Determining the Relative Benefits of Pairing Virtual Reality Displays with Applications

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Abstract

Over the last century, virtual reality (VR) technologies (stereoscopic displays in particular) have repeatedly been advertised as the future of movies, television, and more recently, gaming and general HCI. However after each wave of commercial VR products, consumer interest in them has slowly faded away as the novelty of the experience wore off and its benefits were no longer perceived as enough to outweigh the cost and limitations. Academic research has shown that the amount of benefit a VR technology provides depends in the application it is used for and that, contrary to how these technologies are often marketed, there is currently no one-size-fits-all 3D technology. In this paper we present an evaluation framework designed to determine the quality of depth cues produced when using a 3D display technology with a specific application. We also present the results of using this framework to evaluate some common consumer VR technologies. Our framework works by evaluating the technical properties of both the display and application against a set of quality metrics. This framework can help identify the 3D display technology which provides the largest benefit for a desired application.

Keywords: virtual reality, evaluation framework, 3D displays, 3D applications.

1 Introduction

Virtual reality (VR) is the name given to the concept behind the group of technologies whose purpose is to realistically create the perception of virtual objects existing in the real world through manipulation of human senses without physical representations of the virtual objects. The virtual scene is typically either an interactive computer simulation or a recording of a physical scene. The degree to which the real world is replaced with the virtual one gives rise to a spectrum of alternative terms for VR (Milgram and Kishino 1994) illustrated in Figure **1**.

While virtual reality in general deals with manipulating all the human senses (sight, smell, touch etc.) the largest portion of research into VR is related to the visual and to a lesser extent auditory components. This paper focuses solely of assessing visual VR technologies and other aspects of VR are not discussed. Computer displays are the established method of producing the visual component of virtual reality with displays that are designed to achieve a high degree of virtual presence called “3D displays” or “virtual reality displays”. Virtual presence is the extent of belief that the image of the scene presented to the user exists in real space and is largely determined by the number and quality of depth cues a display is able to recreate.

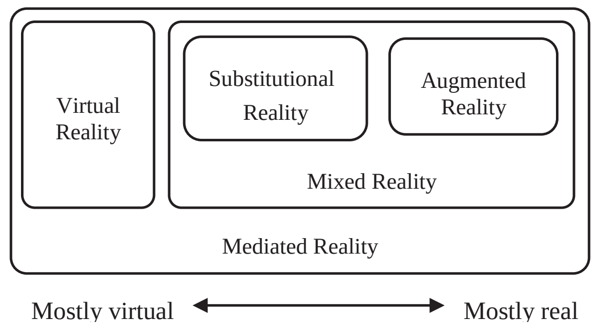

Figure 1: Spectrum of VR-related terms

Depth cues are the mechanisms by which the human brain determines the depths of objects based on the images received by each eye. These cues have been well known since the 18th century and are usually grouped as shown in Table 1.

Group	Depth Cue
Pictorial	Perspective Texture Shading Shadows Relative Motion Occlusion
Physiological	Accommodation Convergence
Parallax	Binocular Motion

Table 1: Groups of depth cues

Many common applications can be considered partial implementations of virtual reality despite rarely being considered as such. Any application that involves a user viewing or interacting with a 3D scene through a computer falls into this category, including examples as common as: 3D gaming, television and movies, computer aided design (CAD) and videotelephony. Despite the fact that these applications are typically not considered forms of virtual reality, they do still stand to gain better virtual presence through the use of more advanced VR/3D display technologies. Stereoscopic displays are one such technology that has seen limited success in these applications (Didyk 2011) but as of yet is the only technology to be widely used in this area.

This paper exists to help determine why stereoscopy is the only technology that has achieved widespread consumer adoption and to identify applications where alternative VR display technologies may be potentially better.

2 Related Work

Relatively little work has been previously done regarding the relative benefits of alternative display technologies for applications, especially considering the large amount of general VR research available. What has been done has typically fallen into one of the following categories:

- Enhancing specific display technologies for particular applications.
- Comparing and evaluating display technologies through user testing.
- Developing classification systems for grouping different display technologies.

A large part of the current literature relating to the relative benefits of different VR display technologies is incidental and a by-product of the larger field of developing and analysing these technologies in isolation. Most of this research involves user testing to validate a developed technology, usually with a comparison to a few control displays. Since different papers use different testing setups and tasks, it is difficult to compare a broad spectrum of display technologies using this data.

