Stalking the illusion: space in glass

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PhD by practice

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Abstract

The visual system generates the perception of a world of meaningful three-dimensional objects from a stream of retinal signals – in the psychologist Richard Gregory's words 'images in the eyes'. When this perception is consistent with information from other sources such as the ears and the muscles that guide movement, all is well and we are almost entirely unaware of this process. But when it is not, we see illusions. To adopt Gregory's phrase, 'strange phenomena that challenge our sense of reality'[1].

The project is inspired by the work of the German artist Ludwig Wilding (1927 – 2010), who refined approaches to the everyday phenomenon of moiré interference patterns to generate dramatic illusions of depth and movement in shallow box frame structures.

Based on the principle that the intersection of two sets of parallel lines generates the appearance of a third set of lines, or moiré bands, Wilding's innovation lay in the discovery that, by introducing a shallow space between the two layers of printed lines and by tilting and rotating them, the size and orientation of these moiré bands can be manipulated to produce converging contours and texture gradients that are perceived by the visual system as forms in depth.

This thesis builds on these observations to investigate the potential of the material and optical qualities of glass in combination with moiré interference effects to generate inconsistencies between the images in the eyes and the objects that produce them, creating illusions of space.

[1] Gregory Richard L. 1990. *Seeing Through Illusions*. Oxford: Oxford University Press. p186

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Preface

1. Introduction

This thesis has been written to accompany a body of art works developed and produced at the Royal College of Art in London between 2009 and 2013.

The document has been structured to reflect the development of the project in two stages: an initial technical investigation that broadly corresponds to a two-year MPhil cycle which set the framework for the PhD project that evolved in the third and fourth years of study.

An overview of this process is presented in this chapter, with more detailed discussion and illustrations presented in the sections that follow: Chapter 1 reviews the background, while Chapter 2 reviews the frames of reference that informed the main body of the project. The investigation of these themes through the studio practice is discussed in the Chapters 3 and 4, the final Chapter 5 offering some conclusions and questions for future exploration.

Although photographs are included in the text, the reader is also invited to consult a DVD that accompanies the document, providing additional images and brief video clips. The appendices offer more detailed notes on the technical development as well as transcripts of a selection of the interviews with artists, scientists and curators carried out in the course of the project.

2. Project outline

i. Starting points

Having worked for a number of years as Artist in Residence at the Bristol Eye Hospital, the original project submitted to the Royal College of Art in Spring 2011 proposed to combine printed medical scans with studio glass-making techniques to make models of the structures of the eye and optic nerve. The aim of the project was to materialise these invisible pathways to support a more personal dialogue between clinicians and patients.

Exposure to new materials and ways of working during the early months of study led to a review of the underlying assumptions, including the decision to work with glass.

The Victorian art critic John Ruskin's declaration that this costly and demanding material could only be justified in situations that celebrate its unique qualities of transparency and ductility provided the criteria for studio development[2].

ii. Material concerns

While continuing to negotiate the ethical and practical aspects of the clinical project, these two criteria were used to inform and evaluate a series of technical investigations that aimed to encapsulate detailed printed images within tactile glass forms.

However as this work progressed, it became apparent that, far from enclosing and representing a fixed and delimited space, these objects appeared unusually open and permeable, both affecting - and affected by - their surroundings in unexpected ways. They seemed to demonstrate rather than illustrate the mechanisms of visual perception - in the artist Patrick Hughes' words, they seemed to 'show rather than tell.' [3]

[2] For the full quote, please refer to Chapter 1, Origins, in this document.
[3] Transcript of conversation with Patrick Hughes, please see appendix

iii. Ambiguity

These observations led to an investigation into the underlying mechanisms of perception, starting with Richard Gregory's model of a visual system that interprets retinal signals as meaningful objects based on how the world usually appears in a given context. These may be 'innate', such as the expectation that light will shine from above, or learnt through experience, such as the knowledge that a red traffic light usually means 'stop'. When information from the eyes and other sources such as the vestibular system and the muscles that direct movement are consistent, this process is largely unconscious[4].

However, as this description suggests, the visual system evolved to interpret signals from the eyes in a natural world in which the free passage of light through a space is likely to signify a void. Transparent materials such as glass produce inconsistencies between visual and other inputs - in Gregory's words, 'strange phenomena that challenge our sense of reality.' [5]

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[4] Gregory, Richard. L., and Zangwill, O.L. 1987. *The Oxford companion to the mind*. Oxford [Oxfordshire]: Oxford University Press.
[5] Gregory, Richard. L. 2009. *Seeing Through Illusions*. Oxford: Oxford University Press. p186

The fascination of a solid and yet transparent material perhaps underpins Ruskin's remarks, materialising, in the sociologist Jean-Didier Urbain's (b1951) wrds, an oscillation 'between the desire for disclosure… and the temptation of the void.' [6]

In his work *La Vie des Formes*, the art historian Henri Focillon (1882 – 1943) proposes that we experience potential images and forms as a *'*fissure through which we can introduce a mass of images aspiring to be born in an uncertain realm.*'* [7]

The way that these simple glass objects seemed to encapsulate a mobile, potential space recalled the historian Linda Darymple Henderson's research on new approaches to representing the fourth dimension that emerged at the turn of the twentieth century, a realm 'just beyond the reach of visual perception' [8] and the artist Lásló Moholy-Nagy's (1895 – 1946) observation that 'the space-time experience is a biological function as important as the experience of colour, shape and tone.*'* [9]

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[6] Gamboni, Dario. 2002. *Potential Images: Ambiguity and Indeterminacy in Modern Art*. London: Reaktion. p381

[7] Focillon, Henri. 1947. *La* Vie *Des Formes*. Paris: Presses Universitaires de France. p4

[8] Dalrymple Henderson, Linda. 2013. *The Fourth Dimension and Non-Euclidean Geometry in Modern Art*. Cambridge, Massachusetts: The MIT Press. p15

[9] Moholy-Nagy, László, and Hoffman Daphne M. 1947. *The New Vision: 4th Rev. Ed. and Abstract of an Artist*. New York: Wittenborn, Schultz. p37

Reviewing the studio practice in the light of these observations, it became apparent that the lettering and graphics used to date seemed to inhibit this fugitive, indeterminate quality. The eye motif was especially dominant: the mere hint of a gaze seemed to persist from every angle, overpowering the subtler ambiguities of the optical effects.

In order to concentrate entirely on the paradoxical appearance of space generated by the glass itself, the decision was taken to work only with the simplest possible graphic elements: the line and the point.

iv. Cues to depth

The inconsistencies that 'challenge our sense of reality' can perhaps best be understood in relation to how this reality usually appears. In the everyday environment, a number of patterns can reliably be interpreted as indications of relationships in space. The particular cues to depth can be divided into those that are not found in pictures only in the real world and others that are found in pictures.

-When an object in the world at a particular distance is fixated with both eyes there is an *accommodation-convergence reflex*.

This both adjusts the shape of the lenses of the eyes and the vergence angle, or direction of the eyes, generating occulo-motor signals that pass to the brain. Each eye has a slightly different image of the object due to the separation of the eyes in the head this is known as retinal disparity - which is the cue used by 3D movie makers. We are constantly moving in the world and objects at different distances move at different velocities in our eyes- a cue known as movement parallax. If we fixate a distant object, it will remain still, but if we move to the right nearer objects will appear to move to the left.

This principle underpins stereoscopic photographs and films: images are recorded from two viewpoints, equivalent to the separation of the two eyes. The left and right eyes of the viewer are then presented with the corresponding image.

Information about the position of objects in space is also given by motion parallax: objects at different distances from the viewer appear to move at different speeds.

There are many cues available in flat pictures. A key picture depth cue is that of size, the size of an object decreases with distance, so for example a road will appear to converge due to the change of size giving the perspective cue, and texture reduces in size with distance to produce texture gradients.

The scale of familiar objects such as human figures also provides information about their distance from the viewer, while occlusion, or inter-position indicates their relationship: nearer objects will hide more distant ones. Height in the visual field is also a guide: lower objects are judged to be closer distant than higher ones. Tone is also used to judge form and depth: shadows suggest shape and the colours tend to appear less saturated with greater distance.

v. Constructing space

Psychophysical experiments tend to use distilled versions of these cues to test the variables of spatial perception, while, since the development of linear perspective in the early 14th century, artists exploit the same mechanisms to produce the appearance of space on a two-dimensional canvas.

It is interesting to note that the earliest paintings, such as those found in the Lascaux caves of Southern France, tend to emphasise the tactile and conceptual qualities of their subjects rather than their visual appearance.

This approach was progressively displaced by representational systems designed to indicate hierarchies of power or value until the point at the end of the 13th century where pictorial space had been distilled to a series of horizontal bands upon which stylised figures and objects were arranged as a series of signs for an initiated audience[10].

The invention of linear perspective at the beginning of the 14th century could be described as a liberation from this rigid ecclesiastical framework, a generation of polymaths who believed in progress through observation and self-determination - 'the sign of a beginning, when modern "anthopocracy" first reared itself.'[11]

By the end of the 19th century, the 'systematic levelling' [12] of geometric linear construction and increasingly virtuosic trompe-l'oeil styles had come to dominate a new market for art described by the art critic Clement Greenberg[13] as 'ersatz culture, kitsch, destined for those who, insensible to the values of genuine culture are hungry nevertheless for the diversion that only culture of some sort can provide.' [14]

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[10] Bunim, Miriam Schild. 1970. *Space in medieval painting and the forerunners of perspective*. New York: AMS Press. P40
[11] Panofsky, Erwin. 1991. *Perspective as symbolic form*. New York: Zone Books. p72
[12] Bunim, Miriam Schild. 1970. *Space in medieval painting and the forerunners of perspective*. New York: AMS Press. p42
[13] Clement Greenberg, American essayist and art critic (1909-1994)
[14] Greenberg, Clement, 1939. *Avant-Garde and Kitsch*, in Phillips, William, and Rahv, Phillip. 1962. *The Partisan Review anthology*. London: MacMillan.

vi. Deconstruction and abstraction

A succession of scientific discoveries such as Wilhelm Röntgen's[15] discovery of the X-Ray in 1895 and the work on radio waves by Heinrich Hertz[16] by the turn of the 20th century offered scientific proof of a fourth dimension, a concept that tapped into a broader 19th century popular interest in the 'ether of space' and the occult. [17]

The First World War contributed to this atmosphere of fragmentation from which a generation of artists, writers and composers emerged to challenge the dominant representational style.

Greenberg defines the deconstruction of linear perspective in terms of a rejection of the stable hierarchies that it implies[18], while Dalrymple Henderson describes these developments as a search for a more accurate representation of a universe that was no longer restricted to visible light and three-dimensional Euclidean space.

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[15] Wilhelm Röntgen, physicist (1845 – 1923)
[16] Heinrich Hertz, German physicist (1857-1894)
[17] Henderson, Linda Dalrymple. 1983. *The fourth dimension and non-Euclidean geometry in modern art*. Princeton, N.J.: Princeton University Press.
[18] Greenberg, Clement. 1960. *Modernist Painting*. Forum Lectures. Washington, D. C.: Voice of America

In an interview with the art critic Herschel B. Chipp[19] in 1952, the artist Jean Metzinger[20] declared that the fourth dimension 'represents the immensity of space eternalising itself in all directions at any given moment…It is space itself, the dimension of the infinite. The fourth dimension endows objects with plasticity'. [21].

This search for a formal vocabulary with which to express an underlying reality led to experiments by groups such as the Concrete artists, characterised by Theo van Doesburg (1883 – 1931) in the Concrete Art manifesto in terms of a search for 'absolute clarity' and a 'focus on the essential qualities of each medium'.[22] The essential quality of painting being the flat canvas, proponents of this approach such as Piet Mondrian [23] experimented with ways of evoking the intersection of space and time on a flat surface.

[19] Herschel Browning Chipp, American art historian (1913-1992)
[20] Jean Metzinger, French painter and writer (1883-1956)
[21] Chipp, Herschel Browning, Peter Selz, and Joshua C. Taylor. 1968. *Theories of modern art: a source book by artists and critics*. Berkeley: University of California Press. p224
[22] Doesburg, Theo van. 1930. *Base de la Peinture Concrète*, Art Concret, nr. 1 April 1930 http://commons.wikimedia.org/wiki/File%3AArt_Concret_Manifesto.jpg, accessed 25/10/2013
[23] Piet Mondrian, Dutch painter (1872 – 1944)

Much of his later work explored the expressive potential of rectilinear areas of tone, arranged according to mathematical formulae or other systems to generate rhythmic effects described by the curator Marlene Lauter as ‘structural-organisation-made-visible’.[24]

Paradoxically, this search for a purely pictorial, or optical language, led to a return to many of the cues to depth used by Renaissance painters such as converging contours and chequerboard tiling patterns. *The Responsive Eye* exhibition at the Museum of Modern Art in New York in 1963 brought this aesthetic to a new audience, challenging the divide between the formal institutions of the art market and the increasingly cosmopolitan world of product design, fashion and architecture.

[24] Lauter, Marlene, and Reese, Beate. 2002. *Konkrete Kunst in Europa nach 1945 = Concrete Art in Europe after 1945*. Ostfildern: Hatje Cantz. p99

vii. Ludwig Wilding – interference effects

One of the artists represented in this exhibition, the German Ludwig Wilding (1927-2010) developed a distinctive approach to this broader theme of multiple dimensions of space and time within a single apparent reality.

Trained in fine art and building a successful career in textile design, Wilding initially worked with traditional painting and printmaking techniques.

However, following a visit to Paris in the mid 1960's and following the advice of his teacher Willi Baumeister, he decided to focus entirely his on an exploration of the dramatic illusions of movement and depth generated by moiré interference patterns. These occur when one set of lines is printed on a transparent sheet and overlaid on another set of printed lines that have a similar frequency, producing distinct moiré fringes that appear almost ghostly, shifting and changing scale with the viewer,

In the course of his research, Wilding discovered that, by introducing a narrow space between the layers and by adjusting the relative frequency, density and rotation of the lines, he was able to design dynamic compositions combining patches of tone or texture that appear to run at different speeds and in different directions across a single, stationary surface, phenomena discussed by the psychologist and artist

Professor Nick Wade in his book *The Art and Science of Visual Illusions*[25].

By tilting one of the layers, the progressive shift in the apparent frequency of the lines produces sloping bands that are interpreted by the visual system as converging contours in depth. These paradoxical spatial effects, arising from the transparent qualities of the material combined with high-contrast printed lines, related directly to the effects observed in the early studio development and provided the inspiration for the next phase of the project.

For a demonstration of these effects, please see the illustrations in Chapters 3 and 4.

viii. Studio development – suspended planes

Building on Wilding's research, my initial experiments investigated the parameters of frequency, density and rotation of lines printed on layers of glass and paper, noting the impact of tone, viewing conditions and orientation on the visual effect.

While intrigued by the rich temporal qualities of the work, the focus of the investigation remained on the exploration of cues to depth that could be generated by the particular optical and material qualities of glass.

[25] Wade, Nicholas J. 1982. *The Art and Science of Visual Illusions*. London: Routledge & Kegan Paul. Pp35-39

For example, a sheet of glass is rigid, removing the need for a frame. The box structures of the early works offered a stage across which the effects seemed to play more fully, but at the same time to fix their status as artificial phenomena operating in the separate domain of objects, removed from the immediacy of a world in which the viewer may be called to act.

This observation led to the production of a series of larger printed pieces made entirely of layers of glass without the paper support. Placed in grooves of routed wooden panels, on open shelves or pegs these open works seemed to generate a particularly paradoxical, uncertain and yet convincing experience of receding surfaces and forms suspended in space, surprisingly different to the emphatic impact of the framed pieces.

As the patterns were suspended on transparent layers, it was possible to combine silver and white printed lines, noticing unexpected tonal effects when the patterns were viewed against different backgrounds. This investigation of silvering was extended to include the potential of mirrored surfaces to generate converging contours through reflected interference patterns. However, the reflections disrupted the interference bands to such an extent that the spatial effects were lost and this approach was set to one side.

Paradoxical forms

Returning to the classification of cues to depth outlined earlier, the effects produced by these pieces built from parallel layers or sheets of glass broadly correspond to cues that can be given by a two-dimensional picture. The perspective cue given by converging lines is especially powerful, and has been explored to great effect by the artist Patrick Hughes[26].

Wilding's discovery of the converging contours and texture gradients by tilting one layer of lines relative to the other formed the basis for a series of studio experiments to identify the optimum relationship between the densities and frequencies on the two layers. Building on these effects, Wilding also discovered that, with particular combinations of line frequencies, the left and right eyes received slightly different images that could be fused, generating the appearance of three-dimensional forms that either projected from, or receded in depth beyond the actual surface of the work. Taking photographs from two positions to represent the left and right eye views confirmed that the moiré interference bands presented to each eye had a far greater disparity than the actual form of the object would suggest, generating an amplified appearance of space.

[26] Patrick Hughes, British artist (b. 1939)

The project built on these observations to explore the depth cues produced by three dimensional glass forms, encapsulating multiple layers of bubbles and lines within hot glass. In addition to the interference bands, the optical qualities of the material produced surprising size scaling phenomena: distant elements appeared larger than close ones, while altering the angle of view resulted in a progressive change in their relative size and a mobile, almost liquid appearance.

Shining a strong light through the forms suggested another intriguing quality: bubbles and internal spaces that appeared bright in reflected light cast dark shadows that were subtly distorted by the grain or cording of the material. These were explored through a collaborative project with a video artist that was presented in the context of an expanded cinema event at the National Portrait Gallery in April 2012.

Although this performative dimension offers clear potential for future development, the focus of this project remained on the potential of glass to produce visual illusions of space – challenges to our sense of reality - a proposition that assumes a material reality as its point of departure.

ix. Rivalry and disparity

Preparations for a paper for presentation to a meeting of vision scientists in Germany in August 2013 led to a series of investigations to refine the parameters involved in generating the binocular disparity.

The early works had selected combinations of line density and frequency of the lines to produce converging contours that were so different in the left and right eyes that they could not be fused, producing the appearance of a flickering, mobile surface.

By adjusting the relative frequencies of the lines to generate interference bands that were more subtly different in each eye, the contours could now be resolved or 'fused' by the visual system. As the disparity between the views from the two eyes was still greater than the actual depth of the object would usually create, these shallow objects produced a coherent and mobile – if somewhat ghostly – experience of fugitive forms.

3. The research question

In summary, the project builds on the research of the German Modernist Ludwig Wilding to investigate the potential of moiré interference effects in combination with the material and optical qualities of glass to produce 'strange phenomena' that challenge our sense of space.

As Gregory suggests, illusions that expose these normally unconscious mechanisms at work may perhaps offer some insights into the 'secrets of mind and brain,[27]'

4. Methodology

The iterative and reflexive approach taken for this project can be described in two broad phases. The first consisted of a series of material investigations designed to develop the technical expertise required to fulfil the original aims of the project: the ability to locate and manipulate medical scans in small-scale glass objects for a clinical setting.

[27] Gregory, R. L. 2009. *Seeing Through Illusions*. Oxford: Oxford University Press. P1

The techniques selected for testing in the studio and refinement through specialist courses in external settings such as West Dean College and the Corning Studio in New York were suggested by contextual research conducted in museums, galleries, libraries and online. The results of these experiments in turn informed the direction for reading, visits and dialogue with curators, artists and historians, further refining the material process. These strands of theoretical and practical observation together informed approaches to evaluation and presentation of the research in academic, fine art and scientific settings.

Observing visitor response to the paradoxical spatial effects generated by these tests set the foundations for the second phase in which this technical expertise and graphic vocabulary were applied to an investigation of the mechanisms of visual perception of space.

The life and work of the artist Ludwig Wilding provided the framework for a contextual review that included analysis of examples of original art works, exhibition catalogues, visits to specialist museums in the UK and in Germany, interviews, and a survey of relevant scientific papers. These insights informed the studio practice which, as with the earlier experiments, was approached as a series of questions.

However, in this phase of the project, the outcomes were evaluated in terms of their spatial qualities rather than their illustrative potential.

Alongside the technical parameters of print and glass processes, the impact of scale, framing and lighting as well as curatorial decisions on the overall effect was explored through a series of group and solo exhibitions at the RCA, the Science Gallery in Dublin, the Bate Museum of Musical Instruments in Oxford, the Centre for Alternative Medicine in London, the Institute for Advanced Studies at the University of Bristol, and the European Conference on Visual Perception in Sardinia. These installations provided the basis for tutorials with experts drawn from creative and scientific fields as well as with members of the public, their insights informing and shaping the ongoing development of the research.

Alongside these iterative and reflexive strategies, the methodology benefited from the structured analysis and synthesis required by presentation to academic conferences, including the international printmaking conferences Impact 07 and Impact 08 and the meeting of vision scientists held at Professor Bernd Lingelbach's 'Barn' in Leinroden in Germany in August 2013.

The written thesis draws on these papers and presentations, alongside reports and notes from the contextual and material investigations over the course of the project.

5. Acknowledgements

Completion of the project is thanks to the guidance and encouragement of the supervisory team of Martin Smith and Priscilla Heard with the constant support of Alison Britton and a team of technicians not only from the Ceramics and Glass Department, but from Printmaking, Photography, Moving Image, Rapidform, the Darwin Workshop and the lighting crew. A wide network of professionals has also offered advice, sponsorship and swift responses: the FotoCeramic, Gaffer Glass, Compugraphics, DK Holdings and the photographer Ester Segarra and the to name but a few.

Gratitude is due to the AHRC for financial support, to Marabu and BASF for sponsorship and to family and friends for their patience and kindness, especially in the last months of this long expedition.

And for the opportunity to set out on the journey at all, I will always be grateful to my French and Italian friends.

Figure 1: Examples of public engagement and technical research, 2008-2009[28]

Chapter I. Origins

1. Introduction

This section charts the early stages of the project as it evolved from the initial proposal to combine printmaking and studio glass techniques to illustrate the structures of the visual pathway as a communication tool for staff at the Eye Hospital, to a realisation that these very same graphic and optical qualities could also serve to expose these dynamic mechanisms at work, in Patrick Hughes' words 'the shift between telling and showing'.[29]

2. Context

The original proposal to the RCA was designed to draw together the technical and contextual strands of my practice to date: an Arts Council-funded project had demonstrated the creative potential of encapsulating digital prints in glass, while informal workshops with nurses and blind and partially-sighted patients at the Bristol Eye Hospital had suggested that interactive illustrative artworks could provide a catalyst for more engaging and holistic dialogue for all concerned.

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[28] RNIB patient workshop 2008: Bristol Eye Hospital surgeon meeting 2009: NGC Sunderland conference 2009: student demonstrations, UCA Farnham 2009: Arts Council project documentation 2009.

[29] Interview with Patrick Hughes, December 2012, see appendix for transcript.

Figure 2: Bristol Eye Hospital, nurse holding glass sculpture[30]

Figure 3: John Ruskin (1819 – 1900)

[30] Image by Shelley James, 2009

The project aimed to develop a series of interactive models combining the material qualities of glass with the graphic precision of print for use by clinicians with the aim of exploring the therapeutic potential of art works in a clinical setting.

3. Orientation

With this in mind, a series of material investigations were undertaken to refine the process of reproducing detailed graphics and images in a range of studio glass techniques.

The induction process included exposure to an extraordinary range of practices, and exposure to a new domain of durable, transparent, workable and affordable synthetic materials and skilled technical staff. A growing awareness of the contrast between these and the heavy demands of glass led to the decision to persist with this material only if its use could be justified, in Ruskin's [31] words, by a celebration of its 'peculiar qualities… namely, its DUCTILITY when heated, and TRANSPARENCY when cold.'[32]

[31] John Ruskin, portrait by and after Elliott & Fry, half-plate glass negative, (1882), National Portrait Gallery online archive, reference NPG x81996

[32] Ruskin, John, and J G. Links. 1964. *The Stones of Venice*. New York: Hill and Wang


Figure 4: 2nd century AD mould-blown vessel[33]


Figure 5: Rene Lalique. 1927. *Les Bacchantes*, mould-blown vase[34]


Figure 6: Erwin Eisch. 1976. *Eight Heads of Harvey Littleton*, mould-blown sculptures[35]

He goes on to declare that: 'All work in glass is bad which does not, with loud voice, proclaim one or other of these great qualities.'[36]

With this in mind, the studio development drew inspiration from the way that these 'great qualities' have been celebrated through the history of glass production.

i. Ductility

The earliest vitreous enamels or faience, formed by melting crushed coloured minerals with ash were used to seal and embellish stone age vessels, and, by around 3500BCE, craftsmen had perfected the process to the point where the ceramic support was no longer needed. This uniquely versatile glossy, tough yet pliable material was pressed into moulds, then carved and polished using lapidary techniques. The Romans increased the working time of the material by controlling the heat in their furnaces, blowing the still-molten hot glass into moulds made of wood or sand. This technique was revived in the early 19th century by a generation of French industrial designers such as Lalique and revolutionised by the advent of industrial glass production in the early 20th century.

