Development of a visual impairment simulator using the Microsoft XNA Framework

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ABSTRACT
This paper describes the development of a visual impairment simulator based upon a virtual environment developed using Microsoft's XNA framework and High Level Shader Language. Shaders were developed to simulate the effects of cataracts, macular degeneration, glaucoma, myopia and hyperopia. These were then used to impair the real time display of an explorable 3D virtual environment. The simulator was evaluated by a qualified optician and trialled with a group of students. The paper concludes that further development is required to fully and accurately represent the impairments, however the simulator remains effective in improving participants level of understanding of visual impairments.

1. INTRODUCTION
There are around 2 million people in the UK who have a significant visual impairment. Due to a lack of familiarity with the symptoms and a lack of awareness of the dangers an additional 1.9 million people with diabetes and 250,000 people with early-stage glaucoma also have a high risk of needlessly losing their sight. Furthermore, understanding how visually impaired people see the world is also extremely useful for people who need to assist them, or those who design the environments around which they are expected to move. Finding effective methods to increase awareness of the symptoms of eye diseases and to demonstrate the difficulties faced by visually impaired people is therefore an important and challenging task.

Historically the simulation of visual impairments has mostly been achieved through the use of 'artist impressions'. Photographs which have been modified to recreate an impression of visual impairments remain widely used as the standard training tool for medical professionals. More recent approaches have utilised physical interventions to modify vision, for example Fine and Rubin's (1999) use of frosted acetate to simulate the effect of cataracts. This method has been extended to a range of visual impairments utilising customised lenses. These can be seen in SimSpecs, a set of special glasses designed to represent a variety of impairments (Aballea & Tsuchiya 2006). SimSpecs offer many significant benefits, they are simple to utilise and cheap to implement. Unfortunately there is an inherent danger associated with moving around a physical space with impaired vision, limiting the range of activities which can be attempted while wearing the spectacles.

Computer technology has been employed to create simulations of impaired vision. Software tools have been developed which enable designers to view 2D images modified according to the degree and nature of an individuals colour deficiency (Walraven & Alferdinck 1997), as well as simulating the effects of myopia, macular degeneration, cataract, glaucoma and retinopathy (Hogervorst & van Damme 2006), (Goodman-Deane et al 2007), (Banks & McCrindle 2008).

There have been several notable attempts to simulate visual impairments within the context of a VR virtual environment. Jin et al. (2005) developed an immersive virtual tour of an apartment. This desktop application simulated age-related macular degeneration, glaucoma, protanopia and diabetic retinopathy. The simulator was “designed for patient education, health care practitioner training, and eye care specialist education”. Maxhall et al. (2004) developed a simulator, again based upon an apartment which was designed to emulate visual anomalies which may occur following a stroke. The visual representation of these anomalies included motion blur, camera movement (to simulate dizziness & nausea) and hiding objects on the left and side of the view (to simulate unilateral neglect). The apartment was viewed through a head mounted display; movement was via an adapted wheelchair and interaction facilitated through pinch gloves.
Despite having a graphical fidelity which was far removed from what many would regard as 'realistic', and offering only a limited scope for the user to truly explore or interact with the environment these studies highlighted the potential of this kind of simulation. Jin et al. (2005) concluded that the application developed can “...be used for the education of patients and the training of ophthalmologists”. It continues to say that experiencing a first-person view of visual impairments “...can be used to teach medical professionals to recognise the kinds of problems that their patients may be experiencing”. Maxhall et al. (2004) found that their simulator was “useful for training caregiver’s empathy for stroke patients, possibly creating an increased understanding for stroke patients daily problems”.

Previous work by the lead author (Lewis et al. 2011) developed a simulator by implementing a game mod based on the Unreal Tournament 3 (Epic 2007) game. Visual impairments were applied to a virtual environment of a refectory using the graphics post processing chain available within the game editor. In this implementation the impairments are more representative than realistic. There is no simple way of modifying them on the fly to be able to represent a range of impairments and the authors do not consider the representation of the impairments to be an accurate simulation of impaired vision. Despite this the results of testing were very encouraging. Opticians who reviewed the software rated the effect as highly realistic, a visual impairment awareness advisor confirmed the utility of the application as an educational tool, and effectiveness testing appears to show a substantial increase in the test subjects level of awareness of visual impairment. This was surprising, considering the short period of time that the test subjects utilised the simulator, and the limited accuracy of the impairments themselves.

