Dynamic Visualisation in Three Physical Dimensions

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ABSTRACT
Recent developments in light emitting diode (LED) production technology mean that high numbers of LEDs can now be used at costs that are no longer prohibitive. This paper looks at various creative and artistic applications of three-dimensional grids of LEDs, when used to produce imagery and volumetric visualisations in three physical dimensions. We focus on two research projects by digital arts group Squidsoup that seek to take advantage of the affordances of such a system. Of particular interest is the additional possibilities granted by the third physical dimension: whether the fact that the visuals inhabit a virtual layer anchored within real space adds to the affective possibilities of digital visualisation systems. The two projects have been publicly exhibited and use an existing LED grid system, NOVA, developed by ETH Zurich.

General Terms
Documentation, Performance, Design, Experimentation, Human Factors.

Keywords
3D LED grid, volumetric visualisation, low resolution, immersion, affect, media art.

1. INTRODUCTION
Various media and modes of creative expression have characterized the art installation and its cultural sites of display. Artists have constantly taken up new technologies [1] and re-appropriated them to find new expressive and immersive potential [2]. Via the malleable quality of the digital, electronic artists have designed installations that tease out relations between the material and immaterial [3]. Digital technologies have been central in the move from the installation as a display to a space for participation [4]. This has been realized through the emerging field of 'new media' art [5,6]. Digitally mediated art installations may be said to be less concerned with the installation and its formal, material characteristics in the fine art gallery space and related discourses of display, and more ones for electronically mediated engagement and both situated and distributed participation [7]. Through our interaction with given mediated affordances, installations are realized as arenas of affective cultural expression [8,9]. This is apparent, for example, in the public digital installation works of Rafael Lozano-Hemmer [10]. In such works, art is mediated electronically, realized via participation, and channeled via our own embodied interaction and its related and relational affect [9]. In new media art installation environments, digital technologies are ubiquitous: they are involved in sketching and constructing, via programming and modes of delivery and enactment; and they constitute the materiality of the works in contexts of access and embodied activation. Digital media as materials are also present, to one degree or another, inside the works themselves, whether in mixed media forms, or in our relations to them as 'mixed reality' pieces where as participants we toggle between physical materiality and digitally mediated states and processes of engagement and realization in these sculptural modes of artistic expression.

One such digital media technology is the LED. Artists and technologists have re-appropriated this technology to open up possibilities for visualisation in three dimensions in physical space. Large numbers of individually controlled LEDs formed into a three dimensional lattice, or grid, can be used as volumetric pixels, or voxels, in physical space. These systems require no worn equipment, there are no moving parts or hazardous processes involved, and the 3D visualisations can be seen from any angle. The potential uses for this kind of technique are broad; from 3D object visualisation to stage lighting and entertainment systems (3D televisions and larger displays in public spaces), to fully immersive environments that further blur the boundaries between physical and digital reality. In terms of digital art, LEDs challenge us to consider the relations between the spatial and the sculptural as Rosalind Krauss noted earlier in her work 'Sculpture in an expanded field'. [11]. What is particularly beguiling is the potential to move into the installation space not only as a three dimensional room but to experiment with ways of extending the sculptural via three dimensional mediation through LED as a material and medium.

Several arts projects and systems have used 3D grids of LEDs to display dynamic visualisations in three physical dimensions, but to-date research on LED grids in art installations (or other applications) is scant. Writings tend to centre on technical properties and the development of the systems involved and works that exhibit the qualities of the grids of LEDs. The expressive and affective twists to which artists typically turn when working with digital technologies are at an early stage with regard to 3D spaces realized via LEDs.

