Perceived Smoothness of Viewpoint Transition in Multi-Viewpoint Stereoscopic Displays

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ABSTRACT

Three experiments were conducted to investigate the perceived smoothness of viewpoint transition in multi-view images. Different viewpoints of a stereoscopic scene were generated in real-time. The left-eye and right-eye views of each viewpoint were viewed stereoscopically, from a distance of 120 cm, with shutter glasses synchronized to the display. In Experiment 1, different vantage points of the scene were displayed as the viewer moved his/her head left and right in front of the display. Viewers rated the perceived smoothness of the scene for different viewpoint densities, i.e., number of viewpoints displayed per unit of amplitude of lateral movement, and extent of look-around, i.e., angular separation between the leftmost and rightmost rendered viewpoints. The second and third experiments were similar to the first with the exception that the change in displayed viewpoint was either controlled by the viewer's hand (Experiment 2) or occurred without any intervention on the part of the viewer (Experiment 3). Perceived smoothness improved with increasing viewpoint density in all three experiments. Perceived smoothness of viewpoint transition was affected by the extent of look-around, but the effect varied across experiments.

Keywords: multi-view stereoscopic display, perceived smoothness, viewpoint transition

1. INTRODUCTION

The great appeal of the new autostereoscopic systems is that they do not require specialized viewing hardware (e.g., stereo glasses) for stereoscopic viewing. Such achievement is obtained through the simultaneous presentation of multiple perspectives, or viewpoints, of a scene by means of directionally selective screens. In addition, these systems allow the viewer to perceive the stereo image even when he/she is moving, e.g., a lateral head movement. This critical ability is closely related to the number of viewpoints displayed by the system. However, the number of required viewpoints is also important with respect to other characteristics of such systems. Indeed, past investigations have addressed the number of views to be produced, i.e., captured or reconstructed, for accurate representation of scene content[1], as well as issues related to the quality, e.g., parallax discontinuity or "flipping"[2], naturalness[3], and comfort[4,5], of the stereoscopic image.

In this study, we examined another factor that might influence the subjective quality of the stereoscopic image in multi-view systems, namely the perceived smoothness of viewpoint transition. In a multi-view stereoscopic system, only one stereoscopic view is visible to a viewer at any given time for a specific head position. As the viewer moves his/her head from one point in space to another, the stereoscopic view that is being displayed changes correspondingly. A high quality multi-view system should provide viewers with images that do not change exceedingly between neighboring viewpoints. In part, the amount of change between viewpoints is determined by the disparity content of the image. However, the smoothness of the change might also be affected by the frequency with which new viewpoints are

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displayed for a given extent of head movement and the angular separation, in real space, between any two successive viewpoints. To assess the role of these two factors in determining the smoothness of viewpoint transition, we conducted three experiments. In Experiment 1, different viewpoints of a stereoscopic scene were generated in real-time and displayed as the viewer moved his/her head left and right in front of the display. We measured perceived smoothness of the scene for different levels of viewpoint density, i.e., number of viewpoints displayed per unit of amplitude of lateral movement, and extent of look-around, i.e., angular separation between the leftmost and rightmost rendered viewpoints. To evaluate the effect of head movement per se, we conducted two additional experiments. These experiments were similar to the first with the exception that the change in displayed viewpoint was either controlled by the viewer's hand (Experiment 2) or occurred without any intervention on the part of the viewer (Experiment 3).

2. EXPERIMENT 1

In this experiment, viewers rated the perceived smoothness of a stereoscopic scene as viewpoint density and extent of look-around were manipulated. Viewers examined a computer-generated visual scene as they translated their heads left and right in front of the display. They then rated the images on perceived smoothness. Ratings of perceived smoothness were obtained for different combinations of viewpoint density and extent of look-around.

2.1 Method

2.1.1 Apparatus

In order to perform the research we designed and constructed a test-bed that allowed us to simulate an autostereoscopic multi-view system. An overview of the system is presented in Figure 1. The system delivered high-resolution stereoscopic images and was controlled by a sensitive and low-noise head position measurement system. Computer software was used to generate, in real-time, different stereoscopic renderings of a scene from different viewpoints, each corresponding to a virtual camera position. For each virtual camera position, a left-eye and a right-eye view were generated. The center of the left-eye and right-eye views always corresponded to the center of the computer-generated image. Thus, the system implemented a toed-in camera configuration. The left-eye and right-eye views images were viewed stereoscopically with the aid of liquid-crystal shutter glasses (Crystal Eyes) synchronized to the display. Specifically, we used a time-sequential method so that the left-eye and right-eye images were temporally interleaved and displayed in synchrony with the opening and closing of the shutter glasses. The latter had a neutral light transmittance of 30% and response times of 0.2 ms and 2.8 ms for closing and opening, respectively. The spatial and temporal resolutions of the display were 1152 x 864 pixel and 118 Hz, respectively. Peak luminance was 55 cd/m^2. Viewing distance was 120 cm.