Fortunately there has been some dedicated discussion regarding the relative benefits of different display technologies for certain applications (Wen et al. 2006), the benefits of a single VR display technology over several applications (Litwiller and LaViola 2011), and also measurements of how well these VR technologies compare to actual reality (Treadgold et al. 2001). While this still falls short of giving a complete picture, it does provide validation that such an overview would be useful. The results from these papers and others confirm that users' performance and satisfaction when interacting with the virtual scene generally improves with more sophisticated display technologies that are able to achieve a higher degree of virtual presence. Another common theme with this area is that results vary significantly depending on the exact task performed (Grossman and Balakrishnan 2006). These two points provide motivation for developing a system to predict how beneficial individual display technologies will be for specific applications.

Examples of typical classifications methods are those described by Blundell (2012) and Pimenta and Santos (2012). Blundell describes a classification system where specific display implementations are grouped according to the types of depth cues they support and the need to wear decoding glasses. The differentiating cues were determined to be binocular parallax, parallax from observer dynamics (POD) and natural accommodation & convergence (A/C). Three major display groups are formed by the level of support for binocular parallax: monocular for no parallax, stereoscopic for parallax with glasses and autostereoscopic for parallax without glasses. Monocular and stereoscopic displays are then broken down further according to their support for POD resulting in tracked and untracked variants of each. Autostereoscopic displays are however differentiated by both POD and natural A/C where so called "class I" displays only support discrete POD without natural A/C, while "class II" displays fully support both.

Pimenta and Santos (2012) use a different method for classifying VR display technologies yet end up with similar final groups. Their approach groups displays according to two criteria: the number of views supported and the depth of the display. The number of views refers to how many different images with correct parallax the display can show simultaneously with groups for two, more than two and infinite views (duoscopic, multiscopic and omniscopic). Conventional displays with only one view are not encompassed by their taxonomy, but it is trivial to extend it to include them by adding a monoscopic group. The second criteria regards whether the perceived location of an image is the same as where it is emitted from. Displays which produce an apparent 3D image using a 2D surface are considered "flat" while displays that produce 3D images using a 3D volume are considered "deep". This system results in five groups, two of which can be mapped exactly to those described by Blundell (stereoscopic and autostereoscopic class I) while the other three (multi-directional, virtual volume and volumetric) can be considered subgroups of autostereoscopic class II displays.

Despite this collective effort of investigating specific display technologies and classifying them, we are unaware of any attempt to determine which applications these groups of displays are particularly suited for. This is surprising since various results indicate (Grossman and Balakrishnan 2006) and some authors acknowledge (Blundell 2012) that as of yet there is no one-size-fits-all display technology. This leaves a gap in the literature regarding a systematic way of determining how well-suited a specific VR display technology is for a specific application. Hence this paper attempts to fill this gap by describing an evaluation framework through which the relative merits of different display technologies can be compared to the unique requirements of individual applications. This will hopefully simplify in the future the identification of applications areas which could benefit from the use of non-traditional display technologies.

3 Evaluation Framework

Our paper's contribution to this problem is an evaluation framework with the role of determining how well suited each available display technology is for specific applications. In order to produce what we would judge a useful framework, the following properties were considered important:

- Effective: It would identify applications where using non-traditional display technologies could improve the user's experience and task performance. It would also identify applications where the de facto 3D display technology may not actually be the best choice.

- Lightweight: It should only require easily obtainable technical information about the applications and display technologies of interest, thus making it easier to apply than performing user testing.
- Generic: It should not require information specific to each combination of application and display technology, but rather each of these independently.
- Extensible: It should be easy to extend to include additional applications, display technologies and measurement criteria.

The framework we developed examines the suitability of each pairing between a display technology and application independently to meet the goals of being generic and extensible. Suitability is defined as the quality of the depth cues produced by a specific pairing and other non-depth-based factors as a way to predict the quality of the user experience without needing to take into account subjective factors. As the perceived quality of a depth cue is normally determined by several factors, the quality of a depth cue is measured by a set of quality metrics specific to that cue. Other factors are also measured by quality metrics of the same form. Through this approach, the output of our framework for a single pairing is a vector of quality values representing the suitability of the pairing (where each quality value has been produced by a single quality metric).