[33] Novi Grad, Slovenia, Sarajevo Eart History Museum, http://en.wikipedia.org/wiki/File:Roman_glass_2nd_cent.jpg
[34] Private Collection, Gemeentemuseum, http://www.gemeentemuseum.nl/

[35] Federal Republic of Germany. Collection of The Corning Museum of Glass (76.3.32)
[36] ibid

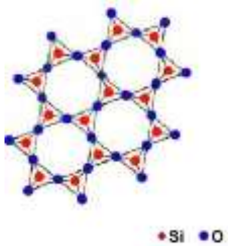

Figure 7: Quartz crystalline structure (Si02)[37]

Figure 8: Quartz crystal formation, Tibet [38]

Figure 9: 1,500 – 1,200 BC, figurine carved in quartz or rock crystal, Anatolia

[37]http://paulingblog.wordpress.com/2012/05/02/the-quasicrystals-puzzle-an-introduction/
[38]http://en.wikipedia.org/wiki/File:Quartz,_Tibet.jpg creative commons image taken by JJ Harrison

Pioneers of the contemporary studio glass movement such as Erwin Eisch[39] adapted these techniques, providing the inspiration for a new generation of makers such as Colin Rennie, Geoffrey Mann and Jeff Sarmiento, many of whom combine digital prototyping techniques with traditional cold working. These hybrid approaches to print and glass both exploit and express the ductile qualities of the material, evoking the same integration of formal and tactile dimensions that lay at the heart of this research project.

ii. Transparency

While the ductile properties of glass would be essential to the way that the patients and clinicians would experience the objects when used in the consultations that were planned as one of the outcomes of the project, the optical dimension were also likely to be equally relevant in the context of explaining the structures of the visual pathway.

a. Geology

Glass is closely related to rock crystal – a regular and stable structure made up of one silica and two oxygen molecules (SiO2).

[39] Erwin Eisch, German glass artist (b1927)

Although this compound is essentially the same as common sand, the conditions needed for its formation as a flawless clear crystal are extremely rare, occurring in deep subterranean fissures carved by water under pressure over millions of years.

The presence of rock crystal tools and ritual objects in prehistoric burial sites in China [40,] Egypt [41] and Ireland [42] suggests that this material was highly prized and associated with the passage between life and death, the seen and unseen worlds. The origins of the word crystal allude to these symbolic qualities. Deriving from the Greek word crystallos, meaning 'frozen ice' [43], it was believed to be a form of ice so cold it could never melt, a perception that persisted until the seventeenth century.[44]

[40] "Peking Man, Beijing Man, Sinanthropus pekinensis, http://www.greatarchaeology.com/peking_man.htm, accessed 05/12/2013

[41] Carolyn Graves-Brown, *Luster, Flint and Arsenical Copper in Dynastic Egypt*, Lithic Technology 2013 38.3 150-160, (http://www.academia.edu/4768248/Post_Print_of_Luster_flint_and_arsenical_copper_in_Dynastic_Egypt_published_in_Lithic_Technology_2013_38.3_150-160, accessed 20/10/2013

[42] Unesco World Heritage Site, "Newgrange Stone Age Passage Tomb - Boyne Valley, Ireland," http://www.newgrange.com/. Accessed 30/11/2012

[43] Crystal, from Greek. krystallos, from kryos "frost," from PIE base *kru(s)- "hard, hard outer surface" (see crust). Douglas Harper, "Online Etymology Dictionary", n.d., http://www.etymonline.com/index.php?term=crystal, accessed 05/12/2013

[44] Walters Art Museum, Baltimore, from Wikipedia commons https://en.wikipedia.org/wiki/File:Anatolian_-_Figurine_of_a_Child_-_Walters_42360.jpg, accessed 05/12/2013

Figure 10: , 1-2C A.D Begram beaker. Afghanistan, enamelled glass[45]

Figure 11: 11th -12th century. Visby lenses, Gotland[46]

iii. Manufacture

As discussed above, the material was initially approached as an extension of ceramic glazing techniques. However, by the end of the 1st century BCE, the Greek philosopher Pliny the Elder (23 – 79 AD) remarked that glass vessels had been brought to a 'marvellous degree of resemblance to crystal.'[47]

As the clarity of the glass improved, these new transparent surfaces were approached as a floating 'ground' on which objects and figures were arranged to create layered narratives that shift as the viewer changes their perspective.

By the end of the eleventh century, Venetian glassmakers had refined techniques to produce the celebrated 'cristallo', a secret formulation of refined silica and ash that could be cut and polished into remarkably clear decorated vessels and lenses.

[45] National Museum of Afghanistan, Photo: © Musée Guimet / Thierry Olivier

[46] http://www.kleinesdorfinschleswigholstein.de/buerger/oschmi/visby/visbye.htm accessed 05/12/2013

[47] Plinii C. Scundi. "Historia Naturalis", Book XXXVII, Chapter 10 "*Luxury Displayed in the Use of Crystal and Remedies Derived from Crystal*", from translation published by the Perseus Project at Tufts University: http://perseus.uchicago.edu/perseus-cgi/citequery3.pl?dbname=PerseusLatinTexts&getid=1&query=Plin.%20Nat.%2037.10 accessed 05/12/2013

Figure 12: 1575 – 1650. Venice, Goblet[48]

Figure 13: *The Harrowing of Hell,* 1480. Stained glass window, Gloucester Cathedral[49]

Examples of these objects have been found in burial sites across Europe such as the site discovered in Gotland dating from the 11th or 12th century, suggesting their high value[50]. Although crude in comparison with the Venetian material, glass production continued across Europe, with gradual refinements including colouring techniques that were perhaps employed to compensate for the lack of optical clarity.

The early 13th century saw the production of flat discs and panels of stained glass, used to dramatic effect in the new cathedral architecture.

Strips of lead were used to draw the contours of the earliest architectural glass images, an approach soon superseded by techniques that allowed for greater detail and expressive range: 'Additive' processes involve mixing ground coloured minerals with a glue or gum, painting and then firing this onto the surface of the glass. By contrast, in 'subtractive' techniques, two layers of glass are fused together – usually a clear base and a coloured overlay. The coloured layer can then be selectively removed to create a motif 'suspended' on a transparent ground.

[48] Soulage Collection at the V&A London, http://collections.vam.ac.uk/item/O1406/goblet-unknown/

[49] www.gloucestercathedral.org.uk accessed 05/12/2013

[50] R. W. Douglas: 1972. *A History of Glassmaking*, G T Foulis & Co Ltd, Henley-on-Thames.

The search for an affordable alternative to the clear Venetian cristallo continued until the invention of flint glass, or lead crystal, by George Ravenscroft (1632 - 1683), a development that paved the way for a new generation of optical instruments and the observations of scientists including Newton, Hook and Kepler.

iv. Dark arts

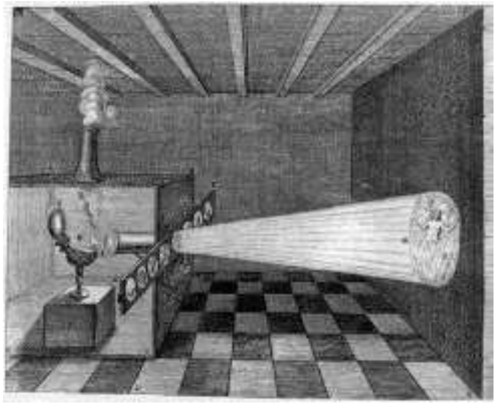

Figure 14: 1646. First printed illustration of a magic lantern projection[51]

Exploiting these new production techniques in the 17th century the Jesuit scholar Athanasius Kircher (1601 – 1680) assembled an impressive collection of disorienting 'crystalline machines' at the Collegio Romano in Rome, giving an account of the underlying mechanisms of catoptrics, or the study of mirrors, in his work *Ars Magna Lucis et Umbrae* of 1646[52]. These optical toys effectively introduced a new distinction between the natural world where images were produced by light reflected from an object and the projected or transmitted image with no need for a material support, generated by light as it *'traverses a transparent veil.'*[53]

[51] Kircher, Athanasius. 1646. *Ars Magna Lucis et Umbrae* Quoted in Mannoni, Laurent, Nekes, Werner, and Warner, Marina. 2004. *Eyes, Lies and Ollusions: the Art of Deception*. London: Hayward Gallery. p18

[52] ibid

[53] Paini, Dominque '*Should we put an end to projection?*' trans. Rosalind Krauss, October 110 (Fall 2004). p24

The historian Barbara Stafford describes the link made by these scholars between the science of the visible and the mystery of the divine*: ‘i*n the hands of the Jesuits, such devices demonstrated the fickleness of the human mind, the duplicity of sensory appearances, and the convertibility of the physical universe in contrast to the immutability of an immaterial God.’[54]

The curator Marina Warner suggests that in this age of strong religious conviction, the new optics redrew the boundaries between the seen and unseen worlds to create three classes of illusion: *‘*miracles from God by which the laws of physics were suspended; Natural Magic or the wonderful properties of earthly things; and, last, the illusory work of the devil.’[55]

She goes on to point out the parallel histories of magic and optics: ‘if the devil was able to conjure appearances whereas God truly performed prodigies, it was imperative to establish the truth status of vision.’[56]

[54] Stafford, Barbara and Terpac, Frances.2002. *Devices of Wonder: From the World in a Box to Images on a Screen*. Paul Getty Research Institute, Los Angeles. p 27
[55] Mannoni, Laurent, Werner Nekes, and Marina Warner. *Eyes, Lies and Illusions: The Art of Deception*. London: Hayward Gallery, 2004. p14
[56] ibid p14

v. Optical instruments

While more than adequate for dramatic effect, the demands of increasingly sophisticated scientific techniques exposed the need for greater control over the optical qualities of the material. By the beginning of the 18th century, other elements such as sodium and borosilicate were introduced to alter the physical properties of the material such as response to heat, ease of cold working and the angle of refraction – the alteration in the direction of light as it passes from one transparent medium into another.

While this knowledge was largely empirical, the Bavarian optician Joseph von Fraunhofer (1787- 1826) established the calibration system that carries his name that paved the way for multi-lens instruments. These were central to the innovations in microscopy and astronomy and early experiments in psychophysiology[57] in the early 19th century that led to a profound shift in the understanding of the relationship between the visible and invisible worlds, with implications for approaches to representing space that will be discussed later in this thesis.

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[57] Brewster, David, Charles Wheatstone, and Nicholas J. Wade. 1983. *Brewster and Wheatstone on vision*. London: Published for Experimental Psychology Society by Academic Press.

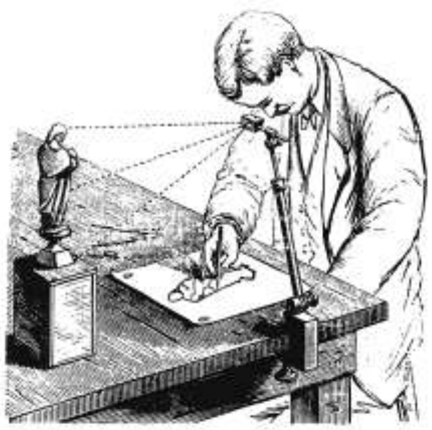

Figure 15: Camera Lucida in use, illustration from the Scientific America Supplement, January 11, 1879[58]

.

At the same time, the British inventor William Hyde Wollaston (1766 -1828) considered the effect of curvature on magnification and projection, building on the optical toys of Kircher to invent the camera lucida in 1807. Founder of the German manufacturing company, the scientist Otto Schott (1840 - 1903), worked with the physicist Ernst Abbé (1851-1935) to investigate the interaction of light and glass to establish the basic specification system that is used in the global optics industry today.

[58] from Wikipedia commons, http://en.wikipedia.org/wiki/File:Camera_Lucida_in_use_drawing_small_figurine.jpg accessed 05/12/2013

Figure 16: Glass panel entering glory hole

4. Studio development

These insights informed a series of technical investigations with the aim of refining the necessary technical skills to produce a series of sculptures for the clinical environment. These can be divided into three broad themes:

- Transparency and surface effects: Locating and manipulating motifs on curved and flat planes, alone or in combination, to explore the production of shadows and patterns within and beyond the object.
- Ductility and form: Exploring techniques for encapsulating images and patterns within the form, exploiting the fluid qualities of the molten material to materialise the layered, sequential making process.
- Colour: considering options for generating clear coloured images to combine the transparent and ductile dimensions of the material

The following section provides a brief outline of the approach and findings, while the detailed methodology and results can be found in the appendices.

Figure 17: Borosilicate tests

i. Transparency and surface effects

For the first series of tests, I worked with transparent borosilicate tubes and rods: commonly used in a clinical setting, this material is robust, can be sterilised and is relatively affordable. The lampworking process is also swift and straightforward, the ideal technique with which to test the basic parameters, comparing screen printed transfer with familiar digital products at different temperatures.

It soon became clear that borosilicate is extremely ‘hard’: even when heated to very high temperatures for long periods in a casting kiln, the material does not ‘flow’ to make an integrated volume, and retains the surfaces and shapes of the original elements, whether larger shards, ground up to frit or even fine powder. The material did not even melt sufficiently to create glossy, transparent or coloured effects. Coloured enamels, minerals, frits and transfer printed images remained ‘chalky’ and ‘on the surface’, forming rough and brittle textures which were not relevant to these tests but had the potential to contribute to the interactive patient engagement phase of the project. However, the silver stain process, in which silver leaf is applied to the surface of the glass when hot, then melted to oxidise, did prove successful, creating rich golden transparent areas of tone that could then be removed by sandblasting to create detailed images.

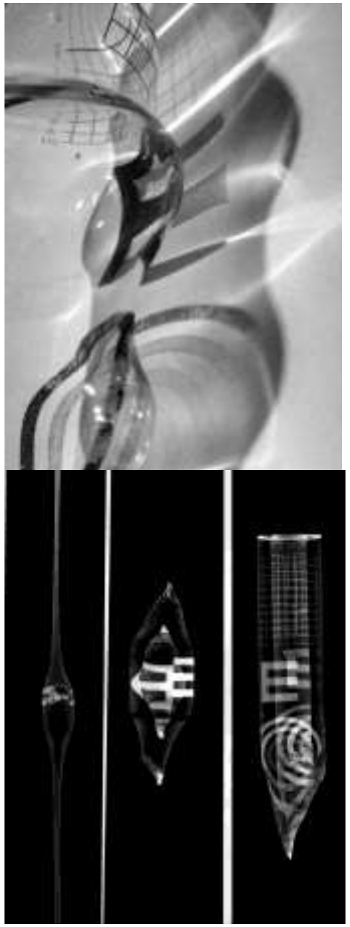

Figure 18: Projection and photograms using printed borosilicate tubes

The material resisted press- or mould-blowing, cooling too swiftly to make any detailed impressions but the optical qualities of the thicker solid rods magnified the prints in a remarkable way and amplified the slightest change in the position of the viewer.

The consistent and stable surface of the glass effectively operates as a transparent 'skin', projecting the print as a crisp shadow onto other surfaces within and around the piece. A series of photograms were produced to explore these phenomena.

Rolling a series of printed cylinders together created a dynamic pattern of moving shadows, a phenomenon that laid the groundwork for an installation of work at Somerset House in June 2013[59].

The ability to seal a number of freely-moving components within a single form was also of interest: these playful, rattling pods provided the inspiration for a collaboration with the Faculty of Music and the Bate Collection of Musical Instruments at Oxford University[60].

[59] http://www.culture24.org.uk/science-and-nature/science-art/art443535 accessed 05/12/2013
[60] http://www.bate.ox.ac.uk/

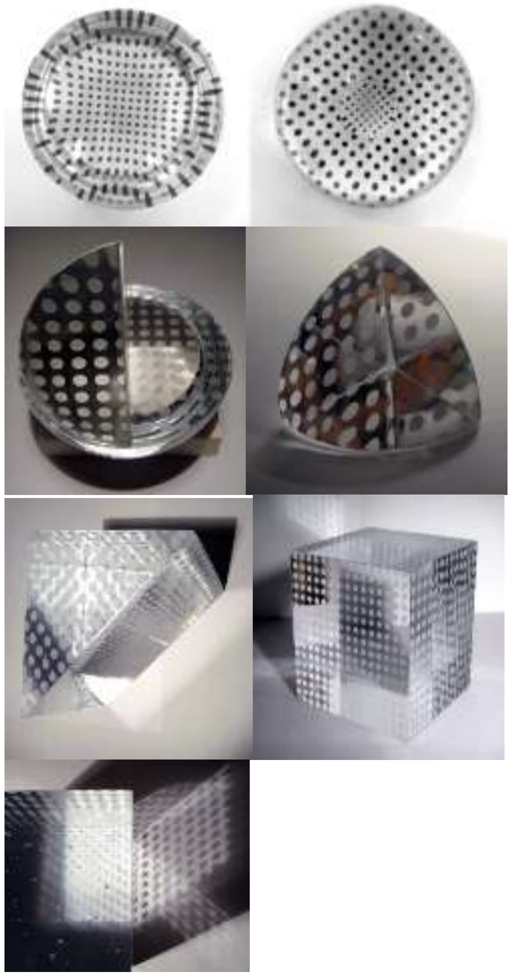

Figure 19: Cast glass tests with sandblast matrices

ii. Ductility and form

The magnifying properties of the solid borosilicate rods and the anamorphic illusions of the Jesuit's optical toys suggested another approach to this essential quality of transparency.

A series of spheres and sections, alongside cones, cylinders and prisms were blown and cast. A simple dot matrix was manipulated to appear 'normal' when seen through the glass, while the artifice was only revealed when the pattern was seen directly.

As well as the paradoxical magnifying and distorting effects, these objects produced unexpectedly rich spatial effects – these floating patterns seemed to multiply and extend into a fugitive dimension that was at once within and beyond the form itself, appearing and disappearing with the slightest movement of the object or the viewer.

However, these compelling effects largely result from the transparent qualities of the material alone and could perhaps be achieved using other materials such as Perspex and acrylic.

Figure 20: Transfer print in hot glass

Figure 21: Transfer print in cast glass

The decision to focus on techniques that express the unique qualities of glass led to a series of tests to consider different ways to encapsulate the printed surfaces inside the object, expressing the fluid quality of the material either by the manipulation of the print, or by the outer form.

Previous experience of transfer printing, suggested that simple, high-contrast black and white graphics are relatively straightforward to encapsulate in hot glass: they generally remain dense and sharp, provided they are not left exposed at high temperatures. Once encapsulated, they retain their integrity through fairly robust stretching and blowing, mapping the movement of the material from solid to liquid states.

These established techniques allow considerable control over the position of the print and the degree or distortion. In order to observe the effects produced by a more ‘random’ approach, small clear billets into which prints had been fused were cast into a deep mould – a ‘fist’ form that had been produced as part of an induction workshop. However, the image was no longer legible, producing a marbling or veined effect – intriguing but unlikely to be a useful route for the Eye Hospital project

Figure 22: Screen print fired onto tecta glass

iii. Approaches to colour

Having established the basic parameters for printing and encapsulating simple graphics in hot glass, my attention turned to the dimension of colour.

Although 'student' or craft-grade coloured enamels typically contain opaque minerals such as titanium to reduce costs and improve density, commercially-printed coloured transfers could be expected to generate bright, clear images similar to those produced by stained glass. However, even when the piece was taken to full casting temperature, the printed images remained opaque, creating dull grey shadows.

The contextual research described above had pointed to the use by Roman and Egyptian craftsmen of minerals used in ceramic glazes such as copper oxide. A series of transfers were screen printed by hand, using this and other metal oxides such as cobalt and iron. While the copper oxide prints were stable and generated a rich blue colour, the others broke up into grainy clouds of tone. A number of reasons for this were discussed, but with limited time, the decision was taken to return to commercially-available options.

iv. Encapsulation

Previous tests had approached the material as a transparent 'skin' or as a ductile form. The investigation of colour built on this structure, testing the options for producing bright, precise images on a thin open bowl or a solid rectangular block. Two broad approaches were considered, referencing the historical review of decorative techniques described earlier:

a) 'additive' techniques: adding colour or tone to clear material either through a transfer print or integration of other elements
b) 'subtractive': taking colour away, through one of a number of processes such as sandblast, engraving and etching block tone and half-tone matrices

Figure 23: Casting process and result with block of red, and with 2mm slice of Kugler 'copper blue' cast rod

a) 'Additive' techniques

One hypothesis for the 'chalky', opaque appearance of the commercially-available coloured printing enamels was the fine grain of the powder: the microscopic bubbles captured between the grains deflect the light and cast a dull grey shadow. This hypothesis was confirmed by the first test in which a blown 'egg' of pure rod colour was ground to a powder, applied to an embryo and encapsulated in hot glass to make a simple 'dish'. However, while the image was substantially brighter and more transparent than the commercial enamels, the colour of the projected shadow was still visibly dulled by the bubbles that remained.

To test the other extreme, a three-dimensional model of the 'E' image was created using the 'Rhino' software, cast in silicon then cast in blowing rod using the lost wax method. This was added to a clear embryo and either left exposed or encapsulated. While the effect was intriguing, the colours were too dense to allow light to pass through at all.

Further experiments resolved these issues, producing a bright, transparent 'E' shape from a 2mm slice of cast colour. However, the shape was 'soft' with rounded corners, suggesting that this would not be a viable approach for detailed graphics.

Figure 24: elements before and after encapsulation

v. Subtractive approaches

This led to the decision to explore subtractive strategies where a fine layer of transparent colour is laid over a transparent base in an overlay or underlay, making a simple cylinder that can then be cut and slumped to produce flat panels of transparent glass with a 'skin' of colour. This can be removed to reveal the clear glass below using a range of techniques that have evolved for applications ranging from architectural stained glass to trophy production and the traditional graal process in which areas of colour are removed from a vessel that is then encased in clear glass.

A series of tests considered variables such as the optimal relationship between the clear base and the coloured overlay as well as the effects produced by combining multiple elements within a single form, combining prints with coloured elements and techniques for placing the elements in the pick-up kiln to reduce breakage and improve speed and precision.

With the ability to position distinct, vivid transparent patterns inside a solid form, attention turned to the question of colour mixing, combining multiple coloured inclusions within a single form and on multiple 'stacked' elements.

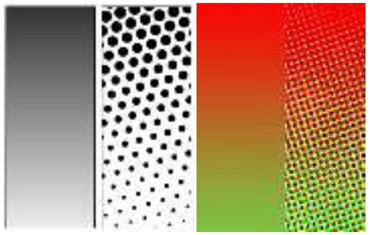

Figure 25: Greyscale and green-red progression magnified to show half-tone matrix

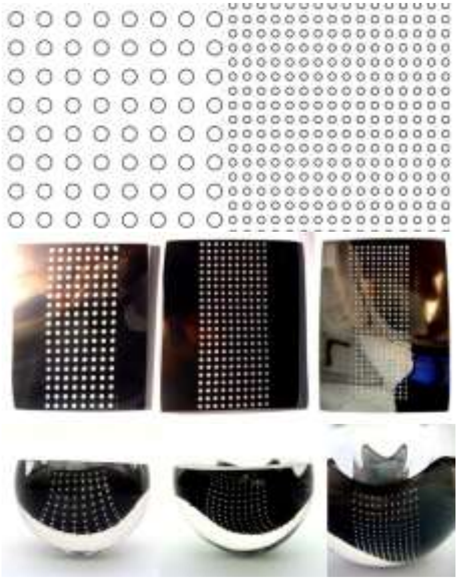

Figure 26: Half-tone matrices, tiles before encapsulation and dishes after encapsulation

vi. Half-tone matrix

The classic half-tone dot matrix used in screen printing to create an impression of a coloured image was the obvious starting point: varying the size of the dot creates an illusion of density, while combining cyan, magenta, yellow and black dots (the 'cmyk' set) produces a coloured effect.

vii. Matrix resolution

The research discussed earlier had shown that self-adhesive plastic sheets cut by commercial laser techniques or by hand provided the most accurate, robust yet flexible and affordable stencils for this type of pattern. The first task was to focus on the half-tone matrix itself – seeking a size and spacing of the 'dots' that would be large enough to remain sharp when heated and encapsulated, but small enough to appear as an even 'cloud' of tone that is critical for the colour mixing effect.

Using sections of a plate carrying a thin layer of black pigment, a series of tests identified the smallest dot size and closest spacing that would survive the heat of the laser beam. As part of this investigation, experiments were also carried out to understand the impact of the depth of dot on the size and shape of the encapsulated bubble. While it was critical that the all the colour should be removed to produce a sharp contour, the depth did not make an appreciable difference to the tonal effect

viii. .Colour mixing

Having refined the process to the point where a sharp, regular dot matrix could reliably be produced, the next step was to apply these principles to colour: the aim was to produce the continuous tone appearance of the screen printer's 'cmyk' set using glass.