Viewers examined the computer-generated visual scene as they translated their heads left to right, and vice versa, in front of the display. A chin-rest connected to a movable carriage was used to guide and monitor viewers' head movement. A viewer could move the carriage, left or right, across a 20-cm long rail. The system provided a maximum of 78 samples of head position for each cm of linear movement on a 20-cm long rail. Thus the total number of head positions that could be recorded was 1560. To control the velocity of head movement, viewers were instructed to move their head in synchrony with the beats of an electronic metronome, which provided a periodic beep at a rate of 20 beats per minute. This resulted in a nominal velocity of 6.7 cm /sec of lateral head movement.

The position of the chin rest, and hence of the viewer's head, was used to update the position of the virtual camera. As the viewer moved his/her head along the 20-cm long rail the position of the virtual camera, whose optical axis was always centered at the center of the computer-generated scene, shifted along a corresponding virtual semicircular track. Accordingly, each head movement resulted in a new view of the scene, which corresponded to a new and different vantage point. The total number of viewpoints that could be rendered and displayed for a complete left to right movement equaled the total number of head positions that could be recorded, i.e. 1560.

Viewpoint density was measured as the number of rendered views presented per one unit of distance, in cm, of lateral movement along the 20-cm path. Note that 1cm on the 20-cm long rail equaled, at a viewing distance of 120 cm, 0.48 degrees of visual angle. Look-around extent was measured as the angular separation between the leftmost and rightmost rendered viewpoints (see Figure 2). Values of viewpoint density varied from 0.5 to 18 views/cm. Values of look-around extent varied from 9.5º to 180º. Ratings of perceived smoothness were obtained for different combinations of viewpoint density and extent of look-around.

Different combinations of viewpoint density and look-around extent were presented, in random order, to each viewer in a series of trials. Viewers used a game pad controller to start the presentation of each trial and to input their judgment of perceived smoothness response at the end of the trial.

Figure 1. Apparatus used to monitor the head position of the viewer, display the stereoscopic images, and record the viewer's response.

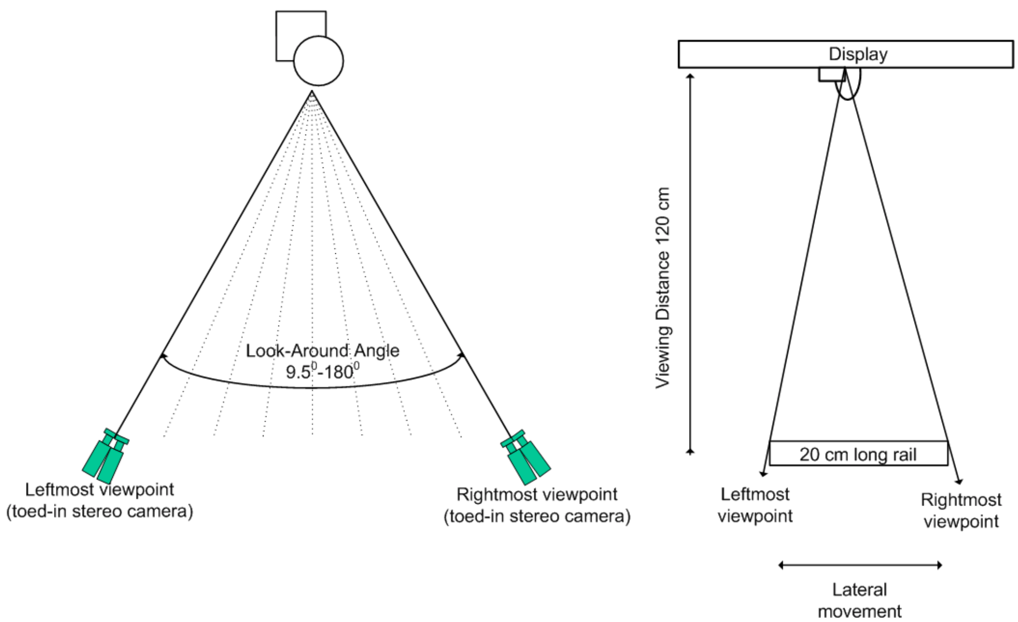

Figure 2. Definition of look-around and lateral movement used in this study.

2.1.2 Stereoscopic Scenes

Two computer-generated stereoscopic visual scenes were used. One scene, termed "Ball" consisted of a soccer ball positioned in front of a textured cube. The second scene, termed "Fantasy", consisted of several solid shapes consisting of a collection of cubes, spheres and a triangular block, placed at different distances from the camera. For each viewpoint, a left-eye and a right-eye view were generated by means of virtual stereoscopic camera. The inter-lens separation between the left-eye and right-view cameras was 65 units, which were taken as representing 6.5 cm. Both cameras were positioned 1200 units (i.e., 120 cm) from the centre of the scene, which was illuminated with a single light source. Thus, the stereo cameras were positioned at a distance that equaled the viewing distance of 120 cm. At this viewing distance, maximum disparity, either crossed or uncrossed, was 34 minutes of arc for the "Ball" scene and 28 minutes of arc for the "Fantasy" scene. Selected viewpoints for the "Fantasy" scene are shown in Figure 3.

