PHOTOTYPE PRESS
PAMPHLETT No. 1

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ARTIST

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PRESERVES THE TENOR OF

CONVERSATIONS

WITH A

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PHYSICIST:

LESSONS ON THE BEHAVIOUR OF

CAUSTICS.

A COLLABORATION OF ARTISTIC EXPERIMENTS

TO CREATE LIGHT ARTEFACTS CAPTURED ON A LIGHT SENSOR

INFORMED BY THE SCIENTIFIC EMANATIONS
OF A CONSULTING PHYSICIST.

MMXV

PAM MCKINLAY

On Caustics: A Conversation

Figure 1 (opposite). Frontispiece for pamphlet originally printed for the Art and Light Exhibition, a collaboration between the Dunedin School of Art and the University of Otago departments of Physics, Botany, Anatomy, Physiology and Computer Science, hosted by the Otago Museum, 15-30 August 2015. Printed by Phototype Press at the P Lab, Dunedin School of Art, on a Risograph RA-5900. Typesetting and layout by Gregory Thomas. Etching from drawing by James Clerk Maxwell, *Diagram of the Lines of Force and Equipotential Surfaces*, plate from *A Treatise on Electricity and Magnetism*, vol. 1, 1873.[1] The lines of force depicted here visually resemble some of the caustics which we would later produce whilst experimenting with the light cast from the projections.

LIGHT AT THE JUNCTURE

Light is the juncture between the known and the unknown. For the scientist, light is a meeting point for classical and quantum physics, it is the location of special relativity and the photon. Because the speed of light is the speed of information, it is the speed of the possibility of knowledge. For the artist, it is first and foremost a natural phenomenon.

PROJECTED HISTORIES: SPECIAL RELATIVITY

The installation *step into my light cone* emerged during the Art and Light Project as a series of images captured from interactive projections producing caustic effects. They came from a response to ideas about research into the properties of light in vacuums and rainbow caustics and the images explored where we find ourselves situated in our experience of spacetime—within a continuum of personal and intersecting histories (across time) and within the universe (space). They were made with a mind full of light cones and "dark bodies," along with ideas percolating down from the time of Plato—ideas which have been affected by a cast of a thousand bright sparks including Newton[2] and Young,[3] many of which are however now deemed null and void.

Theories about light changed radically with Maxwell and Einstein and underwent rapid evolution within the timespan of special relative and muse Esther McKenzie. Esther was a member of the Society of Friends, better known as Quakers, for whom "light" is a spiritual concept. Great grandmother, and born around the time of the discoveries of special relative-ity, Esther only very recently stepped out of her final light cone.[4] We set about making projections in an experimental project space which we could walk through to encapsulate this myriad of ideas from across time and space. The documentation of the experience of this event eventually settled into a series of silhouette portraits of Esther's great-grandson, exhibited at the Art and Light exhibition.

2015: THE SUMMER OF LIGHT

Following in the footsteps of Henri Poincaré, in this International Year of Light, I turned to personal experience to question some of the alluring properties of light. Poincaré was a French philosopher and scientist much admired by Einstein, who advocated the analysis of relationships of everyday experience in one's habitual surroundings to aid analysis of scientific concepts.[5]

This summer, on sunny days with blue skies, I spent a lot of time swimming at the saltwater pool at St Clair. I'm no Esther Williams.[6] I like to swim at a certain time of day when there aren't many people around. With the sun behind me, I love to see the light/waves arcing out in front of me and the overlapping curve as the next set of waves push forward and intersect and cross over as I glide behind them. This only happens when you are swimming in one direction in the pool. Swimming back the other way always feels like pushing against the tide—there's no sun-rippling waves to swim with. I don't know the "why" of what is happening, but it is beautiful. It makes me happy and I KNOW something about the world and the way in which light plays amongst us and dances on the bottom of a pool. These are my personal experiences of a property of the radiating waves (water) and the effects of diffraction (light) as the light changes and "bends" as it encounters the boundary at the surface of the pool.

