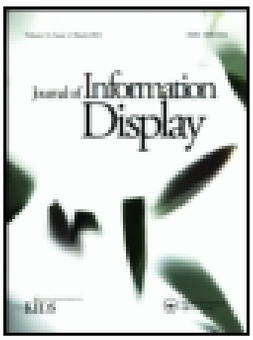

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Do users perceive the same image differently? Comparison of OLED and LCD in mobile HMDs and smartphones

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ABSTRACT

The two leading panel types in the current smartphone market are OLED (organic light-emitting diode) and LCD (liquid crystal display). Even though OLED is known to show more vivid and brighter colors, however, LCD is still dominant in the market. In the rising era of HMDs (head-mounted displays), the present study examined which panel the consumers prefer in the smartphone and HMD context by investigating the characteristics of panels as perceived by the consumers as well as the consumers' VR (virtual reality) material preferences. The characteristics of the different panels as perceived by the consumers were extracted, and the users' VR material preferences were ranked. The study findings indicate that OLED should be used for HMDs to increase the consumers' satisfaction. Furthermore, the users did not find any significant difference between the two different luminance values of the OLED panel that was used for the study, which indicates that the luminance of the panel can be optimized for a comfortable and satisfying HMD viewing setting.

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HMD; smartphone; OLED; LCD; perceived characteristics; luminance

1. Introduction

Mobile display technologies are rapidly developing, and display panel types like OLED (organic light-emitting diode) and LCD (liquid crystal display) became important criteria for consumers to consider when purchasing a smartphone. Manufacturers promote their smartphones focusing on the display panel type used, arguing that the panel provides their consumers better user experience. Under this circumstance, much attention has been given to the technical distinction between the panels, such as the energy consumption, viewing angle, resolution, and flexibility. Even though the importance of the user experience on top of the technological specifications should not be ignored, the psychological effects of the different display panels on the user experience have not yet been investigated much and deeply [1]. Furthermore, while the world is witnessing the rapid upsurge of the mobile HMD (head-mounted display) market [2], the consumers' different perceptions of OLED and LCD have not yet been investigated.

As such, in this study, what display panel the consumers prefer for both smartphones and mobile HMDs was investigated. In particular, it was investigated if there is a specific type of display panel that the consumers prefer for mobile HMDs, and if the consumers prefer the same display panel for their smartphones. The consumers' perceptions of the characteristics of the display panels were also investigated. The paper was concluded by discussing the possible ways of providing a panel that the consumers can enjoy and feel comfortable with.

This study has two key contributions. First, the perceived characteristics that the users employ to evaluate images on HMDs and smartphones were revealed and explained. Second, the study empirically investigated the users' preference between OLED and LCD for HMDs and smartphones, and showed that the users' display panel preference may differ depending on the context. Lastly, the study proved that the users do not necessarily prefer brighter luminance for their HMDs when the luminance reaches a certain level, as the users in this study did not find any significant difference between the two different luminance values of the OLED panel that was used for this study.

2. Related works

The advancements in display technologies and other capabilities, including a superior computer graphic interface, have made HMD popular as a consumer product [3]. The use of HMDs in entertainment and video gaming

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has increased significantly of late. More than 200 million consumer HMDs are expected to be sold worldwide by 2020 [4]. Even though all the predictions point to the growth of the HMD market, however, the high prices of HMDs are hindering the users from experiencing the VR (virtual reality) technology.

The consumers are currently more inclined to purchase mobile HMDs, as can be seen from the sales numbers. With the highest sales, Gear VR is the most widely owned HMD in the market, apart from Google Cardboard, showing over 5 million sales. According to a market analysis conducted by IHS Markit, Samsung Gear VR will surpass the US$10 million sales mark in 2018 [2]. Mobile VR technologies like Samsung Gear VR and Google Cardboard, with the most affordable headsets, offer the industry the best chance at early market penetration. With the introduction of mobile HMD to the public consumer market, VR has become widely accessible in the market [5]. The low-priced Google Cardboard and Samsung Gear VR were launched in 2015, and Facebook launched its Oculus Rift Consumer Edition in 2016, followed by HTC Vive and Sony PlayStation VR. The consumers are becoming increasingly aware of VR, and the entry cost for VR is becoming lower.

