Exploring the Effects of Foveated Rendering on Virtual Reality Game Graphics

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***Abstract*—This study explores foveated rendering for its quality impact on players in virtual reality (VR) video game settings. Foveated rendering has the potential to decrease the performance cost by only rendering the part of the scene where the user is looking at a higher resolution, which it achieves with the use of an eye tracker. A user study is conducted to test the perceived visual quality by playing a fast-paced shooter game that requires many eye and head movements using a head-mounted display (HMD). The game is played with three different types of foveation: no foveation, static, and dynamic foveated rendering. Results show that the majority of participants did not notice a difference in the visual quality between the foveated and non-foveated game versions.**

***Index Terms*—Foveated rendering, Virtual Reality, Interactive Video Games**

I. Introduction

With the recent trend towards graphically complex games containing more populated and realistic scenes, the computational demand from video games has never been higher. Additionally, the recent move towards virtual reality (VR) makes it more crucial than ever that the games run with high, consistent frame rates. When running applications in VR, the framerate is essential, as a decrease can adversely affect the user experience [18]. VR also increases the pixel resolution requirement that needs to be rendered with high fidelity to immerse the player in the video game fully. Many techniques have been developed to minimize this computational demand, and foveated rendering is one of them [11]. Foveated rendering is a performance optimization technique that detects the game regions the user is looking at using an eye tracker. It renders this region at a higher resolution and reduces it in the peripheral vision, thereby optimizing the rendering resources. However, the effect of foveated rendering is not well-explored in the context of VR-enabled video games.

The human visual field is 135° vertically and 160° horizontally and is not uniform as the focus area only makes up around 5°. The acuity of human vision falls off rapidly outside the fovea [5]. This implies that only a small part of any HMD screen, corresponding to the fovea, rendered at a high quality might suffice to shape a good user experience. With foveated rendering, the gained performance can be used to render the scene with a higher FPS, which is preferable in video games and other real-time applications.

In this paper, we study the influence of foveated rendering on the perceived user quality in a VR-enabled game [15]. The chosen application is a first-person shooter game in VR, as it requires the user to focus and involves rapid eye movements. Furthermore, it necessitates low tolerance for latency and visual defects due to the amount of shifting gaze. The game has been designed around these requirements to make the user look around to find their target in the VR environment. Multiple studies have been conducted before to explore foveated rendering in a VR setting. However, this work is vital because foveated rendering has not yet been tested for visual quality when used for a video game set in virtual reality. To the end of the utility of this study, widespread adoption of foveated rendering could potentially make virtual reality games more accessible to a wider audience.

II. Related Work

A. Foveated Rendering

Foveated rendering is not a new technique; it has been further optimized each year that has passed. A survey by Wang et al. [19] shows how foveated rendering has been developed in the past decades and some still open questions and optimizations that could be made. Especially the topic of how to make people not notice the foveation masks has been studied thoroughly and has thus yielded multiple successful results. One of those studies includes Weier et al. [20] where they tested to see if people could confidently tell if foveated rendering was being used in the shown scenes or not. These environments had varying colors and patterns to test if any was more suspectable to artifacts, and one specific scene consisted of noisy and displaced geometry. Afterward, 15 participants had to answer a Likert scale on which most people said they could not reliably distinguish between foveated rendering on and off when the foveation mask was bigger than 10 degrees.

Weier et al. also studied the visual artifacts perceived by the users when a scene was still compared to moving. The results showed that the moving mode was rated significantly better in terms of visual quality. [20] Roth et al. [13] studied this as well and interpreted it as evidence for the visual tunneling effect, where the human brain filters out artifacts on its own when it is focused on the target. The concept was brought up again in another study, where it is mentioned that video games would need the extra computing power for physics calculations or AI agents that foveated rendering could provide. [14].

The potential performance gain in rendering was shown in a study by Meng et al. [11] to be over three times. However, these results were obtained by using raytracing rendered at a resolution of 3840×2160p, which is not realistic for a VR headset. Xiaoxu Meng also found a speedup of over two times when rendering the same scene with a rasterizer at a resolution of 1920×1080p. This shows that foveated rendering can potentially reduce the computational requirements for virtual reality video games. In a study by Diedrich et al., [4], the user impact of fixed-foveated rendering in VR was considered. Assuming that people preferred to look at the center of the HMD, that region in the scene was rendered at a high resolution. However, the results were still not satisfactory, and an eye tracker with a dynamic moving mask was suggested as the next thing to explore. Krajancich et al. [6] proposed attention-aware foveated rendering to reduce the computational bandwidth used for rendering.