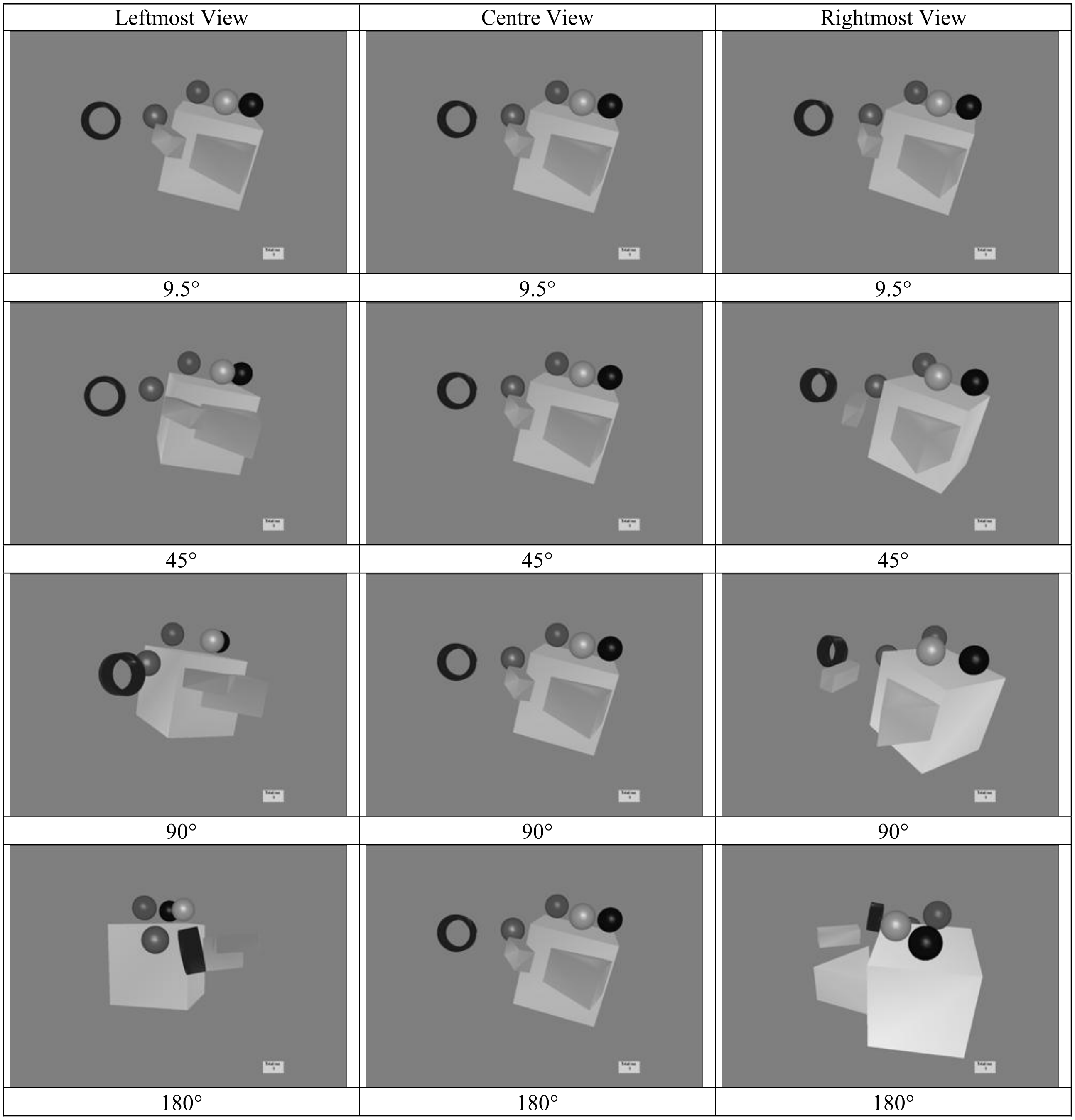

Figure 3. Leftmost, centre, and rightmost views from the "Fantasy" scene for different extents of display look-around.

2.1.3 Viewers

Eighteen viewers, with a mean age of 23.6, participated in this experiment. All viewers were screened for normal visual acuity and stereoscopic vision. Viewers had no knowledge of the purpose of the experiment, although most of the viewers had at least some previous experience with stereoscopic displays.

2.1.4 Experimental Design and Procedure

Changes in perceived smoothness were investigated for four extents of look-around: 9.5º, 45º, 90º, and 180º. Each extent of look-around was presented with a viewpoint density that was selected from the following: 0.5, 1.5, 3, 8, 18 views/cm. Therefore, there were 20 conditions (4 levels of look-around x 5 levels of viewpoint density), which required a corresponding number of trials for each viewer. Note that, at the viewing distance of 120 cm, the 20-cm long rail subtended a visual angle of 9.5º. Therefore, the 9.5º look-around exactly reproduced the viewpoints that would have been observed under natural conditions.

For each trial, the viewers were asked to look carefully at the images on the screen while moving their head left and right along the 20-cm long rail in synchrony with the beats from a metronome. Viewers were instructed to look at the display for as long as required and then rate the perceived smoothness of the stereoscopic images using an adapted ITU-R Rec. 500 scale[6] (see Figure 4). Viewers provided their subjective ratings by setting a slider that controlled the position of a marker on a rating scale on the display. The ratings of the two visual scenes: “Ball” and “Fantasy” were completed in separate sessions.

Figure 4. Continuous quality scale used for rating of perceived smoothness.