2. OBJECTIVES

The aim was to develop a simulation tool suitable for use in situations where an accurate representation of an individual’s vision might be necessary. This might be as an educational tool in an optometric, ophthalmologic or nursing training to highlight the range of impaired vision that a particular problem can cause, or, for example as a better method for an optometrist to explain a child’s visual impairment to family members. It was hoped that a configurable simulation would offer flexibility in representing the range, as well as the the nature of visual impairments and enable them to be more effectively understood and accounted for. In this context the authors were also interested in whether the substantial increase in reported understanding, noted by Lewis et al. (2011), would be replicated.

To achieve this required a programmable rendering system. High Level Shader Language (HLSL) is a proprietary language developed by Microsoft which operates in conjunction with the Direct3D API. It offers a great deal of flexibility in this context, able to leverage the full capabilities of modern graphics cards and allowing access to the full range of visual effects seen in AAA computer games. Additionally using HLSL enables the same shader algorithms to be utilised in a wide range of development and simulation environments. Specifically in this case the development also sought to establish whether the Microsoft XNA framework was a suitable development platform for a simulation of this type, what drawbacks using this framework may impose, and investigate the limitations of rendering computationally expensive shader algorithms in real time on standard PC hardware.

3. DEVELOPMENT METHODS

A visual impairment simulator, based upon an office environment was created using the Microsoft XNA framework and Blender for modelling and 3D scene creation. High level shader language (HLSL) was used to simulate the visual impairments as post process effects. Simulations of myopia, hyperopia, cataract, macular degeneration & glaucoma were developed, and an interface devised to enable these impairments to be combined and adjusted for severity in real time using a set of sliders.

3.1 Shader Methods

Several key components were identified that would be required for use by the impairment shaders. The four main identified components were a blurring technique, colour tinting filter, partial screen overlay and a distortion effect.

3.1.1 Blurring Technique. Blurring techniques can often pose a challenge for development in a shader language as they sample a large number of neighbouring pixels then take an average with some weighting function to determine the result of the blur. This poses a problem for shader languages as the number of pixel samples they are able to utilise without impacting performance is limited. An efficient and effective blurring method which could be utilised within these constraints is a Gaussian blur. Whilst this is not strictly speaking an optically correct way of representing out of focus vision, the subtle difference is unlikely to be noticed.
3.1.2 Colour Tinting. A colour tinting filter is required to simulate the yellowing of the lens due to cataracts. A first simple stage is to create a monochrome representation of the source image with the desired colour. First the luminosity of the source image must be determined. As the human eye is not equally sensitive to the red, green and blue primaries a common method to create a greyscale closer to one perceived by a human eye is to use the equation below. This creates a greyscale according to wavelength function.

\[
\text{Luminosity} = (\text{Red} \times 0.2989) + (\text{Green} \times 0.5870) + (\text{Blue} \times 0.1140)
\]

After the fully tinted image is created, the amount of tinting can be controlled by using different amount of the tinted and original image.

\[
\text{Tint image} = \text{Tint colour} \times \text{Luminosity}
\]

\[
\text{Composite} = (\text{Tint amount} \times \text{Tint image}) + ((1 - \text{Tint amount}) \times \text{Source image})
\]

3.1.3 Partial Screen Overlay. Several impairments require that an area of vision becomes obstructed. In the previous simulation (Lewis et al. 2011) a black image with an alpha channel was used for transparency. This implementation extended that approach by making the shape more irregular and enabling the alpha value to be modified in real time. Alpha values stored are between zero and one. Values at one are completely opaque. Figure 1 demonstrates a sample alpha map used for the macular degeneration overlay.

![Figure 1. Macular degeneration overlay alpha map.](image1)

![Figure 2. Generated depth map.](image2)

To allow the adjustment overlay to adjust how severe the impairment appears the alpha values can be manipulated to change the level of visibility of the overlay. Subtracting values from the alpha map will make the image appear less opaque.

\[
\text{Adjusted alpha} = \text{Source alpha} - (1 - \text{Impairment severity coefficient})
\]

Any alpha value in the overlay lower than the impairment severity coefficient will have no effect, as the images becomes darker the obstruction expands from the centre, it will first appear as a small dot in the centre of the vision, then grow outwards as the severity level is increased.

