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3-D immersive screen experiments

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3-D IMMERSIVE SCREEN EXPERIMENTS

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ABSTRACT

We are currently piloting a range of computer simulated science experiments as 3-D virtual environments. These are rendered on a PC in 3-D and use photographs of specific parts of the actual apparatus as textures to add realism to the simulation. In particular, photographs are used to represent the consequential views of an experiment. These particular views may also be animated depending on the state of the experiment. The work combines the photographic approach of the Interactive Screen Experiments (ISEs) with the advantages of a fully simulated 3-D environment where the user can interact with the apparatus in a more natural and intuitive way. The potential advantages are that users can quickly adapt to the environment and in particular the controls. They gain realistic views of the physicality of the experiment as they are not just seeing it from a particular viewpoint, but from wherever they see fit to place themselves within the experiment's scene. They are immersed in the experiment in a way that mitigates some of the objections to online as opposed to real laboratory experimentation. It is also the case that the results of an initial calibration or setup carry over into the main part of the experiment. This is perceived as an extremely important teaching element of Physics practicals as the user learns that care in setting up an experiment is an essential part of being able to get good results. Furthermore there is no need to represent scales, read-outs or controls as separate parts of the interface; these can all be rendered at their correct physical positions within the experiment. The first of these experiments based on the use of a diffraction grating has been fully implemented and has been evaluated with a Physics A level class. The application and its evaluation will be presented. A more complicated experiment using a spectrometer has also been modelled which raises issues of complexity. These issues will also be discussed.

1. INTRODUCTION

2-D simulations are used extensively in Physics. We can find simulations of a simple pendulum to an atomic reaction in this form. However, there are situations when 2-D is not enough and to gain a true insight into how something behaves we need 3-D. This is the case for the programs described below. The Celestial E-Sphere (2008) was developed to help students understand celestial coordinates and various aspects of the motion of celestial bodies, and it is impossible to see how this could have ever worked as anything but a 3-D program.

The Meade Simulator (Lucas & Kolb, 2009) is used to help students studying the Open University course, Observing the Universe (SXR208, accessed 2008), to gain familiarity with controlling a telescope. It simulates the night sky, a computer controlled telescope and its hand

controller. It is the 3-D that gives this program the look and feel of the actual telescope and enables the students to come to terms with how to control it, enabling them to advance much more quickly when faced with the real thing. This has been in use for several years and has proved itself to be of enormous value in getting the students to a stage where they can master the controls of the telescope without wasting precious dark time at the observatory.

The 3-D Immersive Screen Experiments are a natural progression from these. Having implemented these 3-D programs and then facing the 2-D Interactive Screen Experiments it was at once obvious that the many difficulties that were inherent in the 2-D approach could be entirely avoided by rendering these experiments in their own 3-D virtual world.

2. STYLES OF INTERACTIVE EXPERIMENT

The idea of virtual laboratory resources that can be used on a computer is described in Hatherly, Jordan & Cayless (2009) and in particular the Interactive Screen Experiments (ISE) and several implementations are described, several of which are also discussed here.

ISEs (Bronner et al. 2009; Hatherley, Jordan & Cayless 2009) are perhaps the most common form of experiment that students can interact with on a personal computer. These use photographs to give 2-D views of the actual apparatus in use during an actual experiment. They are basically interactive movies and as such give a comforting feeling of reality. However, due to the combinatorial explosion of the necessary photographs there often needs to be compromises made in the degrees of freedom that the user can access. Despite this there have been many successful implementations and the OU and other institutions are actively engaged in producing these. This lack of ability to cope with multiple degrees of freedom leads to poor flexibility and scope as pointed out in Altherr et al. (2004) where an ISE showing a Michelson-Interferometer is compared to a video which scores the same low value for flexibility but actually does better than the ISE for scope. The terms 'scope' and 'flexibility' are defined within this paper.

It is interesting to note that the following observation about simulations made in Gorghui et al. (2009): *this approach (simulations) can lead to the oversimplification of real experiments. As a simple consequence of this fact, students may run into difficulties facing the complexity of the real world*. In Bronner et al. (2009) we find a similar but stronger statement that *Simulations are optimized to an idealized view on how nature would behave according to the accepted theory*. Although a simulation *may* do this to the detriment of the learning experience and this leads to the oversimplification noted above, a simulation does not *have* to do this; it is free to use photographs of actual experiments in the same way that an ISE does. The simplification inherent in the paradigm of the ISE is of a different nature. The simplification is due the inability to represent multiple degrees of freedom and it is this that has a direct bearing on the usefulness of the ISE as a teaching tool.