As each pairing is considered independently, given a list of display technologies and applications, every possible pairing combination of them can be evaluated using this framework to generate a table of how suitable each pair is. The relative merits of two or more pairings can then be seen and contrasted by comparing the quality values of their rows in the table.

To automate the completion of this task, the evaluation framework was implemented as a short (~150 SLOC not including display, application and metric definitions) Python program that took a list of displays and applications, generated all the possible pairings, ran a supplied list of quality metrics against the pairings and outputted the results as a CSV file.

The evaluation of a pairing consists of several inputs: a display technology, an application, and a set of quality metrics. What constitutes these inputs are described in the following sections with examples listed in Appendix A.

3.1 Display Technology

In the context of our framework, a display technology refers to the mechanism a display uses to present its image to the user. Since the exact mechanisms in real-world displays vary in many details which are insignificant to us, display technologies are generalised cases allowing these differences to be ignored. It should be noted that according to this definition a display technology is not tied to the display itself, signifying that display technologies are interchangeable. This is important as the goal of this framework is to evaluate how certain user experience metrics vary when only the display technology is changed.

Individual display technologies are characterised by a set of abstract and physical properties describing the technology. What exactly these properties are is determined by what the quality metrics require in order to be computed. Examples of display properties are the produced image space, image resolution and the number of independent images shown at any single point in time.

Even with grouping many display technologies often have near-identical properties, e.g. polarised stereoscopic displays and time-interlaced stereoscopic displays. This makes it natural to organise several related display technologies as a tree structure where child nodes inherit common property values from a generalised parent. Such groupings turn out to be similar to previous classifications, including that produced by Blundell (2012) found in Table 1 of his paper. Since we were mostly interested in practical applications, and considering that parent nodes tend to represent non-existent technologies (e.g. “pure stereoscopic” displays do not exist), we only considered leaf nodes in our evaluations. Regardless of how display technologies are organised, it becomes inconsequential later as they are evaluated independently leaving such grouping useful only for organising input data.

3.2 Application

An application is any common scenario in which some display technology is used to present 3D content. An example application might then be watching a movie at home on a TV set. The technology being used for the display (the TV set in our example) is not considered part of the application as it is one of the independent variables in the evaluation.

Applications could be further generalised as a combination of a task the user is performing on the display and the context in which this is performed. In the previous example the task would be “watching a movie” while the context is “at home on a TV set”. This split arises from the fact that the same task or context may appear in many applications, e.g. a movie can be watched in a theatre, on TV, on a mobile device or on a plane, across which it is likely that requirements for a high quality user experience will change. Our framework however, was designed to ignore this detail and instead consider applications as indivisible. This was because we did not expect that accommodating for varying the task and context independently would benefit enough to outweigh the added complexity. Instead, different applications are simply created every time a recurring task or context occurs.

Like display technologies, applications have a common set of properties determined by the quality metrics used, the values of which differ between individual applications. Examples of application properties required by our metrics are typical viewing distance, number of simultaneous users and the amount of user movement relative to the display.

3.3 Quality Metrics

Quality metrics describe how well the pairing produces different aspects of the user’s experience. While these are mostly aimed towards the produced depth cues, they do not need to be, and can measure some other aspect that is affected by the choice of display technology. Examples of metrics are: the disparity between accommodation and convergence, the brightness of the display, the range of motion the user can experience motion parallax over, the weight of headgear needed or the monetary cost of implementing the system.

To enable automated evaluation of these metrics, they are implemented as functions which take the display technology and application as arguments and return a numerical value representing the quality of that pairing according to the metric.

A distinction can be made between quality metrics that are essential for a depth cue to be correctly perceived and those that merely affect the accuracy or quality of the cue. We refer to these as hard and soft metrics respectively.

3.3.1 Soft Metrics

Soft quality metrics are the main component of interest for this framework. Each soft metric represents a single factor that influences how well a user perceives a specific depth cue and is represented by a single numerical value. How the metric produces these values is entirely dependent on the metric in question but is always based solely on the properties of the display technology and application it takes as inputs. There is no common process or calculations between soft metrics and the values they output can be to any scale as metrics are not intended to be compared between. This also allows soft metrics to be created completely independently simplifying the process of defining and creating them. Values produced by a soft metric are however required to be consistent within that metric allowing them to be numerically compared between different display/application pairs to determine which pair better delivers that aspect of the depth cue. By creating a vector of all the soft metrics relating to a particular depth cue, the quality of the entire depth cue can compared between pairings using ordinary vector inequalities partially avoiding the need to compare metrics individually.