3.1.4 Distortion Effect. Screen space distortion effects are commonly used in games to recreate effects like heat waves and refraction in transparent materials. It is a simple process where a source image is taken then resampled, offsetting the value of some pixels to add twists and distortions to the image. Changing the pattern of resampling offsets can vary the effect. To allow the effect to be changed without requiring significant recoding, a shader was constructed to use an image to represent the direction and magnitude of each offset. This allowed the effect to be customised by simply adjusting the image. The offset works in screen space, so sampling offsets can be represented as a two dimensional vector. Another shader technique known as normal mapping stores vectors in texture space using separate channels on the image to represent each component of the vector. As a single texture channel can only store values between zero and one this value is modified to change it into a range between minus one and positive one.

\[
\text{Offset axis } i = (\text{Offset texture channel } i \times 2) - 1
\]

By using two channels in an image to store the offset for each dimension of the vector a unique offset is stored for each image pixel. As a final step the offset image is made smaller than the screen size, so when the offset image is sampled the offsets stored in each pixel are smoothly interpolated. This gives a wavy effect rather than very sharp and sudden offsets. To control the severity of the offset, after the offset vector is calculated it is simply multiplied by the severity amount to increase or decrease the magnitude of the offset.
3.1.5 Depth Based Impairments. Depth of field blurring in games is a particularly difficult feature to implement without causing a significant and negative hit on performance. Although a working implementation of blurring has already been discussed, a method of extracting the depth of each pixel was required in order to modify the degree of blurring based upon focal distance. The traditional graphics pipeline uses vectors to store the position of vertices in three dimensional space, and matrices to transform these vectors into a screen space. Taking advantage of the fact that at the stage before perspective is applied every position vector’s magnitude is equivalent to its distance from the camera (as the camera is at the origin). The position of this vector can be passed down into the pixel shader. This makes it possible to interpolate between the three vectors making up each triangle to give the position of each pixel relative to the camera. From this the magnitude of the vector can be calculated giving the distance from the camera.

As this returns the depth in world units (in this case one world unit is equates to one metre) the results are converted to a range between zero and one to be written to a texture. To accomplish this, the total distance is divided by eight. This limits the range of distances from zero to eight metres. Any values beyond one (eight metres) are limited to one when the depths are drawn to the depth texture.

3.2 Simulation of the Impairments

These component effects were combined to recreate the appearance of a series of visual impairments as detailed below

3.2.1 Cataracts. A Gaussian blur filter was used to allow control over the patient’s loss of visual acuity as light scatters when passing through the lens of the eye. A colour tint filter was also utilised, allowing the control of how yellow and washed out the vision will become. Additionally an overlay of a white cloudy image is used to show the gradual increase in lens cloudiness. The overlay is designed such that the overlay will never be completely opaque even at full severity, leaving the impression of looking though a fog.

![Figure 3. Implementation of cataracts simulation.](figure)

3.2.2 Macular Degeneration. An image overlay was used to simulate the loss of central vision. It was created to allow the loss of vision to occur initially in the very centre of the vision and spread outwards as the severity level is increased. A Gaussian blur was used to show the loss of visual acuity. A distortion shader was used to simulate the effects where straight lines appear wavy to the patient. The higher the impairment severity the stronger the offset values making the line less straight the more severe the condition.

3.2.3 Glaucoma. An image overlay was used to simulate the loss of peripheral vision. A Gaussian blur was also applied to demonstrate the loss of visual acuity that frequently accompanies the impairment.

3.2.4 Myopia/Hyperopia. Barsky et al. (2002) implemented a vision realistic approach by rendering out burred images of the final scene then interpolating between them to get the correct level of blur in the composite image. This method was adapted to work in real time using a quick Gaussian blur to create a blurred image of the scene, using the depth information stored for each pixel to determine the level of focus, then interpolating between the scene and blurred image to make the correct areas appear out of focus.

Blur amount = pixel depth * severity coefficient

Colour = (Source image * Blur amount) + ( (1 – Blur amount) * Blurred image )
4. TESTING

A two stage testing method was employed. The first phase was aimed at validating the accuracy of the tool. To achieve this a qualified optician was consulted to confirm the accuracy of the impairments, and the potential utility of such a tool in her own professional practice. To test the effectiveness of the simulator for training and education purposes a second phase of testing was undertaken. This was based on a sample group of 23 people, university students of mixed gender aged between 20 and 25 years old.