Although ISEs claim not to be simulations - "Note that an ISE is emphatically NOT a simulation" (Hatherley & Macdonald, 2009), in fact many of them are. It is emphatically not the case that every frame that a user sees is a photograph of a state of an experiment, but is most usually a photomontage where the selections, positions and orientations of the photographs are controlled by a program that is simulating the behaviour of the original experiment. This is true of the ISEs discussed here. Whether it is admitted that the ISEs are simulations or not, there is an

inherent oversimplification in the ISE paradigm due the inability to represent multiple degrees of freedom and this has a direct bearing on the usefulness of the ISE as a teaching tool. This point will be taken up later in the paper.

3-D Immersive Screen Experiments also use photographs of a real experiment but these are reserved for consequential views such as a spectrum, rather than the mundane views, such as the back of a voltmeter. The apparatus of the experiment is reproduced as 3-D models. These models are programmatically animated to simulate their real-life behaviour. The user's eye is implemented as a software camera that can be positioned anywhere within the scene in exactly the same way that most computer games are programmed. Indeed a games language is used as it provides many useful facilities such as collision detection. Clearly this approach is much more complicated to program than the 2-D ISE. In fact the modelling of the apparatus needs engineering accuracy so that all parts work properly together. This is where there is a large departure from the games approach, which mostly attempts to fool the user into believing that the operation of a device is realistic by often exaggerating its behaviour, although there are an increasing number of games, particularly of the racing type, that strive to emulate the actual underlying physics.

3. DEGREES OF FREEDOM

To demonstrate some of the challenges of reproducing an experiment on-screen, a concrete example of a simple experiment is used. Figure 1 shows the set-up for a diffraction grating experiment as used on the OU level one course, Exploring Science (S104, accessed 2009). This experiment can be constructed by the student on a dining table and used to obtain the angles of various coloured light diffracted by the grating seen here mounted into a 35mm slide. A bedside or office light illuminates the inside of a shoebox. A slit in the shoebox allows light to reach the diffraction grating that then diffracts the different colours of the light into various directions. A paper protractor is used to measure angles. A pin and length of cotton is a sighting device that the user looks along when determining the direction of a particular colour. The angle of diffraction can then be read from the protractor by examining the pin's position. The diffraction pattern consists of a bright white central region with rainbow coloured regions on either side that repeat themselves several times. The white pattern in the centre is called the zero order and each rainbow of colours is called an order. They are counted outwards with the left and right ones next to the centre being the first order, the next pair moving outwards is the second order and so on.

If this were to be faithfully reproduced by a set of photographs we would need to deal with all the possible configurations. For the sake of performing an experiment we will consider only those that bear directly on the experimental results that are to be obtained. For example, in reality it is always possible when performing an experiment to stand on our heads, but if this has no bearing on the useful visualisation of the experiment, the degree of freedom that allows us to perform such a manoeuvre will be excluded. One might imagine an experiment in which standing on one's head was useful. It is just a question of choosing those degrees of freedom that are of use for the experiment being considered. In reality and ignoring pointless degrees of motion there are three degrees of freedom for the user's eye, up/down, left/right, in/out. There is one degree of freedom in the shoebox that can move to the left or right to centre the zero order
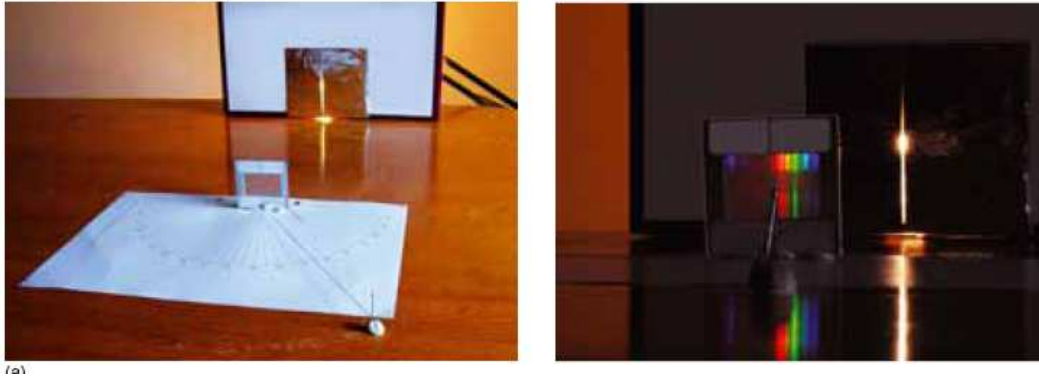
Figure 1: The diffraction grating experiment.