What follows is a short description of our "accommodation/convergence (A/C) breakdown" soft metric, discussed as an example of how soft metrics are defined and how a well-known quality factor of VR displays is handled by our framework. A/C breakdown occurs where the accommodation produced by a display does not match the convergence and is thought to be one of the major causes of asthenopia (eye strain) in stereoscopic displays (Blundell 2012). Such displays are said to have an apparent image space, while displays that correctly produce accommodation and convergence have a physical or virtual image space. Since the sensitivity of both these cues is inversely proportional to distance, the further the display is from the viewer the less of an issue A/C breakdown is. To model this our quality metric M_{bd} follows the equation:

$$M_{bd}(A, D) = \begin{cases} \infty & if\ space_D = 'physical' \\ \infty & if\ space_D = 'virtual' \\ distance_A & if\ space_D = 'apparent' \end{cases}$$

Where A and D are the application and display respectively, $distance_A$ is the viewer distance property of the application and $space_D$ is the image space property of the display.

3.3.2 Hard Metrics / Requirements

Hard metrics are those that determine if a display technology is capable of producing a specific depth cue for all the users of the application in the pairing. Unlike soft metrics, hard metrics do not reflect the quality of the depth cue itself and so are not included in the output of the evaluation. Instead they are used as a check to skip over any soft metrics that would otherwise represent the quality of a cue that is in fact not present. If a hard metric does not pass a specific threshold all the soft metrics dependent on it are given a value indicating they are not present (this value is different to what they would have if they were merely of poor quality).

Examples of requirements for depth cues are: to achieve binocular parallax the display must present at least 2 independent images to the user's eyes, to achieve motion parallax the display must present a different image according to their eye location, and so on.

As with soft metrics a hard metric does not need to pertain to a depth cue. If it does not, it indicates whether the pairing is possible according to some other logical requirement, e.g. the number of simultaneous users supported by the display technology must be greater than or equal to the typical number of users of the application.

4 Results

To test the effectiveness of the framework we performed an evaluation with a set of 12 general display technologies and 10 consumer oriented applications. As with the selected applications, the included display types were mostly sub $1000 NZD consumer-grade technologies with a few specialised and theoretical technologies added for the sake of comparison. 20 soft quality metrics were used to judge the pairings with restriction by 5 hard metrics. Lists of these can be found in Appendix A. For the sake of brevity we have excluded the values of display technology and application properties, as well as the inner formulae for each metric. 34 pairings of the original 120 were eliminated by the hard metrics leaving 86 suitable pairings.

A portion of the raw results table can be found in Appendix B with the values of each metric normalised so that higher values are always desirable over lower values. In this way a value of positive infinity indicates that a quality metric is flawless in that pairing, although finite values can also indicate a perfectly met metric depending on what might be considered perfect for that metric. Values are also colour coded with white being bad, green being good and grey indicating a failed hard metric for that depth cue. Since the scale of the quality metrics is arbitrary and varies between metrics, individual values are not meaningful by themselves but are useful for comparisons between pairings.

5 Discussion

5.1 Findings

Among the interesting pairings identified, one potentially worthwhile area of investigation is head-coupled perspective on mobile devices. Our evaluation showed it to perform better among the general metrics than the stereoscopy-based alternatives. This is interesting because several mobile devices have already been released with parallax-barrier autostereoscopic displays suggesting that mobile devices with head-coupled perspective should be a feasible option.

A to-be-expected result was that fish-tank VR ranks consistently high for the entire range of desktop applications. This makes sense as it ranks high in both binocular and motion parallax metrics while other display technologies only rank highly in one of them. Fish-tank VR does not rank well in other applications however as its single user requirement usually causes it to be eliminated by the "number of viewers" hard metric.

5.2 Validity

As a method of predicting the suitability of real-world pairings, it was important to validate our framework so that the results it produces can be considered reliable and applicable to the pairings when they are physically implemented.