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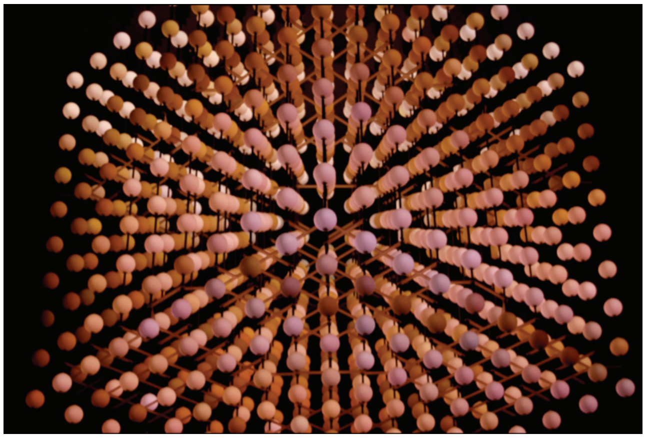


Figure 1. NOVA unit

From a practice-based digital arts research perspective, this paper analyses two recent works by digital arts group Squidsoup [12], based on the ETH Zurich/Horao GmbH built NOVA system [13]. These works are both concerned with the possibilities the technology affords for eliciting subjective meaning from embodied interaction combined with dynamic visual clues in three physical dimensions. The paper also discusses the strategies employed to respond to the low resolutions of such grids; how the spaces between the points have been used as leverages for affective engagement in the work.

2. BACKGROUND

The use of fixed points of multi-coloured light to simulate motion and image is not new. The television is a good example. The brain smooths over the gaps between the dots, actively creating (subjective) information where there is none. This is illustrated in *Church on 5th Avenue* (Jim Campbell, 2001), where Campbell reduces the information presented from video sources to a bare minimum of monochrome, low-resolution grids of light [14]. A frosted sheet of perspex is placed over the grid, at an angle, to alter the amount of blur the perspex introduces. The blur acts as a lens on the information displayed, in certain circumstances allowing the brain the freedom of high levels of illusory creativity.

Hansen [15] argues that similar processes are at play, but in the temporal dimension, in Douglas Gordon's *24 hour Psycho*. Gordon's dramatic slowing down of Hitchcock's thriller to the point where each frame is eagerly anticipated allows the viewer to actively explore and embellish the space between the frames, as well as what is on each frame. It also triggers a re-evaluation of time, and what is considered as *now*. Here, as Hansen says, we see an instance of 'new media art deploying technology in order to expand self-affection' through 'a technical enlargement of the now'. There are clear parallels between these two approaches: one focuses on the spatial gaps between finite points of information; the other on the temporal gaps between frames in a film. Both see this as a rich area for affect and subjective interpretation.

This idea of affect, along with subjective emotional content, being able to be leveraged from small amounts of carefully placed information, is an important aspect of the creative potential of many media. If this can be combined with the affordances of physical 3D, then the potential for affect, and evocative creative

Figure 2. Church on Fifth Avenue, Jim Campbell (2001)

output in general, seems pregnant with possibilities. There has been little critical evaluation or analysis of the potential of 3D LED grids beyond the technical [e.g. 16], yet there are several practical examples of projects that have explored three-dimensional grids of light. Possibly the best-known recent examples of such applications are UVA's *Volume* [17] (initially shown at the V&A, London, 2007) and the stage lighting shows devised by Andi Watson for the band Radiohead's 2008 world tour. The physical set-ups in both cases have high vertical resolution, but are very limited on the horizontal plane – in effect, both projects use the arrays as multiple interdependent columns of light. The attempt is to reference a dynamic horizontal surface that moves fluidly in the vertical direction, but the illusion is hard to experience because of the distance between columns, and the potential is limited by lack of horizontal movement. The focus on synchronised vertical columnar movement is further developed to beguiling effect in UVA's *Constellation* (2008) and *Array* (2008). These projects both attempt to surround the viewer, as they are designed to be viewed from within. Jason Bruges Studio's suspended *Pixel Cloud* [18] attempts more than vertical movement, using true volumetric algorithms as the basis for an abstract visualisation system that combines local and global weather patterns to create a 'perpetually evolving colour-space' [19].

Several 3D LED cube grids exist today. James Clar's 3D Display Cube [20], Seekway's 3D LED grid [21] and the ETH Zurich/horao GmbH built NOVA system [13] are the most prominent. Clar's and Seekway's cubes are both smaller objects into which 3D animations can be played and viewed. Both are designed specifically for the purpose of 3D visualisation, can be configured in various resolutions, but rely on predetermined patterns. This makes interactivity effectively impossible. The NOVA is also modular, but is larger, and was originally built specifically for visualizing 3D scientific data. Additionally, each point of light can be addressed individually and directly, enabling real-time interaction. A NOVA suspended from the ceiling at Zurich Central Station is at time of writing the largest volumetric display system in existence. It is this NOVA system that has been taken up in the two experimental works we cover below in which time, space and embodied interaction and affect are at play.