Let me prevail upon you to read a diary entry for 2 May—"What's This ?!"(a 3-D light artefact)

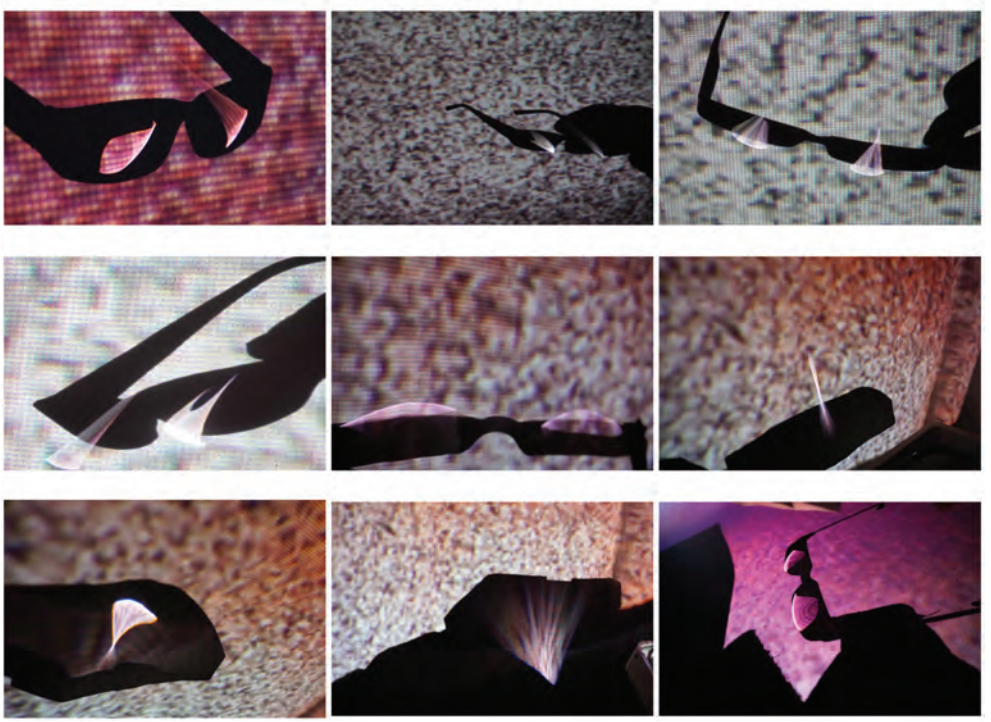

Figure 2. Pam McKinlay, initial experiments with standard reading lenses creating caustic arrays. Note: the caustic effect is very small and there is no sign of the expected second set of patterns; also there is an absence of colour.

I found the opportunity to delve into this question when I joined the Art and Light Project. I had the good fortune throughout the project to have several conversations with Dr Terence Scott, from the University of Otago—hence the title of these pages, which preserves the tenor of those meetings. I thank him for his extraordinary generosity and time in bringing me up to (light) speed on the properties and behaviour of photons, and sharing his thoughts on the high-speed pursuit of virtual

particles (a quixotic allure for many quantum physicists) and new research into the Casimir effect.[7] With these ideas in tow I took a sedate journey through the annals of light-science history[8] in order to grasp how our understanding of light has come about in the twenty-first century. It was in these travels through virtual dusty tomes (sans dust motes) that I had my first encounter with the writings and etched drawings made by the "father of light," physicist James Clerk Maxwell. In 1873 Maxwell wrote that light and electro-magnetism share the same ultimate nature, both being electro-magnetic radiations.[9] Maxwell's equations, derived from concepts of the duality of electricity and magnetic forces, are now hailed as the beginnings of our current understanding of "light."[10]

CAUSA SUI

From an early age we learn that light is both a particle and a wave.[11] As we daily observe in nature, waves are conveyed through a medium (ripples through water, sound through air). This poses the question that if waves need a medium to travel through, then how do light "waves" travel through a vacuum? What is doing the waving? At the time when Maxwell was devising his theory of electro-magnetism it was thought that the universe was filled with a substance called the *luminiferous aether*, which was thought to be the medium by which natural light travelled through space.[12] This idea held sway until 1905, when Einstein explained that light travelling through space forms sui-generating waves.[13] Einstein's hypothesis that light was in a way its own medium spelled the end for the *luminiferous aether*, and from that time the *aether* was consigned to the realm of magic, phantasmagoria and steampunk fictions.

Figure 3. Pam McKinlay, *Oculi, tanquam speculatores, altissimum locum obtinent*.[16] (The [laser] eyes, like sentinels, hold the highest place in the body.), digital inkjet prints on Hahnemuhle torchon matte paper, 410 x 273 mm. From *step into my light cone*, Art and Light Project Exhibition.