diffraction pattern so that its position reads zero on the paper protractor. Finally, the pin can be moved along the edge of the protractor adding one more degree of freedom. If one hundred photographs are used for each degree of freedom, 10 billion photographs would be needed to represent the entire experiment in all its possible configurations. Note that the required number is the product of the number required for each degree of freedom. This perhaps is why it is sometimes said that '*the whole is more than the sum of its parts*' as in a very real sense the whole is the product of the parts. This can be simplified by not allowing the eye to move forward or backwards or up and down. A further simplification would be to have the experiment already calibrated. So what remains are only the eye and pin moving in a plane. This would need 10,000 photographs. In practice this proves too many and the ISE that was actually produced combines the pin movement with the eye movement (Hatherly, Jordan & Cayless 2009). See figure 2, where the image of the slide is superimposed onto an aerial photograph of the experiment's current configuration and the eye is assumed to be on a line from the centre of the slide to the pin.

This is perhaps one compromise too far, as we now have the diffraction pattern changing as the pin is moved which is emphatically not the case. The diffraction pattern seen depends only on where the eye or camera is. This is an example of how the combinatorial explosion at the heart of the ISE forces such compromises often with unfortunate effect. Some might say, and exactly this has been heard, that it is obvious that the viewpoint is along a line through the pin to the slide. This was said by a lecturer of Physics at university level, so doubtless it was obvious to him. However, such assumptions should never be made of a student who potentially comes to this experiment with no expectations of its behaviour at all. Additionally, there is nothing intuitive about how the image on the diffraction grating appears to move as the viewpoint changes, if anything it is counter intuitive upon first viewing.

In practice the purely photographic approach of the ISE restricts us to reproducing just one degree of freedom at a time. Bronner et al. (2009) states 'Obviously, it is not feasible to include all degrees of freedom in a single ISE', this would seem to be an understatement and rarely more that one degree of freedom is seen in an ISE. Reproducing the experiment as a 3-D simulated environment allows all useful degrees of freedom to be retained but at the expense of a much more complicated simulation.
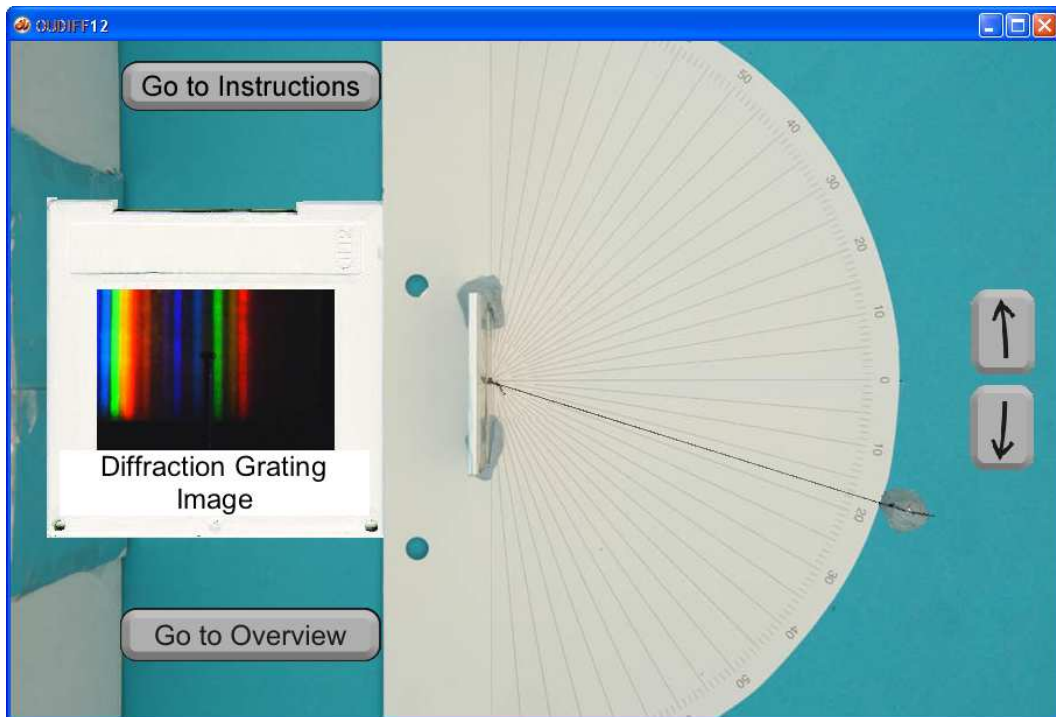
Figure 2: The diffraction grating ISE.

