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Modelling Sustainable Lighting with Eyetracker and Spatial Syntax techniques

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Abstract. This research provides an integrated methodological approach based on the combined use of spatial syntax modelling and eyetracker analysis techniques for lighting sustainability aimed to adaptive reuse of all the spaces with high historical, architectural, philological value of Cultural Heritage (CH). MosLESS (Modelling Sustainable Lighting with Eyetracker and Spatial Syntax techniques) is the proposed method, that can suggest fundamental guidelines for dynamic and static lighting in the museographic and museological areas, but also for reuse, conservation and enhancement of historical and CH buildings integrated with efficient energy management and conservation and protection needs. The National Museum of San Matteo in Pisa (Italy) was the pilot project. Particular environments were chosen for the experimental measurement campaigns carried out to assess dynamic and static visual fields, vision and perception. Methodological approach and results can be useful tools for exhibition planning with important energy, social and cultural effects. A further objective of the research will be to facilitate cultural exchanges, communication and new procedures for the digital management of the transmission or modification of museographic and exhibition projects, up to relations with public clients, as well as integrated management of information and decision-making processes.

1. Introduction

Many museums in Italy are housed in historic buildings that belong to the Cultural Heritage (CH) and therefore not only often their original intended use is transformed and completely converted into another, but they cannot offer the energy performances required for newly designed buildings: in this field the EU supports the complex principle of the “Adaptive re-use of the built heritage”, i.e. the wide possibility to modify the functional and distributive use of the indoor environment of any historical building [1].

While on the one hand they have a good mass and thermal inertia, they often present inadequate windows with very poor light transmission characteristics and artificial lighting systems without controls. The light and its entries to the environments, was conceived and designed for other uses and therefore, the use changing of building, as well as the reorganization and functional distribution of its indoor spaces, results in a general poor lighting [2-4]. The extensive use of LEDs has led to the development and application of automatic control/regulation systems on light flux and spectral composition of the emitted radiation at a fixed colour temperature, have provided important support for lighting designs, visual comfort, people health and safety, energy and economic saving [2,4,5]. Nowadays, lighting techniques, availability of low-cost sensors and highly used supervision-home automation systems, provide high flexibility and great possibilities for quality, sustainable and adaptive lighting designs. However, recently, all lighting standards and guidelines (for example, CEN Standards, Italian National Standards, French International Commission on Illumination or CIE), are



undergoing continuous modifications and revisions mainly due to international research and technological, as well as industrial development, even if they are differently oriented [6-10]. Recent researches on the impact of using LEDs for lighting design based on light quality, conservation and maintenance of artworks, have provided significant and crucial information on this issue [2-5]. Several literature studies concerning the optimal and lighting design for museums have also demonstrated that cognitive psychology and new technologies such as eye tracking for assessing, interpreting, and measuring eye movements, respectively, can be used in museums and exhibition environments [11-14]. Many studies have demonstrated how eyetracking techniques can be used to derive meaningful values on a quantitative scale, to quantify the complexity of individual switching patterns, for scanning behaviour of different observers and for assessing the distribution of eye fixations (i.e. attention and interest) over different AOIs (Areas of Interest) of artworks. These researches have also shown the importance of using of eye tracking for testing fixations inside different AOIs to obtain a gaze plot and gaze guidance related to different visual paths. Physics, optics-photometry, and eye-tracking techniques application can be important supports for lighting design addressing energy sustainability, information and communication by the quality of light, visual perception, visual comfort, in particular when it addresses CHs [5,12,13]. MosLES (Modelling Sustainable Lighting with Eyetracker and Spatial Syntax techniques) is the proposed integrated methodological approach, that can suggest fundamental guidelines for dynamic and static lighting in the museographic and museological areas, but also for reuse, conservation and enhancement of the historical and cultural heritage integrated with efficient energy management compatible with conservation and protection needs. The National Museum of San Matteo in Pisa (Italy) were the pilot project and in particular some of the most significant exhibition rooms.