FROM INNER TO OUTER LIGHT

The way we have thought about "seeing" over the centuries has undergone some major shifts, and with it the way we view the world and our place in it. It used to be thought that the reason we "saw" was that the eyes emitted a sight ray, which bounced off objects and travelled back into our eyes in a theory known as extramission. Based on the observation of "fire" gleaming in animals' eyes, this idea was recorded by ancient writers like Pliny and developed into the "visual ray" hypothesis by natural philosophers including Plato and Pythagoras.[14] Following the irrefutable logic of the Islamic scholar Ibn al-Haitham Al Hazan, who argued that since the moon and stars are so far away, it is impossible for a ray from the eye to reach them and thus illuminate them, it became the accepted wisdom that vision was rather the result of rays from light sources *reaching* the eye by a process known as intromission.[15] Originating from sources such as the sun or a lamp, we characteristically see light scattered off an object's surface; objects that generate light—such as a television set—are reasonably uncommon in our everyday experience.

The "visual ray" idea is a likely root of the laser-eye meme in 1950s sci-fi movies (see Figure 3)—it still gets an occasional outing as an alien or mutant superpower in comicbook heroes and their translations to film, such as in the X-men and Superman movies.[17]

THE MOSAIC OF LIGHT—FORMING AN IMAGE

Vision is one of the most important senses studied in humans. Sensory ecology looks at relationships between the behaviour of an organism and the information it obtains from its environment. In terms of our perception, our eyes are instruments that have evolved in a certain way to interpret the *human* experience of "seeing" light.[18] The human eye is a sensor capable of capturing a *discrete* subset of light rays which we call the visible spectrum and decoding these as images.[19] We distinguish visible forms by detecting the subtle differences between colour or tone and light and shade. Our eyes determine the luminance or brightness of the light[20] and also the frequency or wavelength of the light, which we experience as colour. This is the basis of our vision and the way in which we recognise things and see images.

PHOTONS—LIGHT AFTER THE EVENT AND THE LIGHT CONE OF MINKOWSKI

Light is the means by which most of us navigate or gain our sense of space. The effects of what we know about looking at light over space AND time are summed up in a diagram first described by Minkowski in 1907 known as the "light cone."[21] The light cone diagram provides a way of visualising a flash of light moving through *space and time* (a theoretical construct of four-dimensional spacetime). At its simplest, a light cone diagram resembles a sand-glass or egg-timer in appearance. It consists of two cones which meet at their apexes, the point at which a given instance of a light event originates/d. The idea of a "light event" is key to Einstein's theory of special relativity. Any event in spacetime comes to us in some way by transfer of information. Light has the ultimate velocity so it is the ultimate propagator of information, whether the moment originates from the sun or in the writing of a letter or page of a book that one might read many years after it was written.

It becomes apparent that light is not only the juncture between the seen and the unseen in terms of our own personal vision, but between the known and the unknown—and maybe even the unknowable

in the universe. Everything we see is light coming to us. It is always relative to us, the observer. Every event has its own light cone, and some of them overlap. Einstein extended the idea of the light cone to posit a "past" light cone, the point of which was to imagine the world *before* the event. The light cone diagram demonstrates how the past can influence the present, and if light cones overlap it means there is potential for events to interact or influence each other.[22] Thus the diagram is central to ideas of causality (collections of events have a causal past in common if you track back down the extended "past" light cones). While we have a connection to "events" in our cone, "events" that happen outside our light cone are ultimately unknowable because they are not connected to us and sit in a kind of "elsewhere" spacetime.[23]

"THE PAST IS ALWAYS IN FRONT OF ME"—TAME ITI[24]

At first when I visualised myself placed in the imaginary construct of the light cone diagram, I imagined that I would be looking "out" to where the light was extending (i.e., going away from me). As you would, for example, when experiencing the artwork *Standing within the Projection* by Anthony McCall, where one can physically stand in a shifting stream of cone-shaped light—facing away from the source, looking outwards.[25] After hearing the quote by Tame Iti, I came to realise that I was "facing" the wrong way. This is only natural, as we tend to avoid looking AT bright sources of light. We can only see what has been, we can't see what is yet to come. This gives us pause to think about communication disruption, the disconnects between intercultural dialogues, and nuances lost in translation which can be caused by differences in the ways we have of accessing both personal and shared histories and cosmologies.

