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Perceptual Quality and Visual Experience Analysis for Polygon Mesh on Different Display Devices

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ABSTRACT Polygon mesh models have been widely used in various areas due to its high degree of verisimilitude and interactivity. Since the mesh models usually undergo various phases of signal processing for the purpose of storage, simplification, transmission, and deformation, the perceptual quality as well as the visual experience of mesh models are often subject to distortions at every stage. Therefore, investigating the perceptual quality and the visual experience of mesh models have become one of the major tasks for both the academia and industry. In this paper, we have designed two subjective experiments to investigate the perceptual quality and the visual experience in both the virtual reality environment and the traditional 2-D environment. Experimental results showed that there is no statistically significant difference in the quality perception between the two viewing conditions, independent of the model content, the distortion type, and the distortion level. On the contrary, there exists significant difference in the visual experience between the two viewing conditions under various factors. This paper helps researchers to better understand the quality perception behavior and the visual experience toward polygon mesh models.

INDEX TERMS Polygon mesh, virtual reality, perceptual quality, visual experience.

I. INTRODUCTION

Recent years have witnessed a continuously popularity of polygon mesh. Due to its simplicity in the data structure and conformance with graphics rendering hardware, mesh models are widely used in many different areas including computer graphics [1]–[4], industrial design [5]–[7] and geometry processing [8]–[10]. Polygon mesh usually undergoes various phases of signal processing for the purpose of compression [11]–[13], smoothing [14]–[16], deformations [17]–[19] and simplification [20]–[22]. These operations will inevitably result in the degradation of the perceptual quality, and may affect the visual experience of mesh models. To prevent the appearance of visual distortions and to improve the visual experience of end users, investigating the quality perception and the visual experience of mesh models are essential.

In early studies, targeting on the perceptual quality of mesh models, mean square error (MSE) [25] and hausdorff distance (HD) [26] are used to measure the distortion of mesh models. These metrics, however, are purely mathematical algorithms and were proved to be less consistent with the quality perception results of the human visual system (HVS) [27]. Therefore, investigating the subjective quality of mesh models and developing quality metrics based on characteristics of the HVS have been the main trends in the research field. Based on the experimental finding that the perceptual quality of mesh models is related to the roughness of the surface, Corsini *et al.* [28] proposed a perceptual metric to evaluate the performance of the watermark algorithms. Inspired by the principle of SSIM metric for the image quality assessment, Lavoué [29] proposed a Mesh Structural Distortion Measure (MSDM) based on the curvature, contrast and structure features of mesh models. Furthermore, Lavoué [30] improved the MSDM taking into account the multi-scale feature of the HVS. Wang *et al.* [32] proposed a fast mesh perceptual distance (FMPD) metric which considers the visual masking effect and psychometric saturation effect of the HVS. More recently, TPDM [33], DAME [34], [35] were proposed which also serve as reliable quality indicators for mesh models.

However, it should be noted that the above quality metrics of mesh models are based on the subjective quality assessment experiments using the flat monitor. As the virtual reality (VR) technologies were rapidly advanced in recent years, mesh models have become one of the most important scene representations in the VR environment. To our best knowledge, the perceptual quality study of polygon mesh models in the VR environment is still in absence. Therefore, investigating the perceptual quality of mesh models using the VR display device (e.g., the Head-Mount Displays (HMD)) is required in both the academic and industrial fields. It is unknown whether the subjective quality perception of end users in the VR environment is still the same as that in the traditional viewing environment. It is also unknown whether the objective quality metrics of mesh models in the literature can still functions as reliable quality indicators of the visual quality perceived in the VR environment.