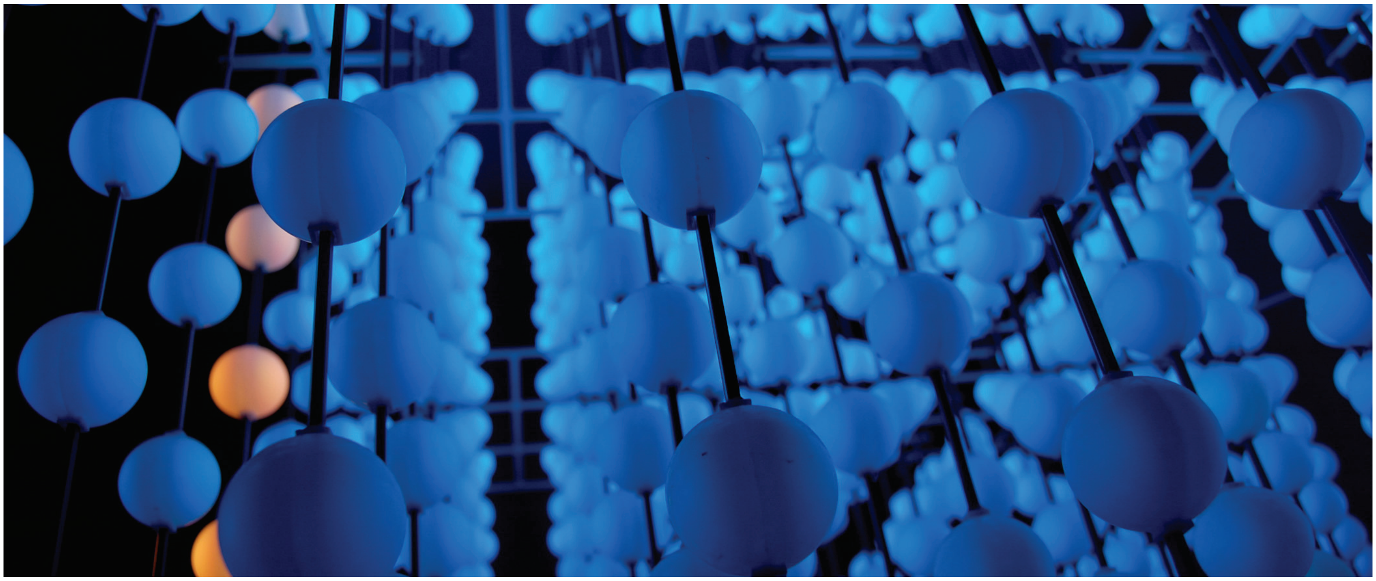


Figure 3. Raindrop animation on NOVA unit.

A single NOVA module is $1m^3$, consisting of a 10x10x10 grid of 4cm diameter balls, pitched 10 cm apart in a regular grid. Each ball houses 12 LEDs, capable of accurately reproducing 24 bit colour at 25Hz. These grids can be seamlessly connected – 25 are placed together at Zurich Central Station. NOVA has several advantages as the platform for these experiments. It is a well-built generic system designed for the purpose of producing real-time visualizations in three physical dimensions, whereas many of the examples above were built to fulfil the requirements of specific artistic or architectural projects. Its modularity means that relatively portable and flexible configurations can be used, and it works in real time.

Using an existing system means that we were not able to experiment with or alter the physical attributes of the system itself. However, this has enabled the work to focus more clearly on the main research areas: to explore and map out the additional affordances granted by being able to produce digitally generated visuals as a layer over physical space through practical experimentation. We seek to answer two research questions: in what ways can real-time dynamic visuals presented through a static grid of points of light and anchored in physical 3D space augment the creative and affective potential of computer generated output? And, what strategies can be developed to overcome the limitations, particularly on resolution available, from such systems?