The first tests sought to create an accurate balance between the densities of the four tones, which is the basic requirement for successful perceptual mixing. For example a dense blue and a pale yellow will not create a vibrant green.

Figure 27: Examples of hot glass tests

A series of experiments used measured sections of coloured bar to produce mould-blown cups in order to compare and refine the densities between the tones. However, it eventually became apparent that it would not be possible to reliably produce the four-colour set in a studio setting: as well as variations between the products, batches and manufacturers, subtle changes in the temperature of the furnace glass and the number of times that the cup was reheated made a difference to the final result.

In addition, using the laser-cut stencil technique, the voids were inevitably etched away from a coloured ground, so the bubbles were always set into a coloured surface. As a result, when multiple layers were combined within a single form, the overall effect was opaque rather than transparent. Although the UV stencils had the potential to resolve this issue, further tests proved that the material is not sufficiently robust to withstand the sandblasting process.

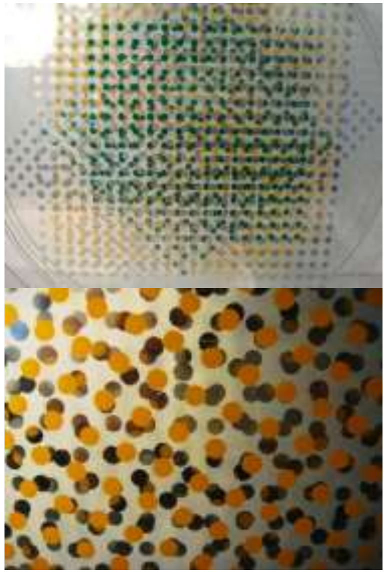

Figure 28: Examples of UV-cured screen print on glass

A conference on architectural glass at the National Glass Centre in Sunderland prompted a series of experiments using UV-cured inks on float glass. The aim was to print each of the colours onto a separate panel of glass, allowing the light to shine between the layers to produce the colour mixing effect. However, although the inks were described as transparent, the light did not pass through the printed areas. This may be due to the fact that these materials are designed for the fine coatings delivered by industrial systems.

However, the silvered matrix did generate subtly shifting spatial effects that suggested avenues for further development.

A number of tests led eventually to the ability to encapsulate a dense, even cloud of bubbles on multiple layers within a single form. Recalling Ruskin's encouragement to celebrate the particular qualities of the material itself, coloured materials were replaced by transparent elements that generated rich nets of mobile shadows that played across the planes within and beyond the object. These generated an oddly mobile and paradoxical sense of space: bright bubbles cast dark shadows, distant elements appeared closer, the central voids appeared silver from some angles, but invisible from others.

Figure 29: *Lacuna*, transfer print in hot glass 2009:
hot glass tests with encapsulated matrices 2009-2010

5. Conclusions

By the end of the second year of the project The Bristol Eye Hospital negotiations were still in progress and it became clear that the focus of my interest had shifted away from the original intention to use print in glass to illustrate the structures of the visual pathway.

The fulcrum for the research now lay in the way that, far from materialising these unseen forms, the simplest objects seemed to generate compelling, ambiguous and mobile spaces that interacted with their environment in unexpected ways, suggesting rather than illustrating the experience of sight.

It also seemed that the presence of a recognisable figure or graphic seemed to lock down this lively fluctuating quality: while the appearance of the dot matrix responded to every variation in the texture or shape of the glass, the least suggestion of a gaze, even a fragment of the eye motif, seemed to be fixed, immune to the rich optical effects generated by the ductility and transparency of the material.

The aim of the next stage of project was to build on these observations: to understand the mechanisms that generate these paradoxical spatial effects and to refine techniques combining print with studio glass to the point where these could be predicted and controlled.

Chapter II. Frames of reference

1. Introduction

The previous chapter concluded with the observation that placing very simple graphic elements on the external or internal surfaces of basic glass forms generated strange and compelling spatial effects that, to borrow Richard Gregory's definition of an illusion 'challenge our sense of reality'.

If an illusion is a challenge to our sense of reality, a useful starting point may be to understand how this reality is usually constructed. Richard Gregory's model provides a valuable framework for a description of the process by which patterns of light falling on the retina are interpreted by the visual system to produce the experience of sight.

This is followed by a consideration of the particular signals that are interpreted as cues to depth, noting the sophisticated exploitation of these mechanisms by artists such as M.C. Escher[61] to generate the appearance of a three-dimensional space on a two-dimensional surface.

[61] Maurits Cornellis Escher, Dutch graphic artist and printmaker (1898-1972)

This sets the context for a brief review of the development of linear perspective, considering the tension between the stable, coherent geometry of these objective constructions and subjective physical experience in the light of the art historian Erwin Panofsky's[62] proposal that approaches to representing space are an indication of cultural attitudes rather than technical skill.

Having noted the development of perspectival systems based on a solid three-dimensional world view, the chapter describes a series of discoveries that challenged these conventions, offering scientific proof of a fourth dimension lying 'beyond the reach of the visible.'[63]

Compounded by the upheaval of the First World War, the art historian Linda Dalrymple Henderson links these themes of flux and fragmentation with new approaches to representing space in the visual arts, literature and music.

[62] Erwin Panofsky, German art historian (1892-1968)
[63] Henderson, Linda Dalrymple. 1983. *The fourth dimension and non-Euclidean geometry in modern art*. Princeton, N.J.: Princeton University Press

Clement Greenberg characterises this attitude as a rejection of the deception inherent in the lyrical 'trompe l'oeil' style with its association with an art market driven by the tastes of an emerging industrial middle class and the authority of the Academies[64]. The Modernist attitude sought to focus entirely on the essential qualities of each medium, freeing the artist from 'historic accretions' and the 'the turgid symbolism of past associations.'[65]

Representing recognisable objects would logically imply a three-dimensional spatial context, contravening this principle, a position adopted by the Concrete artists who experimented with automatic systems such as colour compositions generated from numbers read out from a telephone directory to generate compositional structures, in the curator Marlene Lauter's words, 'structural-organisation-made-visible.'[66].

The chapter concludes with a return to the central theme of the project: visual perception of space is generated by 'bottom up' signals from the retina that trigger a response based on innate and learnt knowledge about how the world usually appears.

[64] Greenberg, Clement.1960. Modernist Painting. Forum Lectures (Washington, D. C.: Voice of America), from http://www.sharecom.ca/greenberg/modernism.html, accessed 05/12/2013
[65] Moholy-Nagy, László. 1947. *Vision in motion*. Chicago: P. Theobald. p 28
[66] Lauter, Marlene, and Reese, Beate. 2002. *Konkrete Kunst in Europa nach 1945 = Concrete art in Europe after 1945*. Ostfildern: Hatje Cantz.p99

Visual artists have exploited these mechanisms in different ways to create the paradoxical experience of a three- (and four-) dimensional space on a two-dimensional surface. Transparent materials, such as glass or Perspex generate signals that do not fit with the predicted appearance of objects in the world, a mis-match that can give rise to compelling paradoxical spatial effects.

2. Ambiguity

The physical eye, if properly directed, was considered an accurate and reliable instrument, the 'light of our body, and God's Sense most mighty[67]' until the middle of the 19th century when research by a number of scientists including Hermann von Helmholtz[68] clarified the basic structures and mechanisms of visual perception.

[67] Dee, John (1570) *The Mathematicall Praeface to Elements of Geometrie of Euclid of Megara*, [EBook #22062] Release Date: July 13, 2007, available from http://www.gutenberg.org/files/22062/22062-h/main.html, accessed 09/03/2013
[68] Hermann von Helmholtz, German physician and physicist (1821-1894)

In his celebrated lecture to the Royal Society in 1868, Helmholtz describes all the lacunae and distortions that result from the physiology of the eye, concluding: '…it is not too much to say that if an optician wanted to sell me an instrument which had all these defects, I should think myself quite justified in blaming his carelessness in the strongest terms and giving him back his instrument.'[69]

He goes on to introduce the process of unconscious inference, a dynamic cycle of hypothesis generation and testing: 'the correspondence between the external world and the Perception of Sight rests, either in whole or in part, upon the same foundation as all our knowledge of the actual world – on experience.'[70.]

[69] Helmholtz, Hermann von, and Atkinson, E. 1873. *Popular Lectures on Scientific Subjects*. New York: D. Appleton. Lecture VI. *The Recent Progress of the Theory of Vision*, trans. Dr. Pye-Smith. p219
[70] Ibid p 315

3. Inference and illusion

Richard Gregory's model, first published in the form shown below in 1997, builds on this basic principle to describe the process through which a stream of signals received by the retina is interpreted to produce the experience of sight.

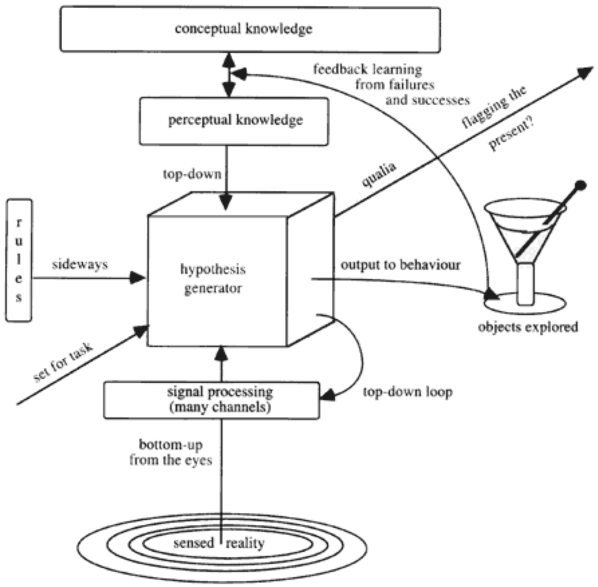

Figure 30: Richard Gregory's model "Knowledge in perception and illusion"[71]

[71] Richard L Gregory *Knowledge in Perception and Illusion*, From: Phil. Trans. R. Soc. Lond. B (1997) 352, 1121–1128. from http://www.richardgregory.org/papers/knowl_illusion/knowledge-in-perception.htm accessed 05/12/2013

As Helmholtz points out, the eye is far from a perfect optical instrument: much of the information is distorted or disrupted by the physical structure itself. Not only is the reception imperfect, the light itself is travelling through the atmosphere: it may be dispersed by dust or redirected by reflective surfaces, and the pattern of signals received by the retina will be determined by the angle of view.

For example, light diffracting through drops of water can appear as a 'solid' rainbow, an oval edge may equally well be produced by a circular surface as by the lip of a hollow tube, and a rectangular box behind a vertical pillar will produce the same retinal pattern as two separate objects. And yet, the interpretation of these ambiguous signals is remarkably swift and accurate: the gist of a scene including features such as the presence and scale of horizontal and vertical objects is perceived after as little as 1/200th of a second[72].

Gregory proposes that this ability arises from a constant interaction between a central 'hypothesis generator' that makes running predictions about the likely meaning of ambiguous physical signals in the light of 'sideways' rules and 'top down' knowledge.

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[72] Rasche, C. and Koch, C. (2002) *Recognizing the gist of a visual scene: possible perceptual and neural mechanisms.* Neurocomputing, 44, pp. 979-98

To the left of Gregory's diagram, the arrow marked 'set for task' points to the role of expectation in the interpretation given to physical signals as well as sensitivity to them: a glass blower will respond to subtle changes in the colour of the material that would pass un-noticed by the spectator.

He adds a further dimension to the model to indicate that, alongside the function of directing behaviour, the visual system also plays a central role in 'flagging the present', maintaining the vital distinction between the inner world of the imagination and the external world: he cites the difference between imagining a glass of water and actually seeing it[73.]

However, there are phenomena that 'challenge our sense of reality', producing inconsistencies between the images in the eyes and the input from other sources such as the muscles that direct movement and the vestibular system.

[73] Gregory, Richard L. *Knowledge in Perception and Illusio*n, from: Phil. Trans. R. Soc. Lond. B (1997) 352, 1121–1128. from http://www.richardgregory.org/papers/knowl_illusion/knowledge-in-perception.htm accessed 05/12/2013

Gregory considered that the study of these phenomena offers valuable insights into the underlying mechanisms of perception, proposing a classification that differentiates between the causes of these phenomena and their type or 'kind'.

Causes → *Kinds* ↓	physics		knowledge	
	optics	signals	rules	objects
ambiguity	mist	retinal rivalry	figure-ground	hollow face
distortion	mirage	Café wall	Muller -Lyer	size - weight
paradox	looking-glass	rotating spiral	Penrose triangle	Magritte mirror
fiction	rainbow	after-images	Kanizsa triangle	faces in the fire

Richard Gregory's Classification of Phenomenal Phenomena[74]

[74] ibid

i. Physics

A decision was taken early in the project to focus almost entirely on the illusions in the first column – that Gregory considers to be caused by the physical properties of light – as these are most likely to arise from the particular optical qualities of glass.

This set of phenomena are part of everyday experience and yet surprising – for example, the position of an object viewed in a mirror does not fit with its predicted location because of the reflective properties of the material, while a distant mountain range will appear paler and less saturated because of the absorption of the light by dust and moisture in the atmosphere.

The second group arise from the mis-application of knowledge. Gregory differentiates between three broad types of knowledge: sideways rules, perceptual, and conceptual knowledge.

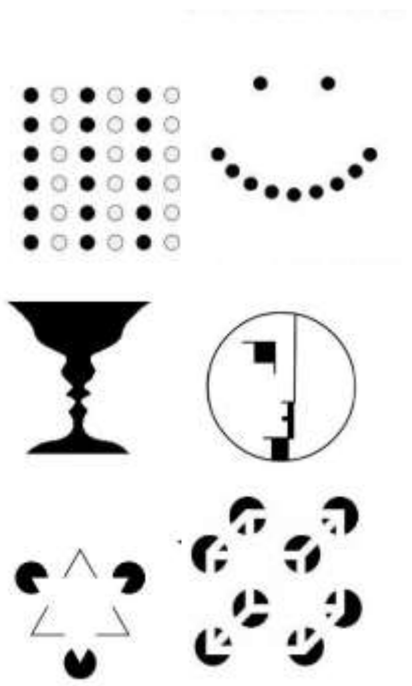

Figure 31: Examples of Gestalt principles: grouping, figure-ground, symmetry, closure

ii. 'Sideways rules'

These build on a set of theories known as Gestalt Principles, first described by the Austrian philosopher Christian von Ehrenfels.[75] This approach, a reaction against the 'atomist' theories that prevailed in the early 19th century considers that the visual system perceives 'whole' forms and only then breaks them down into their component features. He used the analogy of a melody in music, which, although it is made up of individual notes, is perceived as a whole. [76]

The underlying principle of this theory is Prägnanz, literally translated as 'pithiness'. It proposes that that the perceptual system actively seeks out interpretations that are as simple, symmetrical and ordered as possible to satisfy the internal schema or world view.

These are generally described in terms of a number of organising principles, four of which are particularly relevant to this project and illustrated here. The first is known as 'grouping', where objects that are close to each other or that appear to be similar are generally perceived as a group.

[75] Christian von Ehrenfels, Austrian philosopher (1859 to 1932)
[76] Smith, Barry. 1994. *Austrian Philosophy: The Legacy of Franz Brentano*. Chicago: Open Court. p244

The figure-ground rule describes the tendency to structure a scene in terms of an object and a background. Preference for symmetry results in the prediction that patterns on one side of a vertical or horizontal median are likely to be repeated on the other, even if they are not visible, while lines or forms where there is a gap or a break are assumed to be closed.

Figure 32 Hollow face illusion[77]

iii. Perceptual and conceptual knowledge

Gregory's model distinguishes between these basic organising principles and interpretations that are based on more specific knowledge about how objects usually appear in the world. The hollow face illusion, in which a mask pivots slowly on a spindle, is a good example. As faces are almost always convex and not hollow, the interpretation of the object as a solid face persists, despite the obvious error.

[77] Gregory, Richard L. *Knowledge in Perception and Illusio*n, from: Phil. Trans. R. Soc. Lond. B (1997) 352, 1121–1128. from http://www.richardgregory.org/papers/knowl_illusion/knowledge-in-perception.htm accessed 05/12/2013

Interestingly, when a participant in a psychophysical experiment is asked to flick a magnet placed at the deepest part of the nose, the hand aims at the correct depth, demonstrating that visual stimulus can have completely opposite effects on conscious perception and visual control of fast action.[78]

Gregory also notes the potential to extract meaning from visual stimulus as an abstract or conceptual code: the ability to interpret a set of black marks on a white page as the words of a book or the notes of a musical score for example.

iv. Cues to space

In this context, the process through which an arrangement of marks on a flat surface is experienced as a convincing pictorial space is a daily example of Gregory's 'strange phenomena that challenge our sense of reality.'

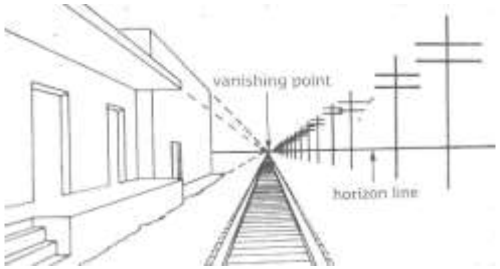

Figure 33: Perspective cues

In order to achieve this effect, the artist composes the image combining cues to depth that will trigger the essentially automatic 'sideways rules' and may also engage perceptual and conceptual knowledge.

[78] Króliczak, Grzegorz; Heard, Priscilla; Goodalea, Melvyn A; Gregory, Richard L. *Dissociation of perception and action unmasked by the hollow-face illusion*. BRAIN RESEARCH 1080 (2006) 9 – 1 6

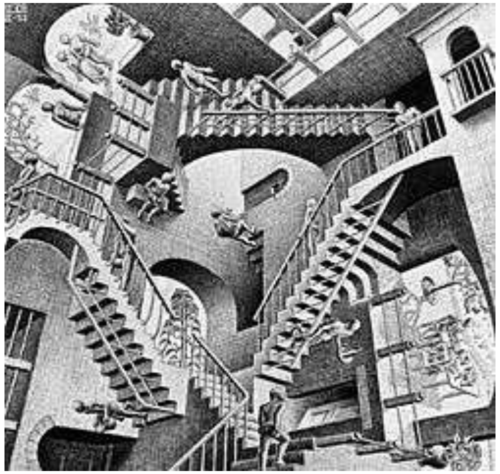

Figure 34: M.C.Escher. 1953. *Relativity*, lithograph[79]

The most dominant cue to depth is perspective, or converging contours or edges. This is based on the principle that, as objects in the world recede into the distance, the retinal image becomes smaller. The artist M.C. Escher[80] exploited this mechanism in combination with other cues to produce complex ambiguous spaces.

One of his most densely-layered works, the lithograph titled *Relativity*, shown above combines the essential paradox of a three-dimensional pictorial space on a two-dimensional surface with a construction based on four opposing 'gravity wells'. The design offers a rich demonstration of the interplay between different depth cues.

The shading on the steps, walls and door arches exposes the way that areas of dark tone that border lighter regions are interpreted as shadows cast by the sun by a form or a structure in space. The even distribution of clearly-defined light and dark areas across the image produces the overall appearance of a coherent scene. And yet, the light apparently shining through the opening along the top right edge of the image should, logically, result in a shadow on the flight of steps that run diagonally from left to right. This cue to orientation is further confounded by the position of the figures on these steps: they appear to be walking at right angles to each other.

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[79] Lithograph, image from: http://en.wikipedia.org/wiki/Relativity_%28M._C._Escher%29 accessed 05/12/2013

Occlusion is another cue exploited here, in which one continuous outline that breaks across another is assumed to indicate two objects, one ‘in front of’ the other. The apparently solid walls of this space are punctuated by lighter areas that are initially interpreted as windows that open onto a garden that lies ‘behind’ the foreground structure, an impression reinforced by a mechanism known as ‘aerial perspective’, in which the scattering of light by the atmosphere results in distant objects appearing less saturated and distinct than near ones. However, as with the figures, the normal rules of gravity are suspended and each vista is defined by a different horizon.

Escher also plays with a mechanism that uses the apparent scale of the objects and figures to gauge relationships in space. As a general rule, an object that is nearby will appear larger than the same object that is further away: the closed door on the lower left of the image is significantly larger than the one in the upper centre of the image, producing an impression of a depth that is not consistent with the length of the stairs or the scale of the figures nearby.

Although the usual notions of 'horizon' are suspended in this image, a further principle that is subtly manipulated here relates to the position of objects in the visual field: elements that are higher are perceived to be at a greater distance. The exaggerated relative size of the door example is reinforced by its location in the composition.

Figure 35: Sydney Richard Percy. 1883. *Grizedale Westmoreland,* oil on canvas[81]

The unnatural, paradoxical quality of Escher's spaces is strengthened by the lack of another cue to depth known as defocus blur: when the gaze is directed to an object at a given distance, it will be in sharp focus, while the rest of the scene will appear less distinct[82]. Photographers and painters seeking a more naturalistic effect emphasise this differentiation to indicate the centre of interest and to suggest multiple planes in depth as seen in this oil painting by Sydney Richard Percy.[83]

[81] from http://www.haynesfineart.com/artists/sidney-richard-percy.htm accessed 05/12/2013

82 Mather, George, 1996. *Image Blur as a Pictorial Depth Cue Proceeding*s: Biological Sciences, Volume 263, Issue 1367, pp. 169-172

[83] Sydney Richard Percy, English landscape painter (1821-1886)

These examples illustrate the power of these simple graphic cues to trigger a compelling experience of a three-dimensional space on a two-dimensional plane - a mechanism that underpins the ability of linear perspective, in the philosopher Jean Luc Marion's (b1946) words, to transform a: 'poor and flat surface without depth or secret or reserves in which to conceal the least behind the scenes and which nevertheless deepens itself to a bottomless depth.'[84]

v. Constructing space

The art historian Martin Kemp points out that linear perspective does not correspond literally to the way we see, 'but it does ape certain features of the array of visible information presented to us and it does so in such a way as to exploit a set of fundamental perceptual responses which ultimately lie beyond cultural conditioning.'[85]

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[84] Marion, Jean-Luc. 2004. *The Crossing of the Visible*. Stanford, Calif: Stanford University Press. p6
[85] Kemp, Martin. 1990. *The Science of Art: Optical Themes in Western Art from Brunelleschi to Seurat.* New Haven: Yale University Press. p7

Miriam Bunim concurs with this point of view, suggesting that changing approaches to representing space should be understood as an indication of shifting attitudes to tactual experience and optical sensation.[86]

In the first, the scale and relationships of figures and objects in pictures are arranged to suggest other abstract dimensions such as meaning and movement. By contrast, the compositions generated by an optically-driven approach tend to 'broadly imitate the retinal image'.[87]

Panofsky explores this thesis in his book *Perspective as symbolic form,* suggesting that representing space should be considered a factor of style, a 'symbolic form (in which) spiritual meaning is attached to a concrete, material sign.'[88]

[86] Bunim, Miriam S. 1970. *Space in Medieval Painting and the Forerunners of Perspective*. New York: AMS Press. p6
[87] Ibid p8
[88] Panofsky, Erwin. 1990. *Perspective as Symbolic Form*. New York: Zone Books. pp 40 - 41

Figure 36: ca 15,000 BCE. Cave painting, Lascaux, France[89]

Figure 37: ca. 2051–2000 BCE.Relief of Nebhepetre Mentuhotep II (detail), Egypt[90]

Figure 38: 6th century AD. Fresco. *The Sleeping Bachanite, Baccanate Addormentata,* Pompeii.[91]

Citing cave paintings as an example of the conceptual attitude, Bunim proposes that a concern with action rather than with objects or with the environment can be deduced from an emphasis on the features of qualities of animals and figures rather than whole forms, and the distribution of these marks on untreated walls and other materials such as bone and ivory. [92]

Egyptian relief paintings indicate a shift in this approach to encode temporal and cultural hierarchies as well as spatial relationships through scale and position on the picture plane. By the end of the 5th century BC, the picture plane had become an active and positive element of pictorial space with elaborate coloured borders and backgrounds and the introduction of foreshortening to describe angles of view. Despite the introduction of these optical dimensions, Panofsky notes that this remained an essentially conceptual approach: 'bodies and the gaps between them were only differentiations and codifications of a continuum of a higher order.'[93]

[89] Lascaux caves, France. Photo courtesy of Prof Saxx, Wikimedia Commons. http://commons.wikimedia.org/wiki/File:Lascaux_painting.jpg accessed 05/12/2013
[90] http://www.metmuseum.org/toah/works-of-art/07.230.2 accessed 05/12/2013

[91] Image from http://www.artship.org/inquiry_paper_magnagraeca.html, accessed 05/12/2013
[92] Bunim, Miriam S. 1970 *Space in Medieval Painting and the Forerunners of Perspective*. New York: AMS Press. p1
[93] Panofsky, Erwin. 1991. *Perspective as Symbolic Form*. New York: Zone Books. p41

Figure 39: Cinabue 1280-1285. *Madonna on the throne with angels and four prophets.* Uffizi Gallery, Florence[94] [95]

Figure 40: Giotto di Bondone ca1305, *Life of Christ, Marriage at Cana,* Cappella Scrovegni, Padua [96]

Although only fragments of his original work survive, detailed reports of the panoramic paintings of the Greek artist Polygnotus (6th century BCE) suggest that he was the first to introduce parallel horizontal undulating ground lines: objects and figures were now fixed together in a visible physical world that obeyed the laws of gravity. Roman frescoes and mosaics show the introduction of shadows as a device to suggest form and to further bind elements to the picture plane[97].