2. 2 Results

The pattern of ratings of perceived smoothness was similar for the two scenes; hence, the results were combined. These results are presented in Figure 5. In the figure, the symbols represent the average of the ratings obtained for the two scenes from all viewers. The lines are fitted curves calculated using the following logistic function:

$$Y = \underline{a} / (1 + \underline{b} * \exp(-\underline{c} * X))$$

where $\underline{a}$, $\underline{b}$, and $\underline{c}$ are the parameters controlling the curve’s asymptote, location, and slope, respectively.

As it can be seen in this figure, perceived smoothness increased as a function of viewpoint density up to an asymptotic value, after which ratings either leveled off or increased very slightly. The 45°, 90°, and 180° look-around conditions appear to level off at approximately 2-3 views per cm., whereas the 9.5° look-around conditions appear to level off at approximately 7 views per cm. From Figure 5 it is also apparent that perceived smoothness did not change significantly with extent of look-around. Specifically, the 45°, 90°, and 180° look-around conditions yielded very similar ratings of perceived smoothness at all viewpoint densities, and were only marginally better than those from the 9.5° look-around condition. However, this difference appeared to be more pronounced for larger viewpoint densities.

To corroborate these observations, a statistical analysis, the Analysis of Variance (ANOVA), was performed on the observed data. There were two factors: viewpoint density and extent of look-around. The analysis confirmed the presence of a highly significant main effect of viewpoint density ($p < 0.01$), but no effect of extent of look-around ($p = 0.15$). The interaction between viewpoint density and extent of look-around was also significant ($p < 0.01$).

Note that, given a constant viewpoint density, larger extents of look-around imply larger angular separations between two successive viewpoints. The observation that the 45°, 90°, and 180° look-around conditions provided higher ratings of smoothness indicate that larger angular separations between views do not necessarily correspond to a loss of perceived smoothness. It might be speculated that in these situations viewers experienced a type of "apparent movement" by which changes in the position of objects in the scene from one viewpoint to the next was not perceived as "jerky jumps", but rather as smooth movements. Perhaps, the sizeable changes and timing in viewpoint typical of the 45°, 90°, and 180° were more conducive for this apparent movement to be observed for the 9.5°condition. To evaluate the effect of head movement per se, we conducted two additional experiments.

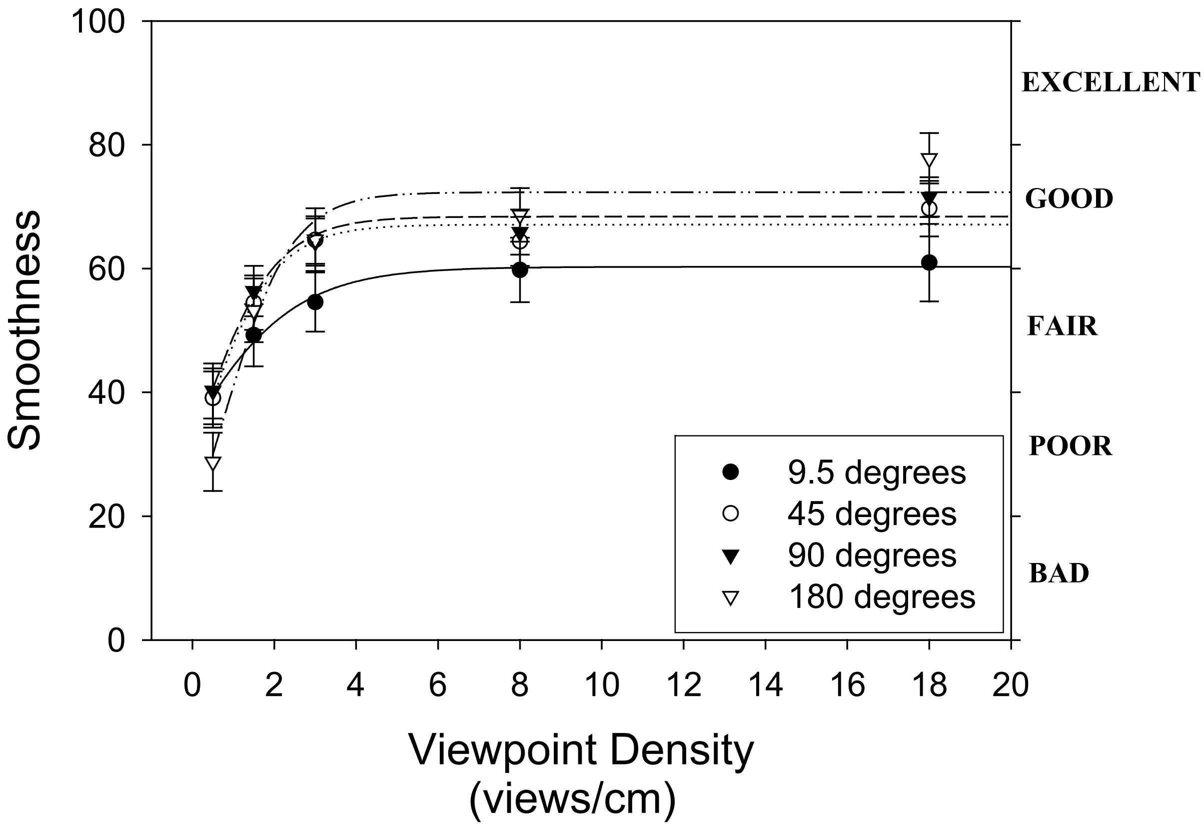

Figure 5. Results of Experiment 1. Perceived smoothness as a function of views per cm and extent of look-around. Each data point represents the average of the ratings obtained from eighteen viewers for the two visual scenes: "Ball" and "Fantasy". Error bars represent ± 1 SEM. 1 cm is equal to 0.48 degrees of visual angle.