Figure 3 shows the same diffraction experiment rendered as a 3-D graphics simulation. Here the user can move his eye (the software camera) in all three directions. It is possible to move behind the shoebox and see what kind of light bulb is being used (the experiment is commonly performed with an ordinary tungsten filament and an energy saving bulb which produce quite different spectra). Note that there is no way of knowing what bulb is being used in the ISE other than reading the notes *which are not part of the simulation*. The pin can be moved independently and the shoebox can be moved left and right to perform the calibration. The final point is significant because the position of the zero order is one of the points plotted on the graph used to calculate the frequency of the various colours of light. And it is the accuracy of this point that needs to be taken account of when plotting a best-fit line. That there is an issue of accuracy concerning this point is very hard to appreciate if it is assumed that the apparatus has been set up with no possibility of moving this position. It is also necessary to perform this calibration with some care. This is a point worth emphasising because it is a major learning outcome that taking care in any set-up or calibration procedures affect the quality of the results that can subsequently be obtained.

This '1-degree of freedom at a time' often leads to a 'flattening out' of the experiment into a linear set of objectives where one degree of freedom is used to achieve the first goal and once achieved the experiment moves on the achieving a second goal using another degree of freedom now completely divorced from the first. Physics experiments are not like this, they are overwhelmingly built from many interacting facets.

Figure 4 shows a spectrometer. The tube with the square appendage is the collimator used to

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Figure 3: The diffraction grating 3D Immersive Screen Experiment.

produce a narrow beam of light. The other tube is a telescope with a reticule eyepiece used to align accurately on whatever image is produced by what is placed on the central platform. Commonly a prism or diffraction grating is placed on the table and the telescope is moved on the central vertical axis to view the spectrum. Essentially the spectrometer can be used to perform a very accurate version of the shoebox-and-protractor diffraction experiment described above. Performing the experiment with a spectrometer, however, means that the user must know how to use this piece of apparatus and be able to control it.

Before measurements can be made with the spectrometer it is important to focus the telescope on a distant object. In reality we point the telescope out of a window in the laboratory and focus on a distant tree or building.

The ISE of the spectrometer experiment requires that the user focus the telescope before being allowed to continue with the measurements. Once focused, the telescope is always focused. It is no longer possible to un-focus it. In reality it is the quality of the focus obtained by the student that has a direct bearing on the results he obtains. Part of the knowledge acquired by the student is how to deal with this parameter, the quality of the focus. He learns that a deal of care in performing the focus pays off in the result he gets. He may not learn this the first time he uses a spectrometer, but it is all part of the experience that he gains in a real laboratory. The ISE will always give him the results of a perfectly focused telescope, hence the user will have

Figure 4: A commercially available spectrometer.

no experience of trying to garner readings from a less than perfectly focused instrument and is unlikely to learn either the significance of the focusing or the consequences of it. The user is simply being made to jump through a hoop to achieve the necessary focus to proceed.

Figure 5 shows the spectrometer experiment rendered as a 3-D graphics program. Here the telescope is being focused on a distant pylon visible through the window of the laboratory.

The user is able to move his eye/camera in all directions. The various parts of the spectrometer can be moved by either dragging with the mouse or using keys. The various knobs, such as the focus knob, can be turned by placing the mouse over them and then using the mouse wheel. This gives a very intuitive feeling for the focusing in particular; note that whatever focus is achieved is carried over into the experiment itself. If the telescope is poorly focused the user will find it difficult to obtain accurate readings as in the real experiment.

Another compromise that we find with the purely photographic ISE approach is that the view

Figure 5: The Spectrometer 3D Immersive Screen Experiment.

presented of the experiment will not necessarily yield a usable view of the scale that is being used for data collection. In the case of the spectrometer (Hatherly, Jordan & Cayless 2009) it is necessary to represent the vernier that is used for measuring the angle of the telescope by a different window. This is an artifice that does not shed light on the workings of the spectrometer but obscures them. The student will almost certainly know how a vernier works but seeing it in its rightful place and being able to see its readings change when the telescope is moved gives the student a much better opportunity to understand it within the context of the experiment. Figure 6 shows how the vernier of the 3-D Immersive Screen Experiment is read by simply moving the eye or camera up to it.