B. Eye Tracking

Aizeman et al. [1] studied eye movements in a VR gaming environment by having people play four different video games, wherein one included a first-person shooter game. The results showed that people tended to make big head movements with smaller eye movements. That is to say that the participants mostly looked at the center of the headset instead of in the peripheral due to the restricted field of view in the HMDs. Albert et al. [2] performed a user study to find the acceptable amount of latency for the eye tracker in a VR application. Then, the participants view the same scene with varying levels of latencies multiple times. It was concluded that the acceptable latency level for humans ranged around 50 - 70 ms, while larger latencies produced an adverse effect. Arabadzhiyska et al. [3] also study system latency for foveated rendering applications, where they discuss and test some influencing factors, such as the orientation of the eye movement, the depth change, etc., for a model that would accurately predict fast eye movements to decrease the latency.

III. Method

Based on the prevailing assumption of foveated rendering, we have defined a hypothesis for our study:

Hypothesis: Participants will notice a difference in visual quality when the dynamic eye-tracked mask is active compared to standard rendering. While it is worth noting that the core concept of the proportional degradation in quality outside the mask would be comparable in both raytracing and rasterization settings, this work will be solely focused on rasterization.

A. Application

The developed application for this study was a first-person shooter game made by using the standard template in Unreal Engine (version 5.3) for VR games and the engine's programming language called Blueprint. The use of a first-person shooter game is justified for this study since it involves multiple fast eye movements and accuracy and precision to shoot them. The visual graphical quality in games could be affected by foveated rendering, which is important to explore further. This also places high demands on the foveal masks to keep up with the users' eyes.

The application consists of an immersive 3D environment where the player is given a gun to shoot at targets. After a target has been hit, it temporarily disappears for 0.2 - 2 seconds and then respawns at a given position. A total of five spawn points exist and will be randomized every time until the target has been shot 10 times. The reason behind this design is that the player should be unable to predict the target's place and stay focussed on the game. The spawned target positions are at most 90 degrees to the right and left from the center to get the user to turn their head and eyes around the scene. To simplify this study, the participants remained stationary at the place of the three arrows by the gun and could see the game environment in three dimensions while being able to move the camera with their head [15].

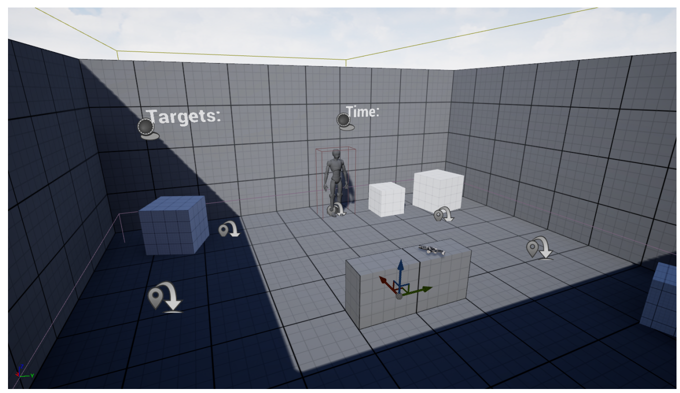


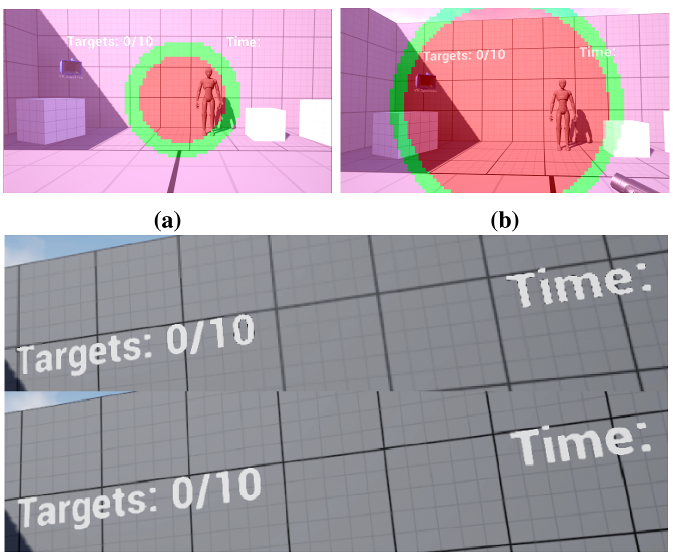
Fig. 1: An overview of the VR game environment where the players tested the foveation masks. The arrows placed on the floor are the different spawn locations for the target dummy.

