Chapter 7

Conclusions, Contributions, and Future Research

In order to enhance human navigation performance in virtual environments, it is necessary to understand the navigational requirements of the particular task to be performed, within the framework of limitations of human information processing capabilities. An extensive literature survey was conducted at the beginning of this project to learn about the complex domain of navigation in VEs. As a constant process of route planning and moving about in a space, successful navigation frequently requires the correct understanding of “where am I?”, “where should I go?”, and “how can I get from my current location to the next immediate destination?”. These questions reflect the two challenges users typically face during VE navigation: a *cognitive* challenge, which involves the checking and updating of one's position relative to other objects and to the world, and a *physical* challenge, which requires the navigator to locomote from one location to another.

Following the model of frames of reference for navigation (Wickens and Prevett, 1995), it is possible to identify the supportive relationship between the information about different frames of reference and the two navigational challenges. Dynamic viewpoint tethering was introduced and investigated in this study with the goal of (1) seamlessly integrating information from both egocentric and exocentric frames of reference, and (2) overcoming some of the functional limitations of current navigational display systems and facilitating efficient navigation in large scale virtual environments.

The concept of dynamic viewpoint tethering and the mathematical description of a dynamic tether have been explained in Chapter 3. Modelled as a 6 degree of freedom mass-spring-damper system, a dynamic tether has three major parameters: spring constant, damping coefficient, and tether length. A three dimensional dynamic tether space was formed by mapping these three tether parameters onto three independent axes. Three experiments were conducted in this study to explore design constraints in the dynamic tether space, by investigating the effectiveness of dynamic tethered display parameters in comparison with conventional display formats. In all cases, an effort was made to identify the optimal parametric tether configurations for supporting efficient navigation.

7.1 SUMMARY OF EXPERIMENTAL FINDINGS

Experiment 1 was a base-line experiment, in which an empirically nominally-defined dynamically tethered viewpoint was contrasted with three conventional viewpoint formats: egocentric, exocentric, and rigidly tethered viewpoints, using a virtual tunnel flying task. Participants' performance was measured in terms of both local guidance and global awareness. The results revealed that the egocentric and the two tethered viewpoint conditions generated better local guidance performance. Global awareness, on the other hand, didn't reveal any significant difference across viewpoint settings. No significant performance differences were found between the two tethered viewpoints. In terms of subjective preference ratings, the two tethered displays received higher scores than both the egocentric and exocentric displays.

The results of experiment 1 generally confirmed the usefulness of viewpoint tethering for supporting navigation. Although the theoretical advantage of a *dynamically* tethered viewpoint was not explicitly demonstrated in the results, it was speculated that a better configured tether might in fact outperform the conventional viewpoint conditions. Other results identified in Experiment 1 included a significant tunnel effect and a significant display tunnel interaction. Further analysis revealed that a particular tunnel used in the test was more difficult than the rest tunnels due to the constraints imposed by the input device. The significant display-tunnel interaction was mainly caused by the inconsistent performance transition on the exocentric display compared with the rest three displays.

Experiment 2 focused on identifying optimal dynamic tether properties. The combined effects of tether rigidity and viscosity on viewpoint behaviour were analyzed. The implications of the parameters defining the dynamic setting of a tether, i.e. its spring constant and damping coefficient, were investigated. The primary focus of Experiment 2 was twofold: (1) to investigate how local guidance performance was affected by tethered viewpoints with different tether damping ratios, and (2) to identify the optimal tether rigidity for supporting local guidance. The virtual tunnel flying scenario was used again in the testing, and performance in local guidance and global awareness were contrasted for two groups of tether settings, A & B. The results found a significant performance difference between high and low frequency tunnel conditions. It also showed that, at least for one rigidity level, a critically damped tethered viewpoint produced the best local guidance performance relative to its under-damped and over-damped counterparts. A second comparison among a group of critically-damped tethered viewpoints also identified a significant performance improvement under low frequency tunnel condition as opposed to high frequency tunnel conditions. The results revealed that neither the rigid tether nor the very loose tether produced the best local guidance performance scores for high frequency tunnels, but an optimal tether of intermediate rigidity appeared to exist. Significant tunnel effect and display-tunnel interaction were found in both display groups. Further analysis identified the significant tunnel effect and the significant interaction were greatly influenced by data from a limited number of trials. It was suggested that a more stringent experiment control would be used in future experiment. Participants' performance on the global awareness task did not reveal any significant differences across the tested tethered viewpoints, which suggests that global awareness is primarily affected by tether length, a factor that was not tested in Experiment 2.