3. INITIAL EXPLORATIONS

The NOVA unit used for initial tests was suspended from the ceiling, about 3m from the floor. A series of dynamic visual trials were created and tested in various lighting conditions, from different angles, and assessed subjectively. The tests fell into the following categories:

Randomness. Initial trials involved changing the colour of each LED randomly at 25fps. Then, one light was randomly illuminated each frame, and faded out over about 0.5 second.

Raindrops. Points of light were made to 'fall' in a predictable manner to create the illusion of movement. This was also used to test the relative effects of different approaches to anti-aliasing, blur and fades. The subtleties of how to compensate dynamically for the missing information between two points, as illustrated by Campbell's work, is an important factor in the overall impression created.

Simple 3D geometry. Various simple 3D forms were placed on the grid, and the illusive qualities were explored when various effects were applied – primarily movement (linear, rotation, expansion and contraction), blur/anti-aliasing, and whether or not the interior of the form is illuminated.

Surfaces. Sine waves moving across the volume and flat dynamically moving planes were applied to the grid, with contrasting colours on either side of the surface. The application of anti-aliasing to the surface was found to have a profound effect on its illusive qualities.

Reverse projection. These consisted of an exploration into the application of surface texture. Initial trials, applying textures onto a vertical plane, were of too low a resolution to be of much use, but interesting results were achieved by using a form of 'reverse projection'. From one perspective, all lights in the grid align to form a clear image (as if the grid were being projected onto), but the image is abstracted from all other viewpoints as the pixels are only aligned at one location.

Texture content. A range of texture types were used, from still imagery, through video to live webcam feeds. The effectiveness of this technique is determined to a large extent by the source material – the more animated or interactive the texture, the more recognisable are the results.

Trials were also conducted on the large NOVA system at Zurich Central Station. This is viewable from many angles, but not from close-up. The structure appears like a ghostly screen that fades away at the edges - very beautiful, but a distant spectacle, and with relatively limited depth (it is no thicker than the small unit).

The results of the initial trials led us to focus on the small NOVA. Low resolution is a factor to be considered, but its creative benefits were at least as apparent as its limitations. The level of abstraction required at very low resolutions really does allow viewers to 'fill in the gaps', and build their own visual interpretation of events.

4. TWO MAIN PROJECTS

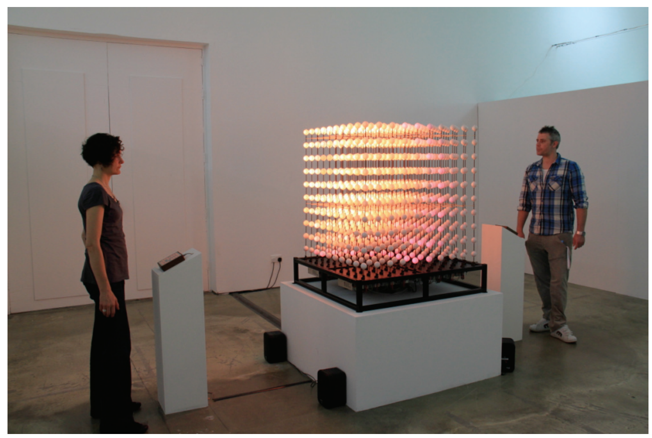
The areas with the most potential appeared to be dynamic control of simple geometric forms, and the reverse projection experiments. Two project ideas were developed – each focusing on one of the areas for further investigation. The projects sought to stretch the material affordances of the LED grid by creating experiences where participants became actively and affectively engaged in an immersive process while allowing them to create their own on-going interpretation of essentially highly abstract phenomena – 'filling in the gaps' between each 3D point on the grid.

4.1 The Stealth Project

The most immediately promising use of any 3D LED grid is to visualise the movement of small and very simple forms – single dots at its most primitive, but other dynamic forms are possible.