With respect to the structure of the framework itself, the principal condition of it being valid is that the quality of a user's experience in interacting with a 3D display technology can be measured at least partially by properties of the display technology, the task being performed and the context in which this happens. This is not an unreasonable claim as virtually all previous research in 3D display technologies shows measurable differences in user experience based on what technology is being used and what task the user is asked to perform (Wen et al. 2006, Litwiller and LaViola 2011, Grossman and Balakrishnan 2006). From this we can conclude that the general premise of the framework is valid.

The other area in which validity must be questioned is with regard to the quality metrics themselves. One point that must be considered is that the quality metrics chosen for evaluation must measure factors that have some noticeable effect on the quality of the user experience. This effect can be noticed either consciously or subconsciously. Factors that are consciously noticeable are simple to validate by asking users whether it is something that affects their experience. Subconscious factors are slightly more difficult to validate as users may only notice the effect of them, not the factors themselves. Fortunately quality factors in virtual reality is a well-researched area making validating subconscious quality factors an exercise in reviewing the literature (e.g. the A/C breakdown cue discussed in section 3.3.1). Since user experience is subjective by definition it must be ensured that a reasonable sample of people is used to validate quality metrics to ensure they remain representative of the population of interest.

5.3 Limitations

While the developed framework does achieve its goal of providing a lightweight method to uniformly compare 3D display technologies within the context of the applications in which they are used, certain aspects of the design cause some problems to arise when analysing the results. Most of these limitations arose from a balancing issue where increasing the simplicity of the framework counters how sophisticated the performed evaluation is.

The main area our framework falls short is in providing an intelligent reduction of the raw results. Instead it requires manual inspection to identify pairings of interest. Since the number of results generated by the framework grows quadratically with the number of displays and applications, this inspection can become labour-intensive when more than a few of these are evaluated at once.

A smaller issue found with our method was the need for single values for application and display properties. This can become an issue when realistic estimates of the value are near the threshold of a hard metric. A display/application pairing may be unnecessarily rejected because of this depending on which side of the threshold the chosen value lies. An example of this happening with our data is the rejection of the pairing of console gaming with head-coupled perspective. Since our chosen value of the typical number of users for this application was greater than the single user supported by HCP this pairing was rejected even though console games are also frequently played by a single person.

Another problem is the use of ordinal scales for quality metrics. While this makes them easy to implement, it also makes anything other than better/worse comparisons impossible without understanding the range of values produced by the metric of interest. This undermines the simplicity of the framework and the validity of its conclusions, as even if one pairing is determined to be better than another, how much better it is cannot be easily quantified.

Not having a common scale between different quality metrics also hinders comparisons between them. Being able to do this would be useful as it would allow better comparisons of pairings where both pairs have some metrics than the other pair. Such scenarios are very common with real display technologies which have many trade-offs, and only theoretical technologies are generally able to be better in every way than others.

The final major limitation is not specifically with our implemented framework, but with its design goals. Our framework is intentionally designed to only consider the technical aspects of using a 3D display technology and not so much the subjective aspects. An important subjective aspect relevant to our framework is how much each of the quality metrics actually affect the quality of the user's experience. The reason we decided to ignore this aspect comes mostly down to the amount of effort it would take to collect the required data. Since the extent to which a quality metric affects the user experience depends on the application, user testing would need to be performed for every combination of application and quality metric to determine the magnitude of this effect. This would likely cause performing an evaluation using our framework to take more effort than ordinary user testing which would defeat its purpose of being quick and lightweight.

6 Future Work

The major area for improvement with our system is to solve the problem of reducing the raw results to something more manageable and easy to analyse. An unintegrated solution would be to find another suitable evaluation method which could then further analyse the results of our framework. Alternatively this would also partially emerge from overcoming the other limitations that complicate comparing the quality of different pairings.

One of the simplest changes that could be made to improve our framework would be to require soft quality metrics to conform to a common scale. This could be continuous (e.g. 0 to 10) or discrete (e.g. unacceptable, poor, average, good, perfect). This would make the values returned from quality metrics much more meaningful and would partially facilitate comparisons between metrics. That is, several good or perfect metrics might be able to compensate for a poor one regardless of what the metrics are.