4.1 Validation Testing

The optician was shown how to operate the simulator, and then allowed to experiment with moving around the environment and adjusting the impairments with assistance to facilitate where required. Qualitative feedback was gathered through dialogue throughout the process, and through conversation afterwards.

4.1.1 Cataracts. The optician identified that the cataracts simulation did not give a good representation of the variability of cataracts. Additionally comments were made on the level of severity offered by the simulator.

“When I turn the settings right up it gets to around the point where a patient may be referred. A patient needs 6/12 vision to get a referral in Lincolnshire.”

From this it is clear that at this stage the simulation is not capable of recreating the full range of cataracts in type or severity. The level of severity is however sufficient to simulate up to the point where a patient would require surgical treatment.

4.1.2 Glaucoma. The simulation of glaucoma was described as generally accurate, two suggestions were made to increase the fidelity of the simulation.

“There is a gradient between the parts that are normal and have no vision, I would expect the change to be much more sudden.”
“When I turn the effect right up I can still see quite a large area in the middle of the screen, I would expect this to be a much smaller area.”

Although this highlights that the simulation does have some significant flaws in the representation, the changes required are not problematic to implement.

4.1.3 Macular Degeneration. Macular degeneration was identified as the impairment that required the most significant changes to improve accuracy.

“The blind area does not grey in gradually, smaller blackened areas would appear during the initial stages. These would grow larger as the condition progresses.”

“Blurring and waviness would only happen the centre of the vision, the peripheral vision is not effected.”

“The angle of effect is much smaller, around 7 degrees.”

“I can just look to the side of the blind spot.”

These points illustrate a limitation present in all investigated visual simulations. In order to very accurately simulate the impairment it is necessary to align it with the foveal area of vision. As this area is extremely mobile any solution will require the use of eyetracking. The associated latency of this, combined with the graphical complexity of the shaders may prove to be pushing the boundaries of what is possible on current hardware. Modifying the display in real time depending upon where the user is looking however remains a highly desirable goal.

4.1.4 Myopia & Hyperopia. When the severest settings were simulated it was noted that the effects were insufficiently pronounced with little blurring within a metre.

“The symptoms are very mild, the far point of clear vision is much longer than I would expect. I have myopia and unless I hold something up here (within close proximity to the face) it appears out of focus.”

“The slider doesn’t make much sense, it would be nicer to have the effect measured in dioptres.”

This point is understandable from an optician’s point of view as these are the terms opticians are used to working with. It does however highlight the question of how an adjustment of this type should be labelled for a more general audience, and to what level of severity the simulation should extend.

4.1.5 General Evaluation of Simulation. The opticians review provided some evidence in support of the hypothesis that increasing the amount of interactivity in a visual impairment simulator is an important factor in representing the impact of visual impairments.

“Moving around and seeing things come in and out of focus really highlights how your world is really in the first meter of your vision. We tried something similar with our website on images but interacting gives a better sense of having the impairment.”

In addition to the large number of suggestions for improvement the optician did give a very positive reaction to the simulation.

“It would be of huge help when trying to explain the effects of impairments to patients.”

“Organisations like the RNIB are desperate for methods to inform the public about visual impairments and a program like this could really help this.”

By following the suggestions and increasing the accuracy and usability of the simulation it seems that this tool could have serious potential for a real world application. The results highlight the utility of having an experienced vision specialist involved during the development process, as following an iterative development of refining the impairments based upon expert feedback will eventually lead to more accurate and nuanced implementations of impairments than a standardised ‘textbook’ image.

4.2 Effectiveness Testing

The effectiveness testing on students utilised questionnaires to establish the participants level of awareness about visual impairments. Part one was taken before use of the simulation; the participants were asked to describe their knowledge of visual impairments in general and then questioned about specific impairments. Participants were then given a short demonstration of how to use the simulator tool and allowed to utilise the simulator for as long as they wanted. When they had finished with the simulator they were asked to complete
the second questionnaire. This asked a similar set of questions designed to show any change in awareness after using the simulator.