The Stealth Project [22] was built for *Late at the V&A*, in association with London's Victoria and Albert Museum's *Cold War Modern* exhibition. It was shown at the V&A in October 2008 and subsequently at ISEA (Belfast, 2009). It is a two-player game loosely based on the classic counter game, Connect Four. Two players sit or stand on opposite sides of the NOVA, which is at eye level. In front of each player is a square grid of buttons, each one a missile launch trigger. Pressing a button in the (2D) grid launches a missile of light across NOVA space, with starting position equivalent to the position of the button pressed. The missile continues its progress across the NOVA grid until it is detected by radar, hit by another incoming missile, or makes it across to the opposing side, grabbing that point. The aim is to get a line of four connecting points - then the inevitable result of nuclear warfare occurs. The winner is only winner for a fleeting instant before the entire NOVA space is engulfed in nuclear armageddon. Slowly expanding spheres of light, gradually increasing in intensity to a scorching pure white, burn through the grid. This sequence is particularly effective, not only for its dramatic effect, but because it builds on a clear link between these scale model burnout visuals and the all too familiar images of nuclear destruction.

The piece explores the materiality (or not) of the 3D grid. As Hansen [9, p213] argues, at the outset depth is 'a space without "original " analogical correlation in human activity.' It is through enactment of shared, imaginary 3D visualisations that pass through the grid that a space of activity is realized. Missiles are represented as small points of smoothly flowing light – compressed energy, present yet chimaeric, reflecting and reinforcing the overarching quality of this form of visualisation. The missiles have a presence, an ominous glow, as they fly inexorably across the NOVA sky. The NOVA grid becomes a scale model of airspace. Yet, simultaneously, the grid is an abstract representation, as the radar sweep (a classic rotating green line with trails) is superimposed onto the model in a parallel visualisation. Collisions between converging missiles result in spherical orange explosions appearing at the point of impact – a literal interpretation and again reverting to the notion of the NOVA grid as airspace. At either end vertical walls of the grid represent game boards and bombed urban spaces in twin twisted vertical cities.



Figures 4&5. Stealth at the V&A, London, October 2008
Figure 6. Stealth at ISEA, Belfast, August 2009

The Stealth Project superimposes various forms of 2D and 3D spatial representation into a single volume, and uses the materiality of light to represent and superimpose at least three phenomena (physical objects in physical space, explosions, diagrammatical information). The visuals are accompanied and enhanced by quadraphonic sound that reinforces the imagery, spatialisation and overall experience of the piece.

As the game uses physically anchored controllers both active participants are in relatively fixed positions, but non-participating viewers can see the visuals from anywhere in the room. Additionally, the participants themselves are rarely truly static, moving and tilting to see the grid from slightly different positions, both aiding in general 3D perception and to overcome the occlusion issues mentioned previously.

4.2 Discontinuum

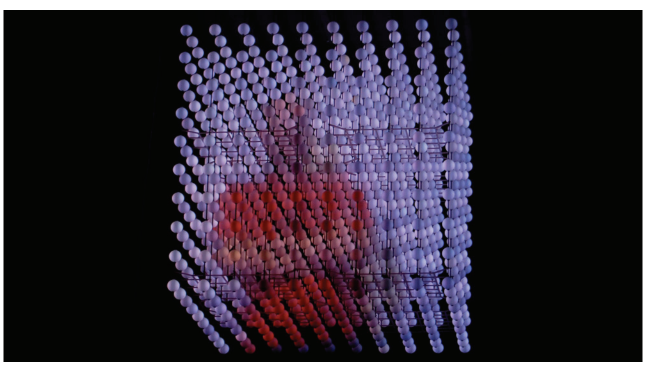
Discontinuum [23] uses 3-dimensional volumetric display techniques more abstractly, deploying the space to create a visually deconstructed 'secret' mirror. From all viewpoints except one, it appears to be a responsive but essentially abstract flow of data in the form of light - but from one particular position, the flows align to reveal the portrait of the viewer. As Hansen argues, this is '… a capacity of the body to experience its own intensity.'

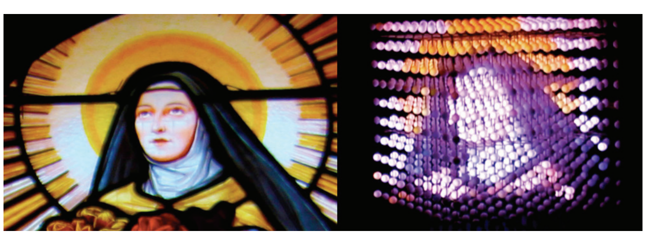
The piece uses the volumetric nature of the visualisation system to temporally deconstruct a video-camera stream in real time. An abstract take on the notion of the space-time continuum, *Discontinuum* extrudes live video imagery over time, visualising the flow (of time and movement) within NOVA's volumetric display.