3. EXPERIMENT 2

This experiment was aimed at assessing the role of head movements on perceived smoothness of viewpoint transition. The experiment was identical to Experiment 1 with the exception that the change in displayed viewpoint was linked to the position of the viewer's hand, rather than their head. Thus, in this experiment the task resembled the case of a viewer exploring a three-dimensional scene by means of a device such as a computer mouse or a joystick.

3.1 Method

3.1.1 Apparatus

The apparatus was the same as in Experiment 1.

3.1.2 Stereoscopic Scenes

The video material was the same as in Experiment 1.

3.1.3 Viewers

Fifteen viewers, with a mean age 22.8 years, participated in the experiment. All viewers had normal stereo depth perception and they were not aware of the purpose of the experiment.

3.1.4 Experimental Design and Procedure

The experimental design, procedure, levels of look-around, levels of viewpoint density were the same as in Experiment 1. In this case, however, viewers controlled the movement of the chin-rest connected to the movable carriage using their hands rather than their heads. To match the conditions of Experiment 1, also in this case, the viewers were instructed to maintain a velocity of movement of 6.7 cm/sec using, as an aid, the beats of the metronome.

3. 2 Results

The pattern of results for the two scenes was similar. The combined results are shown in Figure 6. As in the previous figure, the symbols represent the average ratings whereas the lines are fitted curves using a logistic function.

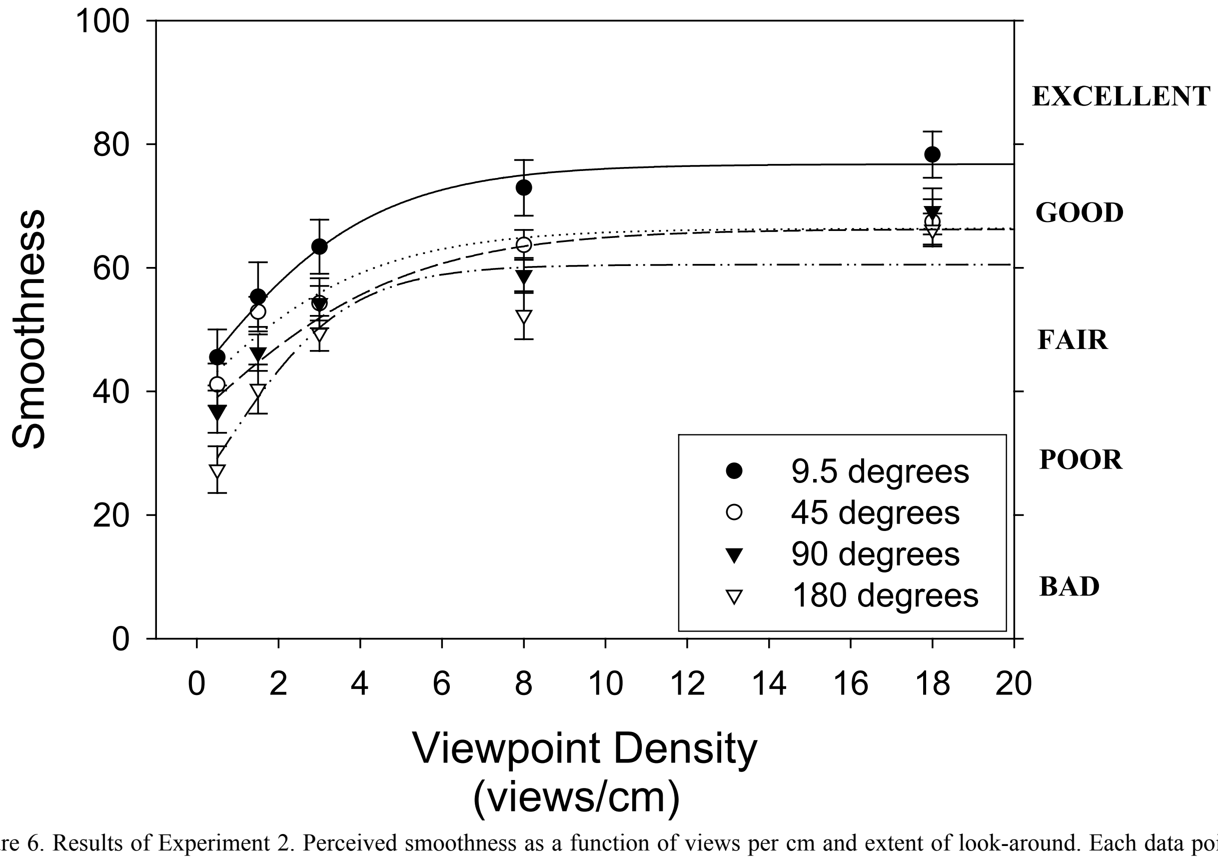

Figure 6. Results of Experiment 2. Perceived smoothness as a function of views per cm and extent of look-around. Each data point represents the average of the ratings obtained from fifteen viewers for the two visual scenes: "Ball" and "Fantasy". Error bars represent ± 1 SEM. 1 cm is equal to 0.48 degrees of visual angle.