Moreover, in recent years, the user-centric analysis of visual experience was introduced to measure the service quality as perceived by users, which gradually became a research focus in both academia and industry [36]. Therefore, besides the study of the perceptual quality, investigating the visual experience of mesh models is also necessary. In the VR environment, the visual experience of mesh models may be different from that obtained with traditional flat monitors due to the sense of presence and immersion [37]. It thus triggers the need to investigate how the viewing environment can impact the visual experience of end users. To our best knowledge, studies in this aspect only focused on investigating the presence of observers using dedicated questionnaires (e.g., presence questionnaire [38], Slater-Usoh-Steed questionnaire [39], [40], and the Temple Presence Inventory [41]). There is still a lack of study on the overall visual experience of mesh models. For mesh model designers and VR device manufacturers, it is significant to clarify the difference of the visual experience obtained with flat monitors and with VR devices. Research outcomes can provide guidelines to improve the quality of experience of end users and to enhance the performance of display devices.

In this paper, to address the issues as mentioned above, we designed two experiments to investigate the difference in both the perceptual quality and the visual experience between the VR environment and the traditional 2D environment. As standardized methodologies for conducting subjective quality assessment experiment of polygon mesh have not yet appeared, we first setup suitable experimental procedures for both viewing conditions. Then, a comprehensive statistical analysis in different aspects was conducted to analyze the quality difference of mesh models. In the second experiment, we designed a questionnaire from three perspectives, namely, the sensory factors (SF), the control factors (CF) and the realism factors (RF) to investigate the visual experience of end users. A comprehensive analysis was performed based on the questionnaire replies. Detailed explanations were made on the visual experience discrepancies between the two viewing conditions. Results of the subjective experiments can provide heuristic guidelines for further research studies.

This paper is organized as follows. Section 2 describes the setup of the two subjective experiments. Section 3 analyzes the experimental results in details. Statistical analysis is also conducted to check the statistical significance of the results. Conclusions are drawn in Section 4.

II. EXPERIMENTAL DESIGN

To address the issues as raised in the previous section, two experiments were designed. The first experiment targets on exploring the impact of viewing conditions on the subjective quality of mesh models. The second experiment aims at investigating the difference of visual experience between the two viewing conditions. Details of the experimental design are stated as below.

A. TEST ENVIRONMENT AND PARTICIPANTS

The mesh models were displayed on a 21-inch LCD monitor and a head-mounted display (e.g., HTC Vive), respectively. Both the monitor and the HMD feature a resolution of 2K. Note the HTC Vive provides the users a stereo vision with the monocular resolution being 1080×1200.

For the subjective quality evaluation of polygon mesh on the monitor, since standardized methodology do not exist, we thus referred to the rendering conditions proposed in [28] and followed the evaluation standard established for assessing the video quality (i.e., ITU-T Rec. P.913 [42]). Details regarding the test condition are shown in Table 1.

TABLE 1. Units for magnetic properties.

Viewing distance	about 60cm~75cm
Peak luminance	from 70 cd/m2 to 200 cd/m2
Illumination	about 500 lux
General chromaticity	white

For the subjective quality evaluation using the HMD, we also followed the rendering condition in [28], but further adapted it according to the viewing behavior in the virtual environment. The adjustments were made as follows:

- Scene interaction: in the VR environment, participants can change their viewpoints by rotating their head and moving around (as shown in Fig. 1). They can also scale

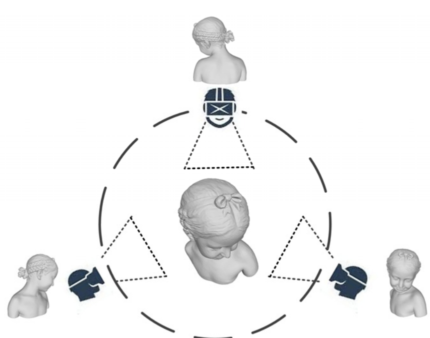


FIGURE 1. Illustration of scene interaction.

FIGURE 2. Illustration of five-point rating scale.

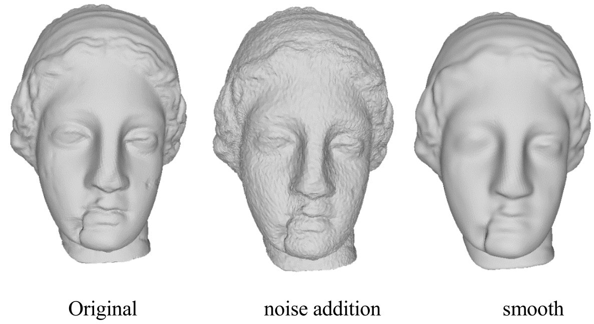


FIGURE 3. Illustration of the distortion types.

the mesh using the HTC Vive controller provided along with the HMD.