The primary concern of Experiment 3 was to investigate the effect of the length of a tether on overall navigational performance. As one of the major factors determining the nominal viewpoint location, the length of a tether affects the relative centricity of a viewpoint. With an increase of a tether's length, performance improvements in global awareness and performance deterioration in local guidance were expected. Six tethered viewpoints with varying tether lengths were contrasted in this experiment, using the same airplane flying scenario. The results confirmed the advantage of a longer tethered viewpoint for supporting global awareness. As an apparent trade-off between the available preview information and the spatial resolution of the display, the best local guidance performance was observed for an intermediate length tethered viewpoint. Significant tunnel effect and display-tunnel interaction were also found. A follow-up Tukey pair-wise comparison found that a particular tunnel generated larger errors than two other tunnels. Considering performance with respect to both local guidance and global awareness, therefore, overall navigational performance was deemed to be best supported by an intermediate length critically damped tethered viewpoint.

The highlights of the results can thus be summarized very briefly as follows:

1. Modeled as a mass-spring-damper system, dynamic viewpoint tethering provides a wide design space for characterizing display efficiency. By exploring the dynamic tether

space, tethered viewpoints with various configurations can be constructed to accommodate different navigational task requirements.

2. As a way of seamlessly integrating information from egocentric and exocentric frames of reference, dynamically tethered viewpoints appear to support both local guidance and global awareness navigational subtasks simultaneously.

3. Local guidance performance is greatly affected by the tether dynamic parameters, i.e. the tether spring constant and its damping coefficient. An optimal tether setting appears to comprise a critically damped configuration with a rigidity value in the intermediate range of its rigidity spectrum.

4. Performance in both local guidance and global awareness are significantly affected by the length of a tether. With an increase of tether length from its minimum value, improvements in global awareness and reduction in local guidance performance are observed. The overall best navigational performance appears to be supported by an intermediate length dynamically tethered viewpoint.

Collectively the series of analyses and broad exploratory experiments in this thesis have convincingly supported the theoretical advantages of dynamic viewpoint tethering for enhancing user navigation performance. Design guidelines generated from this study are expected to provide general support for navigational display system implementation.

Furthermore, the experimental data should advance our understanding of human navigation behaviour in virtual environments.

7.2 LIMITATIONS

Although the test environments and tasks were carefully designed to maintain their representativeness and reduce the likelihood of a total disconnect from the real world, as a common problem faced by most scientific laboratory experiments, the lack of real life variability and the absence of a real-life context in the testing may arguably diminish the impact of the experimental conclusions.

The winding tunnel-like 3D virtual environment used for navigation in all three experiments is not very similar to most geographical environments with which most people are familiar. The lack of landmarks and the irregular orientation of the tunnel-like space thus limit the transferring of subjects' real life navigation experiences to the testing conditions. Although this tunnel-like environment is suitable for the airplane flying scenario used in the testing, it is worthwhile to conduct follow-up experiments employing other types of navigation metaphors, such as a walk-through metaphor, and using other forms of virtual environments, such as a city-block type of environment.

The tunnel-like virtual environment has another implication on the measuring of participants' global awareness. Due to the simplicity of the environment, the current global awareness task (i.e. tunnel shape recognition) arguably can be completed by direct perceptual mapping, especially for exocentric viewpoints which allow participants to view the entire virtual environment directly. With a reducing of viewing distance, tethered viewpoints are less susceptible to this problem. However, in order to completely resolve this problem, it is necessary to adopt complex environment models in the simulation. Then it is possible to introduce other types of global awareness measures, such as judging distance or estimating directions between two known landmarks, which will yield more accurate performance results.

