Exploring the Impacts of Human-Centric Lighting Spatial Patterns on Elderly Residents mood and preference – An Architectural Content Analysis

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The aging population is growing rapidly. The population is aged 65 and older increasing from 9 percent in 2019 to 16 percent by 2050, which means one in every six people in the world will be aged 65 or older. One of the problems of an aging population is that older adults are at higher risk for sleep dysfunctions, anxiety disorders, and depression leading to mental stress and cognitive impairments. Studies have shown that lighting parameters are among the most significant indoor environmental qualities that can potentially play an important role in improving health and wellbeing in older adults.

Human-Centric light is an approach in lighting design, which investigates the impact of different variables of lighting such as temporal pattern, light level, the light spectrum and, the spatial pattern on both visual and non-visual outcomes of humans. While previous studies have investigated the impact of different light variables on elderly visual and non-visual outcomes, there is a critical need to identify the impact of spatial patterns of light on elderly residents' outcomes.

This study is an initial effort in recognizing and developing a spatial pattern framework that can be used as a design pattern to guide spatial light patterns relating to elderly people's preferences and moods. After a picture content analysis of 36 images of assisted living facilities living rooms and bedrooms, the Visual Attention Software (3M-VAS) was used to identify the most efficient visual hierarchy in the images according to lighting elements and furniture arrangements. The main contribution of this study is the creation of a proposed spatial pattern framework that can be used as a design pattern to guide spatial light patterns relating to elderly people's preferences and moods. Findings from this research will provide new insights into the scope of human-centric lighting design of assisted living facilities.

KEYWORDS: human-centric lighting, lighting design, spatial pattern, elderly people, cognitive function

PAPER SESSION TRACK**:** Public Health and Human-Centered Design

INTRODUCTION

Appropriate lighting condition is one of the significant indoor environmental qualities that could potentially play an important role in improving the living environment and enhancing health and wellbeing in older adults (Lu et al., 2019). Lighting design for the elderly settings, however, has not received much attention from researchers and designers. Human-Centric light is a new approach in lighting design, which focuses not only on the visual impact of light, but also on its non-visual aspects that influence circadian rhythms, sleep, mood, and cognitive performance. Houser, K. W., et al (2020) have defined four main categories of lighting variables that contribute independently through designing lighting systems for the built environment: Temporal pattern (i.e., the timing and duration of exposure), Light level (i.e., the quantity of light in radiometric and photometric units), Light spectrum (SPD) (i.e., spectral power distribution that governs color quality) and spatial patterns (i.e., the luminance distribution of the three-dimensional light field). Illuminance, an important quantitative attribute of lighting, has been shown to have a positive impact on individuals' alertness, vitality, task performance, agitation, depression, sleep quality, and cognitive performance (Satlin et al.,1992; Yamadera et al.,2000; Riemersma et al., 2008). In addition to Illuminance, researchers have proposed different metrics for quantifying the effectiveness of the non-visual and psychological impact of light on the human body. Equivalent Melanopic Lux (EML) is a more recent metric developed after Lucas et al (2014) to measure the biological impacts of light on humans' bodies. Studies investigating the impact of the light spectrum have shown both monochromatic short-wavelength light and blue-enriched polychromatic light are more effective than longer wavelengths of light at suppressing melatonin (Brainard et al., 2001), regulating the circadian clock (Revell et al., 2005), and enhancing alerting effects and improving mood (Chellappa et al., 2011). There is firm evidence among building sciensce researchers that the temporal pattern of electric light in the indoor environment that follows the same natural pattern of daylight (morning bright light, dim evening light) provide a better non-visual outcome for humans, especially for elderly people (Yamadera et al., 2000; Riemersma et al., 2008; Figueiro, 2008).