B. Research method

The impact of foveated rendering on the visual quality was studied through an experiment conducted as a user study. It involved participants playing the same game in three rounds with different versions of foveated rendering. Afterward, a questionnaire was answered regarding the user's experience. The tested variables are dynamic foveation, fixed foveation, and no foveation. Dynamic foveation is achieved using an eye tracker, wherein the foveal mask dynamically shifts to align with the user's gaze, focusing only on the specific area where their eyes are directed within the scene. Fixed foveated mask differs in that it does not follow the eyes and instead stays focussed around the center of the headset's display. In the non-foveated version, the whole display always gets rendered in full quality. These techniques will be the only independent variables tested for this study.

As a part of the questionnaire, the dependent variables included a timer to measure how long it takes for the participants to complete the objective in the gameplay and the number of targets to shoot for each test. The participants were also allowed to express their subjective opinions in the survey. The use of VR for a prolonged time is also known to cause discomfort, which could contribute negatively to the results. To mitigate this as much as possible, the experiment was run in a randomized order as well as to get a non-biased result. This way, it can be explored if any of the masks have more of an impact than the others. The participants were also offered short breaks between the test runs to minimize the feelings of discomfort further.

Foveated rendering: The masks used for foveated rendering consist of two layers, where the inner layer (the red part) has a higher sampling than the outer one (the green part), see Fig. 2. The remaining scene outside the foveated mask is rendered at the lowest resolution. For the dynamic foveation, the inner mask area covers 15%, and the outer mask area covers 20% of it (Fig. 2a). When fixed foveation is used, the inner area is 35%, and the outer area covers 40% (Fig. 2b). These sizes were chosen as they were distinct enough to possibly receive different responses from the users, as well as trying to get as much performance gain as possible. Fig. 2c shows the quality difference in the text using the corresponding masks, where the top instance shows the text being rendered with the dynamic mask while the bottom shows the scene being fully rendered with no special mask in use.



(a) (b) (c)

Fig. 2: The mask used for (a) dynamic foveated rendering, (b) static foveated rendering, and (c) the image and text quality visible to the participants corresponding to these masks in our VR game.

We used *variable rate shading* rendering method available in Unreal Engine 5.3, as it can allocate varying amounts of rendering resources in different regions across the scene. This implies that the innermost sampled area in the mask has a resolution of 1x1. The next layer, the green zone, has a resolution of 2x2, where the pixel shader is called upon for every fourth pixel, and the outmost area is called upon once every 16 pixels, with a resolution of 4x4 [16].

Hardware: The computer used in this test was an Intel i5-9400F with NVIDIA RTX 2060 GPU and 16 GB of RAM. The VR headset was a modified Meta Quest 2 by Tobii, which has a resolution of 1832×1920 per eye and a refresh rate of 90Hz [12]. It was also calibrated for every new person before the tests started so as not to affect the visual quality.

C. User Study

For the user study, the participants were asked to consider the quality of the scene while playing each game and then required to answer the questions following each round (dynamic foveated, static foveated, not foveated). All participants were also given the option to try the game itself before the formal round began. No other information was given, as the participants should be able to play the game freely. The whole procedure, on average, took about 5-10 minutes.

The questionnaire was divided into three parts; the first part was conducted before any game was played to get some preliminary information. This included information on participants' age, gender, familiarity with VR, and playing video games. After each game round, the participants were asked targeted questions regarding the game they had just played. These questions asked about the sharpness of the scene and how much eye strain was felt. There was also the option to provide qualitative comments if they wanted to. When the questions about the final game were answered, a few more inquiries about the overall experience were presented. This included asking the players if they noticed any difference between the three games in terms of visual quality.

