illusion. They found students from different university majors significantly differed in their ability to observe their escalator illusion. Furthermore, different subjects reported different directions of rotary motion lasting for different amounts of time. However, they also noted, the weakness of their illusion may tease out the polymorphic aspects of it, suggesting a motion illusion with a stronger effect, would like affect most observers in the same way. Another study by Billino, Hamburger and Gegenfurtner (2009) showed the motion effect also becomes less effective as people age.

The polymorphic aspect of the illusion relates to an important consideration for any design, the link between design intention and manifestation. Not everyone can experience motion illusions, and even within those that can, there is a degree of variability in their observation of the same scene. An intervention such as this is unlikely to have a ubiquitous effect for all observers. Motion illusions should not be entirely depended on for a particular design intention, like directional cues. However, in many instances, merely the illusion itself can be a compelling visual feature and need not be so reliably predictable, or it could be used in conjunction with other design features for a more reliable effect. It is case for almost any design intervention, experience is subjective and unlikely to be the same for all observers.

7.5 Future work

The design studies on Fraser-Wilcox illusions began to illustrate the important role of context in the creation and observation of illusory motion. Most research suggests the illusion is driven by luminance and/or contrast gradients, but this explanation alone might not arrive at the whole picture. Arrangement, number of RAPs and RAP form were important variables in the three design studies, suggesting they play a key role in generating illusory motion. From these observation, a hypothesis is presented to integrate this new information into a model for explaining illusory motion. This hypothesis can be tested through further design prototypes and could expand the potential ways in which illusory motion could be incorporated into design.

7.5.1 Background

The act of seeing seems so effortless, it is difficult to fathom the sophisticated mechanisms
underlying the perception of three-dimensional environments (Eagleman, 2001). The retinal image is only 2d, which means 3D shapes within a scene must be extracted from other visual cues. There are many aspects of optical stimulation, like motion, binocular disparity, and texture gradients, which ‘provide perceptually salient information about an object’s 3d form’ (Epstein & Rogers, 1995). Shading is an example of optical simulation whose predictable characteristics have been incorporated into the visual system’s mechanics to efficiently guide visual processing (Ramachandran, 1988; Kersten, Mamassian & Knill, 1997). These automatic assumptions are predicated on consistent patterns in the environment, like single, overhead sunlight and the predictable way light casts onto objects. Scenes which do not obey such rules create unnatural conditions, which the following hypothesis suggests, underlies motion illusions based on RAPs.

7.5.2 Hypothesis

To begin to explain this hypothesis, Figure 31 provides a useful start. Illuminated spheres arrange into rows with opposite shading patterns generate both a motion illusion and stereopsis effects. Now

Figure 31: Illuminated spheres illusion. Alternating rows of spheres with opposite shading patterns creates a motion illusion and stereopsis (image created by author).
take, for instance, the white and black colours in the swarm study (e.g Figure 11) and consider them to represent the lit and shaded side of the blue eyelid-shaped object, much like the light and dark sides of the illuminated spheres (Figure 31). The colours of RAPs represent abstracted features of 3D shapes, much like the abstracted but still recognizable features within an impressionist panting. Because of the arrangements of shapes in each composition, both the swarm illusions and the spheres image, create ‘impossible’ shading or perspective conditions. Each individual shape has a discrete, slightly different light source, which does not influence adjacent forms and their discrete light source. Each has distinct localized shading, an unlikely condition to ever encounter naturally in the environment.

Compelled to assume single, stationary light sources as a predictable framework for establishing the three-dimensional forms in a scene, the unnatural light patterns represented by RAPs do not fit with the brain's assumptions about lighting. It fluctuates between different percept states to grapple with conflicting information created by RAPs, flipping back and forth to alternate conceptions of perspective or object forms. Ramachandran (1988) showed if two identical objects are illuminated from different angles, we can only accurately perceive the three-dimensional shape of one of them at a time. If RAPs are indeed the abstracted primitives of 3D shapes or unnatural lighting patterns in an environment, their patterns very much fit into Ramachadran's model. Not all RAP forms can accurately be perceived at the same time, so this fluctuation to different states becomes interpreted as motion.