- Model rescale: in order to make sure the initial size of the models displayed on the HMD are the same as those viewed on the monitor, a rescale factor is determined for each model to adjust its size when viewed on the HMD.

Seventeen people aged between 20 and 27 years old participated in the subjective tests (average age = 26.5, standard deviation = 2.3), including 7 females (41.2%) and 10 (58.8%) males. All participants were university students in different grades and were screened for visual acuity and color blindness. None of them had previous knowledge about polygon mesh models. They were all voluntary for the test using their leisure time. To avoid potential visual fatigue, the maximum duration of observation was 15 minutes.

B. EXPERIMENT I: SUBJECTIVE QUALITY

1) STIMULI

According to the research finding in [31], the visual distortions induced during the process of mesh models can be generally divided into smooth and noise-like distortion. Therefore, we simulated these two types of distortions with Original noise addition smooth each in three distortion levels. Moreover, we distributed the above distortions to the reference mesh in four ways, namely the uniformly distribution over all areas, localized distribution over smooth areas (smoothing was not applied on smooth areas), localized distribution over rough areas and localized distribution over transition areas. Finally, a total number of 88 models were obtained for the experiment (4 original models + 4 models × 3 levels of addition noise × 4 distributions + 4 models × 3 levels of smoothing × 3 distributions).

2) PROCEDURES

In this experiment, participants were requested to score the quality of mesh on both the HMD (e.g., the HTC Vive) and the monitor, respectively. A rigorous training session was conducted to familiarize the subjects with all the distortion types as well as the distortion levels. Each subject was asked to observe 15 models (different with the content in the formal session) which cover the full quality range from bad to excellent. Subjects were expected to form their quality perception after the training session. In the formal session, the distorted models were randomly divided into 4 groups with each containing 21 models. Participants were requested to score the model quality following the ACR method as specified in [42]. A five-point categorical scoring scale (recommended by ITU-T P.913 [42]) was adopted in our experiment with the semantic terms being "Excellent," "Good," "Fair," "Poor," and "Bad" respectively. After observing each stimulus, a scoring interface was displayed to the participants, as shown in Fig. 4. To ensure the continuity of the experiment, the participants can directly score the mesh using the Vive controllers provided along with the HTC Vive headset without taking it off. Finally, a total number of 1428 (17 × 84) reply samples were obtained for each device.

FIGURE 4. The scoring interface used in the experiment.

C. EXPERIMENT II: VIEWING EXPERIENCE

1) STIMULI

In order to conduct a comprehensive investigation on the visual experience of polygon mesh, a total number of 20 models in different content were employed in the experiment, including four from the LIRIS EPFL GenPurpose database [31]. Among these 20 models, 6 were made by CAD, and the rest 14 were generated by 3D scanner. These models cover a wide range of diversity in terms of their visual complexity and their facet numbers (i.e., from 20K to 100K). Figure 5 illustrates three models chosen for the experiment.

2) QUESTIONNAIRE DESIGN

We used a questionnaire to acquire the participants' visual experience as questionnaires are widely used in

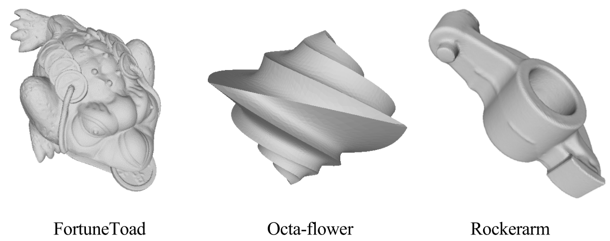


FIGURE 5. Illustration of three example models included in the experiment II.