IV. Results and Analysis

The experiment was conducted inside our university campus. We excluded participants who did not have a normal or corrected normal vision for this experiment, as it was essential for them to judge the potential degradation in visual quality. The experiment took three consecutive days to complete, and a total of 23 individuals volunteered to contribute to the results. Out of all of them, five wore vision glasses. However, only three participants mentioned they had difficulty answering questions regarding the quality of the game. Hence, they were excluded from the results, resulting in a total of 20 valid responses. The gender of the participants was dominantly male, with only one female. On average, the people were unfamiliar with VR gaming. Almost all of the participants had played VR games a few times or never, with only one being a regular player. However, most participants played a lot of non-VR games. The ages ranged from 18-49, with most people in the range between 18-29 years old, two participants being 30-39 and only one being 40-49.

The latency of the eye tracker was calculated to be 8 milliseconds, and the headset had around 60 milliseconds. As mentioned by [2], this means the total latency was in the acceptable range of 50-70 ms, and hence nondisturbing to the participants. The frame rate of the game stayed above 60 fps at all times.

A. Game Specific Results

In this section, the results of the participants' ratings of the visual quality of each technique, as assessed in the VR game, will be presented. The evaluated techniques involved fully rendered scenes without any foveated rendering, a fixed mask that remains stationary and centered in front of the user, and a dynamic mask that adjusts with the eye tracker. Each participant tested all the masks separately; the order was randomized, and after every play test, they answered a questionnaire.

Players rated the visual quality from 1-5, from "Not sharp" to "Sharp," and always had a choice not to answer at all for every question asked. The participants noticed some degradation in the image quality between different variants of the gameplay (Fig. 3a) insofar as sharpness is concerned (1-not sharp, 5-sharp). However, the score difference is very small when using no, static, and dynamic foveation. Fig. 3b shows the results of how much eye strain participants felt during the playthrough (1- no strain), 5- much strain), where the average score was not much different from each other. Fig. 3c shows the participants' responses to the question about blurriness affecting gameplay. As can be seen, a majority of the players chose the option "No" for the dynamic foveated VR version of the gameplay, implying that the blurriness did not affect the visual quality of the game.

Of the participants, about 61.1% answered "No" to finding any game type to be different in visual quality (Fig. 4). The other 38.9% can be explained by how Fig. 3 has some different ratings for the questions. The static mask had, for example, a noticeable edge if you knew where to look, which could have been seen by the participants who rated it the worst, making the graphics inconsistent between the games.

B. Statistical Significance

Since the data from this user study does not follow a normal distribution pattern, we performed statistical significance analysis using the "Mann-Whitney U" [8], [10] test instead of the T-test [7]. The result is shown in Tab. I. These values support the null hypothesis by rejecting the original hypothesis. For this study, the null hypothesis is: "Participants will not notice a difference in visual quality when the dynamic eye-tracked mask is active compared to standard rendering."

Header:	No mask vs. Static mask:	No mask vs. Eye tracked mask:
Sharpness	0.34827	0.20045
Eye strain	0.31207	0.29116

TABLE I: The statistical significance for two of the questions asked, the first one being how sharp the scene was and then how much eye strain was felt.

V. Discussion and analysis

In theory, the game type with no foveated rendering or "No Mask" should produce the clearest results since the whole scene gets rendered in full quality, as well as leading to the lowest levels of eye strain. However, the findings in Fig. 3 suggest otherwise. The discussions in the following are based on comparing the results for the different masks with the fully rendered "No Mask." Due to the limited number of participants, it may be insufficient to draw conclusive results. However, some trends emerge, which will be analyzed here.

A. Static Foveated Mask

As shown in Fig. 3b, the amount of eye strain was reported to be lowest for the static mask. The reasoning for this might be that the HMD used in this study has distortions at the edges of the display, which might be distracting. The static mask helps mitigate this effect by rendering the edges of a lower quality, making the distortions less noticeable. Regarding the sharpness of the scene Fig. 3a, this mask shows the best results as well. A reason for that could be because it has more contrast between the higher and less-rendered zones, making the users more aware of the sharpness, thereby leading to a higher perceived visual sharpness. Also, as can be seen in Fig. 3c, most people were affected by the blurriness when the static mask was active. Although the overall number of participants who answered "Yes" did not differentiate much between the different masks, this could thus be considered to be the fault of the human factor.

