Chapter 11. Conclusions and recommendations

11.1 Conclusions

This thesis has shown that motion sickness and vection are experienced during visual stimulation from an optokinetic drum and during virtual reality simulations of an optokinetic drum. It was shown that vection and motion sickness are probably separate phenomena. Subject motion sickness scores were not correlated with vection in any of the experiments conducted. Motion sickness could be reduced without significantly changing the amount of vection reported by subjects. Vection could also be reduced without significantly changing the motion sickness symptoms experienced. Vection was also found to vary independently of the frequency of nystagmus or of the slow phase velocity of nystagmus. Vection was found to be controlled mainly by motion in the periphery of vision.

The velocity of the slow phase of nystagmus was found to vary depending on the visual acuity, and the contrast sensitivity to higher spatial frequencies, of subjects. Those subjects who had poorer visual acuity, or lower sensitivity to high spatial frequencies, were found to have slower velocity eye movements, compared to subjects who had good visual acuity. Retinal slip velocity (the difference between the stimulus velocity and slow phase velocity) was higher for subjects with poor visual acuity, or low contrast sensitivity to high spatial frequencies, because these subjects had lower slow phase velocity of nystagmus.

Image slip on the fovea, rather than on the retina as a whole, was found to be a possible error signal in the development of motion sickness. Motion sickness was reduced when subjects focused on a stationary cross in front of an optokinetic simulation (reducing foveal image slip but not peripheral image slip). Motion sickness was not changed when subjects viewed a single dot (only foveal stimulation) or multiple dots (foveal and peripheral stimulation).

Visual acuity was found to be significantly correlated with motion sickness in a standard optokinetic drum and in the virtual reality simulation of an optokinetic drum. Subjects with poorer visual acuity experienced significantly more symptoms of motion sickness. Motion sickness was increased when subjects viewed an optokinetic drum without their vision correction (spectacles or contact lenses) compared to when they viewed it with vision correction.

As mentioned above, foveal image slip was found to increase with poorer visual acuity, hence the hypothesis was developed that motion sickness during optokinetic simulation may be related to foveal slip, with an increase in motion sickness with increased foveal slip (associated with lower visual acuity and lower contrast sensitivity to high spatial frequencies).

Contrast sensitivity as a measurement of visual performance was found to have a much greater variation among subjects with vision correction than the variation of visual acuity among the same subjects. With vision correction, correlations were found between the slow phase velocity and contrast sensitivity at the high spatial frequencies and one of the low spatial frequencies. It may be possible to use contrast sensitivity as a more sensitive indicator of visual function, in order to predict the velocity of eye movements, even in subjects who have good visual acuity.

11.2 Recommendations for future work

The work in this thesis has concentrated on the fundamental understanding of interactions between visual acuity, contrast sensitivity, eye movements, motion sickness and vection. Further research could be conducted upon these lines, in order to further improve the model (Figure 10.1). Work could also investigate means by which motion sickness could be reduced in practical situations, by employing ideas generated by the model.

11.2.1 Fundamental work

Further study of the model could be performed in order to verify the foveal slip idea. An experiment in which the fovea was blocked at all times by a moving blinker system (similar to that used by Van Die *et al.,* 1986) would be expected to reduce motion sickness, compared to a condition without the fovea blocked, because of the reduction in foveal slip. This experiment would help to confirm whether eye movements themselves are a cause of motion sickness because eye movements would still occur, despite the elimination of the foveal input.

Further research to improve the model could look at understanding the interaction of eye movements and the vestibular system. Subjects were not moved in any of the experiments in this thesis, but in normal circumstances eye movements occur as a result of motion of the person and motion of the environment. The vestibulo-ocular reflex serves to stabilise vision during head movements. Optokinetic nystagmus occurs as a complementary system to stabilise vision under conditions of low frequency head movements and constant velocity rotation.

The model could be improved by a greater understanding of the interactions of the two systems. It may be possible to predict eye movements that might occur under combinations of motion of the subject and the environment. It may be able to take visual acuity and the excitation of the fovea and peripheral vision into account. An understanding of the interactions of the vestibulo-ocular reflex, optokinetic nystagmus and other eye movements may enable eye movements to be included in a wider 'sensory conflict' theory, which could be applied to motion sickness occurring in virtual reality, simulators and possibly even in ships, trains, cars and other modes of transport.

11.2.2 Practical applications

Applications to reduce motion sickness in virtual reality environments could be developed by the model. For example, in a perfect virtual reality simulation each head movement would be accompanied by the exact counter movement of the visual world, without any error or delay. This would not be expected to cause motion sickness because it would be indistinguishable from the real world condition.

Virtual reality departs from reality because of errors made either during the real time measurement of head movements or due to inefficient processing and delays in the generation of the computer imagery. Errors will still exist even in an optimally calibrated system because of the inherent delays in updating computer graphics in response to head movements and imperfect head velocity measurement techniques.

One of the results of the above errors is to create a slipping of the images on the retina. For example the user may make a head movement of 10°/s angular velocity. The virtual reality system must move the visual scene by 10°/s in the opposite direction to head motion in order to maintain a space stabilised image (i.e. the world must appear stationary whilst the subject navigates through it). If the head tracking system incorrectly measures the head movement as 8°/s and only moves the visual scene by this velocity, there will be a slipping of the image of 2°/s on the retina. The world will appear to move independently of the subject. The same phenomenon can be created if the computer is slow to update the images so that the world is still moving after the head has stopped moving.

The above problems can be thought of in terms of ‘image magnification errors’ (see Section 2.6.2 for more details). This is similar to a subject wearing magnifying spectacles. The world in this case moves at a different velocity to the head, say 1.2 times as fast. There will be periods during exposure to virtual reality where the image is slipping during and after head movements, representing an optokinetic stimulus.

The effect of visual acuity and contrast sensitivity to high spatial frequencies on motion sickness survival time would be expected to be observed in virtual reality applications. Experiments which look at this possibility could be devised. Additional experiments which use fixation (as discussed in Chapter 5) could help to verify whether this can reduce motion sickness with this type of image motion, in the same way that it reduced motion sickness in the optokinetic drum.

Practical applications of the fixation idea could be generated in a head-coupled virtual reality simulation. The fixation system could be implemented with a fine mesh which could be updated more quickly than the normal content in the virtual reality system. This mesh could appear only during head movements where there is likely to be a slipping of the virtual reality content on the retina. The mesh should be placed so that foveal fixation can occur on the mesh during head movements. The background will still be visible so that performance is not impaired. The hypothesis is that fixation in virtual reality, created by means of a visible mesh, could reduce motion sickness by reducing foveal image slip.