Visuals are built so that from one particular viewpoint only, the imagery is in alignment and can begin to be deciphered. However, even from that perspective, the imagery is a compression of several seconds of video at once, which, if the subject is fast moving, still appears abstractedly as a blur. As the video imagery is in fact a live feed from a camera trained at a slowly moving sweetspot, a viewer standing at the right place - and standing still – will in fact see their own image coming in and out of alignment within the NOVA grid.

The video stream is applied onto the grid using a kind of reverse projection method where, from one viewpoint, all the points of light align, creating an image with up to 1,000 light points. This method also allows for higher resolution imagery than that afforded by the obvious flat planar application.

Discontinuum aims to exploit the ephemeral nature of the NOVA grid. It focuses on slowness, subtlety and a feeling of the piece slowly revealing its secrets. The low resolution nature of the imagery, the fact that the imagery only coalesces and makes sense at a single point, and that the temporal aspect of the piece means that in order to achieve clarity, the viewer must remain stationary, all add to this ephemerality. A certain ghostliness of the piece is achieved, as though the eye has to see through to another dimension to decode its owner's portrait.





Figures 7&8. Discontinuum – showing realtime webcam image and display comparison

The work was shown in a church at Bains Numériques (a digital arts festival in Enghien-les-Bains, Paris) during June 2009. The pace of the piece, and its chimaeric, contemplative nature resonated with the church location in which it was placed. The live camera feed was interwoven with still images taken from the stained glass windows of the church, the latter using slowly sweeping focal points so that the imagery would appear and disappear, from wherever the piece was viewed.

4.3 Findings

The effectiveness of such a project will of course be determined primarily by its artistic intent - its meaning, the quality of content and modes of interaction - and by the environment in which display occurs. The environment is particularly important in installation-based work, and even more so here as overall perception is determined by the overlap between physical and virtual - both occupy the same physical space. Another important design consideration is the performance, capabilities and attributes of the hardware used. NOVA has a strong impact; its physical design, resolution, frame-rate, colour, size and luminance all affect the overall experience.

Whatever the design characteristics of the hardware, there are two main properties of any 3D light grid based visualisation system that need to be taken into account when considering potential uses for such a system. Firstly, they are relatively low resolution – not only for technological reasons; occlusion problems increase with density. Secondly, they inhabit physical space, and so have at least some of the properties of physical objects.

The projects considered in this paper aimed to produce dynamic, responsive, meaningful, comprehensible, aesthetic and above all affective visualisations in three physical dimensions.

As a range of techniques were tried during the development of these projects, and some were more effective than others, it is possible to extract a few design principles and guidance from these projects that can be applied more generally.

4.3.1 Visualisation and content

Simplicity, at very low resolutions, is a necessity. Attempts at realism are likely to fail, and representing solid, static objects is difficult. Movement can be successfully suggested through a judicious use of timing, subject matter and, critically, anti-aliasing (both temporal and spatial, see below), as these help merge or connect the gaps between the points of light.

Discontinuum highlights the effectiveness of motion and video over still images when working at low resolutions, and the directness of the interaction created by the use of a webcam is surprisingly effective. *The Stealth Project* focuses more on abstracted semiotic forms of visualisation, often using symbols within a spatial context to impart messages.

4.3.2 Low resolution

Flat-on textures are undecipherable at 10x10 resolution - Campbell's work (and others) suggests that planar textures start to become comprehensible at resolutions of around 24x32 and above. Such very low resolutions suggest a revisiting of the issues faced by screen designers in the early days of computer graphics, but there are other considerations. NOVA can achieve 25 fps, and has a palette of 16 million colours, which allows for considerable subtleties to be enacted.