social surveys. Recently, these questionnaires manifest themselves as effective in analyzing the user experience in the VR environments [38]–[41]. Famous design of questionnaires includes presence questionnaire [38], Slater-Usoh-Steed questionnaire [39], and the Temple Presence Inventory [41]. However, these questionnaires were mainly designed for investigating the immersion and presence of viewers in the VR environment. Some items contained in these questionnaires are less relevant to the visual experience of viewers, such as the items about auditory, haptic and interface quality. Therefore, in this experiment, we only selected relevant items from these state of the art questionnaires to form a new one that targets on the difference of visual experience between using the HMD and using the flat monitor. This questionnaire includes three kinds of factors, namely the sensory factors (SF), the control factors (CF) and the realism factors (RF). For the SF aspect, influential factors such as the stereoscopic vision (Item 1), the presentation of models (Item 2, 3), and the background (Item 4) were mainly considered. For the CF aspect, the location of viewpoint (Item 7), the distance between models and subjects (Item 5), and the disturbance of surroundings (Item 6) were considered. For the RF aspect, the vertiginous sensation, the visual fatigue to the model (Item 9 and 11), the impression and attraction to the model (Item 12, 13), and the consistency with real-world experience (item 10) were considered. A full version of the questionnaire is shown in Table 2.

Similar to the research in [37] and [38], a five-point rating scale is used in this experiment. A rating score from one to five corresponds to different levels of subject's perception [43]. For example, Figure 6 illustrates the rating scale for item 12 where a score of one indicates the model is not attractive at all while a score of five denotes the model is very attractive.

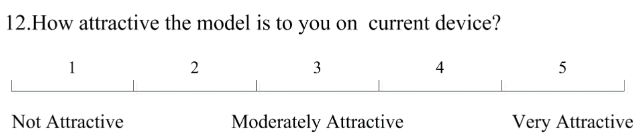


FIGURE 6. Illustration of the five-point rating scale.

3) PROCEDURES

At the beginning of the experiment, a training session was conducted to familiarize the subjects with the necessary operations (e.g., zooming and rotating) for viewing the mesh models on both the monitor and the HMD. In the formal session, the subjects were asked to fill the questionnaire after observing all models on the monitor and the HMD, respectively. This process resulted in two sets of replies corresponding to the visual experience using either the HMD or the monitor. A total number of 238 (17×14) reply samples for each device were obtained.

TABLE 2. Items of questionnaire.

Items	Subscale
1. How about the stereoscopic impression of the mesh model on current device?	Sensory Factors
2. How do you think the silhouette of the model displayed on the current device?	
3. How do you think the details of the model displayed on current device?	
4. How will the background interfere with you?	
5. How closely could you examine the mesh model?	Control Factors
6. How the surrounding interfere you when observing the mesh models on current device?	
7. Can you observe the model comprehensively from any viewpoint?	
8. Does the observe manner is in accordance with your habit of observing object in daily life?	
9. Do you feel vertiginous when observing the model on current device?	Realism Factors
10. Does your visual experience on current device consistent with your experience in the real-world?	
11. Do you feel visual fatigue when observing the model on current device?	
12. How attractive the model is to you on current device?	
13. How impressive the model is to you on current device?	
14. Do you think current device is proper for viewing the mesh model?	

III. EXPERIMENTAL RESULTS

A. RESULTS OF EXPERIMENT I

In this subsection, we aim to clarify whether the subjective quality of mesh models perceived in the VR environment is the same (or least in the same trend) as that perceived with a flat monitor. To do so, we first validated the reliability of the data obtained by the subjective experiment. We calculated the Pearson correlation coefficient (PCC) between different subjects for both viewing conditions. Experimental results show that the mean PCC values (i.e., calculated by averaging

TABLE 3. SROCC between objective metrics and subjective quality.

	FMPD	MSDM	3DWPM1	3DWPM2	RMS	GL1	GL2
Monitor	0.822	0.81	0.622	0.762	0.306	0.372	0.438
HMD	0.793	0.774	0.592	0.716	0.37	0.439	0.506

the PCC values between each subject's opinion score and the MOS) are 0.809 for viewing with the HMD and 0.819 for viewing with the monitor. Since both values of PCC are greater than 0.8, the result of subjective quality assessment can be used for further analysis [42].