By the early Christian period, the ground and rear wall planes of Roman paintings were formalised to the point where they became strata or bands of colour onto which figures and objects were arranged according to a strict code of meaning to be read by the initiated.

The 14th century artist Giotto di Bondone[98] is credited with the first experiments in linear perspective with the production of a series of frescoes commissioned for the Capella Scrovegni in Padua.

[94] Cinabue, Florentine painter and mosaic artist, also known as Cenni Di Pepi (c1240 – 1302)

[95]Iimage in the public domain, part of the collection of reproductions compiled by the Yorck Project, copyright for the compilation held by zeno.org. accessed 05/12/2013

[96] Wikimedia commons http://en.wikipedia.org/wiki/File:Giotto_-_Scrovegni_-_-24-_-_Marriage_at_Cana.jpg
[97] Ibid p31
[98] Giotto di Bondone Florentine painter (1267-1337)

Figure 41: Fra Angelico. 1441-1450 *Annunciation*, Convent of San Marco, Florence[99]

This work is doubly remarkable because it is painted onto a vaulted ceiling: one three-dimensional space is used to create the illusion of another. Kemp suggests that this extraordinary innovation was made possible by the attitude of Giotto's patrons, who aspired to 'rational perspectives'[100] and self-determination, believing that the visible world could be measured and known. Seen in the context of the rigid formalism of the Byzantine style, this approach was a radical departure, providing a framework for representing not only the pre-ordained relationships of the church but the rich variety and accident of the everyday.

From Giotto's central 'vanishing area' construction in which objects converge on a central zone rather than a point, over the following century, increasingly sophisticated systems were developed to define relationships of objects and figures within the picture plane and relative to a viewer, who was assumed to be positioned at a single, 'ideal' vantage point.

[99] From Wikipedia commons, http://en.wikipedia.org/wiki/File:Giotto_-_Scrovegni_-_-24-_-_Marriage_at_Cana.jpg

[100] Kemp, Martin. 1990. *The Science of Art: Optical Themes in Western Art From Brunelleschi to Seurat*. New Haven: Yale University Press. P14

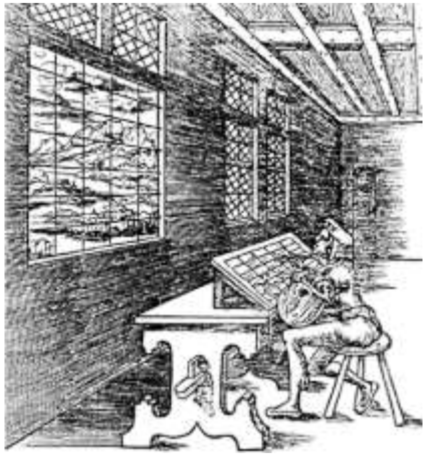

Figure 42: *Alberti's window*, illustration of technique for drawing landscapes with linear perspective construction[101]

Texts by artists, architects and mathematicians including Alberti[102], Leonardo[103] and Brunelleschi[104] offer a graphic illustration of the process of reconciling the fundamental differences between geometry and physiology, particularly when objects are placed at extreme angles or at the edges of the visual field.

Panofsky points to the chequerboard tiling or vaulted ceilings that were frequently exploited by artists to demonstrate their technical prowess as well as providing *an* 'index for spatial values… as much for the individual bodies as for the intervals between them.'[105]

By the early 15th century, a broad consensus had emerged on a system of spatial representation through linear construction

101 **S**ystem for drawing scenes in linear perspective using threads stretched across a window, from: *Brunelleschi's mirror, Alberti's window, and Galileo's 'perspective tube'* published by Scielo: História, Ciências, Saúde-Manguinhos, http://www.scielo.br/scielo.php?pid=S0104-59702006000500010&script=sci_arttext accessed 05/12/2013

102 Leone Battista Alberti, humanist polymath (1404-1472)
103 Leonardo da Vinci, Renaissance artist (1452-1519)
104 Filippo Brinelleschi, Renaissance architect (1377-1446)
105 Panofsky, Erwin. 1991. *Perspective as Symbolic Form*. New York: Zone Books. p59

Figure 43, Masaccio, 1424-1427. *Holy Trinity*. Santa Maria Novella, Florence[106]

As Kemp points out, although this does not correspond literally to the way we see, it does 'ape certain features of the array of visible information presented to us and it does so in such a way as to exploit a set of fundamental perceptual responses which ultimately lie beyond cultural conditioning'[107].

He cites the fresco depicting the Holy Trinity painted by Masaccio[108] in the early 15th century as an outstanding example of the potential for the artist to use the construction of linear perspective as a framework within which to introduce tactual and conceptual dimensions: 'differentiating in depth between the mortal world this side of the plane and the indubitably spiritual realm inhabited by God, Christ, Mary and John.' [109]

[106] National Gallery, Washington DC, Empire of the Eye video series, released June 03 2008, accessed 05/12/2013 http://www.nga.gov/content/ngaweb/audio-video/video/empire-part-1.html

[107] Kemp, Martin. 2000. *Visualisations: the Nature Book of Art and Science*. Oxford. Oxford University Press. p21

[108] Masaccio, born Tommaso di Ser Giovanni di Simone, Renaissance painter, 1401-1428

[109] Kemp, Martin. 2000. *Visualisations: the Nature Book of Art and Science*. Oxford. Oxford University Press, p21

Figure 44: Pere Borrel del Caso. 1874. *Escaping Criticism*[110]

Over the course of the following two hundred years, the depth effects produced by perspective and size scaling cues were reinforced by shading, occlusion and texture cues to create ever-more theatrical pictorial spaces. This dominant model of systematic and coherent construction could perhaps be understood in terms of the prevailing view of a stable relationship between time and space – and of the eye as a reliable instrument for observation and measurement.

However, by the end of the 19th century, empirical research by scientists such as Hermann von Helmholtz and the philosopher and psychologist William James (1842-1910) were pointing out the different degrees of sensitivities to what James termed the 'space-element' across the visual field, likening this to variations in the ability to distinguish between points of touch on the skin – the hand being more sensitive than the thigh or the arm[111].

[110] Pere Borrel del Caso, Spanish painter and ilustrator (1835-1910). Image from from the National Gallery of Art, Washington DC, http://www.nga.gov/images/decor/trompefs.htm accessed 05/12/2013

[111] James, William. 1890. *The Principles of Psychology*. New York: H. Holt and company. Chapter XX, from http://psychclassics.asu.edu/James/Principles/prin20.htm#j1 accessed 09/09/2013

Figure 45: Wilhelm Röntgen, 1896. X-ray picture of Albert von Kölliker's left hand [112]

vi. Deconstruction

Helmholtz' and James' work coincided with a number of scientific discoveries that offered proof of a fourth dimension such as the first x-ray photographs in 1896, the discovery of the electron by J.J.Thompson[113], and invention of the telegraph based on the work of Heinrich Hertz[114] in the 1880's.

The art historian Linda Dalrymple Henderson suggests that this notion of an invisible reality that lay 'just beyond the reach of visual perception' [115] drew together aspects of a broader 19th century concept of the *"ether of space*" that ranged from the geometry of mathematicians such as Henri Poincaré[116] to the mystical visions of writers, architects and philosophers such as Hinton[117], Bragdon[118] and Oupensky[119].

[112] X-ray picture (radiograph) taken at a public lecture by Wilhelm Röntgen (1845–1923) of Albert von Kölliker's left hand. Image from Wilkipedia commons, http://commons.wikimedia.org/wiki/File:X-ray_by_Wilhelm_R%C3%B6ntgen_of_Albert_von_K%C3%B6lliker%27s_hand_-_18960123-02.jpg, accessed 05/12/2013

[113] Joseph John Thompson (1856-1940)
[114] Heinrich Hertz, physicist (1846-1894)
[115] Henderson, Linda Dalrymple 2013. *The Fourth Dimension and Non-Euclidean Geometry in Modern Art.* Cambridge, Massachusetts: The MIT Press. p15
[116] Henri Poincaré, mathematician and philosopher (1854-1912)
[117] Charles Howard Hinton, mathematician and writer (1853-1907)
[118] Claude Fayette Bragdon, architect (1866-1946)
[119] Pyotr Demianovich Oupensky, philosophe (1878-1947)

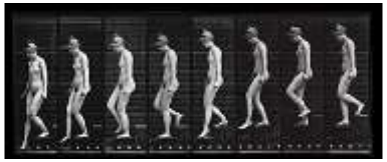

Figure 46: Edweard Muybridge, 1890. *Woman descending a staircase* [120]

Figure 47: Umberto Boccioni, 1915. *Charge of the Lancers*[121]

She notes the presence of articles discussing Albert Einstein's[122] Theory of General Relativity in the collections of the Bauhaus and of artists including Duchamp[123], van Doesbourg[124] and Mondrian[125] as an indication that these figures were keenly aware of the scientific context in which they conducted their own experiments, 'liberated from visible light' and from a world that was understood to be three-dimensional.[126]

Alongside these new mathematical and physical models that broke the bond between the 'visible' and the 'real', psychologists including Brewster[127] and Wheatstone[128] explored phenomena such as persistence of vision, relating to the Gestalt theories discussed earlier in this chapter that proposed that disparate cues are grouped by visual system to produce the experience of a 'whole'. Furthermore, Freud's research suggested that the conventional concept of the self as an integrated identity should more accurately be described as a complex dialogue between multiple perspectives.

[120] Edweard Muybridge, photographer 1830-1904. Image from http://en.wikipedia.org/wiki/File:Eadweard_Muybridge_1.gif accessed 05/12/2013
[121] Umberto Boccioni, painter 1882-1916. Image from http://www.wikipaintings.org/en/umberto-boccioni/the-charge-of-the-lancers-1915 accessed 05/12/2013

[122] Albert Einstein, German-born theoretical physicist (1879-1955)
[123] Marcel Duchamp, French artist (1887-1968)
[124] Theodore van Doesbourg, Dutch artist (1883 – 1931)
[125] Piet Mondrian, Dutch artist (1872-1944)
[126] Ibid p15
[127] David Brewster, optical scientist (1781-1868)
[128] Charles Wheatstone, psychologist (1802-1875)

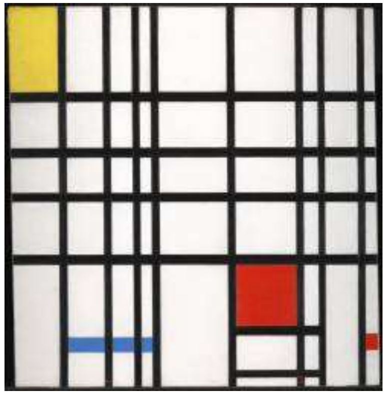

Figure 48: Piet Mondrian. 1937-42. *Composition with Yellow, Blue and Red*[129]

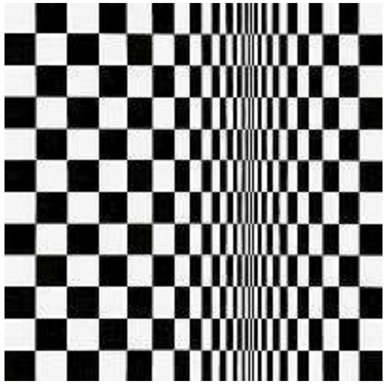

Figure 49: Bridget Riley. 1961, *Movement in squares*[130]

New steel manufacturing processes were used by architects such as Gustave Eiffel [131]to design daringly light and open structures that were no longer limited by the physical properties of stone and wood. New forms of entertainment, including shops, museums and galleries grew to serve a new class of professionals and industrialists.

The Italian Futurists, the Bauhaus in Germany, Constructivism in Russia and the Dutch De Stijl circle were formed in this atmosphere of flux and fragmentation compounded by the chaos and destruction of the First World War.

Leading the project to re-establish the Bauhaus school in 1947, Lasló Moholy-Nagy's essay *Vision in Motion* rejects the illusionism of linear perspective, declaring the need to 'free the elements of existence from historic accretions, from the turgid symbolism of past association.'[132]

[129] image from http://www.tate.org.uk/art/artworks/mondrian-composition-with-yellow-blue-and-red-t00648 accessed 05/12/2013

[130] image from http://www.southbankcentre.co.uk/find/hayward-gallery-and-visual-arts/hayward-touring/past/bridget-riley-flashback accessed 05/12/2013

[131] Gustave Eiffel, engineer and architect (1832-1923)

[132] Moholy-Nagy, László. 1947. *Vision in Motion*. Chicago: P. Theobald. pp 28

Greenberg's lecture of 1960 defines the Modernist approach in terms of a search for the 'characteristic methods of a discipline'[133] in order to distil and clarify its unique expressive potential, noting for example that the only essential quality of pictorial space is visual or optical.

Representing recognisable objects contravenes this principle as it implies the depiction of a three-dimensional space that these objects would inhabit. He contrasts the conventions of classical painting that aim to depict spaces that 'one could imagine walking into' with a Mondrian work that can only be 'seen into…literally, or figuratively travelled through with the eye.' [134]

The logical extension of this idea is to reject figurative reference altogether, an approach adopted by the Concrete artists, characterised by their systematic approach to composition and form. In the words of the critic Margit Weinberg-Staber, 'structural-organisation-made-visible.'[135]

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[133] Greenberg, Clement. 1960. *Modernist Painting*, Forum Lectures (Washington, D. C.: Voice of America), 1960, from ttp://www.sharecom.ca/greenberg/modernism.html, accessed 05/12/2013
[134] ibid
[135] Lauter, Marlene, and Reese, Beate. 2002. *Konkrete Kunst in Europa nach 1945 = Concrete art in Europe after 1945*. Ostfildern: Hatje Cantz.p99

Figure 50: *The Responsive Eye* exhibition, 1965, MOMA, catalogue cover [136]

Figure 51: Visitor to the *Responsive Eye* Exhibition[137]

This elimination of narrative and personal reference, even in the titles of the works, was designed not only to ensure that no layers of meaning beyond the direct presence of the work might be implied, but also to expose the role of the audience in 'a playful consciousness of seeing'[138] in Duchamp's words 'c'est le REGARDEUR qui fait l'image*',* often translated as 'the viewer makes the picture'.[139]

The 1965 exhibition *The Responsive Eye* curated by William Seitz for MOMA in New York, brought these principles of active seeing to a wider public, representing a number of artists who worked in this purely optical style, arranging high-contrast graphic elements to trigger perception of depth and movement.

One of the artists represented in the exhibition, Ludwig Wilding wrote of his aim to create objects that would appear to project into the room, to 'break free of the static two-dimensional plane of classical painting', to 'provoke and irritate', generating an 'experience of restless motion'.[140]

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[136] Seitz, William C. 1965. *The Responsive Eye*. N.Y: Museum of Modern Art, in collaboration with the City Art Museum of St. Louis [and others)

[137] Still from *Eye on New York* television programme recorded for CBS by Mike Wallace
For copies of this broadcast, please see http://www.youtube.com/watch?v=XSVQqJo0Pmk

[138] Elkins, James. 1999. *Why are our Pictures Puzzles?: on the Modern Origins of Pictorial Complexity*. New York, Routledge.

[139] Find reference

140 Wilding, Ludwig, Hoffmann, Tobias and Bauer, Ines. 2007. *Ludwig Wilding: visuelle Phänomene*. Köln: Wienand. p18

Quoted in the press release, Seitz declares 'these works exist less as objects to be examined than as generators of perceptual responses in the eye and mind of the viewer… These new kinds of subjective experiences are entirely real to the eye, even though they do not exist physically in the work itself.' [141]

Interviews with exhibition visitors for the television show *Eye on New York*[142] suggest that this was a radical proposition, not only challenging established ways of engaging with a work of art, but the boundaries of the art market itself. For example an artwork by Bridget Riley (b1931) was controversially adapted to produce a dress fabric.

This may perhaps be analogous to the shift represented by the invention of linear perspective that expanded the structured liturgical space to encompass the secular and the anecdotal.

Seitz declared 'it's really the absorption of modern art into modern life.'[143]

[141] Press release from the Responsive Eye exhibition, http://www.moma.org/docs/press_archives/3445/releases/MOMA_1965_0021_19.pdf?2010
[142] http://www.youtube.com/watch?v=XSVQqJo0Pmk
[143] http://www.youtube.com/watch?v=XSVQqJo0Pmk

4. Conclusion

Building on the 19th century physicist Helmholtz' theory of unconscious inference, Richard Gregory describes visual perception as the result of a largely unconscious stream of decisions about the likely meaning of ambiguous signals from the eye.

This interpretation is based on many different types of knowledge, some considered 'innate' while others may be the result of learning and memory over time. Gregory's model points to the underlying tension between the physical, conceptual and optical dimensions of space.

Artists have taken different approaches to the problem of representing these overlapping dimensions on the picture plane, a choice that, in Panofsky's words, should be considered one of style or 'symbolic form' rather than one of skill.[144]

[144] Panofsky, Erwin. 1991. *Perspective as Symbolic Form*. New York: Zone Books.p40 - 41

Their thesis is supported by the observation that periods of intense scientific discovery such as the early 14th and late 19th centuries coincided with radical changes in representational systems: the invention of linear perspective describes a stable and newly rational 'observable' world, while the Modernist approach broke these conventions to evoke a new understanding of a fluctuating relativity between the visible three dimensions and the invisible fourth dimension of time.

In this context, the Concrete artists rejected all representation of recognisable objects with their inevitable association with conventional static sculptural space, to produce unstable optical effects from simple graphic elements often arranged according to systematic generative techniques. In the critic Frank Popper's words, these lines and patterns in black and white create a 'coercive suggestion of movement.[145]'

The Responsive Eye Exhibition in New York in 1963 introduced this provocative aesthetic to a mainstream audience, redrawing the boundaries between 'modern art and modern life'.

[145] Popper, Frank. 2009.
http://www.oxfordartonline.com/public/;jsessionid=5D6DBBE15C09DEE8B329B4608FE6BCE3

The curator Seitz notes another boundary redrawn by this approach – between the viewer and the work itself, commenting that 'each observer sees and responds somewhat differently.'[146]

This attitude is emphasised by the artist Ludwig Wilding who declared 'I set the rules of the game for the viewer to play according to their vision.'[147]

In a career spanning nearly fifty years, Wilding developed a distinctive approach to these underlying themes. Working almost entirely in wall-based shallow box frames, he combined the strong optical cues of high-contrast black lines with the ambiguities generated by transparent Perspex panels to produce interference patterns configured to generate compelling motion and depth effects that 'challenge our sense of reality'.

Wilding's work provides the inspiration for the studio development described in the following chapters.

[146] Press release from *The Responsive Eye* exhibition, http://www.moma.org/docs/press_archives/3445/releases/MOMA_1965_0021_19.pdf?2010
[147] Wilding, Ludwig, Hoffmann, Tobias and Bauer, Ines. 2007. *Ludwig Wilding: visuelle Phänomene*. Köln: Wienand.

Chapter III. Strange phenomena - monocular effects

Figure 52: Ludwig Wilding at work [148]

1. Introduction

Beginning with the observation of the inherent ambiguity of visual perception, the previous chapter discussed a range of approaches adopted by visual artists to represent the subjective experience of space and time, concluding with a brief introduction to the German artist Ludwig Wilding and the relevance of his research to this project. This chapter considers his work in more detail as the starting point for a review of the studio practice inspired by the underlying principle that the interaction of two sets of lines generates a third pattern or moiré feature and that small differences in the relative density, frequency, rotation or movement of the component lines are amplified in this new pattern as discussed by psychologists including Nick Wade and Lothar Spillman.[149]

The patterns discussed here are said to be 'monocular' – visible to a single eye or camera lens and are present in flat pictures. Those in the subsequent chapter engage the mechanisms that gauge depth in three-dimensional objects. Many of these are based on mechanisms that rely on feedback from both eyes, known as binocular cues.

[148] Wilding, Ludwig. 1973. *Ludwig Wilding: räumliche Irritationen, optische Interferenzen, perspektivische Täuschungen*. Köln: Kölnischer Kunstverein p61

[149] Wade, Nicholas J. 1982. *The Art and Science of Visual Illusions*. London: Routledge & Kegan Paul.

Figure 53: Willi Baumeister at the Stuttgart Academy, 1947-8[150]

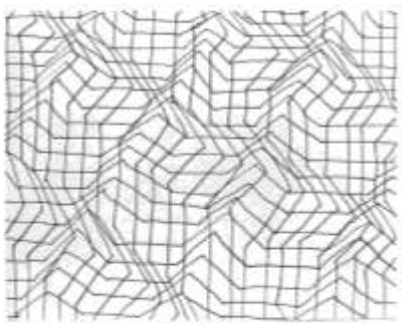

Figure 54: Ludwig Wilding. 1955, *Gitter-relief* (lattice relief)[151]

2. Ludwig Wilding

i. Beginnings

Born in 1927, Ludwig Wilding's early life was marked by the upheaval of the Second World War. During an interview with Wilding's widow Ingeborg at their home in Bucholtz near Hamburg in July 2013, she mentioned his memories of the suicide of his Jewish neighbours and the occupation of the family home. She described his determination to pursue his own creative ideas, studying fine art with the painter Willi Baumeister against the wishes of his father who was keen for him to become a teacher. On graduation, Ludwig became a successful textile designer while continuing to explore dimensions of rhythm and surface through his own painting.

Ingeborg noted a turning point in Wilding's career during a visit to Paris where, observing that other artists were exploring the same themes, he recalled Baumeister's advice that an artist should find a field where no one else is working and make that their own.

[150] Willi Baumeister Foundation website (http://www.willi-baumeister.com), accessed 05/12/2013
[151] Wilding, Ludwig. 1987. *Ludwig Wilding: Retrospektive, 1949-1987.* Kaiserslautern: Die Pfalzgalerie. Catalogue no.7

.

Figure 55: Ludwig Wilding, c1955, *Detail of early work*. White hand drawn lines on black paper[152]

Figure 56: Ludwig Wilding 1960. *Objekt mit scheinbewegung mit progressiven winkel-anordnumgen* (object with illusory movement with progressive chevron formation)[153]

Realising a connection between the threads of his textile designs and the spatial effects that he had been exploring with drawn lines, he decided to abandon his previous work to focus on that approach, seeking to emulate the quality of 'filling the room' that he found so inspiring in Baumeister's work. [154]

As mentioned in the previous chapter, Wilding was one of a generation of artists actively experimenting with strategies for integrating the three visible dimensions with the fourth dimension of time. Writing in 2000, Wilding declared that his work should be understood as an expression of the 'pressing and constantly accelerating pace of change' that he considered to be the defining qualities of his era.[155]

ii. Interference

The decision to focus on the optical effects produced by overlapping sets of high-contrast 'threads' or lines led to a series of experiments, first with hand-drawn and then with ruled marks to create moiré interference patterns. By 1957, mechanically-produced black and white parallel lines had almost completely replaced free-drawn marks.

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[152] Photograph by Shelley James 2013, reproduced, with kind permission of Ingeborg Wilding

[153] ibid p79

[154] Interview with Ingeborg Wilding, July 2013, please see full transcript in the appendix to this thesis

[155] Wilding, Ludwig. 2012. *Ludwig Wilding: kunst = traum = illusion = täuschung*. Hamburg: Galerie Renate Kammer. pp6-7

Figure 57: Ludwig Wilding. *1963.Objekt mit scheinbewegung "augenmotiv"* (object with illusory movement with eye motif)[156]

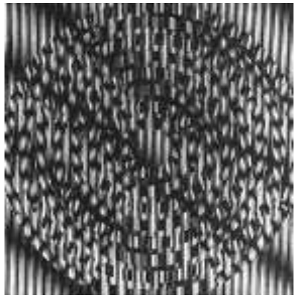


Figure 58: Ludwig Wilding*, 1986. Objekt mit scheinbewegung kreiseförmige gegenbewegung SBST 2811* (object with illusory movement, opposing circular motion *SBST 2811*)[157]

By placing one set of lines on a transparent sheet and altering the density, frequency and rotation of different sections of the composition Wilding was able to generate patches of interference pattern of various densities that appear to move in different directions or at different speeds, producing the compelling illusion of a dynamic array of geometric forms running and rippling across a two-dimensional plane.