A further refinement of fixed scales would be to facilitate calculating weighted sums of all the quality metrics of a depth cue, and/or the entire set of quality metrics. This would again reduce the complexity of analysing the results as pairings could be compared at a higher level than individual quality metrics. The trade-off for this change would be the increased effort in finding the weights for each quality metric. As mentioned in the limitations section, accurate application-specific weights would necessitate user testing. However approximated general weights might also be accurate enough for this addition to be beneficial.

Other future work would be to avoid the previously discussed issue of needing ranges of values for application properties. A trivial solution to avoid this is splitting applications into more specific scenarios. A downside to this is that it would further exacerbate the issue of producing too much output data. A more targeted solution would be to allow a range of values for properties and have the hard metrics tests be a tri-state (pass, fail or partial pass) instead of boolean (pass or fail).

With regards to improving validity, accurately identifying what quality metrics truly affect the experience of using 3D display technologies would give added weight to the results produced by this framework. Such metrics are likely universal and would therefore be useful for other virtual reality research and not just this framework.

7 Conclusions

We have developed a lightweight framework designed to evaluate the suitability of using 3D display technologies with different applications as an alternative to user testing. The evaluation tests suitability according to a list of quality metrics that represent factors affecting the quality of the user's experience. We successfully performed an evaluation on several consumer-oriented display technologies and applications and identified pairings of future research interest. Our framework is mostly held back by the difficulty of efficiently interpreting the results it generates.

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9 Appendix A

9.1 Display Technologies

- Swept volume
- Sparse integral multiview (one view per user)
- Dense integral multiview (many views per user)
- Light-field (hypothetical display capable of producing at least a 4D light field)
- Head-coupled perspective
- Fish-tank VR
- Head-mounted display
- Tracked head-mounted display
- Anaglyph stereoscopy
- Line-interlace polarised stereoscopy
- Temporally-interlaced stereoscopy
- Parallax-barrier autostereoscopy

9.2 Applications

- Cinema
- Home theatre
- TV console gaming
- TV console motion gaming
- Mobile gaming
- Mobile videotelephony
- Information kiosk
- Desktop gaming

- Desktop computer-aided-design (CAD)
- Desktop videotelephony

9.3 Requirements

- Number of viewers
- Display portability
- Variable binocular parallax produced
- Variable convergence produced
- Variable motion parallax produced

9.4 Quality Metrics

9.4.1 General

- System cost
- Cost of users
- Rendering computation cost
- More views rendered than seen
- Scene depth accuracy
- Headgear needed

9.4.2 Pictorial

- Spatial resolution
- Temporal resolution/refresh rate
- Relative brightness
- Colour distortion
- Objects can occlude

9.4.3 Motion Parallax

- Parallax unique to each user
- Amount of induced parallax
- Degrees-of-freedom/number of axis supported
- Latency
- Continuous or discrete

9.4.4 Binocular Parallax

- Amount of wobble
- Stereo inversion

9.4.5 Accommodation

- A/C breakdown

9.4.6 Convergence

No metrics for convergence, assumed constant quality if present.