2. Method and materials

2.1. The case study

National Museum of San Matteo in Pisa is housed in the rooms of the Benedictine monastery in Soarta (<http://www.polomusealetoscana.beniculturali.it/index.php?it/204/pisa-museo-nazionale-di-san-matteo>). The monastery was founded in the 11th century; wide rooms are located around the square cloister, modified in the 16th century with the construction of the portico. The cloistered structures of the 13th century are made of brick; the round arches of the base, support the upper floor where there are mullioned windows with columns and original capitals. In 1949 the new National Museum was born, currently the seat of the largest art collection of the city. Today it exhibits multiple paintings on wood, from the 12th to 13th century. There are the crosses of Lucca and Pisa and many tables and icons; very important is also the art gallery of 14th century with the polyptych by Simone Martini and Francesco di Traino. The first floor, with the most valuable rooms and remarkable artworks (Tab.1 and Fig.1, see also Fig.4), was the pilot project. It is important to note that the artwork in these rooms are lit exclusively with artificial light (Tab.2). The lighting system in the rooms is made up of 50W halogen lamps. The projectors are installed on a ceiling track system with inclination up to 90° on the horizontal plane and a rotation of 355° around the vertical axis. These luminaries are characterized by high-definition optical lenses in thermoplastic material and a die-cast aluminium body. There are 90 lighting fixtures in total.

2.1.1. Experimental measurements campaign

Within the pictorial collections for the experimental lighting set up and measurements some very important were selected: e.g. the compartment of the polyptych of the Carmine with the San Paolo, by Masaccio and other works of remarkable quality, by Ghirlandaio and Beato Angelico. Referring to the artworks, the experimental measurement campaign was carried out according to the method defined and validated in [5]. Integration between spatial syntax modelling (i.e. visual dynamic phase) and eyetracker analysis technique (i.e. visual static phase) investigations were carried out. The main participant sample characteristics are shown in Tab.3. According to [11-14] participants were divided

in two groups depending on their level of expertise: “experienced users” and “general users”. Figs 2-3 show the 8 studied artworks, some of the gaze plot and heat map results obtained with static visual tests. At the end of eyetracker measurements, each participant was tested by a multiple-choice questionnaire on his/her perception and impression due to lighting.

Table 1. List of studied artworks.

ID	Room	Artwork (title and artist)	Dimensions
1	4	Sant’Orsola (Artista toscano)	0.64 x 0.52 m
2	5	Madonna col Bambino (Simone Martini)	1.83 x 3.47 m
3	7	Madonna in trono con Bambino (Spinello Aretino)	1.90 x 3.71 m
4	8	Cristo crocifisso (Turino da Pisa)	1.70 x 0.78 m
5	8	Madonna dell’umiltà (Beato Angelico)	1.55 x 1.94 m
6	9	Sacra conversazione (Domenico Ghirlandaio)	1.55 x 1.61 m
7	9	Santa Caterina d’Alessandria (Maestro della Leggenda)	2.00 x 2.00 m
8	Hall C	San Paolo (Masaccio)	1.00 x 0.72 m



Figure 1. Photos of studied artworks.

Table 2. Lighting systems configuration. List of symbols: H, room height; D, horizontal distance between the luminaire and the artwork; h, distance between the centre of the artwork and the floor; E_{med} , average illuminance value on the artwork due to all the luminaires in the room.

ID Artwork	ID Luminaire	H (m)	D (m)	h (m)	Vertical inclination angle	Horizontal inclination angle	E_{med} (lx)
1	f.6-4	6.5	1.5	2.1	20°	22°	45
	f.21-4	6.5	1.5	2.1	20°	16°	
2	f.2-5	6.5	1.5	2.4	21°	29°	105
	f.4-5	6.5	1.5	2.4	21°	28°	
3	f.2-7	6.6	0.5	1.6	6°	10°	44
4	f.2-8	6.5	1.3	2	17°	16°	39
5	f.7-8	6.5	4.6	2.1	60°	4°	114
6	f.1-9	5.6	2.5	2	40°	16°	61
7	f.9-9	5.6	2.2	1.7	32°	53°	110
8	-	-	-	-	-	-	29

Table 3. Characteristics of the sample of participants to the questionnaire.