The results obtained in this experiment differ in several aspects from those obtained in the previous experiment. First, there seem to be a slightly more pronounced effect of look-around and, contrary to what observed in the previous experiment, the 9.5° look-around condition resulted in better ratings of perceived smoothness than the 45°, 90°, and 180° look-around conditions. Secondly, it can be seen that ratings of perceived smoothness level off at viewpoint densities values that are somewhat higher, about 8 views/cm, than those observed in the previous experiment.

The Analysis of Variance (ANOVA), performed on the observed data, confirmed the presence of a highly significant main effects of viewpoint density ($p < 0.01$) and extent of look-around ($p < 0.01$), but no interaction ($p = 0.261$).

4. EXPERIMENT 3

Both previous experiments involved some form of active interaction with the display on the part of the viewers. In Experiment 1 the displayed image changed as results of head movements, whereas in Experiment 2, it changed as a result of hand movements. The results of those experiments differed somewhat, particularly for the 9.5°, suggesting that the need to interact with the display affected the perceived smoothness of viewpoint transition. In this experiment we investigated the role of the interaction. Specifically, we asked viewers to rate the smoothness of viewpoint transitions that changed without any intervention on the part of the viewer. The task was then equivalent to that of a motionless viewer passively watching a 3D scene that is rotating around its center.

4.1 Method

4.1.1 Apparatus

The apparatus was the same as in Experiments 1 and 2.

4.1.2 Stereoscopic Scenes

The video material was the same as in Experiments 1 and 2.

4.1.3 Viewers

The viewers were those that had participated in Experiment 2.

4.1.4 Experimental Design and Procedure

All aspects of the experimental design were the same as in Experiment 1 and 2 with the exception that, in this experiment, the transition from one viewpoint to the next was controlled by the computer and not by the viewer. The experimental conditions (20 experimental combination of 4 levels of look-around x 5 levels of viewpoint density) were the same as in the previous experiments. For each condition, the timing of change between viewpoints was set so that the total time required to move from the leftmost viewpoint to the rightmost viewpoint equaled the time it would have taken to move the chin-rest\carriage from one side of the rail to the other at a velocity of 6.7 cm/sec. Therefore, the rate of variation in viewpoints was nominally similar to that of the two previous experiments. From the point of view of the viewer, the scene appeared to rotate around the central axis on its own. As in the previous experiments, viewers were asked to rate the overall smoothness of the movement.

4. 2 Results

Figure 7 shows the combined results for the two scenes. The interpretation of symbols and lines is as in the previous figures. The results show that the 45°, 90°, and 180° look-around conditions yielded very similar ratings of perceived smoothness particularly at low viewpoint densities. The 9.5° look-around condition again differed from the other look-around conditions exhibiting better ratings of perceived smoothness at low viewpoint densities but similar, or lower ratings at higher viewpoint densities. It might also be noted that the curves are, in general, steeper than those observed in the two previous experiments and ratings of perceived smoothness leveled off at viewpoint densities values that are somewhat lower, about 2 views/cm, than those observed in the previous two experiments. The Analysis of Variance (ANOVA), performed on the observed data, confirmed the presence of highly significant main effects of viewpoint density ($p < 0.01$) and extent of look-around ($p = 0.05$), and a highly significant interaction ($p < 0.01$).

5. DISCUSSION

Multi-view autostereoscopic systems promise to be the technology that will finally bring stereoscopic imaging within the reach of the general public. However, multi-view autostereoscopic systems are an emerging technology