Existing studies in the field of human-centric lighting for elderly people have mainly focused on quantitative attributes of light such as light level (Sinoo, 2010; Figuerio, 2011); light spectrum (Janosik& Marczak, 2016; Cheng, 2016; Sean et al., 2020); and temporal patterns of light (Gasio et al., 2003; Figueiro, 2008), while there are not enough studies showing a systematic relationship between qualitative attributes of light such as the spatial pattern and luminance distribution with nonvisual outcomes of elderlies (Knez, I., & Kers, C, 2000; Riemersma et al, 2008; Yamadera, et al,2000). A vast majority of gerontology studies have addressed the visual impacts of indoor lighting on wayfinding, mobility, and task performance, while there is a significant gap in understanding the impact of indoor lighting on the nonvisual outcomes of elderly people as mood, behavior, and preference. To address the research gaps in this area and particularly investigate the impact of spatial patterns on mood and preference, this study aims to initially identify the most common spatial patterns of light in existing elderly facilities. Next, the patterns will be modified and combined with the extracted spatial pattern attributes of light from the literature to provide a more holistic approach towards the creation of a proposed lighting spatial pattern framework.

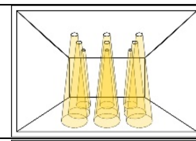
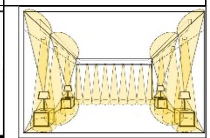
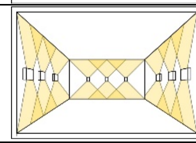
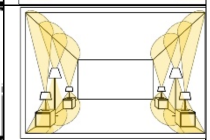
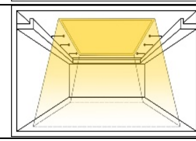
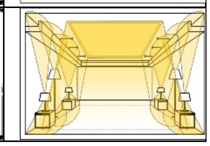
1 FLYNN'S THEORY (SPATIAL PATTERN OF LIGHT AND HUMAN SUBJECTIVE IMPRESSION)

A number of studies in the field of subjective lighting impressions show that inferior retinal light exposure is more effective than superior retinal exposure in suppression melatonin (Glickman et al., 2003) and light exposure on the nasal side of the retina is more effective in biological responses than the temporal side of the retina (Visser,1999). Therefore, the way that light radiation reaches the human eye is very important in its effect on visual and non-visual outcomes. Lighting designs for visual outcomes are at task locations and are often oriented horizontally (DiLaura, D. L., et al, 2011), while non-visual lighting designs are at the plane of the occupant's eyes and are oriented vertically (Houser & Esposito, 2021; Brown et al., 2020).

The spatial pattern of light refers to the spatial distribution of light in the three-dimensional light field and it depends on many parameters of light and environment. In the 1970s, John Flynn published a series of articles (Flynn & JE, F.,1977; Flynn et al., 1979; Flynn et al., 1973); conducted fundamental research about the role of the distribution of light and resulting patterns of the light on human subjective impressions. Flynn et al (1979) defined four main lighting modes in space, which make various impressions in humans. These four lighting modes are the basic attributes that designers consider when they are creating an environment for different purposes: bright/dim, uniform/non-uniform, central / perimeter, and warm/cool. Flynn particularly examined how different "lighting modes" affects Spaciousness / Confinement, Visual Clarity / Haziness, Relaxation / Activation and Private/ Public.

Flynn et al (1973) defined six different light arrangements which had their specific uniformity, centrality, and brightness value so that each arrangement correspond to a specific point in a dimensional space of the different lighting characteristics. The results of this study indicated that there is a significant difference in human subjective impression between different lighting arrangements. According to Flynn's theory of lighting and mood in the 1970s we have defined six main spatial patterns of light that contribute to humans' mood and preference. These six spatial patterns of light have been created according to three main attributes including Spatial arrangement (uniform/non-uniform, centrality (central/perimeter) and, direction. (Table 1)

Table 1: Spatial lighting patterns according to Flynn's theory of lighting and mood (after Flynn, 1973)

	Spatial arrangement	*Flynn's theory arrangement*	*Proposed spatial lighting arrangement*		*Spatial arrangement*	*Flynn's theory arrangement*	*Proposed spatial lighting arrangement*
1	Uniform Central Direct			4	Nonuniform Peripheral Direct/indirect		
2	Nonuniform Peripheral Indirect			5	Nonuniform Peripheral Indirect		
3	Uniform Central Indirect			6	Nonuniform Central/Peripheral Direct/indirect		

Previous studies regarding the spatial pattern of light have mainly focused on the relationship between the control parameters of light and the spatial distribution of light and how it impacts human outcomes. In this section, we have reviewed and discussed spatial arrangement (uniform/non-uniform, centrality (central/perimeter) and, the direction of light as three main independent variables of the spatial pattern of light and their impacts on mood, preference, perception, behavior, performance, and other outcomes of the human according to the literature

1.1 Spatial Arrangement (Uniformity)

Luminaire position in an environment can be arranged in two different ways: Uniform and Non-uniform. In a uniform arrangement, all the lighting luminaires in a room are placed in maximum height and uniform spacing without considering the location of furniture and other architectural elements to illuminate the environment at about the same level. In a non-uniform lighting system, all the fixtures are located at a high level and close to the ceiling, but with irregular spacing. The exact location of each fixture depends on the place of the workstations and machinery and the task that will be performed in that space.