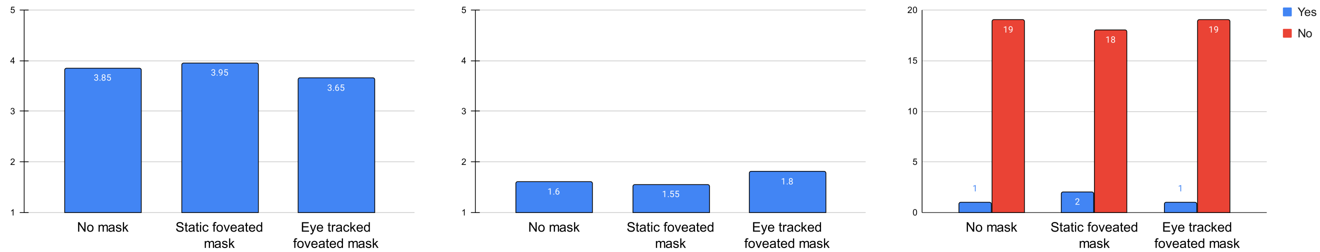
B. Eye-Tracked Foveated Mask

The participants reported that the application of the dynamic foveated mask led to the least perceived sharpness. However, it could result from the eye tracker and display latency, which happens when the participants have to move their heads and eyes around in fast movements. Since the added latency concluded to be around 68 milliseconds, it is still within the preferred interval of 50-70. However, since it is closer to the upper limit of this range, there could still be a negative impact on the user experience. The mask also produced the most eye strain. This could be caused by the latency as well and the HMD making it slow to render the new part of the scene in full quality, which takes a toll on the eyes as it needs to adjust quickly. Furthermore, the area outside the mask was rendered pixelated and not blurry, which does not make it look natural and might strain the eyes more.

C. Comparing the Masks

As noticed before, most people reported an inability to differentiate the visual quality between the game types, with 61.1% answering "No." However, the participants seemed to disfavor the eye-tracked mask since it received a worse rating compared to the other types. The other masks are also expected to be preferred as the fully rendered mask has no drawbacks in this study. Although foveated rendering might prove to be useful for larger and more performance-demanding games. However, since the performance cost is not considered in this study, dynamic foveation proved to not be preferable for the gameplay, and the static mask was preferred the most.

VR also creates a heavy demand for the computer with its special requirements, especially when using a head-mounted display with many pixels to sample. Because of this, blurriness



(a) Sharpness **(b)** Eyestrain **(c)** Blurriness

Fig. 3: Average participant rating for (a) sharpness on a scale of 1 (not sharp) to 5 (sharp), (b) experienced eye strain on a scale of 1 (no strain) to 5 (much strain), (c) if the blurriness affected the gameplay, in our developed VR game.

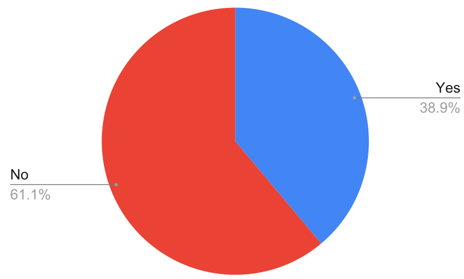


Fig. 4: The number of answers for "Yes" and "No" when asked the question, "Did you notice a difference in the visual quality of the games?".

in the scene is a common occurrence. This means that since most people in this test were not experienced in playing VR games, some answers might have been affected by their lack of knowledge of its blurriness and could have, therefore, given the masks a worse result. Hence, the difference in the masks should be the factor to focus on, not what rating they received.

D. Implications of Results

All of the data shows a small margin in almost all results for our designed game, implying no real difference in the perceived quality of any of the images between different masks employed. If any performance can be gained from using any of the foveated techniques, then it is a clear benefit with almost no drawbacks. This is further explained by Weier et al. [20] and Roth et al. [13], [14] as how people filter out artifacts when focussed on a moving scene, especially in video games where events trigger changes in visuals, causing them to be less susceptible to graphical inconsistencies. This could be further explored by decreasing the mask size or having a worse quality outside of the masks to see at what point people would notice when they are focused on the game. However, to make this study more conclusive, more colored objects should have been included in the scene to see if the mask could handle contrasts.