Mobile displays have been undergoing tremendous advances of late in terms of technology, and the market is currently divided into two dominant panels: OLED and LCD. Within the past 10 years, the research on OLED and LCD has yielded remarkable results. Most LCD screens are being designed with a LED (light-emitting diode) backlight, and such backlight is dynamically controlled with dynamic backlight control [6]. This makes the screen brighter on average, and cleaner white, compared to OLED. The LCD technology has become the dominant display technology for products like televisions, laptops, tablets, and smartphones, but the competing OLED technology has been pushed into the market.

The OLED technology is currently being used in smartphones, digital cameras, and televisions, and continues to become less power-consuming and cheaper as well as having larger applications. Although OLEDs are prone to screen burn-in and although different OLED films have uneven lifespans, OLEDs are being promoted to provide higher refresh rates than LCD. OLED also consumes significantly less power when used on a black background owing to its 'true black' [7,8], higher contrast ratio, and wider color gamut compared with LCD. The users show better visual performance on OLED than on LCD [1]. It is also worth noting that OLED tends to deliver more saturated colors than LCD, which can be positive or negative depending on the user's preference.

LCD is used in the whole iPhone range, in the HTC smartphones, in LG's flagships, in most Xiaomi devices, and in the vast majority of Huawei phones. The advantage of using LCD from the consumers' perspective is that when LCD is used, they do not have to suffer from the burn-in effect to the same extent as they do when OLED is used, but there is no 'true black.' OLED is used in the devices from Samsung, Lenovo, and Nexus/Pixel, and in the whole Xiaomi Mi Note range, to name a few. These screens display 'true black' due to their ability to turn off individual pixels.

Besides such technological differences between the OLED and LCD display panels, however, and besides the consumers' preference of them for use in portable electronic devices, while manufacturers consider the OLED technology the best for VR experiences because it reduces blur and ghosting owing to its faster refresh rate, how differently the users perceive these display panels when applied to HMDs has not been investigated. The mobile environment differs from the HMD environment in terms of its impact on display in that the users are not influenced by the environment luminance when wearing an HMD.

The extant research has mainly focused on the visual discomfort and fatigue that HMD users experience [9–11], but the difference between the OLED and LCD displays are still unexplored to the authors' knowledge. It is reasonable to assume that the users will be able to tell the difference between OLED and LCD because of the aforementioned 'true black' and the contrast ratio that it provides, but would the users really perceive the difference between OLED and LCD? If so, how would they perceive it? Whether the users would prefer OLED or LCD has yet to be determined.

3. Research goal

In this study, the users' perceptions of the characteristics of the OLED and LCD display panels, and the users' display preference, were investigated. For this purpose, the users' perceptions of the characteristics of the OLED and LCD display panels for use in HMDs and smartphones were first extracted. Second, the users' preferences between the two display panels in the HMD and smartphone contexts were compared. OLEDs with different luminance values were also compared as the extant research indicates that OLED is perceived to be brighter than LCD [7,8].

4. Experiment setup

An experiment was designed to extract the display panel characteristics perceived by the study participants and to explore the study participants' display panel preferences in the smartphone and HMD contexts. Two different

Table 1. Technical attributes of the selected devices [12,13].

	Maximum luminance	CCT of white	Color gamut (measured in the dark at 0 lux)
A (OLED)	855 cd/m^2	7445 K	131% sRGB/ Rec. 709
B (LCD)	558 cd/m^2	7241 K	104% sRGB/ Rec. 709

Source: http://www.displaymate.com/

mobile phones with LCD and OLED display panels were used: A and B, which were the latest models in the market at the time of the experiment. As the OLED display panel is known or perceived to be brighter than the LCD display panel with the same luminance, 70% OLED panel luminance was used to make the users perceive the brightness similarly. The following table presents the technical details of the devices that were used (Table 1).

4.1. Subjects

Twenty-two undergraduate and graduate students in their 20s to 30s were recruited for the experiment. All the participants were paid volunteers and were confirmed to have had no color deficiency.