Fig. 7 scatters the subjective quality scores for each mesh model under two viewing conditions. It can be seen that the data points are distributed along the diagonal, demonstrating that the subjective quality perceived on the monitor is almost the same as that perceived with the VR headset. It implies that quality perception of viewers maintains the same when the viewing condition is changed. Moreover, we verified the performance of seven well-known objective quality metrics according to the subjective quality scores obtained in both viewing conditions. The performance in terms of SROCC is listed in Table 3. A Wilcoxon signed rank test was further conducted to check the performance difference in two viewing conditions. Experimental results showed that there is no statistically significant performance difference with $P = 0.499$ (>0.05) at 95% confidence level. It demonstrates that existing quality metrics of mesh models functions in both the viewing conditions.

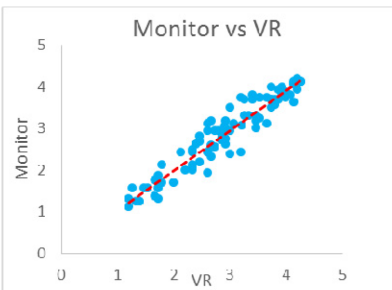


FIGURE 7. Scatter diagram of subjective quality scores.

To also check whether the quality perception difference between two viewing conditions is related to the intrinsic characteristics of mesh models, we further evaluated the impact of model content, distortion type, distortion level as well as the distribution of distortions on the subjective quality.

For different model content, as shown in Fig. 8(a), the quality scores acquired from two viewing conditions are similar independent of the model content. A Wilcoxon signed rank test further proved that there is no statistically significant difference in between for each case, with P>0.05 at 95% confidence level. We also found that, for each condition, "dinosaur" has the highest score in both conditions while "venus" has the lowest score. This is due to that

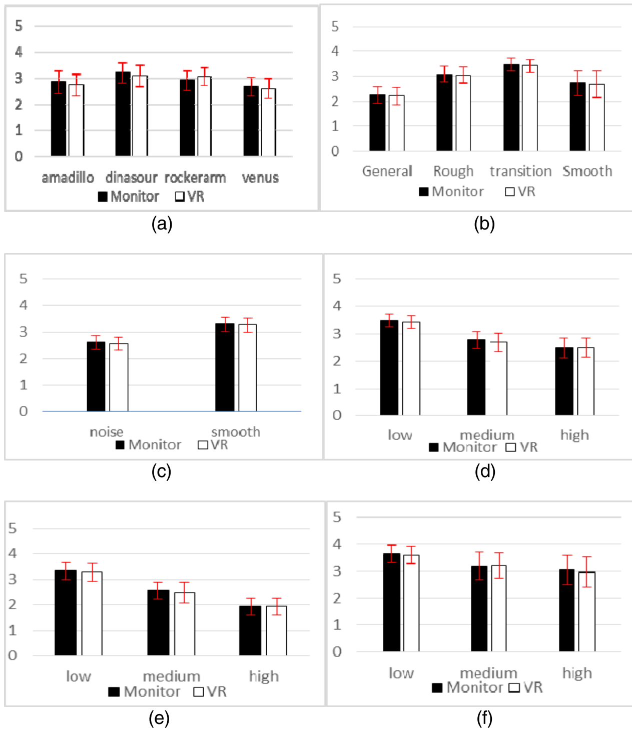


FIGURE 8. Visual quality comparison between using the monitor and the HMD. The height of each bar indicates the subjective quality score. Errorbars indicate the 95% confidence level. (a) Content. (b) Distribution of distortion. (c) Distortion type. (d) Distortion level. (e) Noise level. (f) Smooth level.

the "dinosaur" model contains much more high-frequency information than others. Distortions in this model can be visually masked to some extend [44]. In contrast, the "venus" is a simple sculpture of a head where distortions can be easily recognized around the flat face area, according to the study in [27].