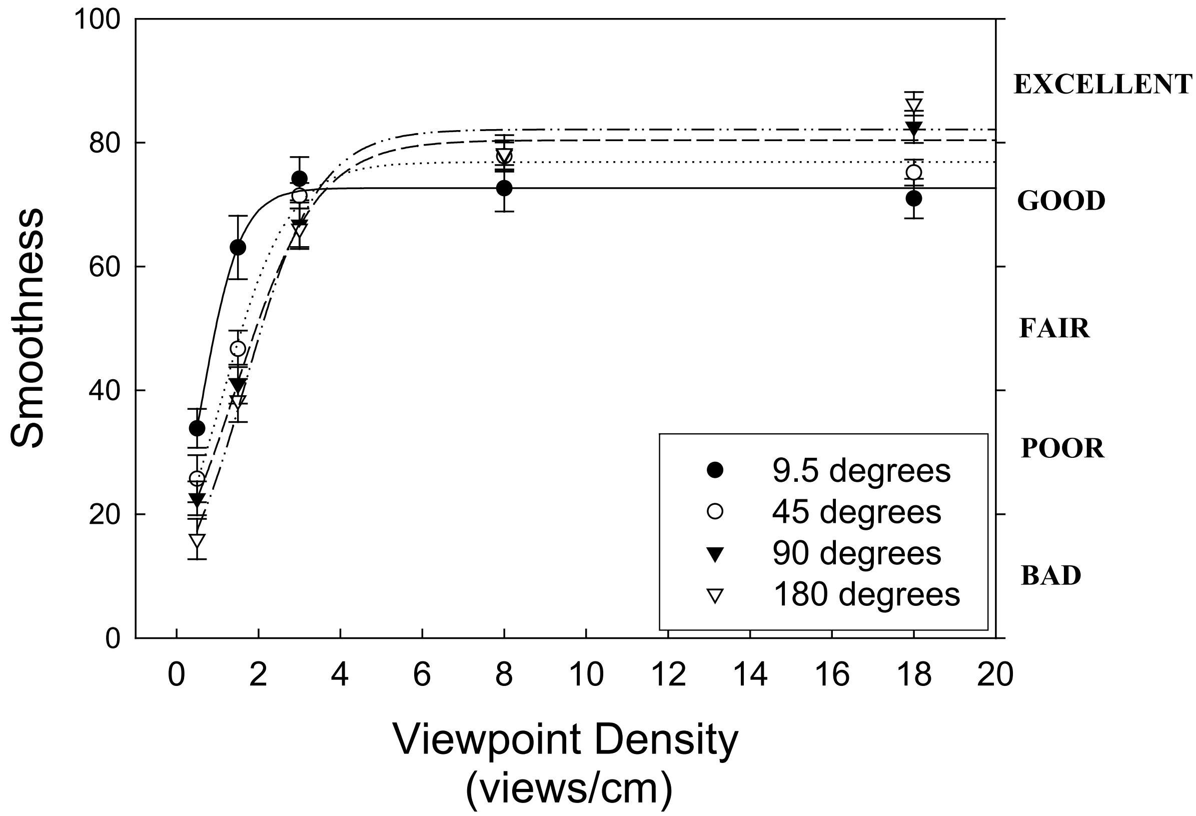

Figure 7. Results of Experiment 3. Perceived smoothness as a function of views per cm and extent of look-around. Each data point represents the average of the ratings obtained from fifteen viewers for the two visual scenes: "Ball" and "Fantasy". Error bars represent ± 1 SEM. 1 cm is equal to 0.48 degrees of visual angle.

whose technical requirements are still uncertain. One important issue is the number of views these systems should provide to deliver a satisfactory viewing experience to users. In this study, we addressed the issue of the number of required views in relation to the perceived smoothness of viewpoint transition.

To summarize the results obtained in this study, we have plotted in Figure 8 the viewpoint density required for a perceived smoothness level of 60, equivalent to "Good" in the quality scale used in this study (see Figure 3), for the four look-around conditions investigated in the three experiments. Note that Y-axis on the left shows viewpoint densities in views per cm, whereas the Y-axis on the right shows viewpoint densities in degrees of visual angle. The conversion between cm and degrees is easily calculated considering that, in the conditions of our experiments, 1 cm on the 20-cm long rail equaled 0.48 degrees of visual angle.

Recall that in Experiment 1 the displayed image changed according to head movements (Head modality), in Experiment 2 it changed according to hand movements (Hand modality), and in Experiment 3 the displayed image changed independently from viewer's action (Independent modality). The results show that the viewpoint density required for a "Good" perceived smoothness for the four look-around conditions varied across modalities of interaction. When the displayed image changed with head movements, viewpoint density was about 2 views per cm for the 45º, 90º, and 180º look-around conditions, but increased to about 7.5 views per cm for the 9.5º condition. The average across all look-around conditions was 3.4 views per cm. When the displayed image changed with hand movements, viewpoint density increased from about 2.5 to 8 views per cm. The average across all look-around conditions was 5.1 views per cm. Finally, with the independent modality viewpoint density was 1.3 views per cm for the 9.5º look-around condition and increased slightly above 2 views per cm for the other look-around conditions. The average across all look-around conditions was 2.1 views per cm.

The average viewpoint density across all conditions and experiments was 3.5 views per cm, or about 7 views per degree of visual angle. Note, however, that in a few instances viewpoint density reached a value of about 8 views per cm, or equivalently about 16 views per degree of visual angle. Accordingly, this viewpoint density might be considered a maximum, or ideal, value for it would provide a good perceived smoothness of viewpoint transitions independently on how such transitions are attained.