4.2. Method

4.2.1. Stimuli

The stimuli in the experiment were 15 VR contents with different characters. Materials for smartphone and HMD viewing were selected considering the color, light, and details to fully investigate the difference that can be caused by the technological difference between OLED and LCD: OLED can show a better color gamut and true blacks5 as well as superior contrast ratio in dark light. Specifically, the selected images included a panorama of natural scenes like mountains, fields, seas, and deserts as well as urban scenes like an airport, a city center, and historical architecture. The images are still images with a minimum of 5000 × 2500 pixels. Figure 1 shows the stimuli that were selected for the experiment.

4.2.2. Metrics

The display panels' characteristics as perceived by the study participants and the study participants' display panel preferences were extracted by conducting a survey, and were then evaluated. The first section of the survey questionnaire was about ranking the three different devices that the survey respondents were using for viewing images in terms of aesthetics, brightness, and realness. In the second section, the survey respondents were told to write more than two adjectives that could best describe each device. Examples were given to stimulate the survey respondents, such as 'realistic,' 'clear,' 'blurry,' 'dull,' 'bluish,' 'comfortable,' 'soft,' and 'dark.'

4.3. Procedure

The study participants were briefed about their task before the viewing. A researcher explained that three devices with different display panels would be used for viewing 15 VR materials, and that the participants should evaluate the devices after watching the materials. After the briefing, the participants underwent a short training/practice for familiarization with the experiment, and when the training/practice had been completed, the participants started the HMD viewing session. The selected VR contents were viewed on a mobile HMD with three different display panels: OLED 100%, OLED 70%, and LCD 100%. The sequence of the contents was made different for every set of experiment to minimize the possible influence by the order of the images on the study results. Each participant was made to watch each material for 40 s per device, and was asked to write down his/her preference by choosing among the gold medal (the most preferred), the silver medal, and the bronze medal (the least preferred). The participants were allowed to revisit the previous devices if they wanted to. After ranking each device, they were asked to write more than two adjectives for the device. Thereafter, the participants began the smartphone viewing session. The same procedure was

Figure 1. Stimuli used for the experiment.

Figure 2. (Left) VR viewing process. (Right) evaluation process.

carried out with the display panels provided as smartphones. The experiment was performed in a controlled lab environment and took approximately 60 min to complete. When the participants had finished their viewings, a researcher conducted a semi-structured interview about their smartphone and HMD viewing experience. The laboratory was lit 500–700 lux (Figure 2).

5. Results

5.1. Perceived display panel characteristics

The overall results showed that the study participants preferred OLED over LCD in the given condition. It is important to note that whereas the study participants did not show a significant difference when watching VR materials on a smartphone, their preferences varied remarkably when watching on an HMD. The HMD users preferred the OLED display panel, but especially the OLED 70% panel, reporting that the OLED 100% panel was too bright.

Regarding the OLED 100% panel, many positive adjectives were given for both the HMD and the smartphone. The study participants reported that both display panels were bright[밝은], clear[깨끗한], and brilliant[화사한]. For the shortcoming of the display panels, a number of study participants mentioned that they were too bright[눈부신] (42 for HMD and 40 for smartphone).

The OLED 70% display panel was also positively evaluated in both the HMD and the smartphone. When used for the HMD, the three most frequently occurring adjectives were 'neat'[깔끔한], 'soft'[부드러운], and 'clear'[깨끗한]. Unlike with the OLED 100% display panel, no study participant reported that the panel was 'too bright'[눈부신]. Although a few participants reported that they found the panel 'dark'[어두운] (18), the positive adjectives prevailed, such as 'comfortable'[편안한], 'realistic'[진짜같은], 'refreshing'[상쾌한], and 'bright'[밝은]. When used as a smartphone, the most dominant adjective that was used was 'dark'[어두운], followed by 'comfortable'[편안한] and 'neat'[깨끗한] (Table 2).

Unlike the evaluation results of the OLED display panel in the HMD, the evaluation results of the LCD display panel in the HMD were dominated by negative adjectives. Interestingly, LCD showed a remarkable difference when used in different contexts. The study participants reported that LCD was 'bright'[밝은], 'comfortable'[편안한], and 'soft'[부드러운] in the smartphone but was 'blurry'[흐릿한], 'dull'[칙칙한], 'comfortable'[편안한], and 'stuffy'[답답한] in the HMD (Table 3).

Table 2. Extracted perceived display panel characteristics from the smartphone evaluation.