Hawkes et al. (1979) argued two main attributes of light define the perception of light in a scape, namely brightness, and interest. Brightness refers to the perceived intensity of light while interest is related to perceived uniformity. There is evidence that shows that task lighting can increase attention to desk works, which improves task performance (Rea et al.,1990). Taylor et al. (1975) found that nonuniform desktop illumination improved task performance. This study shows adults perform better in arithmetic calculations (on paper) in office spaces with nonuniform lighting in comparison to uniform fluorescent lighting or very nonuniform colored lighting. On the other hand, some other studies are indicating there is no correlation between uniformity of light and task performance. McKennan & Parry. (1984) shows different illuminance levels on the desk-based on different lighting distribution does not impact (paper-based) clerical task performance in a comparison of 10 different general and local/general combined lighting installations. Lighting design in theatres shows that areas of high luminance could help to attract the audience's attention, but there is no firm evidence to show how this mechanism can be implemented to provide appropriate conditions for different tasks in other settings (Veitch, 2001). There is a study that investigated the impact of position and number of the light sources on perception of the space atmosphere. position of the light in this study refers to the location of light in the room (symmetrically, left-right, and front-back). The results indicate that adjacent luminaires to walls create a less uniform atmosphere (Stokkermans et al., 2018). In another study, affective impressions of university students were evaluated concerning spatial patterns and luminous environments in their classrooms. They defined six different axes of effective impressions of students including Surprising-amazing; Clear-efficient; Cheerful-colorful; Uniform; Intense brilliant and Warm-cozy. The result showed that Writing-reading tasks need a positioning of light that generate Clear-efficient, Intense-brilliant, and Uniform pattern, Reflecting-discussing tasks require a positioning of light that generates a Warm-cozy atmosphere, and Paying attention task needs a light positioning that creates Clear-efficient, Uniform, and Surprising-amazing atmospheres (Castilla et al., 2018). There are also other studies investigating the impact of spatial arrangement and uniformity on human perception, behavior, and preference (Flynn et al.,1973; Flynn et al, 1979; Chraibi, et al., 2017; Stokkermans et al., 2018). Flynn et al. (1973) and Flynn et al. (1979) as indicated in table 1 showed that uniformity in the spatial pattern of light increases clarity in space, while non-uniformity contributes to more relaxing feelings. Yao et al. (2017) that argues uniformity is a critical attribute of indoor lighting in work efficiency and comfort, have investigated different methods for evaluating uniformity of light in space. These methods include:

(Min: Avg), the coefficient of variance (CV), entropy uniformity (EU, introduced in the article), and a pattern vision-based indicator (U_{HVS}). According to the literature, illuminance distribution in a space can direct attention of the occupant in useful ways. In addition it impacts visual and non-visual performance. Despite these findings,there is a lack of evidence to show how uniform or non-uniform light can impact the mood and preference of a human.

1.2 Centrality (central/ peripheral)

Light sources in a space can be arranged to emphasize horizontal surfaces (central, overhead), or vertical surfaces (perimeter). Flynn et al. (1973) also revealed that in addition to light intensity (dim – bright dimension of light) and interest (uniform and non-uniform dimension of light), there is another factor that impacts the perception of light in a space, namely peripheral – overhead. Flynn showed central arrangement with Higher light levels on horizontal surfaces such as work plane provide more visual clarity, and Uniform peripheral lighting make the space more spacious, while peripheral non-uniform lighting is more helpful in increasing relaxation and privacy (Flynn et al., 1973; Flynn et al., 1979). Another study investigating the impact of the different spatial patterns of light in university classrooms on students' performance showed that each particular pattern of light (central or peripheral) should be modified according to the specific task taking place in the class (Castilla et al, 2018).