4. IMPLEMENTATION

The models used in the shoebox diffraction grating experiment were extremely easy to implement. However the spectroscope demanded some complex programming and modelling.

The spectroscope must be modelled as individual components that are assembled and animated by the program. Every moving part must be constructed as an individual 3-D model. Each component must accurately fit with all associated components so that they work together. For example, the main scale seen above, must be capable of moving accurately against the vernier scale which must give accurate results at all positions. This requires a high polygon count to achieve smoothness and a high degree of precision so that components fit together well. The spectroscope was created using a 3-D modelling program called Milkshape (Milkshape 2009).
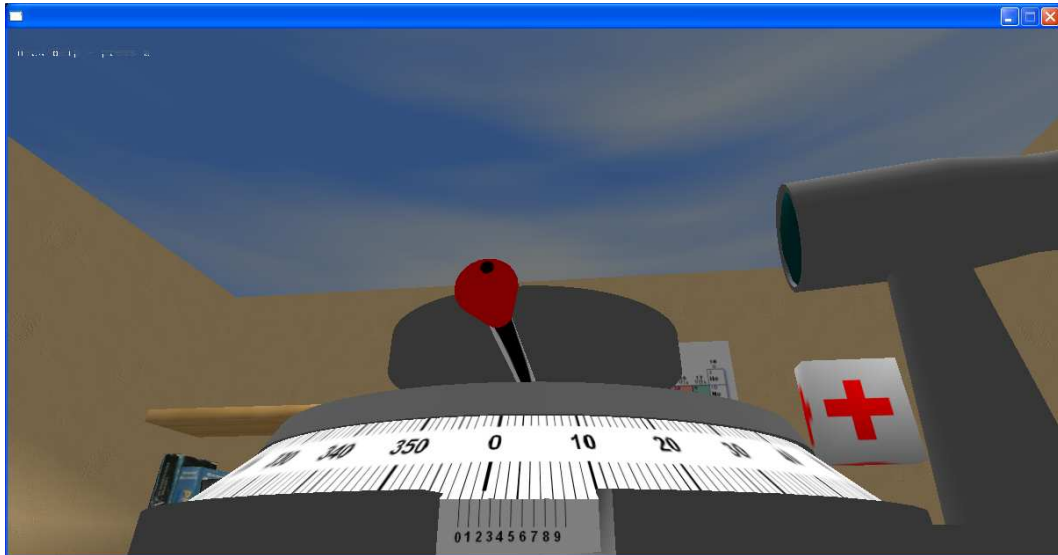
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Figure 6: Reading the vernier scale.

Figure 7 shows a view from within this program of the base and main scale. Construction of such a model is a painstaking business. This model took a total of about 30 hours to build and another 30 to animate correctly. The fixed base and scale account for over two thousand polygons. Although this may seem like a large amount, modern computers equipped with graphics cards can easily cope with an order of magnitude more than this. The knobs and the focus tubes are modelled separately so that turning the focus knob causes the focus tube to move in or out. This enables the student to understand how the focus is achieved and reinforce his understanding of the lens equation.

The telescope is modelled as a single lens magnifying glass. There is a second software camera (the first is the camera used for the user's eye) inside this telescope pointing towards the centre of the spectroscope. This camera copies its view to a buffer in memory. The lens equation is used to determine how the pixels of the telescope's memory buffer are to be dispersed over the eyepiece lens and it is this simulation that gives the focusing its realistic behaviour.

Figure 8 shows an exploded view of the spectroscope.

The Blitz3D games language (Blitz3D 2009) is used to bring all the components together and simulate their behaviour.