Male	Female	Users		Age group			
		Experienced	General	0-29	30-39	40-59	60-79
22	9	8	23	12	9	7	3

The experimental investigation for the visual static field started in room 4 and ended in the hall C: eight artworks were observed by each participant. Measurements were organized in two phases: the first (dynamic visual field) during which each participant was asked to make a "free" visit to the chosen rooms but along marked paths; the second (static visual field) during which each participant remained standing to observe the artwork for 25 seconds. The observation time chosen is not conditioned by the eye adaptation phenomena, because the static vision phase is connected and sequential to the dynamic one. As a matter of fact, the questions about exposure specificity that causes different emotional/visual experience and behaviour; and attention level that can be too low if the visit is too short or if its content is not provided, were considered. In this way, the sequentiality, repetitiveness and identity of the tests was assured and, at the same time, the actual visit path of any visitor was reproduced very closely to the reality. The observation distances were the following: fixed and with a sitting position for the two artworks displayed respectively in the first and in the second room and then of 4.5 m and 4.2 m coincident with setting up and museography concepts of the exhibition curator; variable distances for the remaining 6 artworks, i.e. a minimum and maximum distance shown in Tab.4.

Table 4. Observation distances from the artworks for the static field investigation

ID	Room	Artwork (title and artist)	Observation time (s)	Fixed distance (m)	Minimum distance (m)	Maximum distance (m)
1	4	Sant'Orsola (Artista toscano)	25	4.5	–	–
2	5	Madonna col Bambino (Simone Martini)		4.2	–	–
3	7	Madonna in trono con Bambino (Spinello Aretino)		–	2	2.9
4	8	Cristo crocifisso (Turino da Pisa)		–	3	5
5		Madonna dell'umiltà (Beato Angelico)		–	2.6	3.7
6	9	Sacra conversazione (Domenico Ghirlandaio)		–	2.4	3
7		Santa Caterina d'Alessandria (Maestro della Leggenda)		–	2.4	3
8	Hall C	San Paolo (Masaccio)		–	1.4	1.8

3. Eye-tracking: results and discussion

The eye tracker measurements allowed the visual spatial and temporal sampling, cognitive processes analysis data collection on attention, visibility, mental processing and understanding. E.g. visual fixations assessment provided information about participant attention (i.e. corresponding multiple eye movements revealing the complex cognitive and perceptive components due to the visual/perception experience due to different lighting systems). Results analysis provided basic information on visual/perceptive experience of each participant, due to different lighting connected to the exhibition curator choices. Recorded data were processed to obtain a cluster model, namely portions of the image with the highest gaze points data concentration. Clusters identification and data post processing were carried out simulations with Tobii software. Eye fixations and visits were assessed referring to total number of events and duration. Fixations happened when a target feature of interest was placed on the fovea for a period of time (e.g. 300 ms per fixation); visits happened for each visual entrance and exit from a specific cluster. Results obtained for 3 artworks with natural background together with human figures, are discussed. The exploratory pattern calculation obtained by the 31 participant measurements assessment, with respect to each AOI, the duration and number of fixations and visits obtained, shows that their greatest number and their maximum duration, concerned the faces of the main subject of each artwork (Tabs 5-7). Figures of secondary visual fields, landscape and the rich details of the frames were respectively observed during sequential and subsequent times.