1.3 Lighting Direction

Luminaires can be designed to focus light in one of the following ways: Direct Lighting, Semi-Direct Lighting, General Lighting, Semi-Indirect Lighting, and Indirect Lighting. Indirect lighting, 90 to 100 percent of light radiation from the luminaire reaches the work surface. This type of lighting is a very common lighting design specially for task lighting. The main problem of direct lighting is that it causes glare and unfavorable shadows. In a semi-direct lighting system, 60 to 90 percent of light sources reach the working surface and the remainder of the light is reflected toward the ceiling or wall. In general lighting, the light will be distributed equally in both upper and lower areas of space (Lighting methods, 2017). Semi-indirect lighting, unlike semi-direct, reflects 60 to 90 percent of light toward the ceiling, while 30 to 40 percent only reach the working surface. In indirect lighting, 90 to 100 of light reflects toward the ceiling that increasing diffusion and even distribution. Studies have shown that people prefer indirect lighting in comparison with systems providing direct lighting (Veitch et al., 2008;). Yearout & Konz (1989) found that indirect direct lighting is more favorable than direct lighting among participants doing tasks in the workstation. Operators also prefer brighter illumination in office space and spotlights on walls. Katzev (1992) also showed office employees prefer direct/indirect lighting more than other lighting systems, while there were no significant differences between participants' performance in cognitive/intellectual tasks**.** A recent study investigating the impact of direct and indirect light on health, well-being, and cognitive performance of office workers also demonstrates except for a relationship between reduced job stress severity and direct lighting, there is no meaningful correlation between direct and indirect lighting and cognitive performance (Fostervold & Nersveen, 2008). Another study that investigated the impact of light direction on office workers' satisfaction, visual health, and productivity demonstrates that satisfaction and other subjective lighting rates were higher in an indirect lighting system, while productivity was less influenced by the direction of light (Hedge, et al,1995). Another study that investigated the impact of lighting positioning in workstations has found that two different spatial patterns (varies in terms of number, direction, and position of the light) create different views while do not impact the performance of the users. This study shows that a combination of direct and indirect light is more favorable for the users. They also preferred a non-uniform spotlight on wall painting (Yearout & Konz, 1989).

Various studies investigating the impact of the spatial patterns of light on elderly outcomes have mainly focused on one or two attributes of spatial pattern. However, there is a critical need for a comprehensive investigation of the impact of the spatial pattern of light on elderly outcomes. furthermore, most of the previous studies have not sufficiently addressed the architectural and design perspective of the spatial patterns of light and have mainly examined the spatial pattern of light in an experimental room. To address this critical gap this study has used a multi-method approach to investigate spatial patterns of light in senior residence facilities.

2 MULTI-METHOD APPROACH TO INVESTIGATE SPATIAL LIGHT PATTERNS

In this study, architectural content analysis has been conducted by an inductive approach through three main phases. In phase 1, a Picture Content Analysis (PCA) was conducted for surveyed facilities' websites to determine the most common layout arrangements and properties for Bedrooms and Living Rooms of Assisted living facilities in the US. This phase resulted in the most common typologies of each of the two rooms. In phase 2, Visual Attention Software (3M-VAS) software analyzed the most common room typologies from phase 1 to determine which typology is the most attractive to users and can generate the most viewing interest. In phase 3, the two most attractive views of each room-- based on phase 2 analysis--were selected to implement spatial lighting patterns according to Flynn's theory of lighting and mood (Flynn et al.,1973)

2.1 Picture Content Analysis

In the first phase of the study, to identify the most common layout arrangement, interior lighting quality, and spatial patterns of light in existing senior residence facilities, we conducted a picture content analysis of the online image stocks from surveyed assisted living facilities website. Quantitative or formal content analysis is an empirical method for systematic analysis of different media content such as audio, textual, visual, and/or audiovisual (Krippendorf, 2004; Rössler, 2005). This systematic observational method aims to examine hypotheses about the representation of an event, people, and situations in different media (Fielding et al., 2008). To conduct a picture content analysis main unit, sample unit, unit of analysis, and codebook should be defined. In this study, the main unit of analysis consists of all the images of 50 elderly residents' facilities websites in the US. In the first step, we selected 36 images of assisted living facilities' living rooms (18) and bedrooms (18) as the sample unit of the analysis. Images were selected based on the type of facilities (assisted living facilities), interior space (living room and bedrooms), areas of the spaces (living room<1000 sq ft; bedroom< 450 sq ft), and lighting quality of spaces (including the different spatial patterns of light). The images including the human figures were also excluded from the sample unit to decrease distraction in content analysis. In the second step, five different subjective categories were defined for coding the images of the first phase. These categories include the possibility of having daylight, home likeness, including colorful furniture, the existence of natural elements, and warmness. (Figure 1 and 2). Five images with the highest score of these coding categories were selected for the final visual content analysis via 3M VAS software in phase 2.