10 Appendix B

		Accomodation	Binocular Parall		Convergence	General						Motion Parallax					Pictorial				
Application	Enhancement	A/C breakdown	Non-invertable	Wobble	Present	Depth accuracy	Headgear	Render cost	System cost	Users cost	Wasted views	Continuous	Latency	Magnitude	Number of axis	Per-user	Brightness	Colour distortion	Occlusion	Refresh rate	Resolution
Cinema	Anaglyph Stereoscopy	1	1	10	1	0.75	4	5	∞	0.01	1						0.25	0.5	1	1	1
Console Gaming	Anaglyph Stereoscopy	0.5	1	4	1	1	4	0.5	∞	0.2	1						0.25	0.5	1	1	1
Desktop PC CAD	Anaglyph Stereoscopy	0.5	1	2	1	1	4	1	∞	1	1						0.25	0.5	1	1	1
Desktop PC Gaming	Anaglyph Stereoscopy	0.5	1	2	1	1	4	0.5	∞	1	1						0.25	0.5	1	1	1
Desktop Videotelephony	Anaglyph Stereoscopy	0.5	1	2	1	0.5	4	5	∞	1	1						0.25	0.5	1	1	1
Home Theatre	Anaglyph Stereoscopy	0.5	1	4	1	0.75	4	5	∞	0.1	1						0.25	0.5	1	1	1
Information Kiosk	Anaglyph Stereoscopy	0.5	1	1	1	1	4	1	∞	0.2	1						0.25	0.5	1	1	1
Motion Console Gaming	Anaglyph Stereoscopy	0.5	1	1	1	1	4	0.5	∞	0.2	1						0.25	0.5	1	1	1
Cinema	Dense Integral Multiview	1	0	1000	1	0.75	∞	0.1	0.5	∞	1	0.5	∞	0.1	1	0	1	1	1	1	1
Console Gaming	Dense Integral Multiview	0.5	0	400	1	1	∞	0.01	0.5	∞	0.1	0.5	∞	0.25	1	1	1	1	1	1	1
Desktop PC CAD	Dense Integral Multiview	0.5	0	200	1	1	∞	0.02	0.5	∞	0.02	0.5	∞	0.5	1	1	1	1	1	1	1
Desktop PC Gaming	Dense Integral Multiview	0.5	0	200	1	1	∞	0.01	0.5	∞	0.02	0.5	∞	0.5	1	1	1	1	1	1	1
Desktop Videotelephony	Dense Integral Multiview	0.5	0	200	1	0.5	∞	0.1	0.5	∞	0.02	0.5	∞	0.5	1	1	1	1	1	1	1
Home Theatre	Dense Integral Multiview	0.5	0	400	1	0.75	∞	0.1	0.5	∞	0.2	0.5	∞	0.25	1	1	1	1	1	1	1
Information Kiosk	Dense Integral Multiview	0.5	0	100	1	1	∞	0.02	0.5	∞	0.1	0.5	∞	1	1	1	1	1	1	1	1
Mobile Gaming	Dense Integral Multiview	0.25	0	100	1	1	∞	0.01	0.5	∞	0.02	0.5	∞	1	1	1	1	1	1	1	1
Mobile Videotelephony	Dense Integral Multiview	0.25	0	100	1	0.5	∞	0.1	0.5	∞	0.02	0.5	∞	1	1	1	1	1	1	1	1
Motion Console Gaming	Dense Integral Multiview	0.5	0	100	1	1	∞	0.01	0.5	∞	0.1	0.5	∞	1	1	1	1	1	1	1	1
Desktop PC CAD	Fish-tank VR	0.5	1	8	1	1	2	1	4	0.02	1	1	4	0.5	3	1	1	1	1	1	1
Desktop PC Gaming	Fish-tank VR	0.5	1	8	1	1	2	0.5	4	0.02	1	1	4	0.5	3	1	1	1	1	1	1
Desktop Videotelephony	Fish-tank VR	0.5	1	8	1	0.5	2	5	4	0.02	1	1	4	0.5	3	1	1	1	1	1	1
Desktop PC CAD	Head-coupled Perspective	∞				1	∞	2	∞	∞	1	1	4	0.5	3	1	1	1	1	1	1
Desktop PC Gaming	Head-coupled Perspective	∞				1	∞	1	∞	∞	1	1	4	0.5	3	1	1	1	1	1	1
Desktop Videotelephony	Head-coupled Perspective	∞				0.5	∞	10	∞	∞	1	1	4	0.5	3	1	1	1	1	1	1
Mobile Gaming	Head-coupled Perspective	∞				1	∞	1	∞	∞	1	1	4	1	3	1	1	1	1	1	1
Mobile Videotelephony	Head-coupled Perspective	∞				0.5	∞	10	∞	∞	1	1	4	1	3	1	1	1	1	1	1
Desktop PC CAD	Head-mounted Display	0.5	1	2	1	1	1	1	∞	0.005	1						1	1	1	1	1
Desktop PC Gaming	Head-mounted Display	0.5	1	2	1	1	1	0.5	∞	0.005	1						1	1	1	1	1
Desktop Videotelephony	Head-mounted Display	0.5	1	2	1	0.5	1	5	∞	0.005	1						1	1	1	1	1
Cinema	Light Field	1	1	∞	1	0.75	∞	0	0.5	∞	0	1	∞	0.1	3	1	1	1	1	1	1
Console Gaming	Light Field	0.5	1	∞	1	1	∞	0	0.5	∞	0	1	∞	0.25	3	1	1	1	1	1	1