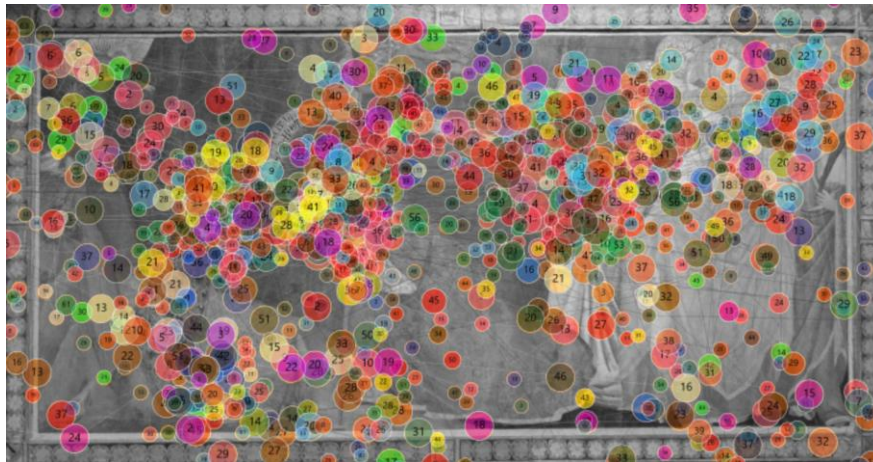


Figure 2. Eyetracker post-elaboration results: Sant’Orsola (ID1) gaze plot. The circles represent the fixation points; the numbers in the circle represent the gaze sequence; the different colours represent the different observers; the size of the circles depends on the duration of the fixation.