5. IN THE CLASSROOM

We evaluated the 3-D Diffraction simulation with two lower sixth form physics classes consisting of a total of 22 students. All students successfully used the program to obtain the necessary readings that enabled them to plot the graphs and calculate the wavelengths of blue, red, and green light. This in itself is very encouraging. The students were immediately able to explore the room containing the experiment to check what kind of bulb was being used and position
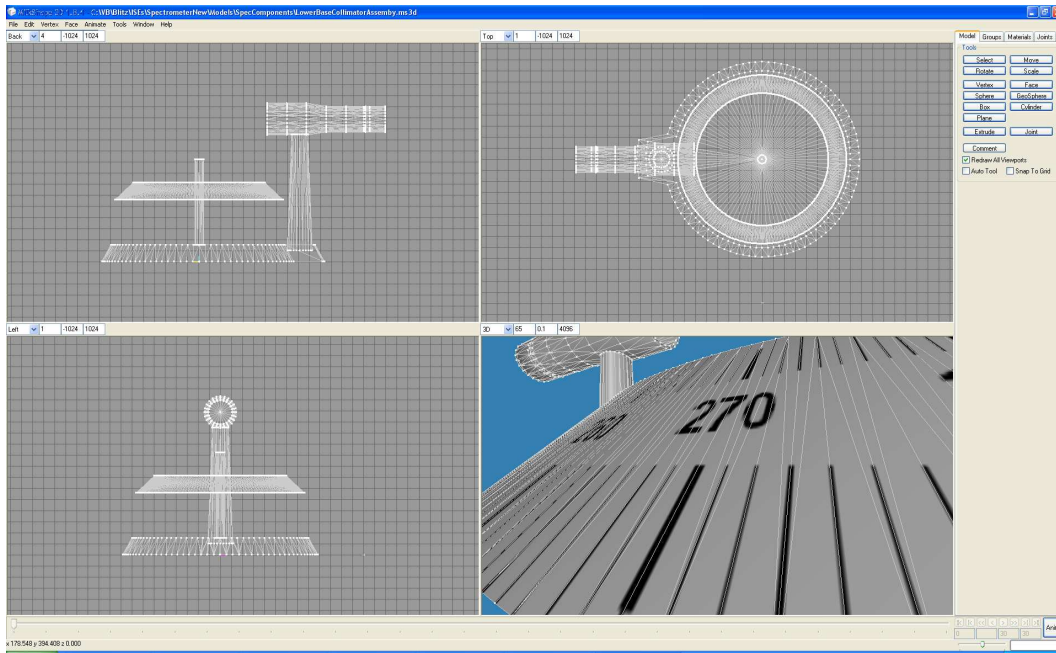
Figure 7: The Milkshape 3D modelling application.

themselves (i.e. the software camera) and the pin in order to take the necessary readings in the space of a single lesson.

They were given two sets of questions. The answers to all questions were given as a number 1 to 5, where 5 indicates 'strongly agree' and 1 indicates 'strongly disagree'. The first set tested their understanding and the second set, asked for their views of the simulation. The questions are given in appendix I and the results in appendix II. On ease of use the responses were extremely positive with all students bar one recording a score of 4 or 5. On being as realistic as the real experiment only 2 out of the 22 rated it poory as 2 or 1, but there were 7 undecided here. On the question of having the same look-and-feel of the actual experiment there were only 5 negatives in total but 8 undecided and 9 positive. Thus on look-and-feel the positives outweigh the negatives by nearly two to one. This is perceived as encouraging for a first attempt at an immersive 3-D experiment where the user interface was restricted to simple key presses. There is clearly scope for improving upon this.

On the idea of replacing real experiments with 3-D simulations they were rather negative which was expected. This was the same for whether they thought that they could learn as much from the simulation as a real experiment.