2.2 Visual Attention Analysis – (3M VAS)

In phase 2 five final images were analyzed by 3M VAS software to investigate which image has met the visual hierarchy goals for our study. 3M-VAS (Visual Attention Software) is a biometric tool that collected and clustered 30 years of eye-tracking data (Salingaros and Sussman, 2020). This software that is mostly applied in website and signage design analyses the images according to three different attributes: heatmap, hotspots, and gaze sequences. The results of analyzing the five final images of the bedroom and living rooms have been indicated in Figures 1 and 2.

2.2.1 Heatmap

This attribute shows the probability a part of visual content is seen within 3-5 seconds of seeing a picture. Among 5 selected images of the living room, room number four with more attention on lighting fixtures and seating area rather than other elements of the room get the higher scores in this analysis. Between 5 images of the bedrooms room, number five with the main focus of heating map on lighting fixtures and bed shows the most attractive typology.

2.2.2 Hotspots

This criterion is a simplified version of the heatmap results which shows the areas of the image that is most likely to be seen. The probability of being seen by a person will be shown by a numeric score on each region of the image. Hotspot analysis among living rooms indicated that Image number 1 and number 4 by 85% and 92% focus on seating areas and 51% and 85% on lighting elements have the highest scores among five different images. Comparative analysis among bedrooms images hotspots revealed that room number 2 and number 4 by 69% and 42% attention on lighting fixtures and 77% and 97% focus on beds can generate the most viewing interest.

2.2.3 Gaze sequence

This parameter shows the four most-likely gaze locations, in their most-probable viewing order. This criterion is important because it shows the visual hierarchy of the scene. For this study, we are looking for a gaze sequence in a scene that attracts the users' attention to lighting fixtures and the significant elements of the room (seating area in the living room and bed in bedrooms). Among five images of living rooms, room number four's gaze sequence shows the most rational sequence: 1- desk light, 2- ceiling light, 3- desk light and, 4- seating area. The gaze sequence analysis among bedroom images also indicated that image number 2 by a gaze sequence from bed to desk light and then to ceiling light and window has a most reasonable hierarchy among room's elements in the scene.

Figure 1 (right): Picture content analysis and visual attention analysis of the Livingroom's images

Figure 2 (left): Picture content analysis and visual attention analysis of the bedroom's images

2.3 Proposed Spatial Lighting Patterns

In the final phase, the two most likable typologies of each room were selected to implement spatial lighting patterns according to Flynn's theory of lighting and mood. First, a virtual space of the living room and bedroom was simulated according to these two most attractive typologies in Autodesk 3ds Max software. Light level and light spectrum in each space were simulated according to the recommended amounts based on the literature (illuminance: 500 lux for living room and 300 lux for bedrooms; CCT:4500 k). Second, six main spatial patterns of light according to Flynn's theory of lighting and mood were implemented in each room to create the final proposal spatial pattern framework in assisted living facilities living rooms, and bedrooms (Figure 3).

The results of this architectural content analysis show that the dominant lighting fixtures in living rooms of assisted living facilities are chandeliers, recessed lighting, and table shade lamps, while in bedrooms ceiling fans and bedside lamps are more common. Although that we have included the images of spaces by the possibility of having daylights, there are a vast majority of facilities without any access to daylight. Elderly residents in assisted living facilities spend 90% of their time in indoor spaces therefore, they are experiencing dimmer days and brighter nights than what they need to experience in nature. The results of visual attention analysis indicated that spatial patterns of light in many of these facilities have created a glare that can be seen in the images. Although glare can create discomfort for all age groups, it takes more time for elderly people to recovery glare effect and can impact their efficiency and activation. The final spatial pattern framework can be implemented in future studies to investigate the impact of different attributes such as centrality, uniformity, and direction of light on both visual and non-visual outcomes of elderly people.