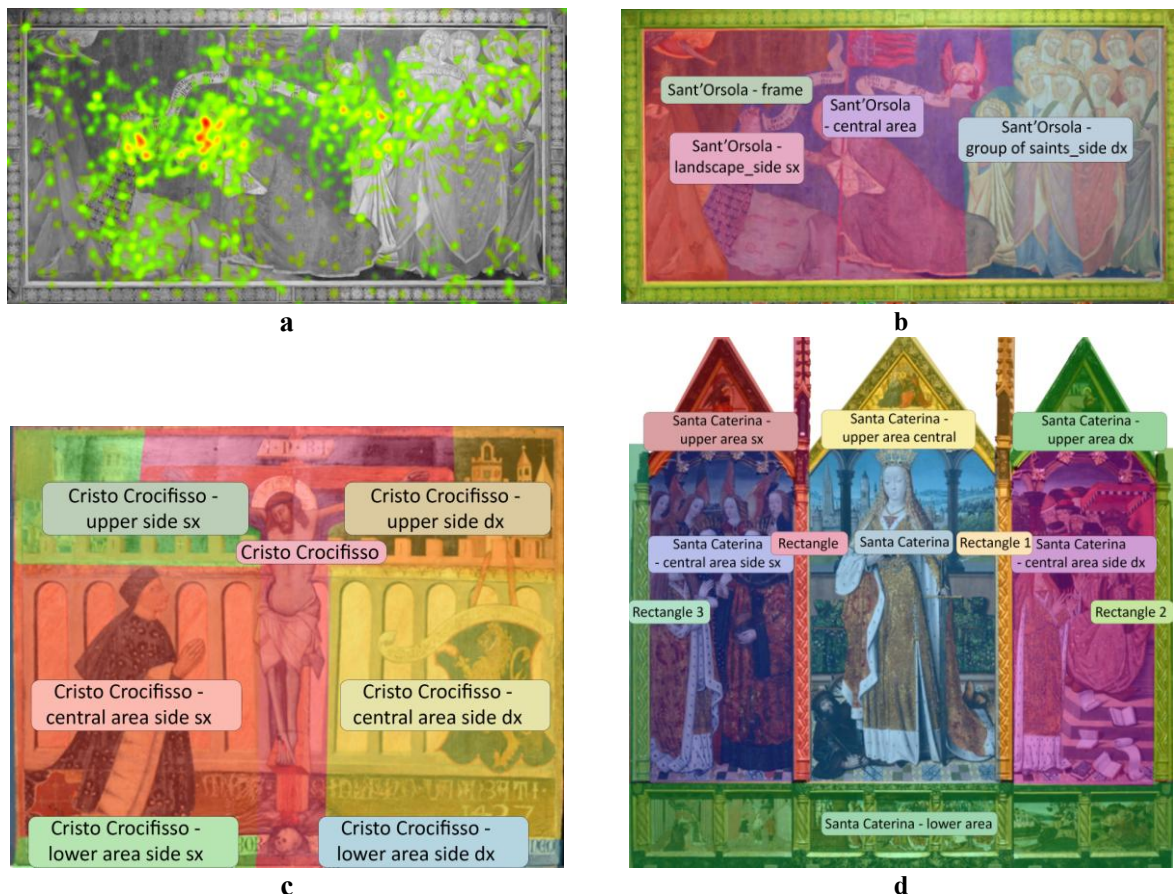


Figure 3. Eyetracker post-elaboration results. (a) Sant’Orsola (ID1) heat map. Areas of Interest (AOIs) for: (b) Sant’Orsola (ID1), (c) Cristo Crocifisso (ID4), (d) Santa Caterina (ID7).

The variation coefficient (Tabs 5-7) provided a basic indication on the dispersion of the visual data distribution. For all the artworks, the AOIs into which the human figures are shown, have lower dispersion. In the AOIs with secondary subjects and landscapes, the dispersion fluctuates on average

values. Higher data distribution dispersion about fixations and saccades belongs to those AOIs concerning wooden frames, rich in details and decorations.

Table 5 Sant'Orsola: fixations assessment for each AOI.

AOI	Variance	Standard deviation	Variation coefficient
Sant'Orsola - central area	6.86	2.62	0.38
Sant'Orsola - frame	0.53	0.73	1.38
Sant'Orsola - landscape side dx	7.7	2.78	0.36
Sant'Orsola - landscape side sx	1.69	1.3	0.77

Table 6 Cristo crocifisso: fixations assessment for each AOI.

AOI	Variance	Standard deviation	Variation coefficient
Cristo crocifisso	5.9	2.43	0.41
Cristo crocifisso - central area side dx	2.48	1.58	0.64
Cristo crocifisso - central area side sx	4.06	2.01	0.50
Cristo crocifisso - lower area side dx	0.56	0.75	1.34
Cristo crocifisso - lower area side sx	0.08	0.28	3.50
Cristo crocifisso - upper area side dx	1.66	1.29	0.78
Cristo crocifisso - upper area side sx	2.57	1.6	0.62

Table 7 Santa Caterina d'Alessandria: fixations assessment for each AOI.

AOI	Variance	Standard deviation	Variation coefficient
Rectangle	0.08	0.28	3.50
Rectangle 1	0.03	0.18	6.00
Rectangle 2	0.02	0.13	6.50
Rectangle 3	0.12	0.35	2.92
Santa Caterina	21.68	4.66	0.21
Santa Caterina - upper area central	0.04	0.2	5.00
Santa Caterina - upper area side dx	40	0.29	0.01
Santa Caterina - upper area side sx	26.67	0.31	0.01
Santa Caterina - central area side dx	2.88	1.7	0.59
Santa Caterina - central area side sx	1.29	1.14	0.88
Santa Caterina - lower area	5.47	2.34	0.43

All the obtained results are in agreement with recent studies and literature experimental evidences and show that when the represented content includes human subjects top-down processes prevail over the bottom-up processes [11-13]. It was also deduced that dynamic representation is strongly guided by the participant attention towards those features that portray actions (i.e. higher attention and visual concentration on the face area) and connected to the basic factors of the theory of embodied perception [11,12]. Comparison between Tabs. 5-7 shows the effects on perception due to light. Results are also in agreement with recent research on vision as a synergistic and interactive result of light activation of the brain supra-chiasmatic nucleus for the transduction processing of (luminous) signals [11,12,14]. All the factors involved in the embodied perception were assessed by means of the detection of activation due to light and specific lighting system. Perception and vision results comparison highlighted how only few of the studied artworks were exhibited considering a correct lighting and perhaps just by change. Results analysis highlighted that when light is not designed to see well, i.e. based on sustainable adaptive concepts and vision and perception quality, the energy linked to the vision is dispersed on boundaries (e.g. areas of little significance of the artwork and/or the surrounding museum space).