One technical limitation in the experiments had to do with the control device, the Spaceball. Although only rotational degrees of freedom (i.e. pitch, roll, and yaw) were allowed in the flying trials, and extensive training was given to participants prior to the testing, manoeuvring in certain degree of freedom, in particular roll, was frequently reported by participants to be unnatural and awkward, due to the mechanical structure of the Spaceball. Other types of input devices should thus be incorporated in future experiments to reduce the severity of these control difficulties.

Another possible limitation of this research is the relatively short participant exposure time to the virtual environments. In theory, longer immersion in the virtual space should allow the use of more complicated environment models and enable participants to develop more complete cognitive maps about the environment. However, due to the various restricting resources of the study (i.e. time and funding), a relatively simple environment had to be used in all three experiments. The longest testing trials lasted for about five minutes. In future studies, the simulation of more complicated geographical environments may allow longer VE immersion, thus making it possible to evaluate more fully-developed spatial knowledge on the part of participants.

7.3 CONTRIBUTIONS

This research has yielded significant contributions to both theory and real world applications. First of all, the concept of dynamic viewpoint tethering provides a theoretical framework for display viewpoint definition, in the sense that most existing viewpoint formats can be regarded as examples of generalised tethered viewpoints with particular tether settings. Serving as a high level abstraction, this framework therefore makes it possible to interpret the scattered experimental results from various viewpoint studies in the literature in a systematic way, and thus to identify the functional limitations of different viewpoint formats and explore potential design spaces.

Secondly, the design guidelines generated from the experimental findings in this study provide many insights for directing the implementation of future navigational viewing systems. Human navigation in real and virtual environments is a complex process, which involves both cognitive and physical challenges. The criteria of successful navigation are task-dependant, and there is no single optimal viewpoint solution for all navigational systems. Following the concept of dynamic viewpoint tethering, it is possible to determine a range of appropriate viewpoint settings to fit specific task requirements and thus achieve maximum navigation efficiency.

In addition to supporting navigation in VEs, the framework of dynamic viewpoint tethering also serves as a starting point for potential research in the area of simulator sicknesses. In the study reported here, minor symptoms of sicknesses were reported by participants under certain viewpoint conditions in the pilot studies. It seemed at that point users were susceptible to sickness symptoms under some viewpoint conditions, such as the abrupt scene changes caused by viewpoint oscillations for some under-damped tethered viewpoints. As a consequence of that finding, all the tether conditions used in this study were carefully selected to avoid simulator sickness. Although this phenomenon is out of the scope of the current research and has not been extensively studied under the framework of dynamic viewpoint tethering, quantitative analysis of simulator sicknesses caused by extreme viewpoint behaviour now becomes possible. Furthermore, the DTS software developed for this research fully incorporates viewpoint manipulation based on the concept of viewpoint tethering. Not only does it serve as demonstration software for the effectiveness of the viewpoint tethering, but also can it be used as a testing platform for future research into this theme.

The research has also contributed knowledge to the body of literature on navigation and orientation. Successful navigation in virtual environments is critical in tasks such as remote vehicle control, telemanipulation, endoscopic surgery, virtual training systems, and certain Computer Aided Design (CAD) systems. In terms of sheer numbers, perhaps the greatest potential impact of the present research is in the area of video games. In all cases, it is important to employ visual display parameters that are compatible with the operator's command inputs, without imposing excessive mental workload. As an engineering thesis, the results of this study provide useful guidelines for the design of such displays. The use of well designed dynamic viewpoint tethering has the potential to reduce local control errors in navigation, as well as the operator's need to perform difficult mental transformations, by maintaining appropriate alignment between display and control reference frames. By incorporating the viewpoint tethering principle into the various applications listed above, it is expected to improve the usability of such systems and thereby enhance users' navigational performance.