To render with a dynamic mask, the headset needs to have an eye tracker built into it as an HMD covers the user's eyes; an external eye tracker would not be enough. This is a requirement that will not always be met as the list of commercial HMDs with eye trackers is limited. However, any headset can use a fixed mask as it is a technique that is made on the computer that renders the images. Judging from the results presented in this study, foveated rendering seems promising as it does not affect the users much. If performance metrics were to be considered on top of it, it could replace the fully rendered scenes.

If more headsets start to include inbuilt eye trackers, foveated rendering could become a popular technique. This study especially shows that most participants did not notice a significant difference between the masks when playing this game. The game has its limitations; however, we anticipate that it provides an informative job of generalizing most games. With the speedup benefit of the foveated rendering or raytracing, as also observed in [11], the requirements for VR games could be decreased significantly.

A potential problem that could occur from using foveated rendering with a dynamic mask is the variance in latency between systems and headsets. As discussed previously, having too high latency might lower the potential gain in performance and lead to a negative result for the user if the mask is too small for their latency. These two techniques can also withstand future changes or developments, as even when computers become powerful enough to render high-quality games, foveated rendering could be used with raytracing. Meng et al. [11] showed a greater increase in performance gain when used with those techniques as well.

1) Headsets: While these results apply to the specific headset used, we believe that the results would not change much when using other HMDs. If a headset with a greater field of view (FoV) were used, more of the low quality of the human fovea would be rendered while the mask sizes stayed the same. A study by Masnadi et al. [9] has found that a headset with greater FoV increased players' ability to distinguish distances in VR. The headset used was a Pimax 5K Plus with up to 200° FoV. If a Pimax 5K Plus were used for this study, the results would most likely look different as the greater FoV would change how big the static mask appears and lead to more of the participants noticing the edges of the mask's zones. The increase in available screen space would also lead to more participants looking more to the sides as more of it is displayed. The results for the dynamic eye-tracked mask should be the same as it would follow the eyes to the sides of the headset.

If, instead, HMD with higher resolution were to be used, the results from this study would probably be the same as well. A study by Wang et al. [17] has found that headsets with higher resolutions lead to a higher-quality gameplay experience and lower symptoms of cybersickness. However, these benefits did not increase further beyond a resolution of 2k. A higher resolution headset would benefit all the masks equally if the FoV is the same. This is because the masks try to render what the user is looking at with high quality, which would be the same for all the tests done in this study.

E. P-Value

Table I mentions that the p-value obtained from analyzing the questions was high at around 0.3. It's worth noting that p-values below 0.05 are typically considered significant. This high p-value suggests that the null hypothesis, which assumes no difference between the masks, is more reliable than the hypothesis. Our hypothesis stated that participants would be able to perceive a difference between the masks, while the null hypothesis implies that the difference between masks would not be noticed. Fig. 3a-3c showing the results also support this claim.

F. Limitations

A limitation of this study includes not having settings derived from a commercially developed game. Objects in the background are also often reduced in complexity to save performance. However, this study did not have any such objects to test how they would interact with foveated rendering. The focus of the lenses for the headset was not fitted for each participant, which could have made the scene seem more blurry than it actually was and, therefore, could have influenced the results to some extent. However, the visual quality would still be consistent through the different masks since it would have affected all of the game types similarly. Another limitation could be the inexperience of some players in using VR environments, leading to a higher or lower critical evaluation.

VI. Conclusion

In this study, foveated rendering in VR was tested for its perceived impact on visual quality in a first-person shooter game. A user study was conducted, and participants were asked for their opinions using a questionnaire. The results showed that most people could not tell the techniques apart and, as such, had no preference between them.This could affect the industry due to the foveated rendering finding a wider adoption of VR-based games for performance optimization, which could potentially lead to VR becoming more affordable and accessible to a wider group of people. However, the dynamic mask, which uses an eye tracker to render only a small part of the screen in high quality, might take time to be adopted into the industry as it requires an HMD with a built-in eye tracker. On the other hand, the fixed mask can be used with any headset and should become a feature for most VR games as it was not perceived to impact the game negatively. In the future, exploring different sizes of foveated masks would be an intriguing topic worth investigating. Another direction to continue this research would be to conduct a similar study in a more action-packed game environment.

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