The first statement put to the participants was “I already have detailed understanding of visual impairments and how they affect the lives of the visually impaired.” No participants “strongly agreed” with the statement, three participants “agreed” and three were “undecided”. Fifteen “disagreed” and two “strongly disagreed”. These results could be interpreted as suggesting that the participants generally have an awareness of visual impairments but without detailed knowledge.

After using the simulator the following statement was put to the participants “Using the visual impairment simulator has improved my understanding of visual impairments in general and how they affect the lives of the visually impaired.” The responses to this question indicate a clear shift towards reporting a greater level of understanding. With seventeen participants saying they “strongly agree” with the statement and the remaining six saying they “agree” it suggests that the simulation was very successful at increasing understanding of visual impairments with every participant believing the simulation offered an improvement on their existing knowledge. As the survey does not actually test user knowledge, only asking for the user’s opinion the results must be used with caution, however it shows a very strong indication that the simulator does improve people’s understanding of visual impairment.

“I am familiar with the effects of ‘impairment’ on the visual system”

Figure 8. Understanding of impairments before using the simulator.

Figure 8 shows the participants understanding of visual impairments before using the simulator. As the data shows, people's base level of understanding about visual impairments is quite variable. Myopia and Hyperopia however tend to have a good proportion of participants who believe they have a good understanding of these impairments. A probable reason for this is that long and short sightedness are simply more well known, and the common names offer a clue as to the nature of the impairment.

“After using the simulator I am now familiar with the effects of ‘impairment’”

Figure 9. Understanding of impairments after using the simulation.
After using the simulation most participants believe they are familiar with the effects of all of the impairments, with the majority strongly believing. Of course, these results were gathered immediately after the use of the simulation when the experience is very fresh in the participant’s minds so the results should be viewed with some caution. They do however show a very strong indication that the subjects believe that the simulator has improved their understanding of visual impairments.

To test the simulations interactivity the participants were asked if “Allowing movements around the environment provided a better sense of the impairments than looking at a still image.” Eighteen of the participants strongly agreed with this statement and the remaining five agreed. This response shows a strong indication that interactivity is a valuable factor when trying to simulate visual impairments. It is worth noting that a significant number of the test participants were known to enjoy playing computer games. This may bias them towards a preference for interactivity; additionally their familiarity with the controls required for navigating 3D environments mean that these participants found this method of interaction familiar and natural, where others may find navigation to be much more of a usability issue.

5. CONCLUSIONS AND FUTURE WORK

The results of the effectiveness testing show a strong indication that the users had gained a good understanding of visual impairments though using the simulation tool. Seventeen users strongly agreed, and the other six agreed with the statement that “Using the visual impairment simulator has improved my understanding of visual impairments in general and how they affect the lives of the visually impaired”. Eighteen users strongly agreed and five agreed that ”Allowing movements around the environment provided a better sense of the impairments than looking at a still image”.

From the qualitative results gained it appears that the severity customization was fairly successful in its implementation, however the range that could be simulated was found to be too limited, with the highest settings not restricting vision enough to accurately replicate a severe impairment. Overall the simulation accuracy appears to be good enough for the application. Further work will be to implement more detailed and computationally expensive simulations, and investigate if an increase in simulation accuracy actually offers significant advantages over the lower end simulation. This is an important consideration as increasing the computational power required to run the system decreases the availability of the hardware needed.

High Level Shader Language was confirmed to have sufficient flexibility and computational efficiency to offer a great platform for the improvement and refinement of the shader algorithms. As the HLSL shader code is not specific to any particular application, it can potentially be integrated into a variety of applications . For example integration into CAD packages will allow architects or interior designers to understand how their spaces would be seen by a visual impaired individual. XNA was found to interface easily with the shader code, and allowed the rapid prototyping of a simple environment. Future work in this system will sidestep the difficulties of creating and lighting a virtual environment using XNA, and instead focus upon using the shader algorithms to create an augmented reality approach using live video.

To further develop an interactive environment, research is currently underway using existing game engine solutions like the Unreal Developer Kit to manage the world creation and interactivity features needed. These systems have much more advanced rendering pipelines than has been implemented by the current simulation and are already set up for complex interactivity. This would allow a much higher quality of rendering, increasing the immersion of the simulation by providing a more realistic environment, with interactive tasks to complete.

6. REFERENCES