7.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The three experiments reported in this dissertation are just a starting point for investigating the concept of dynamic viewpoint tethering on enhancing human navigation performance in virtual environments. During the discovery process, many relevant interesting issues have surfaced. Although these unresolved issues were out of the scope of the current research, the same general paradigm used in this study can be followed to tackle some of these issues. More studies are expected to follow this line of research; two immediate possibilities are proposed here:

1. Experiments comparing tethered viewpoints with different fields of view.

The primary interest of the current study was focused on the dynamic tether, not the viewpoint. Thus, a set of fixed viewpoint parameters, in particular field of view, were used for all testing display conditions. As discussed in Chapter 6, since the field of view (FOV) of a viewpoint also affects the amount of preview information of a display, it will be interesting to see how different FOV settings will affect performance, in particular, how the changes of FOV will affect local guidance and global awareness.

The results from Experiment 3 showed a change of performance as a function of tether length for a fixed FOV. In a proposed follow-up experiment, it would be interesting to fix the length of a tether but vary the viewpoint field of view. For a non-dynamic task, i.e. for a zero or very low frequency input forcing function, these two cases would be essentially equivalent. For dynamic inputs, on the other hand, the results might be quite different. Furthermore, since a small FOV limits the preview information available to the users and a large FOV introduces edge distortion, it is expected that an optimal viewpoint FOV will be found, subject to particular task requirements. The results from such an experiment should give us some insight into designing an adaptive viewpoint which might be incorporated with a dynamic tether model to further enhance users' navigational efficiency.

2. Experiments comparing tethered displays with different nominal viewpoint positions.

The importance of nominal viewpoint position on affecting display field of view was discussed in Chapter 6. For a tethered viewpoint, the nominal viewpoint is determined by the elevation and azimuth angles, as well as the length of the tether. The effect of tether length on users' navigational performance has been investigated, in Experiment 3. However, in that experiment the azimuth and elevation angles of the viewpoint were fixed at a constant 0 degree of azimuth and 30 degree of elevation for all tethered viewpoints. Further experimentation is proposed to investigate navigational performance with respect to different viewpoint elevation and azimuth angles, respectively.

Considering the facts that (1) elevation angles outside the range of -90 to 90 degrees (following the definition of elevation angle presented in Figure 3.6) will introduce display/control reversals, which theoretically will burden users with mental rotations, and (2) elevation angles within the range of -90 to 0 degrees create a rather unnatural viewing situation (i.e. looking up from a position below the controlled avatar), the proposed elevation angle range for future tests is from 0 to 90 degrees. The two extreme conditions, i.e. 0 and 90 degree elevation angles, correspond respectively to conventional 2D profile and top-view displays, which are known to be favourable for distance judgment. It will be interesting to see how performance will change with variations of viewpoint elevation angles between these extremes.

A similar analysis can be performed on the azimuth angles as well. In future experiments, one can thus fix the length and dynamic property of a tether while changing the viewpoint azimuth settings. Besides the dependent measures used in the present research, distance judgment in 3D space can be included as an additional potential indicator of users' awareness performance. Performance variations in relation to the different viewpoint angles may thus provide new insight for generating design guidelines for configuring optimal viewpoint settings.

7.5 CLOSING REMARKS

Examining human-computer interaction through the lens of human ability to develop cognitive models and enhance interface design is, I believe, particularly apt and potentially fruitful. In this study, human navigation ability was investigated on the basis of interaction between users and a large scale virtual environment. It took a total of thirty-six participants, 216 testing hours to complete all three scheduled experiments. Experimental findings enrich the body of literature on navigation and orientation researches. Design guidelines will add to the database for the implementation of navigational viewing systems. Beyond the realm of this particular study lie more sophisticated conceptual models and developing algorithms. I would encourage readers who are interested in carrying research further to expand upon and refine this approach.

As with any project, this one has its weak points and boundaries. Camera movements have been extensively studied in movie industry for more than a hundred years. Strategies of camera settings for enhancing story-telling have been well established in the cinematography (Malkiewicz, 1989; Metuchen, 1987). Those strategies have once inspired the computer game designers to improve virtual camera animation in the virtual game space. They also provide abundant resources for viewpoint optimization in navigational viewing system design. The lack of communication between the academic research and the industrial development limited the pace in offering quality function and interfaces in this research. However, the applying of the conceptual model of dynamic viewpoint tethering into these areas is a natural extension. The future holds more work and more promise.