'Reverse projection', where all points of light are used to increase the resolution of the image displayed, but that image is only in alignment at one point, was shown to be effective in

Discontinuum. The increased resolution (in the case of a 10x10x10 grid, the resolution goes from 100 in a flat application of a texture to 1000 if all lights are used) then has a similar resolution to Campbell's screens, or even the traditional Microsoft Windows 32x32 icon – as with these examples imagery can be effective, but needs to be striking, high contrast, geometric and/or recognisable.

4.3.3 Use of anti-aliasing

A key element of the illusion of using disparate points of light to make the viewer see an image is to help the brain fill in the gaps between the points. Anti-aliasing is crucial at such low resolutions. Similarly, temporal anti-aliasing can be simply simulated using motion blur. Our experiments with anti-aliasing (spatial and temporal) showed that when optimised, a definite feeling of physical boundaries and presence generated entirely by the light visualisation can occur.

The degree to which the anti-aliasing needs to be applied has been subjective in this case, but it is clearly affected by the distance between each light source. Less obviously, it seems to be affected by the size of each source also. This is not only borne out by Campbell's using frosted perspex to blur his image grids but also the fact that the Squidsoup projects needed to exaggerate anti-aliasing (in effect blurring the data) to help viewers overcome the large gaps between each point of light.

4.3.4 Environmental factors and physical location

The arena in which 3D LED grid-based content is experienced has a strong influence on the overall experience. The main projects described here were designed to work with the environment in different ways; *Discontinuum* reflects, working with it, whereas *The Stealth Project* attempts to dominate or ignore it.

Ambient lighting has a strong effect on the visuals, particularly in visualizations where much of the grid is unlit. With low ambient light, strong intimations of depth and layering can be achieved, and viewers are less aware of the physicality of the hardware itself.

The relative position of the grid also affects the overall impression. A straight-on view (as is the case for participants in *The Stealth Project*, but not in *Discontinuum*) accentuates the grid-like structure, which can be a help or hindrance. In the case of *Stealth*, torpedoes move along the grid, so the effect is helpful, but the less geometrical imagery in *Discontinuum* is not aided by a prominent grid effect. Never-the-less, visual design needs to consider *all* possible viewing angles.

These works place the viewer at 1-4m from the display, allowing for a significant sense of depth. At 9m distant, and with a 'thickness' of 1m, the large NOVA at Zurich Central Station loses much of its effective depth. The ability for viewers to freely move around the grid, and see imagery from different viewpoints, helps significantly in their placing the imagery in three-dimensional space; it also reduces occlusion problems.

4.3.5 Reinforcement by other means

Whatever visual techniques and content are used, the understanding of abstract imagery, and the immersive qualities, and affect, of an experience can often be enhanced by additional sensory reinforcement. In the examples used here, the use of spatialised sound and tactile interaction in *The Stealth Project* undoubtedly add to its effectiveness and impact.

5. CONCLUSIONS

As technology develops, the resolution issues may become less of a factor or even disappear (if occlusion issues can be resolved), for systems viewed from outside. However, if one wants the possibility of perambulating physically within the visualisation grid, then with this technology at least there will still need to be sufficient space between the points of light to fit a person. Limitations in resolution may therefore not be merely technology-dependent.

Jim Campbell notes on his low resolution works that [24] '… there's something about the existence of these works right at the level of abstraction that keeps pulling you in, almost on a subliminal or subconscious level, to try to get more from them - even though you're not.' This kind of abstraction through dramatic reduction in resolution, and the potential to allow viewers to immerse themselves within such imagery and experiences, creating their own subjective content, also seems well suited to 3D visualisation systems of this kind. The effect seems to be enhanced by the 3D nature of the work, further drawing the viewer in as the visualisation takes on a form that includes depth and becomes a layer over the physical world. These visualisations thus occupy real physical space, like a physical object, or sculpture. This is fundamentally different to the traditional 2D screen that acts as a window into another, parallel, universe that occupies no physical space.

Discontinuum and *the Stealth Project* have both shown practically that there is much creative and affective potential in visualisations using three-dimensional grids of individually controllable lights. User feedback on both projects was informal but generally very positive; people were able to understand the visuals and their spatial properties, and found the experiences entertaining, memorable, challenging but also comprehensible. The ability to anchor dynamic virtual imagery in true physical space fundamentally alters the relationship between physical and virtual, and how we perceive that relationship. Despite the very low resolutions used in these projects, the visualisations inhabit physical space, and have many of the inherent characteristics of physical objects: they can be seen from any angle, have a defined size, shape and position; they have a presence, though generally a somewhat chimaeric one. The creative, and affective, possibilites opened up by such systems are only touched upon by these projects.