Each one of us is constantly and simultaneously standing at the threshold of a new, existing or changing light cone as an event occurs, continues or is overlapped, interrupted or interfered with, each moment penultimate to the next. At one point, I suggested that this was a moment of simultaneity which I defined as akin to a continuous series of isochronous sequences taking place.[26] However, the term "simultaneity" has such a very specific meaning in the theory of relativity as a temporal location that I quickly abandoned my use of it.[27] This was one of many discussions we had over language as we unpicked the meanings which certain words or phrases had for each of us in our respective fields. As an artist and scientist, we were participating in different language games in which words serve different purposes in different contexts. Ultimately, we "know" things differently because of the meanings we ascribe to the same words. In this way, our histories determine and precondition the way in which we come to KNOW things.[28]

A BURNING WORD FOR THE LIGHT FANTASTIC

To return to the diary entry for 2nd May, the name given to the properties of light I had noted, was "caustics." In the study of first-year physics, the term may warrant only a couple of paragraphs in an introductory textbook. It is such an ordinary and ill-fitting word for something that has such shifting radiance. It is sometimes called a rainbow caustic, but not even this descriptor—often employed as a positive literary and artistic trope—can shift the word from its primary meaning. The word "caustic," from Latin *causticus* and Greek *kaustos*, implies burning. Here it reflects the intensity of light near the caustic occuring at the boundary.

caustic 1: capable of burning, corroding or destroying living tissue. 2: the envelope of rays emanating from a point and reflected or refracted by a curved surface.
First known use: 15th century.[29]

LIGHT AT THE BOUNDARY

The second dictionary meaning is extensively studied in optics and mathematics. In optics, a caustic distribution is the envelope of rays either reflected or refracted at a surface boundary such as a lens, and from which a display of interesting wave effects will emanate. Varying the conditions such as refractive index, focal lengths and/or angle of the lense will alter the contrived effects.[30] Not all lenses produce a caustic, and concave and convex surfaces of different focal lengths will produce different effects. By manipulating the lenses we used, we gained control over the effects. By happy accident we discovered a second set of patterns, hidden in the light and revealed in silhouette. This second manifold of dispersion arrays we found were also outlined in the mathematical descriptions of caustic arrays.

Mathematical caustics allow us to draw a new curve derived from a given curve and a set point, which in our case we can call the light source. In mathematical language, a catacaustic is a set of reflected rays and a diacaustic is a set of refracted rays. Both are studied in differential geometry, for example in predictions for Jacobi fields—they are a means of mapping geometric interpretations of the curvatures of geodesics.[31] Given the right set of variables, the resulting curvatures create a bounded envelope of rays or a "projection." Also in the maths, we found that rather than chaotic patterns there is a whole "hierarchy of structurally stable diffraction patterns produced by optical diffraction in three-dimensional space."[32] Stepping aside from the algorithms and models, we found that we could create some of the predicted patterns as real images and that they did indeed appear as three-dimensional projections of light. (See Figure 4.) In the ensuing works, the mathematical equations went walkabout and I followed the resonance of the word trail from their impact.

STEP INTO MY LIGHT CONE

> When you create boundaries, you always leave something outside those boundaries. The boundaries need not be final or impermeable, but in order to define things some boundaries must be established.[33]

A scientist may conceive of an experiment in terms of parameter or function spaces (a trajectory through a single set of possibilities). While there was an experimental aspect to setting up the projection entailed in *step into my light cone*, the aim was to create a "narrative space"—an abstract space which encapsulated the many "light histories" already mentioned, sweeping through the history of ideas from the now defunct to futuristic notions about light and illumination.