For different distributions of the visual distortions, as shown in Fig. 8(b), the quality scores acquired from two viewing conditions are similar independent of the distributions of distortion. A Wilcoxon signed rank test further proved that there is no statistically significant difference in between for each case, with P>0.05 at 95% confidence level.

For different types of distortions, as shown in Fig. 8(c), the scores acquired from two viewing conditions are similar regardless of the distortion type. A Wilcoxon signed rank test also proved that there is no statistically significant difference in between for each case, with P>0.05 at 95% confidence level.

TABLE 4. Result of Wilcoxon signed ranks test.

	I1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Z	-3.61	-2.84	-.750	-.586	-3.46	-1.22	-3.36	-3.10	-3.14	-3.38	-2.55	-3.58	-3.70	-3.37
Sig.	**.000**	**.005**	.453	.558	**.001**	.222	**.001**	**.002**	**.002**	**.001**	**.011**	**.000**	**.000**	**.001**

"Z" represents the z-score of the Wilcoxon signed ranks test, Sig represents the p value.

For different distortion level, as shown in Fig. 8(d), there is no different in the scores acquired from two viewing conditions. The Wilcoxon signed rank test also proved there is no statistically significant difference, with $P>0.05$ at 95% confidence level.

Furthermore, we explored the distortion level dependency for each distortion type. As shown in Fig. 8 (e) and (f), noise-like distortions dramatically degrade the subjective quality of mesh models while the smooth distortions have a less impact of the quality perception of mesh models. It indicates that viewers may have more tolerance of smooth distortion than the noise-like distortion.

B. RESULTS OF EXPERIENT II

In this subsection, we aim to clarify whether the visual experience of mesh models on different types of display device has the same tendency. We first checked the validity of the data by performing a Cronbach's alphas test based on all the questionnaire replies. The results showed that the values of Cronbach's alphas are 0.805 and 0.866 for the monitor viewing and the VR environment respectively. As these values are greater than 0.8 in both conditions, we can conclude that the data collected in Experiment II can be treated as reliable ground truth [45]. The rating scores were further processed according to the data processing method in ITU-R BT 500.13 [46]. Mean opinion scores (MOS) were finally obtained to reflect the viewing experience of the participants.

To compare the visual experience between using the HMD and the monitor, as shown in Fig. 9, we first classified the scores in three aspects according to the setup of the questionnaire. Generally speaking, the MOS acquired using the HMD is higher than those acquired with the monitor. It should also be noted that the errorbars of the scores in the VR condition are smaller when compared with those in the monitor viewing condition, indicating that the participants are more consistent in their opinions when they observe the mesh models using the HMD. To further check whether there exists a statistically significant difference between the two viewing conditions, a Shapiro-Wilk test was first conducted to check the normality of the data. Since the data are not normally distributed, the Wilcoxon signed rank test, instead of the paired sample t-test, was employed to analyze the difference of experience between two viewing conditions. For the CF aspect, experimental results demonstrated that the viewing experience using the HMD is statistically significantly better than that using the monitor, with $P<0.05$ at 95% confidence level. It implies that the control factors have statistically significant impact on the visual experience. There, however, exists no significant difference for the other two aspects (i.e., RF and SF).

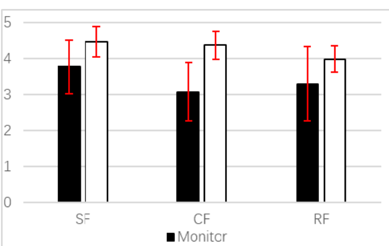
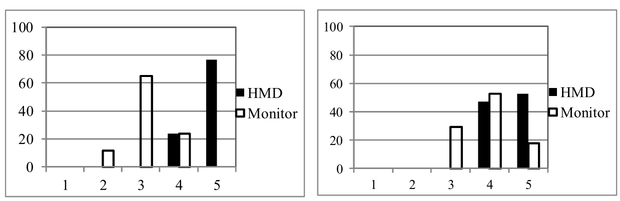


FIGURE 9. Viewing experience comparison between using the monitor and the HMD. The height of each bar indicates the subjective quality score. Errorbars indicate the 95% confidence level.