6. FURTHER WORK

The works covered here have been primarily conducted on ETH Zurich's NOVA hardware. This means that the physical attributes of the work are all treated as givens. This resulted in a focus exclusively on visualisation techniques. Parallel research into the physical design and attributes of the hardware has been touched upon by the hardware manufacturer's own research [16] though further research would be very useful. Experiments and projects are planned that will look at the physical attributes of the hardware and the light grids, using further devices and methods to affect the physical experience (e.g. fog, additional projection, mirrors).

Future plans include experimentation with the physical setup of 3D LED grid systems from a more sculptural perspective, together with an exploration of methods of creating visualisations that can be seen from *within*. The aim of this is to create dynamic visualisations that can be physically entered, rather than viewed from an external object-based perspective, and so allowing for truly immersive (yet abstract) visual experiences.

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8. REFERENCES

(websites accessed July 2009)

[1] Zielinski, S. 2006. Deep time of the media: towards an archaeology of hearing and seeing by technical means. Transl. Custance, G. The MIT Press, Cambridge, MA.

[2] Grau, O. 2003. Virtual Art. From Illusion to Immersion. The MIT Press, Cambridge, MA.

[3] De Oliveira, N. & Oxley, N. 2004 Installation art in the new millennium. Thames and Hudson, London.

[4] Penny, S. 2004. 'Representation, Enaction and the Ethics of Simulation'. In Wardrip-Fruin, N. & Harrigan, P. (Eds). First Person: New Media as Story, Performance, and Game. The MIT Press, Cambridge, MA. http://ace.uci.edu/penny/texts/ethicsofsimulation.html

[5] Rush, M. 2005. New Media in Art. Thames & Hudson, London.

[6] Paul. C. 2008. Digital Art. (2nd Edition). Thames & Hudson, London

[7] Coulter-Smith, G. 2006. Deconstructing Installation Art. CASIAD Publishing. Available: http://www.installationart.net/index.html

[8] Morrison, A. Sem, I. and Havnør, M. (in press) Behind the wallpaper: performativity in mixed reality arts. In Morrison, A. (ed.) *Inside multimodal composition*. Hampton Press, Cresskill NJ.

[9] Hansen, M. 2004. New Philosophy for New Media. The MIT Press, Cambridge, MA.

[10] Rafael Lozano-Hemmer: http://www.lozano-hemmer.com/english/projects.htm

[11] Krauss, R. 1979. 'Sculpture in the expanded field'. October, Vol.8. pp. 30-44

[12] Squidsoup: www.squidsoup.org

[13] NOVA, built by ETH Zurich. http://www.nova.ethz.ch/ and http://horao.biz/

[14] Jim Campbell, http://jimcampbell.tv/

[15] Hansen, M. 2004. The Time of Affect, or Bearing Witness to Life. Critical Inquiry, Spring 2004

[16] Schubiger-Banz, S. & Eberle, M. 2008. 'The NOVA display system'. In Transdisciplinary Digital Art. Sound, Vision and the New Screen. Springer, Berlin. Pp. 476-487.

[17] UVA – United Visual Artists. http://uva.co.uk

[18] Jason Bruges Studio http://www.jasonbruges.com

[19] Quoted from Dominic Harris, http://www.cinimodstudio.com/the-3d-chandelier-aka-pixel-cloud

[20] James Clar, 3D Display Cube http://www.jamesclar.com/piece/2008/3dcubev4/index.html

[21] Seekway, 3D LED Cube http://www.seekway.com.cn/e/ledsys10.htm

[22] The Stealth Project, Squidsoup, 2008 http://squidsoup.org/stealth/

[23] Discontinuum, Squidsoup, 2008-9 http://squidsoup.org

[24] iCI interview with Jim Campbell http://www.ici-exhibitions.org/media/artists_public/j_campbell.html