Because each new viewer brings something into the installation space, it is more mobile in terms of "results." Narrative space is a broad term which is referred to in genres and settings as varied as novels and film (storytelling), theatre/drama and virtual reality (role-playing video games) and real-life environments (such as exhibitions and architecture). If, as Kant says, time and space are two of the fundamental categories that structure human experience, then narrative is how we communicate the story or sense of that experience.[34] It is a way of organising our experiences and making meaning. Is there actually such a thing as a non-narrative space? Since the time of the Renaissance, narrative space in art has also provided a platform for continuous narrative in which several events can be shown in a single setting.[35] However, the story need not be a story in the traditional sense—a narrative space may be a space which is used to convey or explore different themes and meanings, such as a time-scape in a three-dimensional landscape.[36]

In *step into my light cone*, I am exploring the idea of a trajectory across spacetime through the generations. There was also a performance element to the image-making. Each photograph is the documentation of a moment encountered in the light. By capturing the moment of the light effect at the boundary (the caustic array), we also sought to use it as a metaphor to explore what happens at the boundary of the light cone when one light event intersects with another. We also reinforced this notion, in exhibition trials, by the use of a motion sensor to trigger the lighting of the image and thus extend the notion of the "event."

In the early 1920s, artists such as Man Ray[37] and Lazlo Moholy-Nagy[38] created photographic images using a cameraless technique, the photogram,[39] which produced surreal effects. Shapes emerged from the hazy blackness and evoked "internal landscapes." In the words of Tristan Tzara, "These are projections surprised in transparence, by the light of tenderness, of things that dream and talk in their sleep."[40] Here the medium of the photogram is seen, according to Lloyd Godman, as a means of exploring "the subconscious, Gestalt or other related issues."[41]

In *step into my light cone*, the velvety darkness of the human head seen in silhouette was both the means by which we revealed the unseen and a metaphor for the internal landscape. (See Figure 5.) The "dark body" is the means by which the second set of patterns are exposed. In physics, a "black body" is a hypothetical object that is a perfect absorber of electromagnetic radiation (light) at all wavelengths.[42] Where ideas such as "dark bodies" and light cones remain in *step into my light cone*, their presence is now allegorical. A silhouette delineates the outline shape of an object while the interior remains featureless. But much can be read into the "empty" space within.

> The image that is never painted but is implied is just as important as the one that is not.
>
> Lao Tze[43]
>
> Art thou in Darkness? Mind it not, for if thou do, it will fill thee more, but stand still and act not, and wait in patience till Light arise out of Darkness to lead thee.
>
> James Nayler[44]

Figure 4. Pam McKinlay, *step into my light cone*, Art and Light Project space II, digital inkjet prints on Hahnemuhle torchon matte paper, 410 x 273 mm. Strong convergent lenses and other curvatures and light sources were used to create and control the projection of the hidden caustics.

Figure 5. Pam McKinlay, *step into my light cone*, Art and Light Project space II, digital inkjet prints on Hahnemuhle torchon matte paper, 410 x 273 mm. The works show intensification of the caustic artefacts, with spectral shapes captured in the silhouettes.

James Turrell (a Quaker like James Nayler and Esther McKenzie) explores both the ideas of the implied image and light arising from the darkness in *Wedgework V* (1975), which I saw exhibited at the "Light Show" in Auckland in 2014. His work encapsulates notions of the metaphysical in an immersive environment. Viewers were led through a tunnel of darkness into a dim room in which the visual senses became diminished or deprived. As my eyes readjusted to the hazy light, I became attuned to the "presence" of the light in the room as an almost palpable emmission.[45] Superficially, there are similar elements at play in *step into my light cone* (a darkened room and an intimate revelatory moment), but there is neither object nor focus in *Wedgework V*. It employs tricks of the mind to manipulate the viewer's perceptual *vision*.

Figure 6. Pam McKinlay, *step into my light cone: portals, quests, maps and secrets*, digital inkjet print on Hahnemuhle torchon matte paper, 410 x 273 mm.

"We see only the things we expect to see, based on our perceptions"[46]—but what if we don't expect to see anything at all? In *step into my light cone* the phenomena are tightly focussed and the optical effects are accentuated. The work captures an aesthetic response to some of the most pronounced effects of light when the observer strays into their path. These signify an event which would remain invisible unless intercepted and viewed in a certain way. The metaphor it encapsulates is somewhat different: "We *coexist* with invisible worlds, less than a hair's breadth away, superimposed on our reality."[47] Concealed in the light and revealed in the shadows, the silhouette was both the means of recording the projection and of metaphorically projecting both the present and the past onto the intercepting body. As with the rationalised geometry of the light cone, no "information" is lost.[48] The light is always there.

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Terence Scott is a senior teaching fellow in the Physics Department at the University of Otago. He received his PhD from the University of Otago in 2000 for research which involved investigating the dynamics of Bose Einstein condensates.