Over the following years, he experimented with new transparent materials, graduations and rotation, exploring every possible combination of moiré interference effects: speed and direction, parallel and concentric, and with modular and continuous 'all over' compositions.

[156] Ibid p61
[157] Wilding, Ludwig. 1987. *Ludwig Wilding: Retrospektive, 1949-1987.* Kaiserslautern: Die Pfalzgalerie. p131

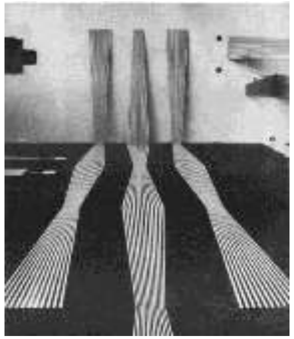


Figure 59: Ludwig Wilding. 1973. Installation, Cologne Arts Association[158]

Figure 60: Ludwig Wilding. 1999. *Trompe L'oeil* TRO5506[159]

iii. Beyond the frame

In 1972 and 1973, Wilding produced the only installation-based exhibitions of his career[160], designing a series of panels painted with parallel black and white lines configured to create illusions of space when seen from a particular angle. He also produced a number of small-scale flat pieces that he called '*anamorphoses*', exploring the role of contour in depth perception.

With these notable exceptions, Ludwig chose to explore his ideas through small scale, wall based works presented in shallow box frames: the vast majority measure between 28 and 150 cm and almost all are square. Ingeborg stressed that each piece was designed to be enjoyed on its own, but, in a gallery context, could be arranged to generate a powerful collective rhythm.

[158] Wilding, Ludwig. 1973. *Ludwig Wilding: räumliche Irritationen, optische Interferenzen, perspektivische Täuschungen*. Köln: Kölnischer Kunstverein. p57

[159] Wilding, Ludwig, Tobias Hoffmann, and Bauer. Ines 2007. *Ludwig Wilding: visuelle Phänomene*. Köln: Wienand. p205

[160] '*Rhine Ruhr Scene 72'* exhibition in Essen in 1972, Cologne Arts Association exhibition in Cologne in 1973

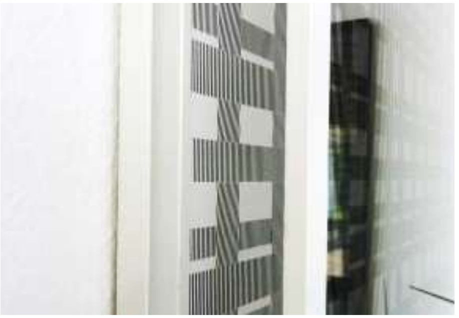


Figure 61: Ludwig Wilding open box frame[161]

Figure 62: Ludwig Wilding. 1990. *Untitled* (detail) Photocopy on paper and board [162]

iv. Technique

Wilding developed his ideas through trial and observation, setting his benchmark as the strength of the effects first hand, although once he had mastered the combination of line and angle to generate the desired effect, he would give a detailed specification to a printer and a framer to produce multiples, usually editions of 100.

He embraced new technology and often drew directly on its patterns, taking polaroid photographs of the linear structure of the television image, using the photocopier to generate the 'fractal' designs or to experiment with scale.

Ingeborg described how Wilding chose Perspex to frame most of the work as it is lighter and more robust than glass. In an era before UV-cured adhesives, he was able to use this material to construct the distinctive 'open-sided' box frames to allow more light into the object.

[161] Image by Shelley James 2013, reproduced by with kind permission of Ingeborg Wilding
[162] Image by Shelley James 2013, reproduced with kind permission of Ingeborg Wilding

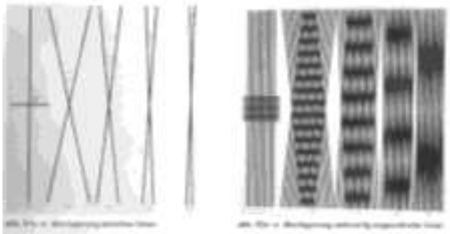


Figure 63: Moiré fringes from rotation illustration[163]

v. Art and science

Wilding's work was a source of fascination for psychologists studying the perception of space, leading to lifelong friendships and collaborations with scientists such as Nicholas Wade and Lothar Spillmann.

He saw himself as a scientist also, observing the effects of small changes in the variables of his essential vocabulary of line and simple forms, with the constant aim of creating spaces that appear to be liberated from the surface of the work by the slightest movement of the viewer, to produce 'multiple images in one object.'[164]

His systematic approach is also suggested by the detailed diagrams included in the earlier catalogues such as the one shown here that explain the effects and how they are achieved.

[163] Wilding, Ludwig. 1973. *Ludwig Wilding: räumliche Irritationen, optische Interferenzen, perspektivische Täuschungen*. Köln: Kölnischer Kunstverein.

[164] Wilding, Ludwig. 2012. *Ludwig Wilding: kunst = traum = illusion = täuschung*. Hamburg: Galerie Renate Kammer pp6-7

3. Studio development: parallel lines on parallel planes

Figure 64: MDF frame built to photograph my studio experiments

Generating compelling, paradoxical spatial effects from simple graphic elements printed onto paper and transparent Perspex panels, Wilding's remarkable research provided the inspiration and framework for my own studio practice.

Basic measurements from a small example of his work set the parameters for the initial experiments, suggesting a line frequency of 11 lines per cm on the base layer and a very similar spacing for the transparent overlay. Adobe Illustrator graphics software was used to generate combinations of line spacing and thickness for printing onto paper and onto the transparent film used for overhead projectors.

Holes were punched along one edge to locate the sheets on a simple MDF frame, ensuring a consistent vantage point for the photographs as the project progressed.

It soon became clear that small differences in the line spacing and thickness on the base sheet in relation to the transparent overlay had a disproportionate effect on the appearance of the interference pattern. The pages that follow illustrate these findings and review some of the art works produced in the course of the investigation.

Base and overlay the same

When both sets of lines are the same frequency and moved horizontally across another, a series of wide, curving contours or moiré bands are produced that appear flash across the surface of the paper at great speed, creating a disconcerting inconsistency between feedback from the muscles directing the hand and information received by the eyes.

This will be illustrated by placing the transparency provided in the pocket of this document over the pattern printed on the following page and moving it horizontally across the page. Raising the transparency slightly above the page creates a shallow three-dimensional object, and a striking difference in the appearance of the moiré bands.

This is because the lines on the transparent sheet will now be relatively closer- and will therefore appear very slightly larger and wider apart - than those on the base layer. In addition, because the top layer is transparent, two eyes will be receiving different images, creating binocular cues to depth that will be discussed in the next chapter.

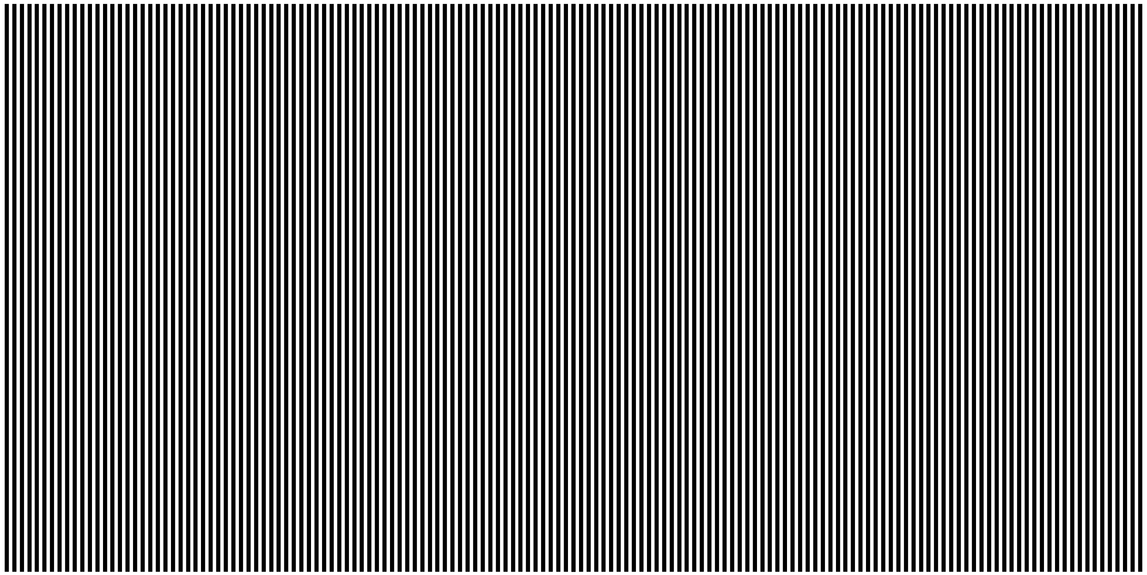


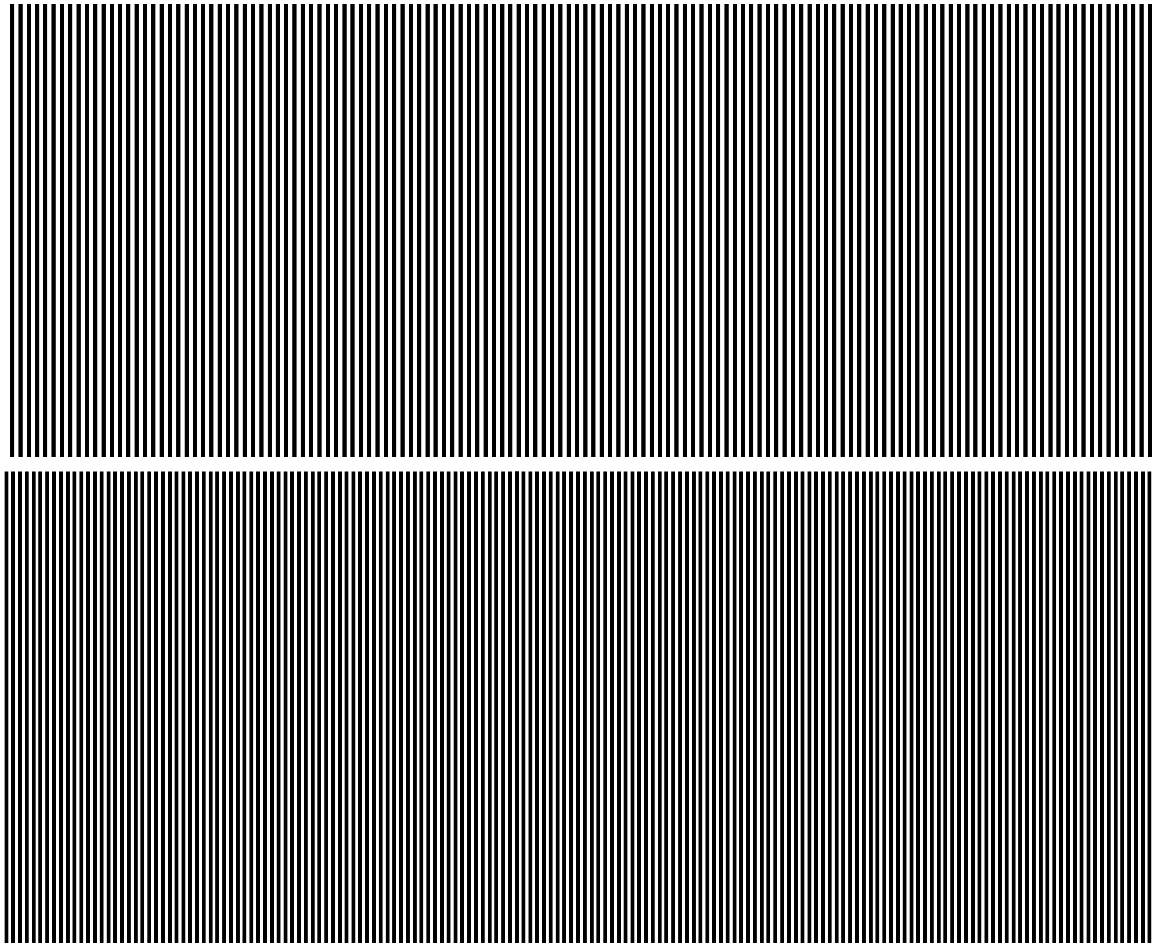
Figure 65: Underlay with the same frequency as the transparency

vi. Different base and overlay

When the lines on the base layer are further apart than those on the transparent overlay, the moiré bands are narrower and their movement more stable and appear to move in the same direction but at a far greater speed than the actual movement of the overlay. This will be illustrated by moving the same transparencies over the top set of lines printed on the following page.

When the lines on the base layer are closer together than the lines printed on the overlay, the moiré bands appear to move in the opposite direction to the actual movement of the overlay and at a different speed. This will be illustrated by running the transparent sheet over the patterns below. Again, introducing a space between the transparent layer and the page will have a striking effect on the appearance of the moiré bands.

Figure 66: Underlay with wider spacing (top) and narrower spacing (below) than the transparency



As discussed in the previous section, the visual system tends to group edges and textures that appear to be similar or to be moving at the same speed or in the same direction to produce the appearance of a single object. Thus, dividing the surface of the underlay into sections with variations in the line frequency generates the appearance of a number of objects running in different directions and at different speeds, producing the paradoxical experience of a single surface containing many independently-moving objects.

The optimum relationship between the two frequencies to produce a dense and consistent moiré feature at different scales was identified through many experiments.

While initial tests took a simple numerical approach (11+12, 11+13, 11+14 lines per cm for example), it eventually became apparent that it is the ratio or proportion that is critical to the effect. Although much of the work produced during the project was based on a 12% difference, insights from later work suggested that an even closer ratio (around 10%) produces a more striking effect.

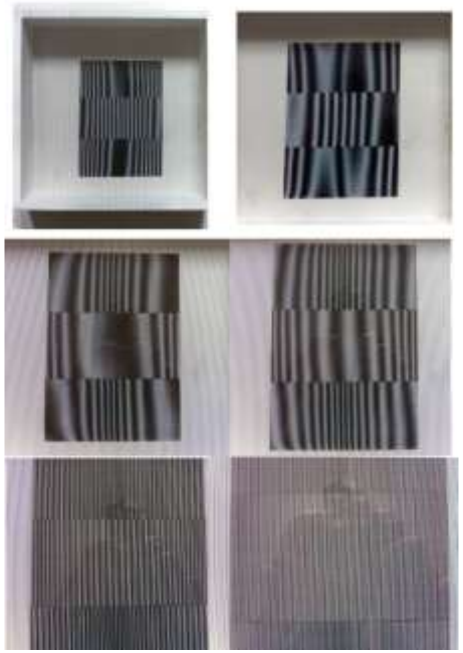


Figure 67: Printed paper with printed glass overlay viewed from different distances

vii. Density and viewing distance

As well as the spacing or frequency of the lines, it became apparent that the relationship between the thickness or 'weight' of the lines was an important factor: when the lines on the overlay were finer than those on the base layer, the gaze seemed to be 'drawn through' the front plane into a mobile texture that appeared to float between or beyond the object. A thicker line on the transparent overlay– even if still too fine to be resolved, seemed to act as a barrier: the effect seemed denser, harder to penetrate and less mobile.

The viewing distance is also critical to the effect. This series of photographs shows a flat sheet of paper printed with series of parallel lines divided into three bands. The top and bottom bands progressively shift from 11 lines per cm to 11.55 lines per cm at the centre (a change of 5% over 10cm), stretching again to 11 lines per cm at the left and right hand edges. In the central band, the spacing shifts from 11 lines per cm on the left and right edges, to 11.55 lines per cm in the centre (again, a shift of 5% over 10cm).

A sheet of glass is placed on top, printed with parallel lines at 11 lines per cm with a coverage of 40% The images are taken from 1m30, 1m, 70cm, 40cm and 10cm to demonstrate the difference in the appearance of the pattern.

Figure 68: Flat mirror and printed glass

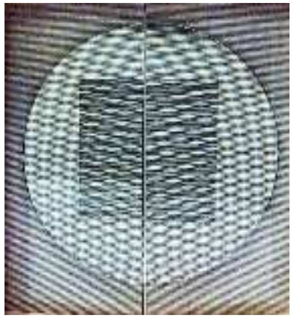


Figure 69: Shallow parabolic mirror and flat glass

Figure 70: Hand silvered flat glass panels and printed flat glass panels, detail

viii. Alternative techniques

Although the vast majority of Ludwig Wilding's work was produced using printed black lines on paper and on Perspex, he had also briefly experimented with ridged glass to generate almost holographic effects.

Reminded of Ruskin's criteria for the use of glass, a series of investigations considered the potential of mirrors and silvered printing ink to enrich the basic interference effects.

The reflections produced by flat mirrored surfaces fragmented the moiré bands to the point where the spatial effects were lost and this approach was set aside. However, a shallow parabolic mirror did produce converging contours, and a rich secondary 'torsade', or twisting cord pattern was generated by sandblasting a set of fine lines through the silvered surface. While this effect was intriguing, the piece constantly reflected the viewer - a distraction in the context of this project and this approach was not pursued.

Printing the lines with silvered inks and arranging these with half-silvered panels did evoke ambiguous mobile depths but the issue of the reflection of the viewer remained. Further experiments suggested that the silvering was not central to the effect and this was also placed on hold.

Figure 71: Leaning panels with white lines, April 2013

Figure 72: Pair of leaning panels installed in front of an internal window, RCA Summer Exhibition, June 2013

ix. Variations

The smaller-scale test pieces were presented in simple box frames, creating an enclosed domain in which the illusion could be sustained without the intrusion of disambiguating cues from the environment. However, having mapped out the centre ground, attention turned to the edges of this territory where reality might become ambiguity.

This led to the decision to abandon the frame, simply leaning the panels onto open shelves or metal pegs to encourage interference between the patterns and their environment: imperfections on the wall were amplified, effects that evoked the diffraction gratings used to gauge stress in engineering and manufacturing. Panels printed with white lines were particularly intriguing, generating the appearance of a rippling depth suspended in an oddly uncertain space that seemed to lie both on and behind the surface of the wall.

Placing a pair of panels on a shelf in front of a window produced a similarly disconcerting effect, the size of the 'ripples' seeming to shift not only with physical movement but simply by the depth of fixation: looking 'through' the panels to the space beyond seemed to increase their scale, while directing the gaze to the front surface reduced them.

Figure 73: Single leaning panel with graduated lines in white, June 2013

Figure 74: Ludwig Wilding. 1968. *Objekt mit scheinbewegung kreise SINGLE 8b* (object with illusory movement circle)[165]

Building on these observations, the work became progressively 'lighter' to invite greater interference between the object and its surroundings, although at a certain point, these patterns fragmented the interference bands and the contour effects were lost.

As the panels became larger, the material started to bow and flex and to vibrate in response to changes in the flow of air and people through the space, producing another dimension of suspense.

x. Studio development: rotated lines on parallel planes

Alongside an exploration of the interference patterns generated by altering the frequency and density of the gratings, Wilding investigated the dynamic effects produced by rotating one set relative to the other. As with the parallel line phenomena discussed earlier, a change in the relative angles of the lines produces an amplified effect on the apparent angle of the moiré feature.

[165] Wilding, Ludwig. 1987. *Ludwig Wilding: Retrospektive, 1949-1987.* Kaiserslautern: Die Pfalzgalerie. p95

Figure 75: Ludwig Wilding. 1971. *Objekt mit scheinbewegung diagonal PS 8c* (object with diagonal illusory movement PS 8c)[166]

These illustrations illustrate the systematic approach that Ludwig took to all his work: each new parameter tested through a series of configurations –first square, then circle, then subdivided combinations[167].

Drawing inspiration from this strategy, the studio practice built on my learning from the previous experiments to explore the effects produced by progressively altering the angle of rotation

i. Base and overlay the same

The lines printed on the following page are the same frequency as the lines printed on the transparent overlay, but have been rotated by just 4°. When the transparency is moved across the printed page, this small change in the angle produces in a dramatic shift in the apparent direction and speed of the moiré bands. The symmetrical arrangement of the panels results in features that appear to run in opposite directions.

[166] Ibid p101

[167] Wilding, Ludwig. 1973. *Ludwig Wilding: räumliche Irritationen, optische Interferenzen, perspektivische Täuschungen ; [Ausst.]* Köln: Kölnischer Kunstverein

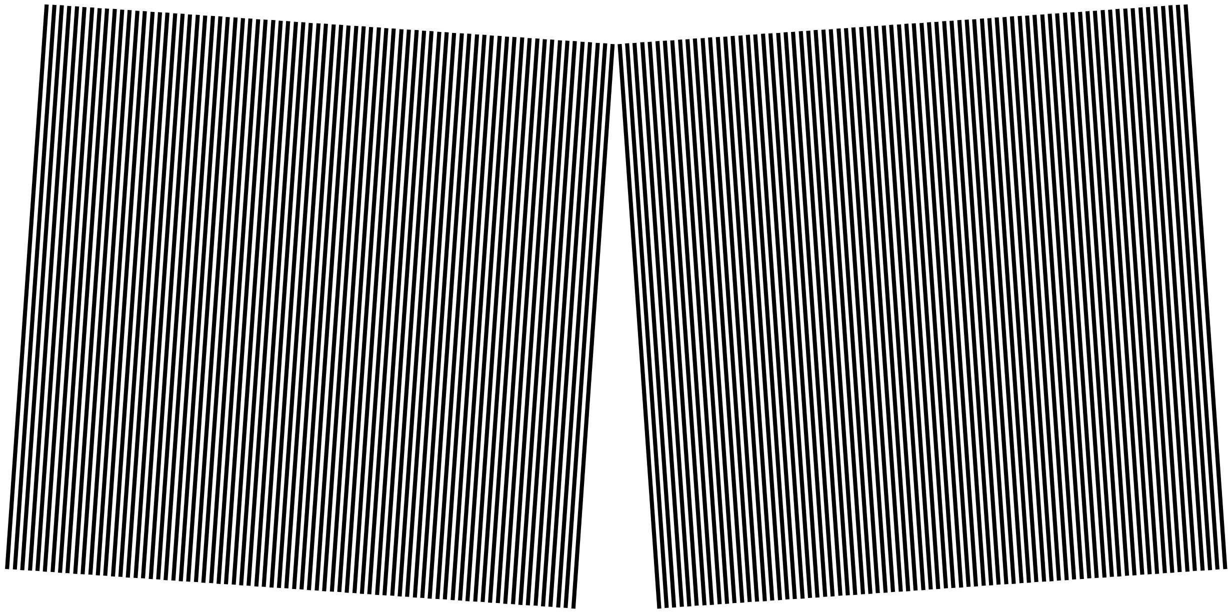
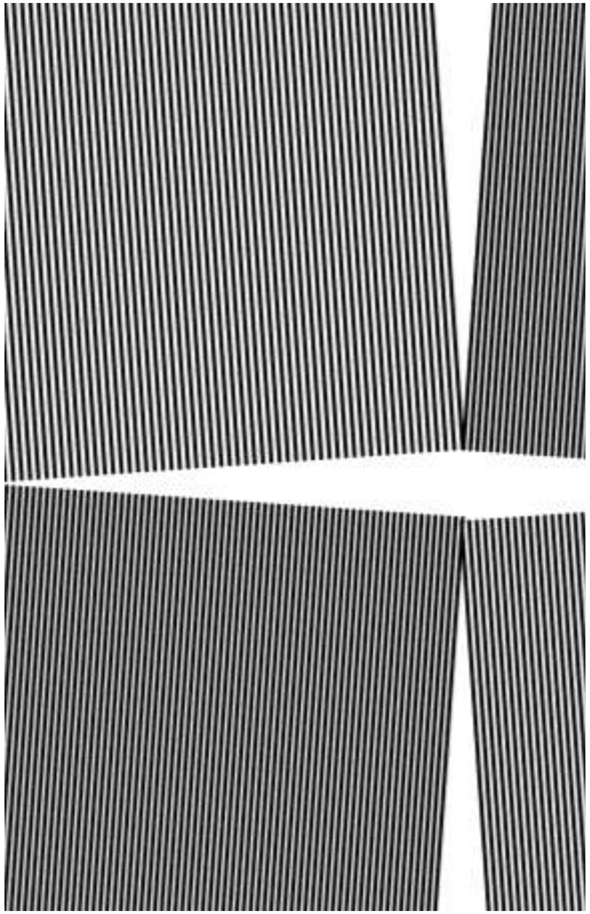


Figure 76: Same frequency on printed page and overlay, 4° rotations

ii. Different base and overlay

As with the earlier example, when one set of lines is a different frequency to the other, the difference between the angle of rotation and the appearance of the moiré feature is even greater. This will be shown by running the transparency across the panels below



iii. Extension

Figure 77: Comparison between rotations of 2, 4, 6 and 8^{o} (top series) and 2, 4, 8 and 16^{o} (lower series)

Figure 78: Example on paper and glass

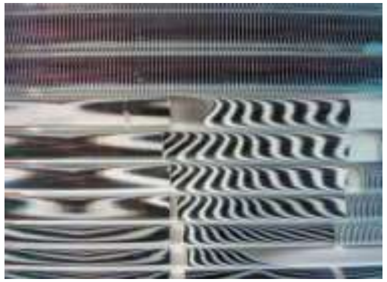


Figure 79: Printed paper and borosilicate rods

Initial experiments combined pieces of printed paper from earlier experiments, trimmed at different angles and glued onto a background panel to identify the minimum area required for the effect to appear (7cm square at 2metres viewing distance) and the maximum angle of rotation before the interference became too dense (12 degrees from the vertical).