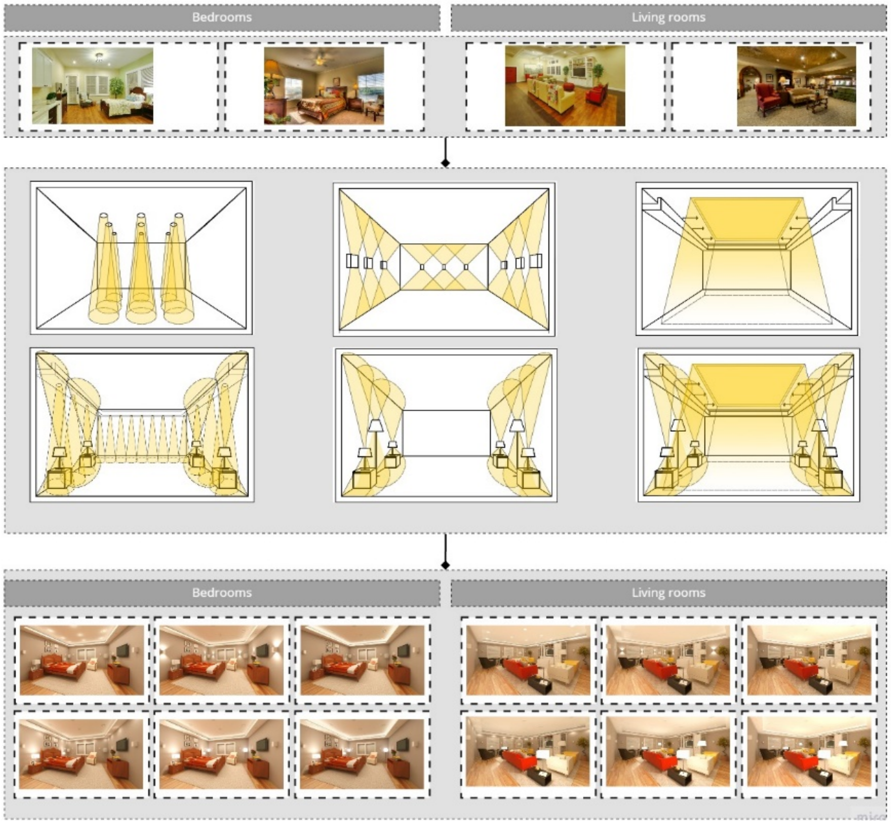


Figure 3: Spatial pattern framework in assisted living facilities living rooms and bedrooms

2.4 The impact of spatial pattern of light on elderly people's mood and preference

The two most likable and common typology of bedrooms and living rooms that selected will be modified according to an actual assisted living facility. An online survey including familiar-looking pictures of interior spaces which have been simulated based on 24(6 spatial patterns*2 CCT* 2types of interior spaces) lighting modes with different spatial and spectral patterns will be sent to elderly people of this facility. Participants will be sked to rate their subjective impression including mood, preference, and aesthetic qualities of images through different questions. Spatial patterns include uniform/non-uniform, central/perimeter and direct/indirect patterns and light spectrum includes CCT (2800 k and 4500k).

3 CONCLUSIONS AND FUTURE STUDIES

Despite the significant impact on the relationship between spatial light patterns and light radiation from the occupant's perspective, currently there is a lack of evidence-based design applications that implement these findings. This knowledge gap suggests a need for further studies investigating affect of spatial light patterns on both visual and non-visual outcomes of elderly people especially mood, behavior and cognitive performance,.

This study is an initial step in recognizing and developing a spatial lighting pattern framework that can be used as a design pattern to guide future lighting design application in settings. The findings of the study can play an important role in providing new insight into the field of human-centric lighting. To address the existing gap regarding the influence of the light spatial patterns on elderlies' non-visual outcomes the final simulated images of this study can be used as a valid and replicable reference of spatial patterns of light in senior living facilities.

The finding of this study can be combined with the results of previous studies regarding the light level, light spectrum, and temporal patterns of light to provide a more integrative framework of lighting design in assisted living facilities that can be used in experimental studies of the future.

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