The authors wish to thank **David Green** for the use of the "chaotic" image from a video piece in "Granular Analysis" for the projection base from which the "predictable" images emerged.

1. James Clerk Maxwell, Plate II, "Lines of Force and Equipotential Surfaces," in *A Treatise on Electricity and Magnetism*, vol. 1 (Oxford: Clarendon Press, 1873), https://archive.org/stream/electricandmagne01maxwrich#page/n473/mode/2up (accessed 9 June 2015).
2. Isaac Newton, *Opticks: Or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light. Also Two Treatises of the Species and Magnitude of Curvilinear Figures* (London: Samuel Smith and Benjamin Walford, 1704), https://archive.org/details/opticksortreatisnewt (accessed 15 Aug 2015).
3. "May 1801: Thomas Young and the Nature of Light," *APS News: This Month in Physics History*, http://www.aps.org/publications/apsnews/200805/physicshistory.cfm (accessed 30 July 2015). Thomas Young disputed Newton's "corpuscular" theory of light. His double-slit experiment demonstrated the wave–particle duality of light.
4. *step into my light cone* was made in memory of Esther McKenzie who died age 104, having lived through a century of leaping advances in science. She was a lifetime member of the WEA. I am told that following the logic of the Minkowski light cone diagram, Esther will continue. Her final light still propagates. The lightcone continues without its source. The sky is full of stars that disappeared millions of years ago. And somewhere out there Esther's lightcone continues to join space and time. We all eventually whakapapa back to the stars. She would have told us that "this was all very marvellous!"
5. Arthur I Miller, *Einstein, Picasso: Space, Time and the Beauty that Causes Havoc* (New York: Basic Books, 2001), 206.
6. See *Million Dollar Mermaid*, dir. Mervyn LeRoy, 1952.
7. "Focus: The Force of Empty Space," *Physical Review Focus*, 2:28 (3 December 1998), reporting U Mohideen and Anushree Roy, "Precision Measurement of the Casimir Force from 0.1 to 0.9μm," *Physical Review Letters*, 81:4549 (1998), https://physics.aps.org/story/v2/st28. (accessed 15 September 2015).
8. As a first port of call for the completely uninitiated, I was recommended *Universe*, 9th ed., by Roger Freedman, Robert Geller and William J Kaufmann (New York: WH Freeman, 2011). It has excellent, user-friendly chapters on light and optics introducing crucial concepts and general theorems essential to this project.
9. James Clerk Maxwell, "A Dynamical Theory of the Electromagnetic Field," *Philosophical Transactions of the Royal Society of London*, 155 (1865), 459-512, at 466: "it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws."
10. Christopher Haley, "James Clerk Maxwell (1831-1879) Mathematical Physicist," *The Victorian Web*, http://www.victorianweb.org/science/maxwell/maxwell1.html (accessed 9 June 2015). Maxwell reports that "he read Faraday's Experimental Researches with delight, extracting from them several ideas to aid his own growing conception of electromagnetism. Among these was the notion of lines of force—a semi-physical, geometric arrangement of lines around charges which, just like iron filings around a magnet, indicated the direction in which a point charge would move if it were to be introduced at any location." This idea was significant in the development of Maxwell's equations.
11. "May 1801: Thomas Young and the Nature of Light."
12. *Isaac Newton's Letter to Robert Boyle, on the Cosmic Ether of Space* (1679).
13. Gérard P Michon, "Final Answers—Theory of Relativity," http://www.numericana.com/answer/relativity.htm. Michon gives a comprehensive explanation of the Michelson-Morley Experiment, Fitzgerald contraction and Lorentz transformation, which dispelled the theory of the luminiferous aether.
14. J Kevin O'Regan, "Ancient Visions," Laboratoire Psychologie de la Perception, http://nivea.psycho.univ-paris5.fr/FeelingSupplements/AncientVisions.htm (accessed 9 July 2015).
15. Thomas Joseph Brown (ed.), "Our Mysterious Visual Ray by Thomas Joseph Brown," http://aetherforce.com/our-mysterious-visual-ray-by-thomas-joseph-brown (accessed 2 July 2015).
16. Marcus Tullius Cicero, De Natura Deorum *(On the Nature of the Gods)*, trans. Francis Brooks, Book II, ch. LVI (London: Methuen, 1896), http://oll.libertyfund.org/titles/539 (accessed 9 July 2015).
17. Another example is Gort, a character in *The Day the Earth Stood Still* (1951). See Richard Harland Smith, "Dynamite with a laser beam!" http://moviemorlocks.com/2013/09/20/dynamite-with-a-laser-beam/ (accessed 15 Aug 2015).
18. Martin Stevens, *Sensory Ecology, Behaviour, and Evolution* (Glasgow: Bell and Bain, 2013), 29. The receptors used for luminance vision are the most abundant type in the eye. Luminance vision is fundamental to many aspects of sight because the visual information we gather from the world around us is encoded by differences in brightness (e.g., the boundaries between objects).
19. Mayatte Patrick-Hughes, *James Turrell—Challenging the Perceptions of Reality and the Meaning of Art*, 2013, https://mayattehughes.wordpress.com/2013/03/22/dissertation. "And so what we think of as space or nothing is full of matter and visa versa. What happens when we see? 'only about 20% of the light that reaches the retina actually registers in the photo-receptive rods and cones. The rest is simply unseen.' Paul Zelaski, from book, Colour. Colour and light. [sic]"
20. Richard Miles, "A Light History of Photometry: From Hippacarchus to the Hubble Space Telescope," *J. Br. Astron. Assoc.*, 117:4 (2007), 172-86, at 172