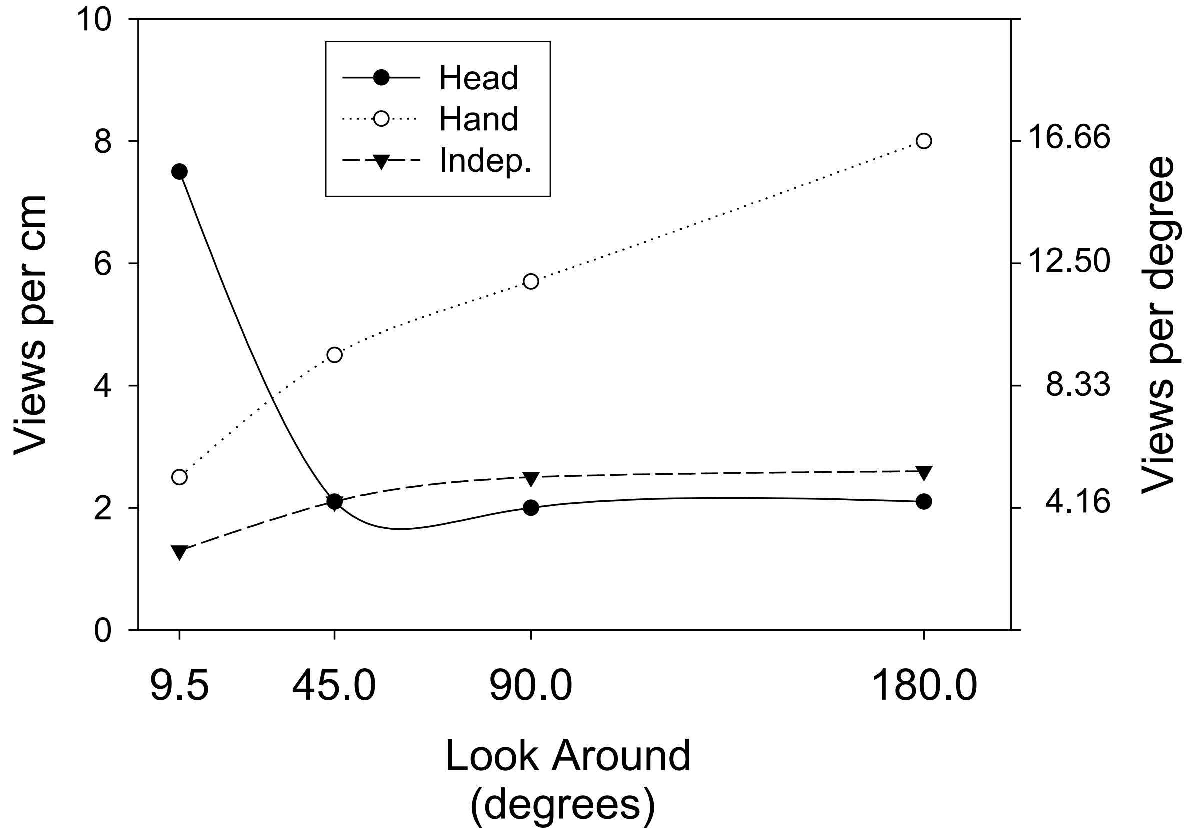

Figure 8. Average viewpoint density required for a perceived smoothness level of 60, equivalent to “Good” in the quality scale used in this study. See text for details.

6. SUMMARY AND CONCLUSIONS

In this study, we conducted three experiments to investigate factors that might affect the perceived smoothness of multi-view images. Computer software was used to generate, in real-time, different stereoscopic renderings of a scene from different viewpoints, each corresponding to a virtual camera position. In the first experiment, as the viewer moved his/her head left and right in front of the display new views of the scene were displayed, each corresponding to a new and different vantage point. Viewers were asked to rate the perceived smoothness of the scene for viewpoint densities: 0.5, 1.5, 3, 8, and 18 views/cm, and extents of look-around: 9.5º, 45º, 90º, and 180º.

The results of the first experiment suggested that the way the viewer interacts with the display might be important in determining perceived smoothness. Accordingly, two additional experiments were conducted to evaluate the effect of head movement per se. The second experiment was identical to the first one with the exception that the change in displayed viewpoint was linked to the position of the viewer's hand, rather than their head. The third experiment was also identical to the first two except that changes in viewpoints occurred without any intervention on the part of the viewer.

The results indicated that the viewpoint density required for perceived smoothness to be rated as being "Good" varied with extent of look-around, but this effect was different in the three experiments. In Experiment 1 (Head modality) the viewpoint density was approximately the same for the 45º, 90º, and 180º look-around conditions, but increased for the 9.5º look-around condition. In Experiment 2 (Hand modality) the same viewpoint density increased with increasing extent of look-around. Finally, in Experiment 3 (Independent modality) viewpoint density was low for the 9.5º look-around condition but increased slightly for the 45º, 90º, and 180º look-around conditions.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. H. Hoshino, F. Okano, and I. Yuyama, "A Study on Resolution and Aliasing for Multi-Viewpoint Image Acquisition", IEEE Transactions on Circuits and Systems for Video Technology, **10**, 3, pp.366-375, 2000.
2. S. Pastoor and K. Schenke, "Subjective Assessment of the Resolution of Viewing Directions in a Multi-Viewpoint 3D TV System", Proceeding of the SID, **30/3**,pp. 217-223, 1989.
3. D. Runde, "How to Realize a Natural Image Reproduction using Stereoscopic Displays with Motion Parallax", IEEE Transactions on Circuits and Systems for Video Technology, **10**, 3, pp.376-386, 2000.
4. T. Honda, Y. Kajiki, K. Susami, T. Hamagushi, T. Endo, T Hatada, and T. Fujii, "A display System for Natural Viewing of 3-D Images", in B. Javidi and F. Okano, *Three-Dimensional Television, Video and Display technologies*, pp. 461-487, Springer-Verlag, Berlin, 2002.
5. Y. Kajiki, H. Yoshikawa, and T. Honda, "Ocular Accommodation by Super Multi-View Stereogram and 45-view Stereoscopic display", The Third International Display Workshop, **2**, pp.489-492, 1996.
6. "Methodology for the subjective assessment of the quality of television picture", ITU-R Recommendation BT.500, 1974-2004.