Noting Wilding's occasional use of ridged glass, brief experiments were conducted with borosilicate rods, the optical distortion producing rich, rippling surface effects. However, this approach did not generate the depth cues that the project aimed to explore and was set to one side.

Returning to the effects of tone movement produced by the different degrees of rotation, two larger pieces were designed: one using the contours of the classic 'vase-face' or figure-ground design to consider the effect of combining the ambiguous depth cues with an ambiguous figure The other based on a simple cube tiling pattern to consider the potential to evoke 'shape from shading cues from these moiré bands.

Figure 80: Figure-ground, version 1

Figure 81: Figure-ground detail

Both were constructed on the same principle – a simple MDF base routed with grooves to receive four vertical panels of glass. In order to respond to health and safety concerns about exhibiting untoughened glass, the dimensions were calculated to fit inside Perspex boxes retrieved from a previous exhibition. The essential configuration of the two works was also the same: the two outer panels were printed with vertical parallel lines at a frequency of 11 lines per cm and at a density of 50% based on the experiments described earlier that had suggested that greater coverage would provide a more coherent and stable effect at this larger scale. One panel was printed in black and the other in white.

iv. Figure-ground

Referencing the systematic 'rule-based' compositional strategies adopted by the Concrete artists, this design was constructed as a 3 x 3 grid, each subdivided with the profile of the classic vase-face stimulus. Sets of parallel lines (11 lines per cm) were placed in this framework, rotated at a series of increasing angles from the vertical (between 0 and 12 degrees). In order to create a secondary composition based on density, and to break up the strong illusory contour generated by the shift in the angle of lines along the border between the vase and the face profile, the thickness of the lines and the orientation of the contours were then manipulated before the final artwork was produced.

Figure 82: Side view of vase-face piece, January 2013.

This combination of parallel and rotated lines successfully produced strong motion 'beating' effects as the viewer moved relative to the work. Different viewing distances generated additional secondary patterns, grids and torsades, while the black and white sides appeared very different, despite the patterns being the same. The patterns on the central panels did not extend to the top and bottom margins, exposing the interference patterns generated by the parallel gratings. The views through these more open areas produced a flickering disruption with the environment.

The grid structure with its systematic variation in the angle of rotation generated a range of beats and densities. However, the rhythms were unevenly distributed across the surface, creating the fragmented sense of a 'sampler' rather than a coherent composition. In the process of generating the secondary composition and breaking up the contours, the vase-face configuration had been disrupted to the point where no complete 'vases' remained. While the face is apparent when there is only one profile present, the visual system does not interpret a single profile as a 'vase'. The marked difference between the effects generated by varying the combination of white and black lines suggested another area for consideration, perhaps relating to cues to form provided by lightness and shading.

As the panels were standing vertically and completely parallel to each other with no framing beyond the MDF base, when the viewer moved from the 'front' to the 'side' of the work, the structure appeared to 'collapse' from three to two dimensions. This seemed to complement the paradoxical visual experience of apparently closed yet undrawn contours surrounding mobile features. The decision to leave the razor-sharp cuts of the panels added an unexpected edge to the piece and justification for its production in glass rather than with Perspex or some other material.

The questions of framing and lighting were also raised by this installation: the Perspex box created an expanded frame or field for the work, while adjusting the lights radically affected the visual effects. However, following Wilding's example the project maintained the focus on the material and optical qualities of the objects themselves.

v. Development

These observations led to the production of a second piece, with the same basic structure, but with the angles of rotation calculated in terms of percentages or ratios rather than a straight linear progression. The thickness of both the parallel and rotated lines was reduced to 70% overall coverage, to create a more transparent lattice that would interact with the environment but not to the extent of fragmentation. This effectively generated an even graduation in the spacing and speed of the beats across the composition and a subtle shimmering effect that appeared as a floating multi-layered fabric through which the gallery and visitors could be seen.

The design of this piece was also calculated to generate contrasting tones in the 'vase' and 'face' areas of the composition to consider the role of contrast in perception of a 'figure' or a 'ground'. However, the difference between the tones was not sufficiently distinct to produce the classic 'flipping' effect. This may be due to the far greater degree of transparency which not only meant that the space beyond the work was more clearly visible, but also that the secondary interference patterns of grids and torsades created an additional layer of texture: the choice was not between two equivalent alternative forms, but between a shifting patchwork of textures.

Figure 83: Penrose panel work installed, April 2013

vi. Penrose

The second design, named after the mathematician Sir Roger Penrose[168] after whom this particular tiling pattern is named, aimed to manipulate the tonal effects generated by the interference patterns. The aim was to generate moiré interference patterns of different densities to suggest tonal relationships that would be interpreted as a series of solid stepped cubes when the work was viewed from a static, frontal position. When the viewer moved, the elements would appear to move at different speeds and directions, destabilising the initial spatial effect.

The first test was not successful: the baseline view, i.e. from the front without movement, did not establish the tonal relationships that would be needed to produce the appearance of a coherent structure in space. So when the viewer moved and the beats shifted in many different directions, there was no conflict or surprise. The second attempt was more successful, creating a distinct paradox as the blocks appeared solid and then to disintegrate.

[168] Sir Roger Penrose, physicist, mathematician and philosopher (b1931)

However, as in the vase-face example discussed earlier, the degree of transparency was too great: the tones and borders between them were fragmented by the interaction with the other panels, the architecture of the gallery and the movement of visitors. In addition, the individual elements, especially when seen from a greater distance, were too small to establish their identity as distinct elements. The distance between the panels blurred the contours further: a lozenge on the front panel was 'offset' relative to the corresponding lozenge on the rear panel.

Figure 84: Moire pattern expressing 'pg' symmetry[169]

The potential for these simple gratings to generate strong rhythmic effects led to conversations with the X-Ray crystallographer Professor Brian Sutton and his team at King's College London. Their analysis of the shadows generated by molecules draws on an intuitive sense of the rhythms produced by different types of symmetry expressed by crystalline structures. The connection led to a series of framed works designed to generate the basic vectors of translation: simple repetition, mirror, reflection and glide.

[169] or simple glide symmetry (a 180° rotation followed by a shift of one-half unit)

vii. Converging lines on parallel planes

Noting the effects produced by rotating parallel lines, the logical step was to experiment with a progressive shift in the relative angles.

This parameter was initially explored through a series of experiments on paper and on glass. The angle between the rays was chosen to achieve a rich interference texture around the periphery while limiting the extent of the 'black hole' produced by the converging spokes in the centre of the pattern. Placing a white circle over the centre effectively removed the problem but the overall effect seemed relatively insipid in comparison with the slightly chaotic, mysterious quality of this zone that evoked the paradox of the 'blind spot' of the visual field: the connections from the light-sensitive rods and cones of the retina converge in a zone known as the optic disc from which this bundle of nerves link to the brain. While all the signals pass through this point, there are no rods and cones there. It is effectively blind.

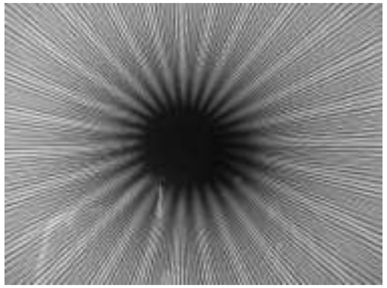


Figure 85: Radial array[170]

[170] Lines at 1.32°intervals printed on base layer, lines at 1.° intervals printed on glass overlay

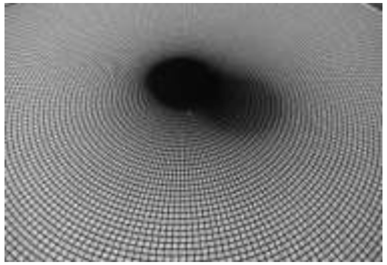


Figure 86: Radial and concentric lines on glass and paper

Figure 87: Concentric lines on glass and paper

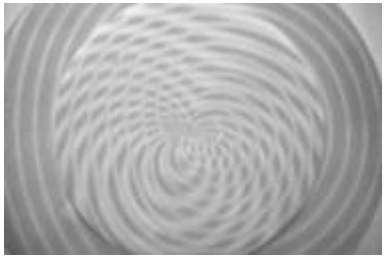


Figure 88: Concentric pattern in white, spiral pattern in black on reverse, spiral pattern on paper base

The effects produced by a progressive shift in the angle of rotation can also be explored through concentric and spiral configurations.

A pitch of 18 turns per cm was selected from a number of tests for its rich, dense effect when viewed from around 2 meters, the 'ideal viewing position' chosen for the work to date. Densities of 33% and 66% coverage were chosen, building on the insights from the experiments described above. An intermediate line thickness (1 point) was also printed to allow further comparison.

Combining radial and concentric patterns did not create the distinctive moiré feature of the parallel configurations and the resulting appearance of multiple planes in depth. But the 'cross-hatching' effect, created by the shadows cast by the printed glass, was visually intriguing.

Equally, the radial and concentric arrays alone did not produce the moiré features that were the aim of the exercise as the angles changed too quickly to build up an area of interference.

However, combining concentric and spiral patterns produced unexpected spatial effects.

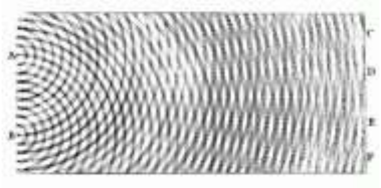


Figure 89: Thomas Young. *1802.* Diffraction pattern from double-slit experiment [171]

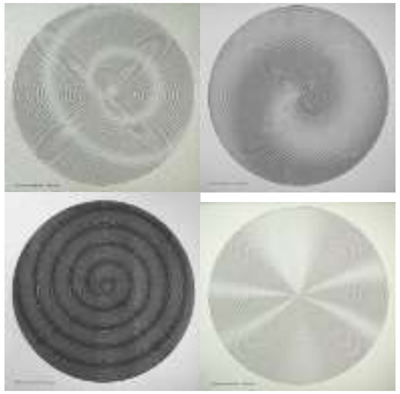


Figure 90: Combinations of concentric and helical patterns in black and white on paper.

This seemed to evoke the tide of rippling and concentric diagrams that ran through the scientific literature in the early 19th century provoked by Thomas Young's[172] celebrated double-slit experiment of 1802 that overturned the Newtonian particle model of light.

These observations led to a dialogue with a team of neurologists led by Professor Geraint Rees at University College London who are investigating the changes in electrical activity in the brain during decision-making based on ambiguous visual stimulus such as the 'vase-face' figure. This can be measured using a technique known as EEG or electroencephalogram scanning. A series of prints were produced based on data from my own brain participating in one of the field tests to explore the link between visual experience and neural activity

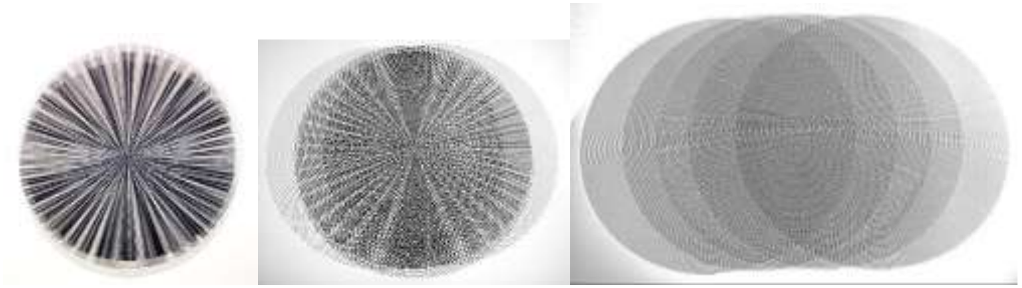


Figure 91: *Interference 1, 3 and 6, Screen prints on paper*

[171] from Royal Society Trailblazer: http://trailblazing.royalsociety.org/commentary.aspx?action=printCommentary&eventId=141, accessed 1 May 2012.

[172] Thomas Young, English vision scientist and polymath (1773-1829)

4. Convergence

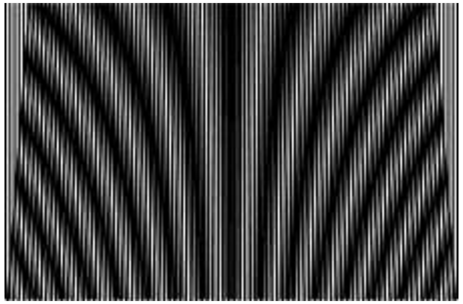
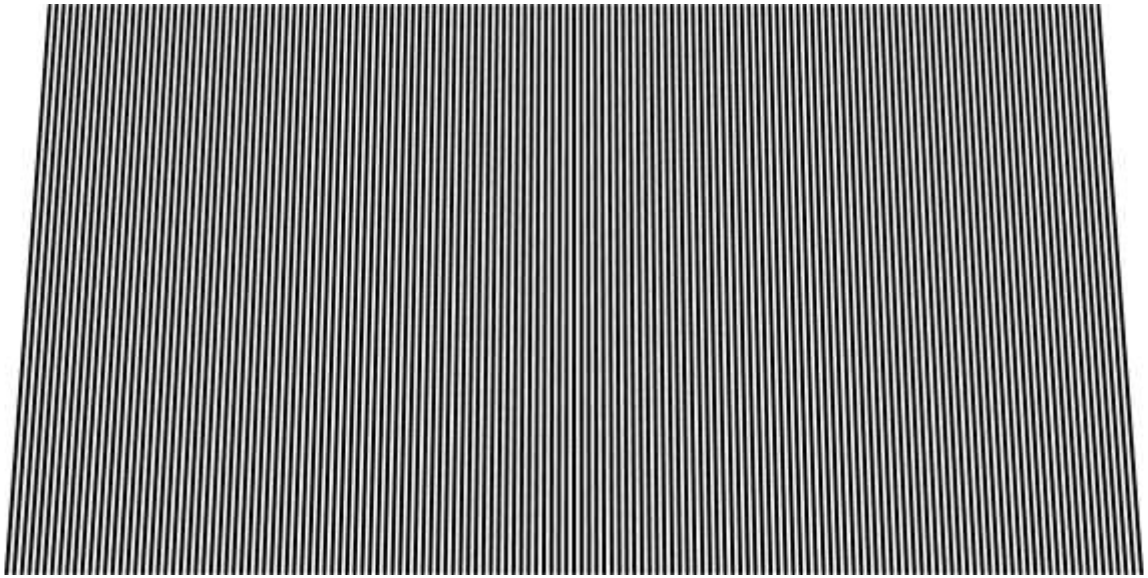


Figure 92: Tapered or angled lines with overlay

These findings suggested that a progressive shift in the angle of rotation between the base and transparent overlay would produce an amplified convergence effect but that this shift should be gradual. Further tests confirmed this prediction, noting that an overall shift between 0 and 4 degrees across a 40cm array permits the establishment of a distinct interference feature that appears curved as shown to the left. Running the transparency across the panel below will generate a similar effect.



When the lines are both tapered and curved, the feature also changes as will shown by runnning the transparency over the panel below.

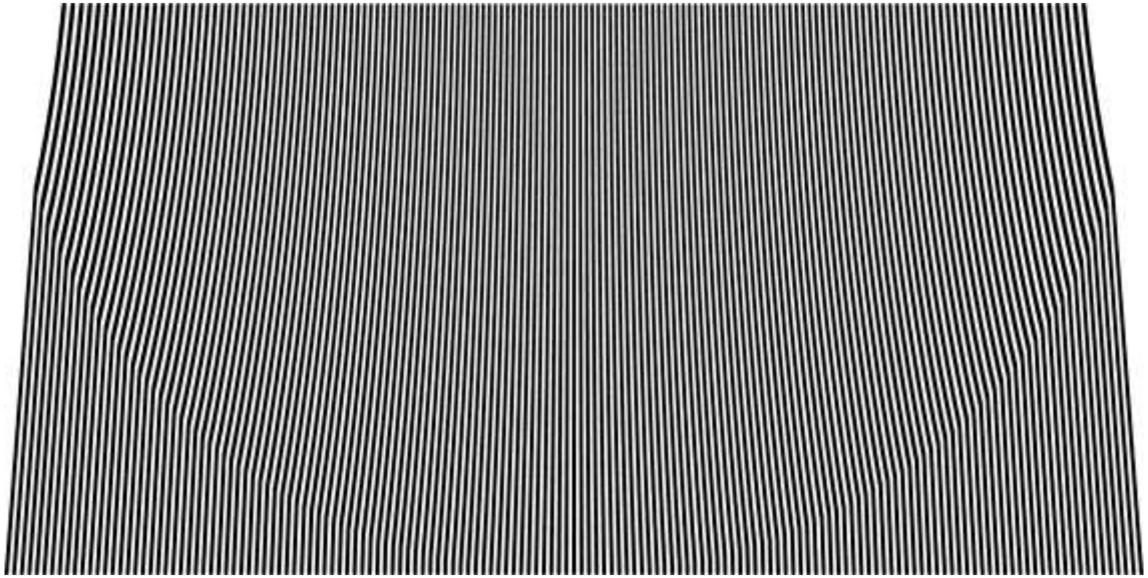


Figure 93: Converging panels together

Figure 94: Converging and parallel panels

5. Extension

Applying these principles to panels of glass produced strangely rich effects: the subtlest variations in the rhythm and orientation of line, the texture of the wall or the arrangement on the simple pegs used to display them were amplified to a remarkable extent, while moving past the works produced the paradoxical experience of being 'followed' by the contours of the interference effects.

Combining converging lines with panels printed in black and in white lines, altering the orientation and order of the pieces produced rich variations in the spatial effects that proved hard to capture with a camera.

Figure 95: Converging panels in white viewed from an angle, converging and parallel panels placed horizontally

6. Conclusions

As Wilding demonstrated through his many years of persistent research, the simple parameters of frequency, density and angle on two sets of parallel gratings can be combined to produce an almost infinite variety of converging contours, tones and rhythms, generating strangely rich and compelling spatial effects that ‘challenge our sense of reality’.

A solid frame encloses and sustains the illusion, especially in the crowded visual environment of a gallery. And yet, exploiting the transparent qualities of the glass to suspend the patterns in space and exposing the simple structure of the work by removing the framing boundary seemed to trigger a different level of engagement with the viewer

This invitation to a 'playful consciousness of the act of seeing'[173] described by Elkins perhaps relates to the art historian Martin Kemp's notion of 'a measure of automatic, even irresistible collusion' in the reading of a two-dimensional picture plane as a three-dimensional space[174.]

The exposure of the structure of the work seems to produce a particular tension between two types of collusion described by Kemp: 'a conscious acquiescence and cooperation based on the spectators knowledge of what is being seen; and perceptual response which results in a compelling reading of certain types of configuration in spatial terms.'[175]

[173] Elkins, James. 1999. *Why are our pictures puzzles? On the Modern Origins of Pictorial Complexity*. New York: Routledge. P3
[174] Kemp, Martin. 1990. *The Science of Art: Optical Themes in Western Art from Brunelleschi to Seurat*. New Haven: Yale University Press, p337

[175] Ibid p337

By generating a combination of engagement and disruption, the work seems to reflect its Modernist inspiration, an attitude characterised by the curator Marelene Lauter as 'the candid disclosure of its principles'.[176]

The following chapter builds on these observations to explore the dramatic spatial effects produced by introducing a shallow tilt or angle between the two layers of lines.

[176] i Lauter, Marlene, and Reese, Beate. 2002. *Konkrete Kunst in Europa nach 1945 = Concrete art in Europe after 1945*. Ostfildern: Hatje Cantz.p99

Chapter IV. Strange phenomena – rivalry and disparity

1. Introduction

The previous chapter considered the moiré interference patterns produced by two sets of parallel lines and the striking depth and motion effects that they produce. These effects can be captured by a camera or perceived with a single eye and are known as monocular cues.

While moiré patterns were explored by other artists of this period including the Venezuelan artist Jesús Rafael Soto[177], in around 1975, Ludwig Wilding started to explore a third variable that became one of the defining features of his work: he introduced shallow folds and curves to the printed paper underlay, this three-dimensional form engaging a mechanism known as binocular disparity – the process that combines the different views from the left and the right eyes to produce stereopsis.

[177] Venezuelan artist (1923-2005)

Following a brief description of binocular vision, this chapter continues with a discussion of Ludwig Wilding's *Paradoxical Forms* and the artist Patrick Hughes' *Reverspective* paintings that combine monocular and binocular processes to generate conflicts between visual and physical cues to depth.

This introduces a series of studio investigations designed to isolate the basic graphic and structural parameters of the effect. Small-scale models and larger works in paper and in float glass were produced in order to test the influence of tone or shading on the way that the form is 'read'. As with the panel works described in the previous chapter, these transparent structures exposed the tension between the density required to generate and sustain the moiré bands, and the subtle disruptions produced by more open textures that extended beyond the object to the surrounding space.

The final section of this chapter discusses a body of work that extends this understanding of the spatial effects generated by the interaction of patterns on separate planes to the interplay of layers and planes in solid glass forms.

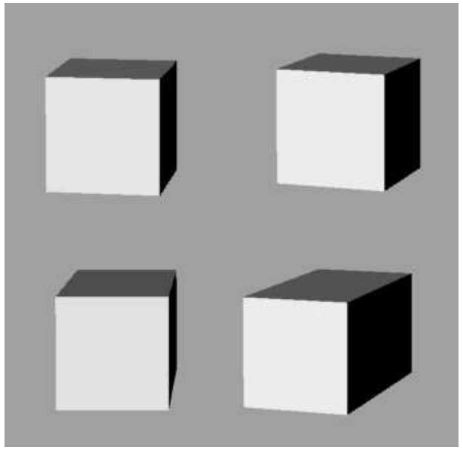


Figure 96: Left and right eye views of a cube and of a rectangular block

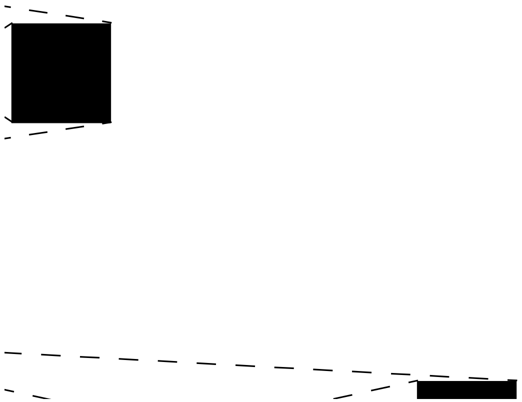


Figure 97: Convergence for near and far objects

Binocular vision

The eyes in the head are in slightly different positions and receive slightly different images. The mechanism known as stereopsis or binocular vision fuses, or combines the signals from the left and right eyes, the difference, or disparity between these two views providing clues to the form of the object in view. The simple image to the left demonstrates this principle, the left and right hand images corresponding to the left and right eye views of a cube and a rectangular block. The images on the left are broadly the same: it would be difficult to differentiate between these forms based on this view. However, when combined with the view from a slightly position as seen on the right, their distinctive forms become apparent.

Feedback from the muscles that direct the eyes to converge on a near or far object provide another set of cues, illustrated in figure 97. When both eyes are directed to a particular object, the two retinal images of that portion of the scene are matched, or fused so that there is no difference or disparity between them.

But, as when overlapping two photographs, when one area is in register, another area is not.

This mechanism is shown here: to the left is a photograph of a 'scene' viewed from above, the position of the viewer is represented by the ruler along the lower edge and a red cotton reel is placed in front of a blue one.

Two photographs taken 6.5cm apart to represent 'views' from the left and right eyes are shown below.

Figure 98: 'Scene' from above

Figure 99: Left eye view

Figure 100: Right eye view


Figure 101: Convergence on the near object, or uncrossed disparity


Figure 102: Convergence on the far object, or crossed disparity

When the gaze is directed to the near (red) cotton reel, the two retinal images are fused together to create a distinct image of the near object as seen to the left. In the left visual field the blue cotton reel is still to the left of the red one – and it is still to the right of the red one in the right visual field. This is known as uncrossed disparity.

Equally, when the attention turns to the far object, both eyes converge on that object and the retinal images are fused in a different way: the red cotton reels 'cross over' - this is known as crossed disparity. As a simple experiment, hold a pencil at around 6cm from your nose and notice the 'double' images that appear when focusing on the pencil, or on an object in the distance.