Rank	OLED 100%	OLED 70%	LCD 100%
1	Bright 밝은 (98)	Dark 어두운 (55)	Bright 밝은 (68)
2	Brilliant 화사한 (46)	Comfortable 편안한 (52)	Comfortable 편안한 (45)
3	Clear 선명한 (44)	Neat 깔끔한 (48)	Soft 부드러운 (43)
4	Too bright 눈부신 (40)	Soft 부드러운 (37)	Neat 깔끔한 (29)
5	Refreshing 상쾌한 (29)	Bright 밝은 (30)	Dull 칙칙한 (28)
6	Neat 깔끔한 (26)	Clear 선명한 (29)	Dark 어두운 (26)
7	Sharp 뚜렷한 (24)	Realistic 진짜같은 (26)	Realistic 진짜같은 (21)
8	Comfortable 편안한 (24)	Dull 칙칙한 (20)	Blue 푸른 (20)
9	Realistic 진짜같은 (23)	Blue 푸른 (18)	Too bright 눈부신 (19)
10	Soft 부드러운 (21)	Refreshing 상쾌한 (15)	Dynamic 생동감 (14)
	…	…	…

Table 3. Extracted perceived display panel characteristics from the HMD evaluation.

Rank	OLED 100%	OLED 70%	LCD 100%
1	Bright 밝은 (57)	Neat 깔끔한 (51)	Blurry 흐릿한 (49)
2	Clear 선명한 (55)	Soft 부드러운 (51)	Dull 칙칙한 (46)
3	Brilliant 화사한 (44)	Clear 선명한 (46)	Comfortable 편안한 (30)
4	Too bright 눈부신 (42)	Comfortable 편안한 (43)	Stuffy 답답한 (29)
5	Soft 부드러운 (34)	Realistic 진짜같은 (38)	Bright 밝은 (28)
6	Neat 깔끔한 (30)	Refreshing 상쾌한 (30)	Soft 부드러운 (25)
7	Realistic 진짜같은 (26)	Bright 밝은 (18)	Dark 어두운 (25)
8	Comfortable 편안한 (26)	Dark 어두운 (18)	Faded 색이 흐린 (23)
9	Refreshing 상쾌한 (25)	Dynamic 생동감 (16)	Dizzy 어지러운 (18)
10	Dynamic 생동감 (19)	Blue 푸른 (15)	Realistic 진짜같은 (15)
	…	…	…

Table 4. Comparison of the top 3 perceived display panel characteristics.

Panel	OLED 100%		OLED 70%		LCD 100%	
Context	HMD	Smartphone	HMD	Smartphone	HMD	Smartphone
Extracted characteristics	Bright Clear Brilliant	Bright Brilliant Clear	Neat Soft Clear	Dark Comfortable Neat	Blurry Dull Comfortable	Bright Comfortable Soft

From the study results, it was found that the same display panel can be sensed differently in an HMD and in a smartphone. Most interestingly, the display panel preference in the HMD was not in the area of personal taste. LCD showed clear limitations for an HMD: what was considered 'comfortable' for a smartphone can become 'dull' for an HMD (Table 4).

Moreover, it is noteworthy that the OLED 70% display panel in the HMD seemed to have had much strength, eliciting a combination of positive adjectives from the OLED 100% and LCD display panels. Therefore, the three display panels were ranked to determine if the study participants had a clear preference among them.

5.2. Device ranking

The 22 study participants evaluated 15 VR contents considering three criteria: aesthetics, brightness, and realness. The overall results showed that the study participants preferred OLED over LCD. Table 5 shows that except in terms the realness of the smartphone, the study participants perceived a statistically meaningful difference between the devices.

The study participants' display panel preference is more outstanding in the HMD context (Table 6). Throughout the experiment, there was a statistically meaningful preference for OLED over LCD. It is interesting to note that the OLED 100% and 70% display panels did not show a statistically meaningful difference.