However, it should be noted, that RAPs are not objects, but representational figures in an image. As previously mentioned, picture perception is not the same as object perception because the usual perceptual cues within the environment are not present. However, based on the design prototypes created in this study, it is suggested that motion illusion effects share similar characteristics in images as 3D forms. However, much more research is need to support this assertion.

The role of luminance and gradient contrast for creating illusory motion need not compete with

Figure 32: RAPs representational of 3D objects. The hypothesis presented suggests RAPs are representational of 3D forms, textures or patterns exposed to light.
this hypothesis, they are still key to generating the effect. However, as the discussion above highlighted the importance of context, the way in which RAPs are arranged induces illusory motion, because an image requires a sort of ‘impossible’ pattern arrangement. In the case of the initial random RAP configuration in the swarm simulation, perhaps too much randomness disengages the effect. There is virtually no relationship between the eyelid shapes, no discernible patterns or framework. Just enough patterning and conflicting groups of RAP clusters, create conditions conducive for the effect. In the 3D roller illusion, the black and white colours could again be interpreted as shading and illumination. Elder, Trithart, Pintilie and MacLean (2004) explain that ‘3-D shape perception is largely eliminated when appropriate contrast rules are not obeyed at shadow boundaries.’ These colours conflict with the real life shadows cast onto and created by the object which could explain the misinterpretations of the Rollers’ true form.

7.5.3 Design implications

This hypothesis is presented not only to demonstrate how this study could offer contributions to the psychology of the illusion, but because it provides additional insight to inform the execution of motion illusions in design contexts. What this hypothesis suggests, and could be used to help prove or disprove it, is the design of unnatural lighting scenes could produce motion illusions. So far these design studies utilized strong colour contrast to create illusions. However, if this theory holds true, one could manipulated light and shadows through clever design techniques, like mirrors, lights and controlled perspective, to create real-world models which create illusory motion without coloured RAPs.
Chapter 8: Conclusion

A common theme throughout this thesis was the importance of context, both for illusionary effectiveness and design application. These studies suggest Kitaoka’s basic rule of repetitive colours sequences can only effectively create motion illusions, if enough RAPs are present and they possess a particular spatial relationship and RAP geometry. Furthermore, this work suggests that any design intervention with motion illusions would require as much a grasp on the context in which it is to be applied, as the fundamentals characteristics of motion illusions.

This work demonstrated how swarm agents provide a useful tool for generating illusionary motion patterns and this thesis only scratched the surface of its potential, in this regard. Future work could expand on the computational program developed, exploring more elaborate swarm behaviour, environmental conditions and simulations in 3D. For instance, as new buildings are generally modelled digitally, such models could be introduced into an illusionary swarm program, allowing agents to react to the environmental conditions and physical obstacles presented by them. This would allow RAP patterns to be tailored specifically to a building or space. Conversely, an illusionary swarm program could be used to design a space parametrically, using swarms as physical entities with predefined motion intentions to create animating surfaces.

The results of the Origami and 3D Roller studies suggest illusory motion can indeed be evoked on 3D surfaces. Motion characteristics appear to be similar for images and 3D surfaces based on the same images. However, much more work is needed to support this assertion, as these studies only provide a few precedents with weak illusory effects as evidence. Future work could also explore anamorphosis-like motion illusions, where RAP patterns are directly tailored to the physical conditions and users of a space, to achieve controlled spatial effects.

In the 3D Rollers study, only subtle illusionary effects were observed. More design work is needed to strengthen the effect and ensure it is feasible in 3D for most observers. The 3D Roller model could also be revisited using more RAPs, as the small visual field in this prototype is believed to have weakened its potential illusory effectiveness. In more refined prototypes, form and illusory motion could be designed concurrently for a synergistic design effect, like wavy surfaces with wavy illusory motion. Future studies could also test design prototypes on pools of human subjects, to compare their effectiveness and illusionary characteristics amongst different observers and in varying contexts.

There are many obstacles to overcome in developing strong, controlled and contextual motion illusions. This thesis has presented several potential design applications for motion illusions, and offers useful considerations for the design process. However, this research remains only a preliminary study, which has only begun to address the design potential of this effect.
Chapter 9: References