The visual system uses this basic rule to judge relationships in space: when objects appear to the left of the view from the left eye, and to the right of the view from the right eye, they are judged to be distant.

As the viewer and the scene move relative to each other, the visual system predicts the likely change in the size and position of the features on each retina, refining the initial impression of the size and shapes of objects and their relationships to build a coherent map of space.

Figure 103:Ludwig Wilding. 2002. *Objekt mit paradoxem körper PAR 4403*[178]

Figure 104: Ludwig Wilding. detail showing construction[179]

2. Binocular effects – reverse perspectives

As discussed in the previous chapter, converging lines and texture gradients are powerful cues to depth that tend to 'win' over conflicting physical signals and contextual knowledge. When the pictorial space includes even shallow physical depth, stereoscopic vision is engaged, with the potential to introduce another layer of conflict and disorientation.

Although Ludwig Wilding was best known for the interference patterns discussed earlier, his interest in the mechanisms of spatial perception led to an exhibition in Cologne in 1973 that featured a series of large-scale unframed panels painted with subtly converging black and white lines to produce paradoxical spatial effects when viewed from particular angles: portions of a flat floor appeared as vertical blocks, while a series of flat works placed against the wall gave the impression of sloping ramps.

[178] Wilding, Ludwig, Tobias Hoffmann, and Ines Bauer. 2007. *Ludwig Wilding: visuelle Phänomene*. Köln: Wienand. p209

[179] Photograph by Shelley James 2013, reproduced with kind permission of Ingeborg Wilding

Figure 105: Patrick Hughes. 2007. *Vanishing Venice*[180]

Figure 106: Patrick Hughes in his London studio, December 2012[181]

He later returned to explore this principle through his *Paradoxical Forms*, small box frames enclosing simple wooden structures, often on black backgrounds configured to produce a direct conflict or inconsistency between the powerful perspective cues of converging contours, size scaling an texture gradients, and the actual form itself.

While reversal of everyday rules of perspective is used by M.C. Escher to design his gravity-defying interiors, the use of shallow three dimensional forms by Wilding and in Patrick Hughes'[182] celebrated *Reverspective* paintings triggers a dramatic physical experience of the tension between visual and other inputs: surfaces that appear to be close due to their relative size or texture are actually more distant.

As a result, when the viewer changes position, instead of remaining stable they move with the viewer, creating the unnerving sense that it is the object and not the viewer that is moving. This paradox is sustained until the viewer is almost alongside the image. The projecting edges of the wooden panels (see figure 112) suddenly become apparent and the illusion breaks down. This experience is remarkably persistent: the eye can be 'trained' to 'read the structure correctly', but the default interpretation remains.

[180] Https://en.wikipedia.org/wiki/File:Vanishing-venice.jpg accessed 05/12/2013
[181] Photograph by Shelley James 2012 reproduction by kind permission of Patrick Hughes

[182] Patrick Hughes, British artist (b1939)

In his paper of 2007, Thomas Papathomas describes this mechanism in terms of the construction of a 3D schema that is then confounded by movement.[183]

i. Reverspectives

Patrick Hughes' works explore these effects using richly-coloured figurative scenes and objects rather than Wilding's monochromatic graphic devices. Hughes describes his approach in terms of a surrealist attitude, "'an exposure or heightening of the essential strangeness of what is considered 'real'"[184].

He considers that, while verticals are experienced as the rational dimension, a 'constant, natural and inevitable result of gravity', the horizontal planes of ground, horizon and sky, represent a more emotional dimension 'projections, subjective reflections of the physical and psychological location of the viewer.'[185.]

[183] Papathomas Thomas V. "*Art pieces that 'move' in our minds – An explanation of illusory motion based on depth reversal,"* Spatial Vision, 21, 79-95, 2007
[184] Interview with Patrick Hughes, December 2012. See appendix for transcript
[185] ibid

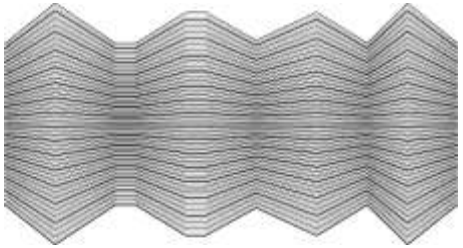


Figure 107: Homage to Hughes design, January 2013

I made a series of experiments on paper built on detailed measurements of the Hughes work installed in the British Library with the aim of finding the simplest-possible configuration that would still reliably produce the illusion. These findings provided the basis for a larger piece installed at the Biennial Research show at the RCA in January 2013.

The converging lines in a classic two-point perspective are drawn from a pair of notional 'infinities', both lying on a horizon line, one to the left and one to the right side of the composition. But in these designs, each set of converging lines is drawn from a different set of vanishing points known as a 'sliding perspective'. Experiments indicated the optimal position of this horizon line is approximately 1/3 below the top edge of the structure, so that when the piece is hung on a wall, it lies slightly above the eye line of the viewer.

Further tests to consider the impact of line weight in the spatial effect suggested that bolder marks generate more definite effects. However, the aim was to understand the boundaries of the phenomenon and the minimum cues needed for its operation.

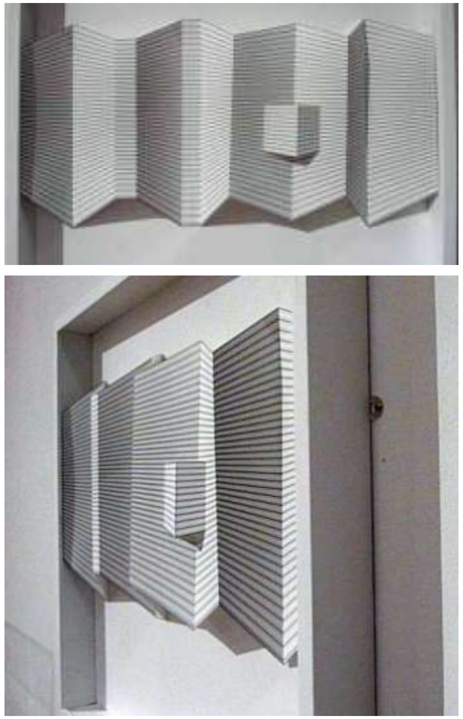


Figure 108: Homage to Hughes, 2013, front and side views

The alternation of line weights between 1.25 and 0.35 points was identified as the lightest weight that would effectively produce the reverse perspective effect, while being perceived as a texture rather than as distinct converging contours, at a viewing distance of around 3 metres.

These observations led to further investigation of the role of the outline. Noting that a strong external border was indeed critical, it became apparent that this could be a visual rather than a physical edge: the contour did not need to be ‘cut out’ in order to produce the reverse perspective effect.

However, inspired by Wilding’s constructions, a larger piece was produced with exposed edges and placed in an open frame without glass in order to consider the relationship between the pictorial space of the construction and the physical space of the gallery. While it was interesting to note the tension between the shadows cast by the folded paper and the perspective cues suggested by the printed contours, the frame cast another set of shadows and blocked the view from extreme angles. Patrick Hughes’ solid structures offer an elegant solution to these issues.

In the course of developing the designs, it became apparent that, particularly when all other cues had been simplified to the bare minimum, it was important to place a strong ‘locating’ structure close to the left edge of the composition - in this case, a flat vertical panel on the left side of the piece.

When the piece was rotated (so that this feature was on the right), the reverse perspective effect seemed harder to ‘read’ and to maintain. It seemed as though the visual system ‘reads’ the image from left to right in order to establish the construct or schema. Having assigned a projecting or receding interpretation to a feature to the left of the composition, the others are arranged ‘to fit’. In order to test this hypothesis, two small cuts in the paper made a projecting ‘cube’ with ‘correct’ perspective: the projecting edges were wider than the distant edges with the converging lines. It appeared that this device reinforced the depth effect, confirming the hypothesis.

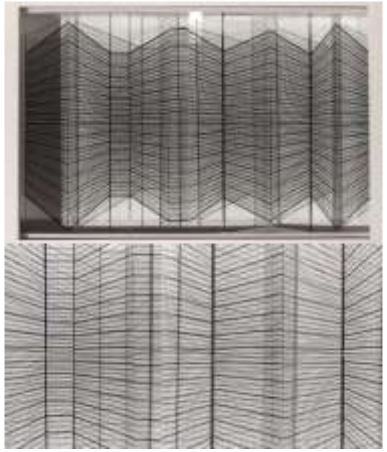


Figure 109: Small glass model of Hommage to Hughes design overview and detail

ii. Observations in glass

These observations in paper posed the question of the role of shading in the construction of the 3D schema: printing the same pattern of converging lines onto panels of glass would effectively eliminate these cues. The same design was printed onto a panel of glass that was then cut along the 'fold' marks. These panels were mounted in a small frame at the same angles as the paper folds. The reverse perspective effect persisted, albeit not as powerfully as the same pattern on paper.

The basic design was reprinted at a larger scale and installed at the Biennial Research Exhibition at the RCA in January 2013.

The reverse perspective effect was completely lost but the reasons were instructive: The wall-based piece had been hung so that the horizon line broadly related to the eye level of the viewer to provide a natural base for the vanishing points. However, the 'horizon line' of these panels installed in an MDF base on a standard plinth was around 1.40m and this cue was effectively lost – the angles of the converging lines seemed almost arbitrary rather than relating to a natural horizon.

Figure 110: View of work in gallery setting, January 2013

Figure 111: View of work against white wall

This was compounded by the installation in the centre of the room: fine lines were lost against the exhibits and visitors: these cues were simply not strong enough to prevail and the tracking effect was lost.

The installation was reconfigured with the addition of a second layer of panels to consider the density of lines required to produce an interference effect.

To meet health and safety concerns, the piece was then covered with a Perspex box. Initially I was disappointed by this constraint, but the cover became an active part of the work itself – a transparent yet solid envelope within which the fragile lines appeared to float. Despite the addition of this framing structure, the patterns remained essentially illegible among the moving visitors and other exhibits. And yet, when viewed in isolation alone against the white wall, the open weave of the fine printed lines produced a subtle rippling effect.

Figure 112: Side view of construction

It was also interesting to note the dramatic shift in the appearance of the work when seen from the side: as with the panel works described in the previous chapter, it seemed to abruptly 'collapse' from three to two dimensions. The lively network of shadows generated by the lines as well as the edges of the glass panels and the Perspex box raised the question of the extent of the work- and the recurring issue of lighting.

However, as discussed earlier, the dimension of lighting was set aside for this project.

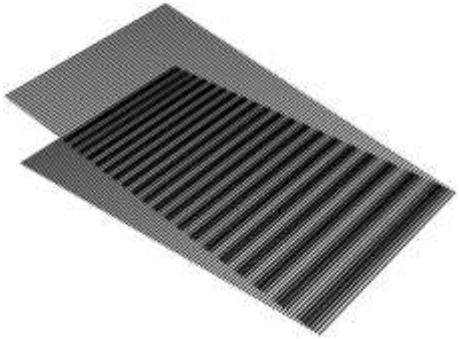


Figure 113: Single fold (12 degrees), under and overlays of the same frequency, fold parallel to the direction of the gratings

3. Binocular effects – tilted planes

As discussed, Hughes' *Reverspectives* and Wilding's *Paradoxical Forms* are designed to provoke a direct conflict between their solid physical structures and the strong converging contours and texture gradient that are painted on their surfaces.

The previous chapter explored the basic parameters that define the shape and orientation of moiré bands: a gradual change in the relationship between the gratings results in a progressive shift in the appearance of the bands, generating texture gradients and converging contours that are interpreted as cues to depth.

In those examples, the gradual change of spacing or rotation was calculated as part of the design of one of the sets of lines while the other stayed constant. The two panels were essentially parallel with each other.

However, the same effect can simply be achieved by tilting one plane relative to the other: as this panel slopes away from the viewer, the spacing between the lines appears to become progressively narrower.

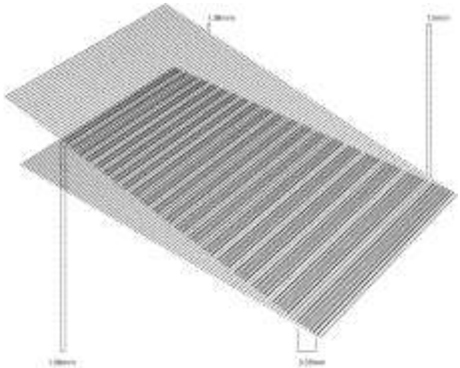


Figure 114: Relationship between line and beat frequency

Figure 115: 'V' fold (12 degrees), under and overlays of the same frequency, fold parallel to the direction of the gratings

As a result, even if the lines on the background and transparent overlay are actually the same frequency, the rhythm at which the two sets of lines go in and out of phase gradually changes. In the initial experiments, the paper was folded in the same direction as the lines, as this diagram shows

As the paper slopes away from the viewer, the moiré features and the spacing between them also becomes progressively narrower.

As seen in the previous chapter, the moiré bands magnify this effect. In this example, the apparent space between the lines on the top layer changes from 1.5mm to 1.38mm at the 'farthest' point on the left of the image, or a reduction of 92%. The width of the moiré band, on the other hand changes from 9.58 on the right to 1.98 on the right – a dramatic difference. These texture gradients with their distinct depth cues seemed promising and early experiments worked with folds in this orientation.

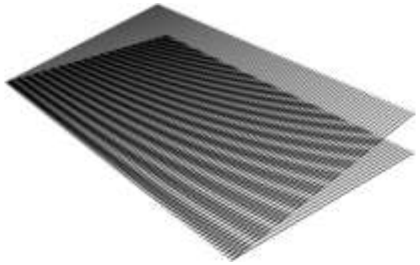


Figure 116: Sngle fold (12 degrees), under and overlays same frequency, the fold perpendicular to the direction of the gratings

Figure 117: 'V' fold (12 degrees), under and overlays same frequency, fold perpendicular to the direction of the gratings

However, the effects were not as compelling as the Wilding pieces had seemed, leading to experiments folding the paper across the lines as an alternative. The texture gradient did not seem as convincing as the parallel orientation when working with a single fold. But, when the sheet was folded to form a 'v', a moiré band appeared that strongly suggested a series of converging contours. These effects are apparent in these diagrams that are essentially monocular – from a single viewpoint.

Wilding's particular innovation lay in his sophisticated understanding of the mechanisms of binocular disparity, demonstrated by his *Paradoxical Forms* and early installation work. As discussed, the visual system uses the differences between the views from the left and right eyes to gauge forms and relationships in space.

As discussed in the previous chapter, when one set of lines is moved relative to another, a moiré band is created that appears to travel more quickly than the actual shift. In addition, depending on the relationship between the two sets of lines, the moiré feature may travel in the same or in the opposite direction to the actual movement.

As a result, the difference between the views from the left and right eyes is far greater than the disparity that would be produced by a 'normal' object of the same depth. This 'amplified' disparity is interpreted according to the 'normal' rules to produce an experience of an object in depth that is far greater than its actual form.

As with the *Reversepective* and *Paradoxical Forms*, once this 3D schema is established, the interpretation persists, over-riding physical, environmental and knowledge-driven cues such as movement of the body - or the presence of a solid wall.

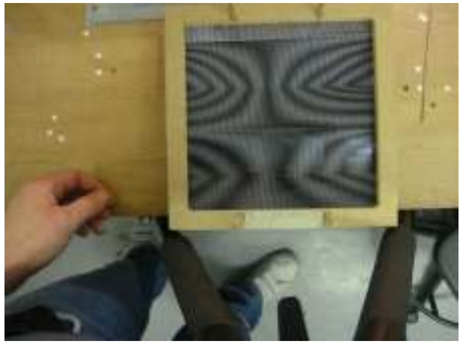


Figure 118: MDF frame with printed paper and plastic sheets

Studio development – basic parameters

This laid the foundation for a series of experiments to find the optimum combination of over- and underlay frequencies to generate a clear, dense and regular 'arrow' beat, exploring a range above and below the 11 lines per cm noted from the Wilding examples and from the illustrations in Lothar Spillman's review of the history of moiré interference effects[186.]

[186] Spillman, Lothar, 1992 "*The perception of movement and depth in moiré patterns*" Perception, 1993. Volume 22, pages 287-308.

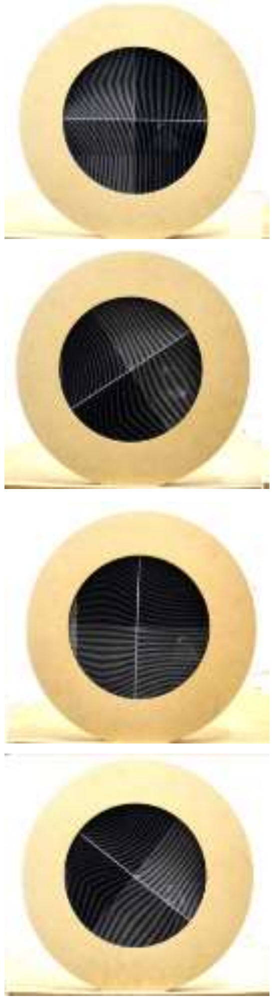


Figure 119: Illustration of the effect of angle on apparent deth

As noted in the previous chapter, viewing distance is also a factor in the choice of frequency: discussing the parameters of these phenomena in relation to Wilding's work, Spillman notes that the most persistent moiré band effects arise between the resolution at which the retinal array is no longer able to clearly distinguish individual lines and when the grating becomes an even 'blur' or tone.

Studio experiments suggested that lines spaced at 14 lines per cm started to blur at around 1 metre, a frequency of 11 lines per cm became a texture at around 2 metres and, when seen from four metres, a frequency of around 8 lines per cm seemed optimal.

4. Disparity

The role of binocular disparity in these amplified depth effects had not been understood from the outset. For this reason, most of the early works were designed with the folds running vertically rather than horizontally.

However, spending time with the work, it eventually became clear that the strength of the depth effect was influenced by the orientation of the lines.

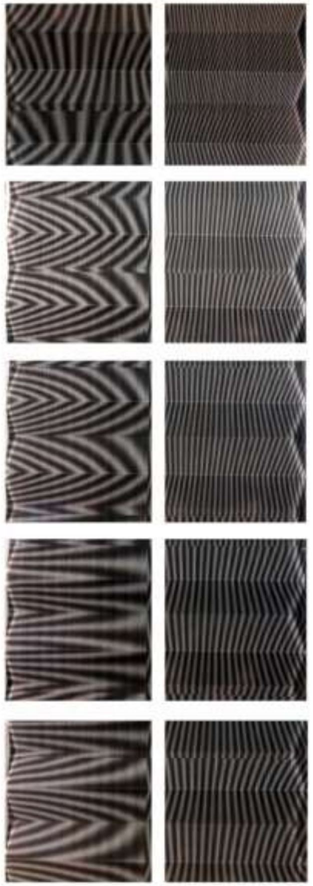


Figure 120: Effect of varying the relationship between the line frequencies

A simple circular rig with a window to hold panels of paper and glass was built to test this idea. Placing this on a turntable and filming the revolving object from a stationary camera offered a clear illustration of the effect of orientation on the depth effect.

For a number of Wilding's contemporary artists such as Max Bill[187] and von Graevenitz[188], experiments with the apparent motion effects of moiré interference led to kinetic work. These dimensions were explored through a series of projects I made with fellow student and film maker Jamie John Jenkinson in which we combined glass, light and movement to produce brief sequences of pattern. These were then either filmed or performed 'live' at events such as the National Portrait Gallery's Friday Late Expanded Cinema event in May 2013. [189]

[187] Max Bill, artist (1908-1994)
[188] Gerhard von Gravenitz (1934-1983)
[189] http://www.npg.org.uk/whatson/late-shift-1/film-movement-in-light-a-contemporary-expression-18042013.php

5. Evaluation

The process of printing the high-frequency lines proved technically demanding: digital prints on transparent plastic were extremely fragile, while screen printing fine lines generated unwanted moiré effects. However, thanks to the skill and patience of the technical team, it was eventually possible to print the full range of frequencies to a standard that would allow the exploration of the full range of effects

Soon realising that an almost infinite variety of combinations was possible, it became important to find a system for comparison and evaluation. As discussed, the spatial effects seemed most compelling when there was a significant difference between the moiré bands presented to the left and right eye views,. This suggested a simple strategy for judging the results: two photographs were taken 6.5cm apart to capture the views from the position of a notional left and right eye, simulating binocular vision.

Figure 121: Comparison between photograph and digital simulation

Comparison between the photographs and observation of the objects themselves confirmed the proposition that strongly different views and opposing contours ('><' or '><') in each eye seemed to generate a strong depth effect.

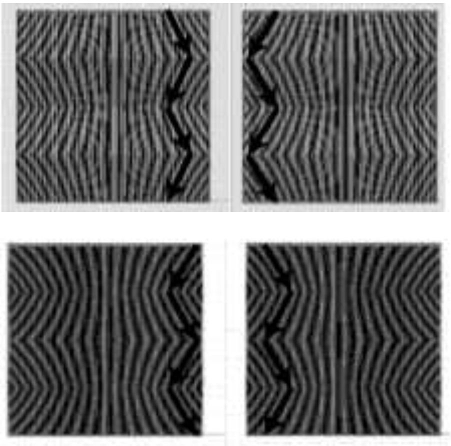


Figure 122: Comparison of left and right eye views for different frequency combinations

It also seemed that, when the arrows at the centre of the image formed a <> (as the illustration in the centre to the left), when looking at the piece itself, the contours seemed to be in depth. This consistently occurred when the frequency of the overlay was lower than that of the folded sheet.

When the arrows converged to form a ><, as the lower pair of images to the left, the contours seemed to come forward from the surface of the work. This appeared when the overlay grating was denser than the underlay.

The 3D design software 'Rhino' was used to generate a large number of variations and to simulate two views with comparable distance and spacing to the photographs. The results were equivalent in terms of the clarity, density, regularity and angle of the 'arrow' as shown here.

The matrix below shows a series of experiments progressing from 9.27 lines per cm to 11 lines per cm (second from left on the third line) to 13.75 lines per cm bottom right. At the scale shown in this document, it is not possible to discern the details of angle and interval, but it is possible to observe a progression from tightly-woven to increasingly strident rhythms as the frequencies approach each other, moving away again into more subtle patterns.

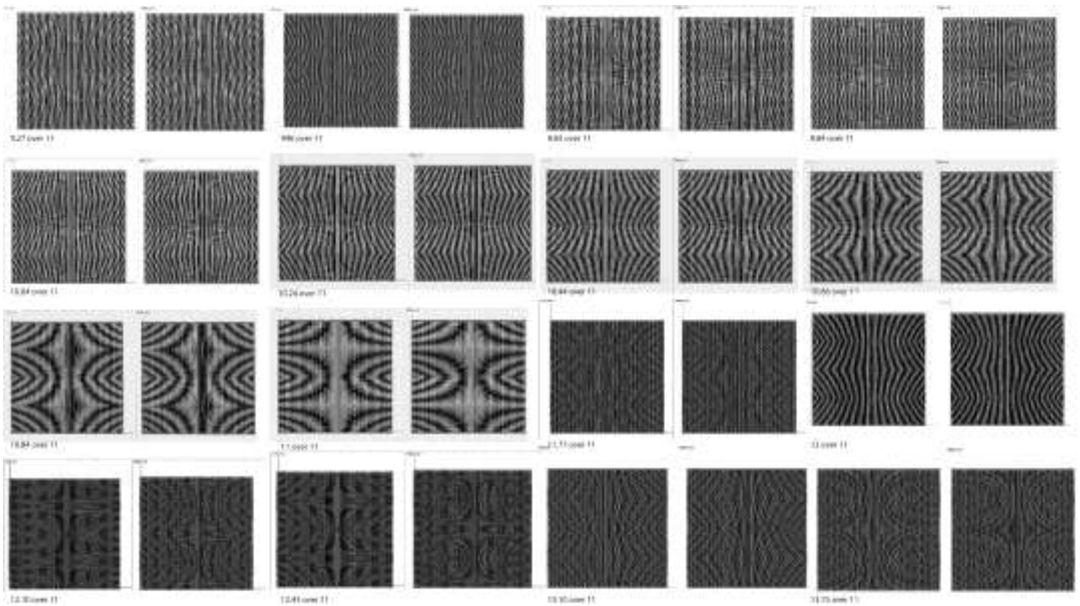


Figure 123: Variations in line frequencies simulated in the Rhino software

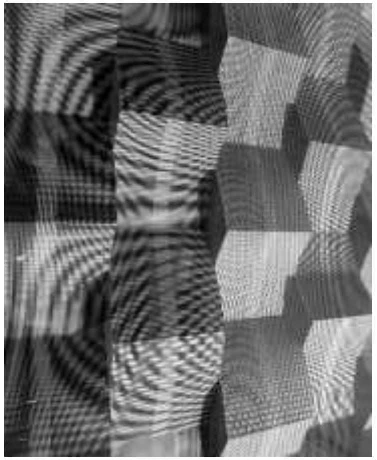


Figure 124: Photograph of framed piece exploring the effect of different line weights

The combinations that generated the clearest effects were then screen printed onto paper and onto glass. During this process it became apparent that the strong contours arose from proportions or ratios rather than absolute numbers (i.e. overlay frequency 10% greater or smaller than folded layer frequency, not 9 or 10 lines per cm).