(British Astronomical Association Presidential Address, 2006), http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?bibcode=2007JBAA..117..172M&db_key=AST&page_ind=0&data_type=GIF&type=SCREEN_VIEW&classic=YES (accessed 12 June 2015). Since the time of Hipparchus, the study of the brightness of light emitted by stars has led to centuries-long enquiries into photometry (the science of measuring the brightness of light) in astronomy. In the twenty-first century, photometry has also been pivotal to developments in the science and art of photography and also to technological refinements in computer graphics, such as the rendering of light fields in filmed sequences and in static visual scenes.

21. John D Norton, "Light Cones," *Spacetime*, http://www.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/spacetime/#Light (accessed 14 July 2015).
22. According to Wikipedia, "A light cone is the path that a flash of light, emanating from a single event (localized to a single point in space and a single moment in time) and traveling in all directions, would take through spacetime." This phenomenon can be readily explained in terms of a light bulb. At a particular time, you switch on the bulb and it shines out brightly, in all directions. The point at which the light was turned on is called the event—from which one imagines a ball of light radiating out in light-seconds as a series of concentric circles which can be graphed as a "light in spacetime" diagram—or more commonly drawn and described as a light cone. See https://en.wikipedia.org/wiki/Light_cone.
23. John D Norton, "What Connects with What," *Spacetime*. See note 21.
24. As spoken in the film *The Price of Peace*, dir. Kim Webby (2015). This comes from the traditional Maori proverb (whakatauki), "Kia whakatomuri te haere ki mua" (To look into the future, our eyes must be fixed on the past).
25. I saw this work exhibited in "Light Show," Auckland Public Art Gallery, in December 2014. McCall's artwork works its magic by exploiting the rectilinear properties of light propagating in straight lines. McCall uses a simple film as an interface to shape the light beam, creating a stream of constantly shifting light in the shape of a cone of changing dimensions from a projection in a darkened room. The shafts of light were delineated by the use of artificial haze in the already dim room, thereby increasing the opacity of the light beams in the projection.
26. See Uri Margolin, "Simultaneity in Narrative," *The Living Handbook of Narratology*, http://www.lhn.uni-hamburg.de/article/simultaneity-narrative (accessed 22 Aug 2015), for a discussion of the different kinds of simultaneous actions in narrative, the modes of their presentation and spatial distribution, and the agency of time in narrative including the telescoping and synchronisation or blending of events.
27. Aashish, "Why 'Time' is not Constant," http://functionspace.com/articles/156/Why--'time-'-is-not-constant. According to Einstein's theory of relativity, simultaneity is not an absolute property in relation to events; what is simultaneous in one frame of reference will not necessarily be simultaneous in another. Thus simultaneity is the property of two events happening at the same time within a single frame of reference.
28. Jonne Arjoranta, "Game Definitions: A Wittgensteinian Approach," *Gamestudies: The International Journal of Computer Game Research*, 14:1 (August 2014), http://gamestudies.org/1401/articles/arjoranta. What is probably the single most important thing we learn from Wittgenstein is that an expression can be understood only when it plays a role in a language game. Our use of language is intelligible only when seen against a background of shared human activities and experiences. Thus, in one way or another, language is useful for different purposes and in different contexts.
29. Merriam-Webster Dictionary, s.v. caustic, http://www.merriam-webster.com/dictionary/caustic. Rainbow caustics were first 'scientifically' explained by Descartes in 1637. See "Descartes Rainbow," *The Rainbow*, http://mysite.du.edu/~jcalvert/astro/bow.htm#Desc (accessed 13 Sept 2015).
30. J B Calvert, "Caustics," *Optics and Visual Perception*, 2004, http://mysite.du.edu/~etuttle/math/caustic.htm (accessed 2 July 2015). "However, the intensity is not increased enough actually to make burning a fact. A caustic is a boundary between regions in which the light intensity is nonzero and zero. A wave cannot be sharply cut off, as the phenomena near the boundary of the shadow of an obstacle show."
31. Oliver Knill and Michael Teodorescu, "Pictures of Caustics on Ellipsoid," HCRP project 2009, http://www.math.harvard.edu/~knill/caustic/exhibits/jacobi (accessed 2 July 2015).
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35. Lew Andrews, *Story and Space in Renaissance Art: The Rebirth of Continuous Narrative* (Cambridge: Cambridge University Press, 1998).
36. Mia Zona, "Narrative and Alternatives for Video Game Space," 9 January 2014, https://mineofgod.wordpress.com/2014/01/09/narrative-and-alternatives-for-video-game-space.
37. "Lecture V—Cognitive Dissonance and Culture Jamming," *Visual Communication & the Designer*, posted 1 November 2012 by Ella English, http://journalvctd.blogspot.co.nz/2012/10/lecture-v-cognitive-dissonance-and.html (accessed 15 Aug 2015).
38. Jonathan Griffin, "Out of the Light, into the Shadows," *Tate Etc.*, 33 (Spring 2015), http://www.tate.org.uk/context-comment/articles/out-light-shadows, (accessed