On all the other questions they were very evenly split, but if divided into two groups, one that did well on the test and those that did not do so well, there is an interesting result. Those that did well are very positive about the use of the simulations for revision and preparation but do not rate the simulation as realistic as those that did not do so well, and this group is less positive about the possible uses for revision and preparation. For example, of the weaker group, 7/10 were positive about the realism but only 2/10 were positive about the usefulness for revision. In the stronger group, only 5/12 were positive about the realism whereas 9/12 were positive about
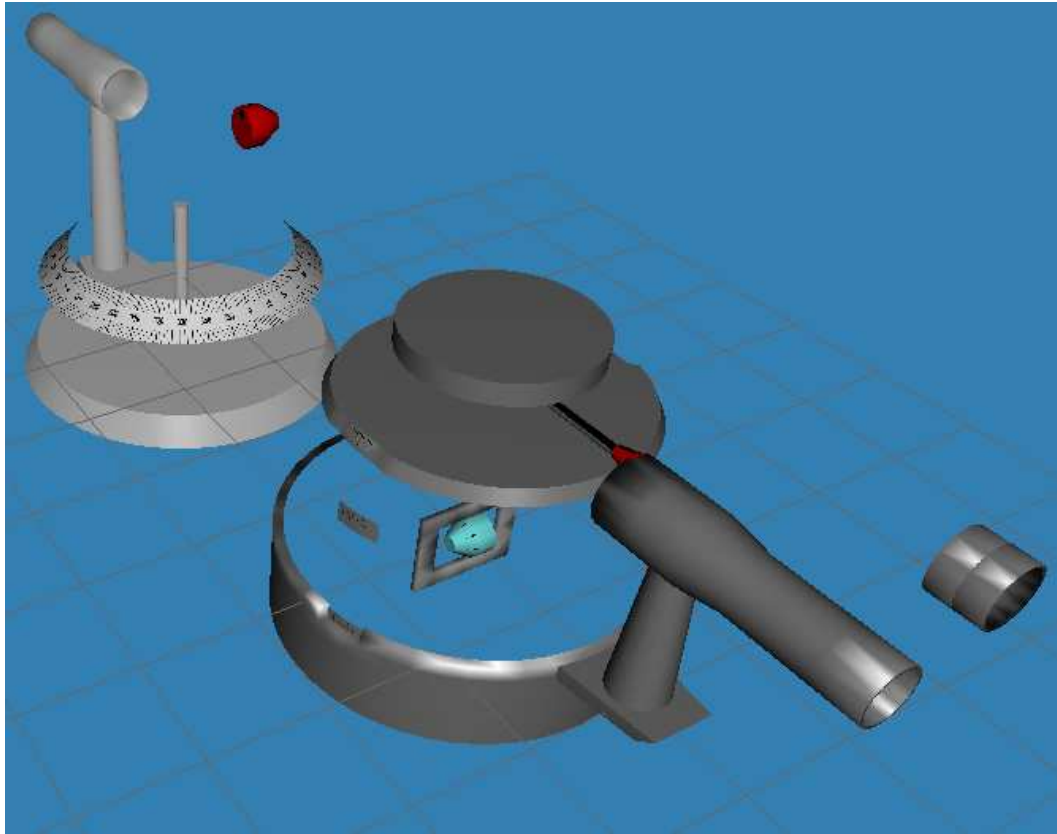
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Figure 8: Exploded view of the spectrometer.

the usefulness for revision. This is perceived as quite logical; those who are very competent can perceive the weaknesses of the simulation (the degree of realism in this case) but also understand its strengths too (that despite the lack of total realism it still has useful potential as a revision aid). In contrast the weaker students are more easily convinced of the realism but perhaps lack the necessary degree of abstraction to perceive its use as a revision aid.

6. CONCLUSIONS

The crucial part of many physics experiments is how all the varying parameters interact, in particular how the set-up or calibration of an instrument has an effect on subsequent measurements. We are clearly able to reproduce this with the Immersive 3-D Screen Experiments that proves very difficult if not impossible with the ISE approach due to the combinatorial explosion of the necessary photographs and this is a problem that impacts on all ISEs. Currently there are no ISEs that have set-up or calibration procedures of any complexity that carry forward the accuracy achieved in this initial phase into the main body of the experiment. The nearest behaviour to this is in the *Diffraction from a steel ruler ISE* (SteelRule2, accessed 2010) where leaving the laboratory light on causes a reduction in the quality of the results (as clearly the spectra are easier to see in the dark). This causes a doubling of the required photographs which remains feasible. A binary set-up procedure such as this is clearly of limited value as set-up

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or calibration procedures are rarely this simple. It is situations such as achieving a focus (i.e. there is a continuous range of values) that are extremely hard if not impossible for the ISE approach because of the huge number of images needed to implement a second or third degree of freedom.

A common criticism of simulations is that they do not reflect reality, but here we are able to exploit photographs from real experiments as textures within the 3-D environment and thereby preserve the realism from the actual experiment just as the 2-D ISEs do.

Furthermore, we do not need to create programming artefacts to represents scales or controls of any kind. These can be represented at the positions that they are found in reality. Classroom trials clearly show that students are receptive to this approach although healthily sceptical that such programs can replace the real thing.

An immersive 3-D simulation using photographs allows us to implement a highly realistic experience of an experiment where we can utilise many degrees of freedom allowing us to retain the physicality of the original experiment as well as the essential feature that the quality of the experimental results are dependent on the care taken with the initial set-up and calibration procedures.