Moreover, we conducted the Wilcoxon signed rank test to further check the difference on individual questionnaire items. The results for each item are shown in Table 4. It can be found that 11 out of 14 items exist statistically significant difference between two viewing conditions. Figure 10 to Fig. 12 also illustrated the score distributions for each item in both conditions, with each corresponds to a single aspect in the questionnaire (i.e., SF, CF and RF, respectively). Among these 11 items, 2 items (Item 1 and Item 2) correspond to the sensory factors, 3 items (Item 5, Item 7, and Item 8) corresponds to the control factors (CF), and 5 items (Item 9∼14) corresponds to the realism factors (RF).



Item 1 (stereoscopic vision) Item 2 (presentation of silhouette)

(a) (b)

FIGURE 10. Distribution of the results from the perspective of sensory factors. The height of each bar indicates the percentage of the users rating a certain score.

For the SF aspects, as shown in Fig. 10(a), all the subjects rated the stereoscopic impression beyond "good" when viewing the models on the HMD, whilst most of the subjects (64.7%) felt a "normal" 3D sense on the monitor. As illustrated in Fig. 10(b), 57% of the subjects considered that there is a ''perfect'' silhouette of the mesh model when displayed on the HMD, while only 17.6% subjects agreed it when the mesh models are displayed on the monitor. The above results demonstrated that the HMD can provide better visual experience especially for the stereoscopic impression and the representation of the mesh. This suggests that the HMD is more appropriate for displaying polygon mesh models instead of the flat monitor.

For the CF aspect, as shown in Fig. 11(a) and 11(b), all the subjects reported a high degree of freedom when selecting the viewpoint and distance using HMD, while only 5.8% and 5.9% subjects thought they are free in selecting the viewpoint using the monitor, respectively. Moreover, as shown in Fig. 11(c), most subjects (91.4%) agreed that the observation manner under the VR condition is in accordance with their observation preference in daily life. On the contrary, only 17.6% of the participants chose monitor viewing condition as their preference. It, therefore, also demonstrated that the user perception research towards mesh models should be carried out with HMDs which mimics the natural viewing behavior of humans in the daily life.

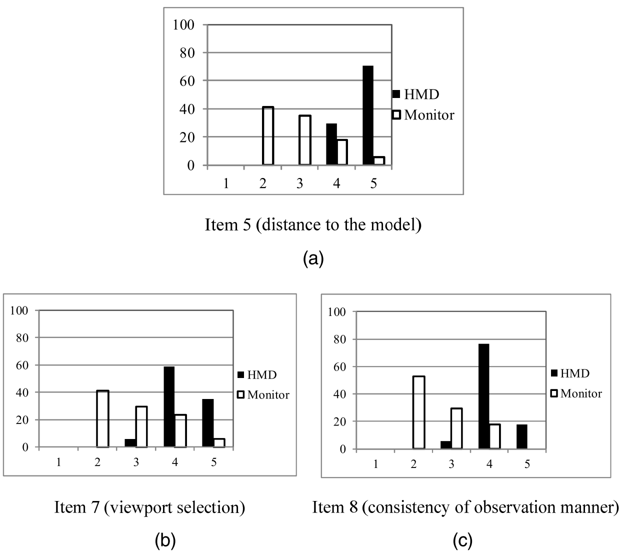


FIGURE 11. **Distribution of the results from the perspective of control factors. The height of each bar indicates the percentage of the users rating a certain score.**

For the RF aspect, as shown in Fig. 12(a) and (c), subjects are more likely to feel vertiginous when observing mesh models on HMD than observing mesh models on monitor. Despite of these negative effects of the HMD, 88.1% of participants agreed that their experience with the HMD is highly consistent with that in the real world, as shown in Fig. 12(b). Moreover, as shown in Fig.12(d) and (e), it can be found that more than 94% subjects agreed that the HMD can bring them a more impressive and attractive experience while only a few subjects (6%) chose the monitor instead. The above results demonstrated that although the HMD display system can trigger discomfort to some extent, it stills bring a better visual experience to users than that the monitor. This can be proved by the fact that nearly all subjects considered HMD as more proper device for displaying the mesh model, as illustrated in Fig. 12(f).