5.3. Aesthetics

Specifically, regarding aesthetics in the smartphone context, the study participants reported the OLED 100% display panel as the best, followed by the OLED 70%

Table 5. Ranks of the display panels in the three categories of aesthetics, brightness, and realness

	HMD Panel	Mean rank	Smartphone Panel	Mean rank
Aesthetics	OLED 100%	1.69	OLED 100%	1.74
	OLED 70%	1.61	OLED 70%	2.07
	LCD 100%	2.70	LCD 100%	2.19
Friedman test	$\chi^2(2) = 242.87$, $p < 0.01$		$\chi^2(2) = 36.71$, $p < 0.01$	
Brightness	OLED 100%	1.70	OLED 70%	1.88
	OLED 70%	1.75	OLED 100%	2.01
	LCD 100%	2.56	LCD 100%	2.11
Friedman test	$\chi^2(2) = 155.00$, $p < 0.01$		$\chi^2(2) = 8.12$, $p = 0.02$	
Realness	OLED 100%	1.76	OLED 100%	1.98
	OLED 70%	1.72	OLED 70%	1.95
	LCD 100%	2.53	LCD 100%	2.06
Friedman test	$\chi^2(2) = 138.51$, $p = 0.00$		$\chi^2(2) = 1.97$, $p = 0.35$	

Table 6. Wilcoxon signed-rank test

		HMD			Smartphone		
		OLED 70% - LCD 100%	OLED 100% - LCD 100%	OLED 70% - OLED 100%	OLED 70% - LCD 100%	OLED 100% - LCD 100%	OLED 70% - OLED 100%
Aesthetics	Z	−12.38[c]	−12.71[b]	−1.19[c]	−1.52[b]	−5.71[b]	−4.36[b]
	Asymp. sig.						
(2-tailed)	< .01	< .01	.24	.13	< .01	< .01	
Brightness	Z	−9.98[c]	−10.52[b]	−.78[b]	−1.31[b]	−2.78[b]	−1.56[b]
	Asymp. sig.						
(2-tailed)	< .01	< .01	.44	.19	.01	.13	
Realness	Z	−9.489[c]	−9.733[b]	−.616[c]	–	–	–
	Asymp. sig.						
(2-tailed)	< .01	< .01	.54	–	–	–	

[a]Wilcoxon signed-rank test.
[b]Based on negative ranks.
[c]Based on positive ranks.

and LCD display panels. The Wilcoxon signed-rank test showed that the OLED 70% and LCD display panels were evaluated similarly and did not show a statistically significant difference in aesthetics ($Z = -4.36$, $p < .01$), which indicates that the luminance of the OLED panel may affect the user's perceived aesthetics.

In the HMD context, however, the OLED 70% display panel was ranked as the highest, with no statistically significant difference with the OLED 100% display panel ($Z = -1.19, p = 0.24$). This result implies that the study participants felt that OLED panels are remarkably better than LCD for HMDs.

5.4. Brightness

The study participants preferred OLED over LCD for both the smartphone and the HMD. This was more obvious in the HMD context, however, where the OLED 70% and 100% display panels were both highly ranked. As shown by the results of a Wilcoxon test, the OLED 70% and 100% display panels did not have a statistically significant difference in perceived brightness, from which it can be concluded that the OLED display panels were considered the best in the brightness category. The display panel preference in the smartphone context was subtler, but the OLED 100% display panel was still preferred over the LCD 100% display panel at a statistically meaningful level.

5.5. Realness

Lastly, the study participants did not show a statistically meaningful preference in terms of realness in the smartphone context ($\chi^2(2) = 1.97, p = 0.35$). Still, when seen as a display panel for HMDs, LCD was still the least preferred in this area. Considering that the study participants showed a similar preference for the OLED 100% and 70% display panels ($Z = -0.62$, $p = 0.54$), it can be said that the HMD users felt that the VR materials were less realistic on LCD than on OLED.

6. Conclusion

The results of this study showed that whereas the users may evaluate LCD positively in the smartphone context, the users concurred that OLED is more visually appealing for the HMD. With regard to the top 3 display panel characteristics that emerged from the experiment in this study [see Table 4], the same LCD was perceived as bright, comfortable, and soft for the smartphone but was perceived as blurry, dull, and comfortable for the HMD. There was also a noticeable change of perception in the case of the OLED 70% display panel; the users evaluated it as dark, comfortable, and neat for the smartphone but as neat, soft, and clear for the HMD. The OLED 100% display panel was positively evaluated for both occasions. That is to say, the study participants showed a strong preference for OLED over LCD in both the smartphone and HMD contexts. More specifically, the study participants found the difference between OLED and LCD more obvious when viewed on the HMD. The device rank results in this study showed the unbeatable dominance of OLED in all the cases.