APPENDIX 1 QUESTIONNAIRE

Questionnaire for evaluation of 3D-ISE Diffraction

(A) UNDERSTANDING OF THE EXPERIMENT

These questions should be answered with a Y for yes or a N for no.

(1) The zero order spectrum is visible at zero degrees from a line drawn from the diffraction grating at a right-angle.

(2) All the diffraction patterns occur in pairs.

(3) When $sin(\theta)$ is plotted against the order, the gradient gives the wavelength of the light

(4) Moving the position of the eye (camera) alters the diffraction pattern that can be seen.

(5) Moving the position of the sighting pin alters the diffraction pattern that can be seen.

(6) The higher order diffraction patterns are brighter than the lower order ones.

(7) Each of a pair of diffraction patterns constituting an order occur at the same angle of view but on opposite sides of the zero line.

The following questions require more than just yes or no.

(8) At the zero order how are the various colours diffracted?

(9) List the sources of the uncertainties in your measurements.

(10) Why are the uncertainties not necessarily the same for all the measurements?

(B) OPINIONS ABOUT THE EXPERIMENT

These questions should be answered by circling one of the values given where 5 is 'strongly agree', 1 is 'strongly disagree'.

(1) I found the controls easy to use. (5 4 3 2 1)

(2) The simulation was a realistic simulation of the real experiment. (5 4 3 2 1)

(3) Using the simulation improved my understanding of the experiment. (5 4 3 2 1)

(4) The simulation had the look and feel of the actual experiment. (5 4 3 2 1)

(5) I would find such simulations useful as a way of revising certain experiments. (5 4 3 2 1)

(6) Simulations like this could usefully replace actual experiments. (5 4 3 2 1)

(7) I would learn as much from this simulation as from the real experiment. (5 4 3 2 1)

(8) It would be useful to do this simulation before doing the actual experiment. (5 4 3 2 1)

SPACE FOR GENERAL COMMENTS

Please feel free to put any comments you like here. In particular we are keen to hear of any suggestions which will help us to improve the simulation.

APPENDIX 2 RESULTS

Student	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	B1	B2	B3	B4	B5	B6	B7	B8
1	1	1	1	1	1	1	1	0	1	1	4	4	5	4	4	3	3	3
2	1	1	1	1	1	1	1	1	1	1	5	2	2	2	4	1	2	3
3	1	1	1	1	1	1	1	1	0	0	5	3	4	4	5	3	3	4
5	1	1	1	1	1	1	1	1	1	0	5	5	5	5	5	2	2	4
6	1	1	1	1	1	1	1	1	1	0	4	5	4	4	5	1	3	5
8	1	1	1	1	1	1	1	1	0	0	3	3	4	3	4	2	2	3
10	1	1	1	1	1	1	1	1	1	0	4	3	3	3	4	1	1	2
11	1	1	1	1	0	0	1	1	1	1	4	3	4	3	4	4	3	4
14	1	1	1	1	1	1	1	1	1	1	5	4	2	3	3	1	4	5
16	1	1	1	1	1	1	1	1	1	0	5	5	5	1	1	1	3	5
20	1	1	1	1	1	1	1	1	1	0	4	3	3	3	3	1	2	3
22	1	1	1	1	1	1	1	1	0	1	5	3	2	2	4	3	2	4

Table 1: Students who did well.

Student	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	B1	B2	B3	B4	B5	B6	B7	B8
4	1	1	1	0	0	1	1	1	1	0	4	3	2	3	3	1	1	2
7	1	1	1	1	1	1	0	0	1	0	5	4	1	2	3	1	1	1
9	1	1	1	1	1	1	1	0	0	0	4	5	2	4	5	2	4	3
12	0	1	0	1	0	1	1	0	0	1	5	5	3	5	3	5	2	2
13	0	1	0	1	1	0	1	1	1	0	4	4	3	3	2	1	1	2
15	0	1	0	1	1	0	1	1	1	0	4	4	4	3	3	3	4	3
17	0	1	0	1	0	1	0	0	1	1	4	5	3	4	5	5	3	4
18	0	1	0	0	1	1	1	0	0	0	5	1	5	1	1	1	1	5
19	0	1	0	1	1	0	1	0	0	1	4	3	4	5	3	4	4	5
21	0	1	0	1	1	1	1	1	0	1	5	4	3	4	3	1	2	4

Table 2: Students who did not do so well.

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