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39. "The photogram is an image made without a camera by placing an object directly on to the surface of a light-sensitive material and then exposing it to light." Ibid. This process was first explored by Henry Fox Talbot in the art of "photogenic drawing."
40. Tristan Tzara, quoted in English translation in Man Ray, *Photographs by Man Ray: 105 Works, 1920-1934* (New York: Dover Publications, 1934), 84. "Rayographs" (photograms) seized the imagination of Tzara, who worked with Man Ray to produce a portfolio of 12 images published in December 1922 under the title "Les Champs Delicieux" (The Delicious Fields).
41. Lloyd Godman, *Photograms: Source & Resource*, http://www.lloydgodman.net/tech/tech/Photograms/photograms13b.html (accessed 6 Oct 2015).
42. "A black body (also blackbody) is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence," https://en.wikipedia.org/wiki/Black_body.
43. *The Heart of the Dragon*, television film, dir. Peter Montagnon, BBC, 1982-83, at 11:36-12:01 min, attributed these words to Lao Tze, the founder of Taoism, 2500 years ago: "give people a void to look at and simplicity to hold, ...in a picture the emptiness of the paper, the blank space is as important as the lines ... the image that is never painted but is implied is just as important as the one that is."
44. James Nayler (1616-60), quoted in *Quaker Faith & Practice*, 5th ed., ch. 21.65, http://qfp.quaker.org.uk/passage/21-65.
45. Patrick-Hughes, *James Turrell*. Turrell's work moves beyond art as object to art as an experience in perception—from something "seen" to "the act of seeing." Turrell exploits traits of perceptual psychology in his use of the ganzfeld effect, which occurs when the brain fills in the image where the senses provide insufficient information and amplifies and estimates the surrounding environment.
46. Zia Haider Rahman, *In the Light of What we Know* (New York: Farrar, Straus and Giroux, 2014), 206-7.
47. Philip Ball, *Invisible: The History of the Unseen from Plato to Particle Physics* (London: Vintage, 2014), 47.
48. Gregory L Naber, *The Geometry of Minkowski Spacetime: An Introduction to the Mathematics of the Special Theory of Relativity*, 2nd ed. (New York: Springer Science+Business Media, 2012).