Interestingly, the results of this study contradict the common belief that the preference between OLED and LCD depends on the user's personal preference; that is, depending on whether the user prefers more vivid colors or realistic colors. The results of the device ranking experiment in this study showed that when viewing a VR material, the study participants preferred OLED over LCD not only on the HMD but also on the smartphone. Among the three criteria that were used in this study (aesthetics, brightness, and realness), a statistically meaningful preference for OLED was found in terms of aesthetics and brightness.

Another interesting finding concerns the luminance of OLED. No statistically meaningful difference was found

between the OLED 70% and 100% display panels in the HMD context in this study. This is contrary to the commonly held belief that users prefer more vivid and brighter images. Seventy percent OLED panel ('A' in Table 1) luminance seems enough to achieve the same level of visual satisfaction on the part of the users (actually, the study participants felt more comfortable with lower luminance). That is to say, not only can using OLED for an HMD increase the user's satisfaction; it can also help the user save energy. Surprisingly, the display panel characteristics perceived by the study participants indicate that the study participants felt more comfortable with the OLED 70% display panel. Based on the results of this study, it can be assumed that the luminance of OLED can be adjusted to make the users feel comfortable and to provide them with a more visually satisfying experience.

7. Discussion

This study showed the limitation of LCD for use as a display panel on HMDs, and that manufacturers should adopt OLED to maximize the user's satisfaction. The study participants' perception of the display panel was surprisingly different between the HMD and smartphone contexts. The most frequently mentioned perceived display panel characteristics were presented in the Conclusion section, but a change in display panel preference was also observed for the viewing of certain VR materials. For instance, a VR material seen on OLED was perceived as too bright and vivid on the smartphone but was considered realistic and bright on the HMD. A number of users evaluated a VR material on LCD as comfortable and soft on the smartphone but as dark and dull on HMD; they did not recognize that they were evaluating the same display panel in different contexts and were surprised when they were told in the wrap-up interview what the device was.

As was mentioned in the Conclusion section, the proper luminance should be carefully considered. The 70% OLED luminance was examined in this study, and the study participants did not show a statistically meaningful difference in their preference between the 100% and 70% luminance of OLED. In effect, even though it was not statistically meaningful, the OLED 70% display panel was often more preferred than its 100% counterpart. The study participants often reported that they felt more comfortable and natural with the OLED 70% display panel while they perceived the OLED 100% display panel as vivid but irritatingly bright. Likewise, this study broke the conventional belief that the users prefer a display panel that is brighter and more vivid. This indicates that an HMD with OLED can reduce the power consumption by reducing the luminance.

There is room for investigation, however, in the user's perception of a different luminance. Even though this study did not examine the differences among all the possible luminance levels, there may be an interesting fact waiting to be discovered. For instance, how will the users evaluate the display panel's characteristics when 60% luminance is given? Will they still like it or will they consider it too dark? What is the most suitable luminance for HMD usage? It is also important to consider the influence of the environmental luminance. The experiment in this study was conducted in a room with the normal 500–700 lux luminance. It is possible for the users to prefer a different luminance level if the environmental luminance at the point of entry is different, such as in a bright outdoor environment. In such case, as Na et al. discovered [14], reducing the luminance gradually to optimize the user satisfaction and the power consumption can be considered.

To note, this study has a limitation in that the display devices that were used therein had different physical parameters that could affect the display image quality. Nonetheless, the best-selling devices in the market were used for the practical implications. The OLED panel that was used for the study had 1440 × 2560 pixels, had a 577 ppi density, and was 5.1 in. in size while iPhone 6S has 750 × 1334 pixels, has a 326 ppi density, and is 4.7 in. in size. To match the pixel density, either a better LCD had to be obtained, which had not been developed, or the ppi density of OLED had to be decreased, which may again raise the question of using an inferior display than one that was already commercially and widely available and with higher physical parameters. Therefore, the best-selling devices were decided to be compared. Also, it would be interesting to look into different target users with more varied contents and interactions in the future studies.

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