Using 11 lines per cm as the folded layer or base frequency, a combination of Rhino-generated prediction and visual checks were used to identify a range of ratios that gave the strongest results, finding that a ratio of 9:8, or 1.125% seemed to give strong, clean interference bands (i.e. 9.78 and 12.38 lines per cm for the transparent overlay, with 11 lines per cm for the base or folded layer). It was interesting to note that the ratio of 9:8 is also the difference between the frequencies of two whole tones in music.

In addition to line frequency, the relationship between the densities of the lines on the base and overlay seemed to affect the quality of the result. A series of experiments indicated that 'complementary' densities (33% and 66% for example) gave the strongest depth illusion.

6. Colour of frame

The panel pieces discussed earlier in this document suggested the subtle interferences between object and environment that could be created by reducing the structural framing elements to a minimum. However, in order to exploit the binocular effects, the panels needed to be set horizontally, raising the basic question of how to physically hold them in place. Gallery visits and catalogue reviews indicated that many of Wilding's work and many kinetic installations are either framed in black or shown in the dark. At the same time the illustrations in the scientific papers are placed directly onto the default white background of the paper. Similarly, the white frame or white cube has become the conventional setting for current art practice.

The frames used for this research had also either been left unpainted, to signify their status as 'rigs' or structures for testing, while those used for presentation were painted white. With this in mind, a small number of black frames were produced for comparison and shown to colleagues for reaction. It seemed that the colour of the surround does indeed affect the way the objects are viewed but more in terms of 'style' than visual effects: black frames were associated with work produced in the 70's and 80's, and adopting this for a contemporary practice was seen as derivative or contrived.

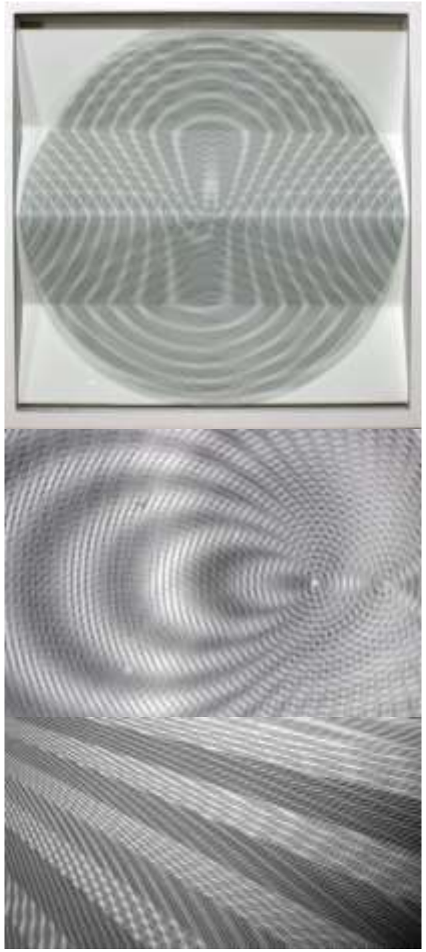


Figure 125: Details of framed pieces combining radial and concentric pattern with folding, October - December 2012

7. Variations

An understanding of the basic parameters provided the basis for experiments combining radial, concentric and parallel lines with the tilt of the panel itself.

While these textures were rich and pleasing, they did not generate the amplified spatial effects that defined the focus of the project and they were set to one side.

Figure 126: Frame construction

8. Observation in glass

As seen in the reverse perspective work, structures made entirely of glass produce markedly different effects to those that include paper, as secondary rhythms are generated by multiple layers of lines, and the interference phenomena extend to integrate the patterns in space beyond the object itself.

The logical development from the experiments described above was to apply these basic parameters to glass, exploring the impact of tone by alternating panels of white and black. The question also arose of whether the position of the tilted panel would affect the pattern (i.e. whether it should lie behind or in front of the flat panel).

A simple MDF frame was designed to consider these issues: two vertical panels with laser-cut channels to hold printed glass panels in the same basic configuration as the paper works (a vertical overlay with a ‘v’ shape formed by two panels tilted at 17^{o} to each other) but with the addition of a second vertical ‘overlay’ opposite the first.

Having found that variations on 11 lines per cm generated consistent, dense interference patterns at viewing distances between 1 and 3 metres, this was chosen as the base frequency and printed on the tilted panels.

Figure 127: Two sides of the installation and detail

In contrast to the glass convergence piece described earlier, the patterns produced by the work, perhaps reinforced by the solid structure of the MDF frame, were dense enough to maintain the integrity of the moiré bands. As a result, the distinctive texture gradient and converging contour cues were clearly visible, producing strong spatial effects. While these were most striking in the sections entirely composed with black lines, subtle beating effects appeared in those areas where white and black gratings were combined.

However, as discussed in the parallel works in the last chapter, white on white effects were also surprisingly rich and subtle. The addition of a second vertical panel enriched these effects further, especially when viewed close up, producing secondary rhythms, vertical lines and twisting torsade patterns that appeared to follow the movement of the viewer

While the spatial and rhythmic effects were rich and varied, the frame itself was not well-designed. The treatment of the ends of the glass panels and the shadows cast by the Perspex rods were a significant intrusion, undermining the clarity and precision of the experience overall.


Figure 128: Transfer prints on solid glass forms

9. Plane and form – surface effects

The examples described so far explore the depth cues triggered by varying the size and orientation of moiré bands to suggest converging contours and texture gradients. Referencing the work of Ludwig Wilding, these moiré bands were generated by the interaction of sets of lines printed on separate planes or surfaces.

These principles were applied to simple cast forms, firing printed lines onto selected surfaces, choosing a single frequency in order to highlight the effect of distance and angle on the apparent scale and the appearance of the moiré bands.

This approach generated distinct moiré bands that reflected - and amplified - the underlying form. This is demonstrated by the slumped piece shown here with undulating patterns that trace the movement of the material. However, the grating chosen for these experiments (9 lines per cm at 40% density) was not sufficiently dense to produce the compelling gradients and contours seen in the panel pieces, especially at the close viewing distance involved for these small objects. In addition, the bands were subtly disrupted by small bubbles and the cording or grain of the cast material. Although tempted to explore the veiling and other organic material qualities, they lie outside the scope of this project and were set aside for future consideration.

Figure 129: Hot glass process

10. Encapsulation

As well as the moiré bands, the solid glass introduced new material dimensions of weight, reflection and magnification. This raised the question of the spatial effects that might be created if the planes were located inside the form rather than on the surface, setting the framework for the tests described here.

Working with the technicians during the first two years at the RCA, we had developed a simple method for encapsulating simple graphic elements and matrices of bubbles on multiple layers or planes of hot glass with the aim of embedding medical scans and other information within a form.

This involved preparing a series of flat panels and heating them in a kiln. A ‘carrier’ bubble or cylinder of hot glass would be prepared and pressed onto one or pre-heated panels, warmed in the glory hole and shaped until the panel and its carrier were fully fused. This could then be dipped or ‘gathered’ in hot glass to encapsulate the panel. This process could be repeated several times, building multiple layers within the object in a single session in the hot shop.

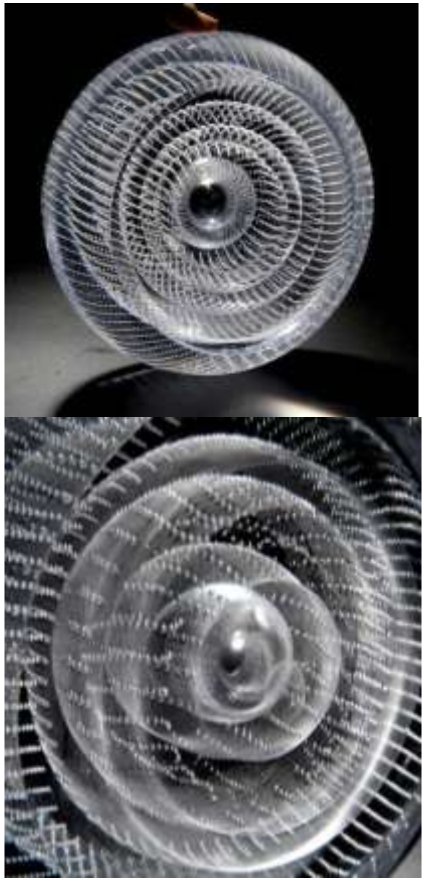


Figure 130: *Moiré Matrix 2 and 3*, May 2012

Having observed that sandblast marks on the panel produce a precise 'veil' or cloudy area in the finished piece, this principle had been extended to explore the effect of sandblasting deeper depressions in the panel.

I had noted that small, sharp-edged dips produced clean, round bubbles as a result of the viscosity of the hot glass which does not 'fill' the hole but seals it, capturing a pocket of air. In this investigation, the small panels of the early tests were replaced by circular plates that could be 'wrapped around' the carrier, the net of bubbles stretching evenly around the edges of the form to generate a rhythmic expression of the process.

The magnifying qualities of the glass generate a form of 'reverse perspective': the texture of distant bubbles appears larger than near ones –the opposite of scaling relationships in 'normal' space. As with the paradoxical forms discussed earlier, this conflict between appearance and expectation produces an unstable and disorienting experience. The curvature of the object amplifies this instability, engaging binocular disparity cues as slight changes in the position of the viewer, or of the object, creates an amplified increase or reduction in the apparent size of the bubbles and a shimmering motion effect.

Figure 131: *Moiré Matrix 5* side and detail view, January 2013

In order to combine these scaling effects with the converging contours of the interference patterns, one set of patterns would need to be positioned or registered relative to another. Various options were explored such as marking the blowing iron and the plates. However, in the course of heating up and encapsulating, the whole piece twisted very slightly, rendering precise registration impossible.

Rather than encapsulating a series of flat plates in a single hot shop session, an alternative, sequential approach was considered, beginning with a cylindrical core 'embryo'. The matrix was applied, the embryo pre-heated, encapsulated and allowed to cool before the application of a second matrix. This enabled the construction of up to six different concentric layers with close registration, resolving issues such as the size and shape of the internal bubble, extending the pattern through the tip of the form.

These designs were inspired by Wilding's 'all over' compositions, the matrices extending across the whole piece on every layer. This approach materialises the concentric quality that is inherent in the process: when seen from the 'end', the patterns appear as concentric circles with clear 'gaps' between them, while from the 'side', the patterns merge to produce a complex but largely undifferentiated texture.

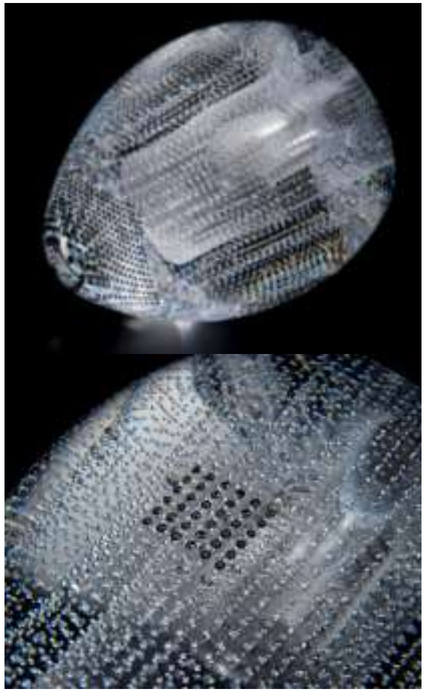


Figure 132: ***Moiré Matrix 6: IGE side and detail, September 2012***

Variations in the size and spacing of the bubbles, and areas of sandblast texture, were then explored to produce structures that could be 'read' both in terms of their actual position on a concentric layer and in relation to other layers in a lateral or radial dimension. With accurate registration, the networks of bubbles on different levels were indeed shifting in and out of phase with each other generating a subtle interference beat. But the matrices were experienced as planes rather than as distinct lines - and so the moiré bands did not appear.

Attempts to produce lines by sandblasting, or to 'join the dots' in the matrix either by drilling, or by reducing the space between the holes in the stencil, were unsuccessful: the sandblast marks were too subtle and the 'joined up' dots simply merged into a series of irregular elongated bubbles – or a single large one.

However, drawing on earlier colour experiments, it was possible to mark out a simple but distinct figure by embedding enamels into selected bubbles. Appearing to emerge from the complex texture of the background, this device seemed to act as a benchmark against which the scaling effects could be judged.

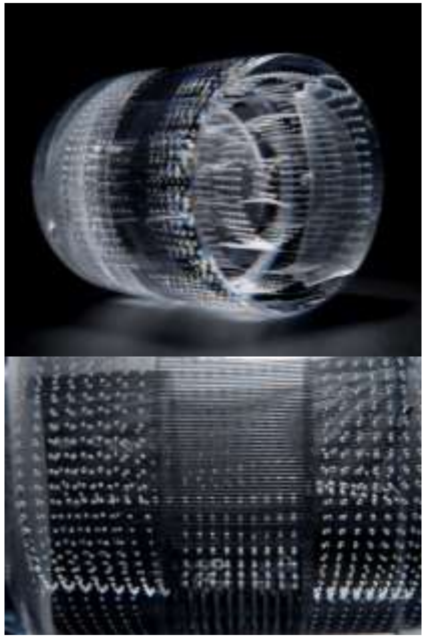


Figure 133: ***Moiré Matrix 8: Alternation 1,*** **May 2013**

The form and position of the internal bubble was also a factor for consideration as the internal refraction generated the appearance of multiple distorted copies of the matrices when viewed from certain angles – but disappeared with a slight shift in perspective.

Observations that the presence of a distinct graphic device seemed to provide a reference, or benchmark, that reinforced scaling and texture gradient effects led to the introduction of printed lines in combination with the matrices of bubbles. These were registered on successive layers or gathers of glass to generate the appearance of forms that run across and between the layers, generating both concentric and radial perspectives.

These pieces do not generate the distinct moiré bands seen in the panel pieces. This may be due to the qualities of the transfer prints that leave a cloudy residue, halting the complete integration of the lines that is needed to produce the interference effect. This may also be due to the curvature of the glass: the relationship between the lines shifts too fast for the interference to be established.

However, the optical qualities of the material do produce paradoxical scaling cues, where distant textures and elements appear larger then near ones, an effect that is compounded by combining flat and curved surfaces to vary the degree of magnification. These texture gradients can be captured by the still image, but are very much more compelling when the object is moving. However, comparing the images from a left and right eye view suggests that the effects are essentially monocular, generated by the optics of the glass rather than from binocular disparity.

Figure 134: ***Moiré Matrix: Hybrid form*****, 2013**

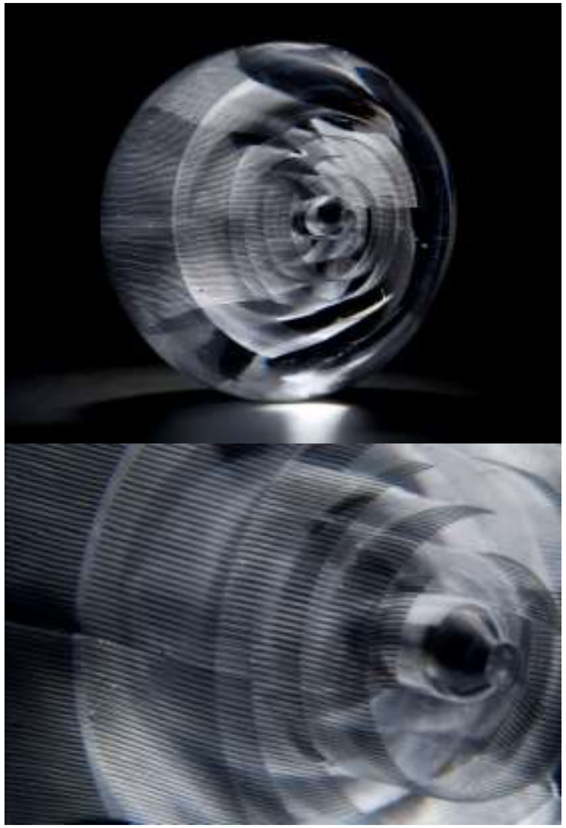


Figure 135: Moiré Matrix: intervals, 2013

Figure 136: Moiré Matrix: curved column, May 2013

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11. Rivalry and disparity

Preparations for a presentation to a group of vision scientists in Germany in August 2013 provided the focus for an interview with Ludwig Wilding's widow at their home near Bucholtz near Hamburg and with Marlene Lauter, curator of the Peter C. Ruppert collection of Concrete Art in Würzburg near Nüremberg.

This process led to a re-evaluation of the outcomes of the research overall and a small series of layered pieces refining the relationship between the line width and frequency to increase the strength of the depth effects.

Returning to the original examples of Wilding's work, the first adjustment explored the relationship between the line frequencies. Research to date had selected a ratio to produce opposing contours in the left and right eye views as these generate restless contours that seemed to suggest both space and movement.

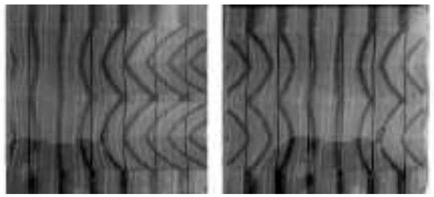

Figure 137: left and right eye views of Wilding piece

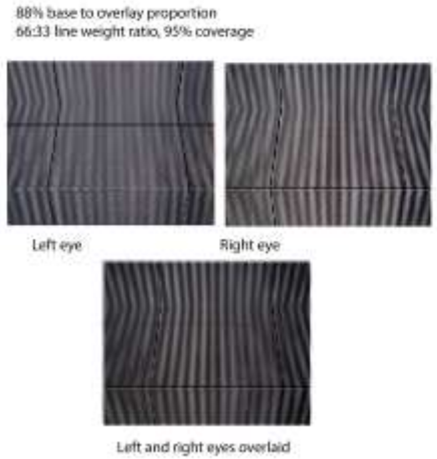

Figure 138: Earlier work (88% ratio, 60:40 line weight ratio)

As can be seen from the photographs of the original art works from a 'left and right eye' position shown here, although the contours were indeed opposed along the margins, there was a far greater area of similarity in the central region than in the studio experiments, presented for comparison: Wilding's spatial effects were a result of binocular disparity – a marked but reconcilable difference between the retinal images. By contrast, the restless contours of the work produced to date seemed to be generated by binocular rivalry – an unstable negotiation between two incompatible perspectives. The shift from rivalry to disparity could be achieved by simply reducing the difference between the two frequencies from 12.5% to 10%.

The second adjustment lay in the relationship between the weight, or thickness of the lines. Working with transparent glass panels increasingly presented without a framing structure to create a 'ghostly' inconsistency in the gallery space, the studio practice to date had sought to produce objects that would present equally rich effects from both sides. However, in Wilding's pieces, the overlay lines are very much finer than those on the base layer. This review also noted the use of a thicker line at intervals of between 15 and 20mm, an addition that generated a strong secondary contour, emphasising the periodicity, or phasing of the effect.

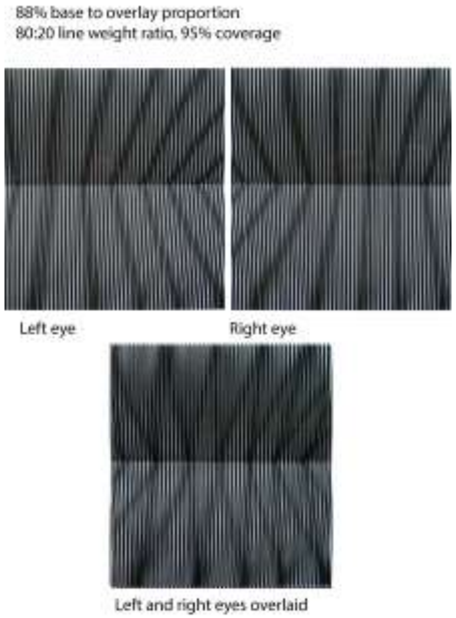

Figure 139: new work (90% frequency ratio, 80:20 line weight ratio)

These observations were confirmed through a small series of printed works that generated more dramatic depth effects from binocular rivalry, suggesting, in the intersection of the three visible dimensions with a fourth dimension of time, in the words of the philosopher Marion:

'Whatever my travels may be, depth will always remain in front of me as that which I will never be able to traverse since, if I advance myself toward and in it, it will deepen that much more so that I am never really able to cover it[190.]

190 Marion, Jean-Luc. 2004, *The Crossing of the Visible*. Stanford, California: Stanford University Press.p5

Chapter V. Conclusions

1. Origins

This project has been rich in personal, intellectual and technical development, beginning with the aim of illustrating the structures of the visual pathway and concluding with the development of objects that invite the viewer to observe these mechanisms at work, generating strange spatial effects that may offer insights into the 'secrets of mind and brain.'[191]

2. Strange phenomena

Questioning the original assumption to work with glass paradoxically led to a renewed commitment to focus on its unique qualities of ductility and transparency. Contextual and material investigation of these two characteristics led to the realisation of its unusual potential to produce inconsistencies between visual appearance and material reality, these 'strange phenomena' exposing the usually unconscious process through which ambiguous visual signals are interpreted to produce the experience of sight.

[191] Gregory, R. L. 2009. *Seeing Through Illusions*. Oxford: Oxford University Press. P1

The material and optical qualities of glass, particularly when combined with simple high-contrast graphics, seemed to generate oddly mobile and fugitive spatial effects, an observation that paved the way for a review of the cues that trigger depth perception.

3. Into space

Artists have exploited these mechanisms in various ways to represent the multiple dimensions of subjective experience on a two-dimensional picture plane, the invention of linear perspective in the 14th century offering a 'beguilingly simple means for the construction of an effective space in painting'[192]. Noting parallels between periods of radical shifts in attitudes to the visible and invisible worlds, and experimentation with representational systems, the artist Ludwig Wilding exemplifies the approach adopted by the Concrete artists in the period immediately following the Second World War.

[192] Kemp, Martin. 1990. *The Science of Art: Optical Themes in Western Art from Brunelleschi to Seurat*. New Haven: Yale University Press

4. Interference

Influenced by the philosophy of the Bauhaus school and inspired by scientific discoveries such as Einstein's *General Theory of Relativity*, Wilding explored the potential of high-contrast lines printed on panels of card and transparent Perspex to generate interference patterns, configured to generate compelling three- and four-dimensional visual effects.

5. Inspiration

Ludwig Wilding's remarkable work laid the foundations for the studio development in my research that aimed to understand the underlying parameters and then to extend this knowledge to exploit the particular material and optical qualities of glass.

6. Insights

The new insights generated in the course of this project have built on the legacy of Wilding's extensive research. Testing the boundaries between the work and its surroundings led to the removal of the frame, exposing the cutting edge of the glass and its paradoxical presence as both flat sheet and solid form.

Fine printed lines generate mobile interference patterns that appear to expand, to contract or to 'run off' the edge of the panel as the viewer passes, a disconcerting effect that is more strident when the lines are printed in black, but subtler when white ink is used.

Presenting these open works in the centre of a room or against a clear window produces the disconcerting appearance of a suspended flickering disruption that suggests the experience of peripheral vision.

Consideration of the particular optical qualities of glass led to the exploration of texture gradient and size scaling cues produced by encapsulating multiple layers of half-tone matrices and parallel lines in hot glass forms. Returning to Wilding's remarkable amplified depth effects led me to refine my understanding of the variables involved in generating moiré interference effects in shallow three dimensional forms. These seek to exploit the mechanisms of binocular disparity in order to achieve the original aim: to exploit the unique qualities of glass in combination with simple graphic cues to generate strange phenomena that challenge our sense of space, inviting the viewer to 'participate in the playful act of seeing.'[193]

[193] Elkins, James. 1999. *Why are our pictures puzzles?: on the modern origins of pictorial complexity*. New York: Routledge.p5

7. Future dimensions

The project has opened many new perspectives for future exploration. New scientific models extend Einstein's four dimensions into quantum dimensions of uncertainty seem particularly relevant to the unusually non determinate surfaces and spaces that these interference patterns seem to generate. The installation of a series of art works at the Hospital Club in central London will provide the starting point for an interdisciplinary seminar with philosophers, scientists and artists at the Institute for Advanced Studies at UCL planned for Spring 2014.

An ongoing collaboration with a team of X-ray crystallographers is exploring these themes in relation to symmetry and reciprocal space in biology with new bodies of work to be installed at the Museum of the History of Science in Oxford and in the Jerwood Space in London in June 2014.

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