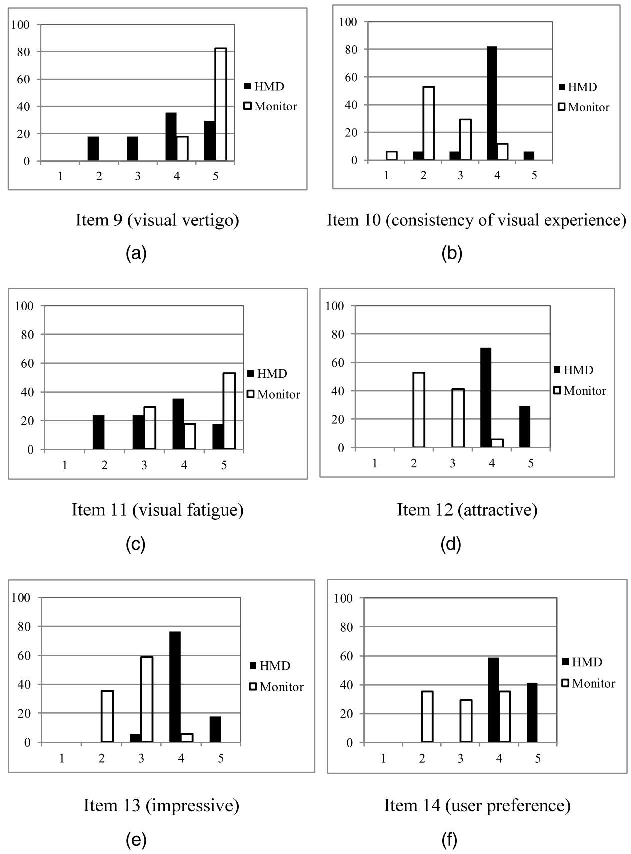


FIGURE 12. **Distribution of the results from the perspective of realism factors. The height of each bar indicates the percentage of the users rating a certain score.**

As discussed above, though the HMD triggers a sense of vertigo and visual fatigue to users, users still favor it as more proper viewing device due to its advantages in model presentation and man-machine interaction.

IV. CONCLUSION

In this paper, we investigated the perceptual quality and the visual experience of mesh models in both the VR environment and the traditional 2D viewing condition. First, we designed an experiment to explore the impact of viewing conditions on the perceptual quality of mesh models. A comprehensive statistical analysis from different aspects is conducted to analyze the quality difference of mesh models between the two conditions. Experimental results showed that there is no significant difference between the quality scores obtained in the VR condition and the quality scores obtained in traditional viewing condition, independent of the model content, the distortion type and the distortion level. Second, to investigate the differences of visual experience between the two viewing conditions, we designed a questionnaire in three aspects, namely, the sensory factors (SF), the control factors (CF) and the realism factors (RF). Experimental results showed that there is indeed a significant difference between the experience scores obtained in the VR condition and the experience scores obtained in traditional viewing conditions especially for the CF. Knowledge as the outcome of this paper is highly beneficial to the immersive media community to have a better understanding of the perceptual quality and the visual experience of polygon mesh. Our findings are valuable to guide developers of computer graphics and virtual reality to optimize the processing algorithms or the performance of devices.

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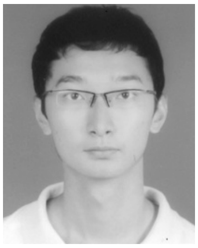

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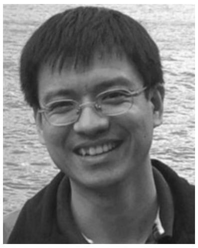

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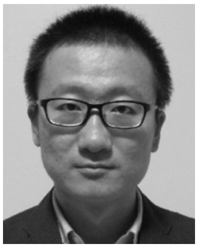

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