4. Space syntax analysis: results and discussion

Space Syntax Analysis allows to understand how users perceive the surrounding space, therefore it is a tool to predict their interaction with it. Space syntax analysis is formed by three kind of analyses: axial analysis, angular analysis and visual graph analysis [15] (VGA). In the first one, the space is

represented by a net of lines which symbolize users' line of sight. Those lines define the users' possible movements; the second subdivides the lines in smaller segments for each change of direction. The third one is based on the concept that users' movements are dictated by surrounding space perception. The space is identified by a cluster of points, each one of which symbolize the users' position. Each point has a unique relation with the remaining ones, based on the visual property linked to it. The polygon formed by the all the area visible from one point is called Isovist [16]. Here, VGA was used. To better understand and analyse a space, it can be subdivided using a grid, the grid must be organized so that each square has the same area of the space occupied by a person. In the case study the grid was formed by 50x50 cm squares. The analyses were run using DephtmapX software. The parameters used for the analysis are the Integration Index (I) and the Connectivity Index (C) [17,18]. Both C and I indexes obtained by the analysis carried out by the simulations, were compared with the horizontal illuminance values, measured using a luxmeter (Delta Ohm 2102.2). Considering rooms 9-10, there exists a correlation ($R^2=0.85$) between C and the average illuminance (E_{med}) can be expressed as follows: $E_{med} = k C - t$, with: $k = 0.76$ and $t = 182.7$. These results show that users' perception and understanding of the surrounding space is strictly connected to how the space is illuminated. Through the analysis of the video obtained with the eyetracker it was possible to trace the 31 participants' paths inside the rooms. The analysis allowed to find the most followed path inside the museums. The most followed path is shown in Fig.4a. The VGA graph of the I index (Fig.4b) compared with it, proves that the most followed path overlaps with the areas where I is higher. Therefore, the Integration index can really be used to predict users' behaviour inside a space.

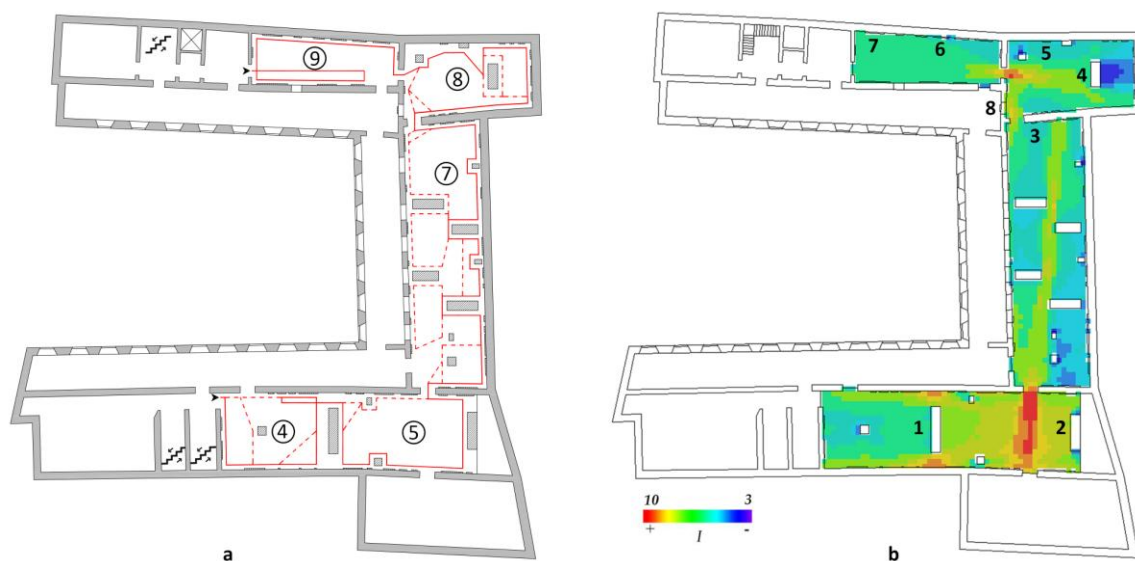


Figure 4. Planimetric views. (a) Most followed path (continuous lines) and main deviations (dashed lines); (b) VGA graph of the I index. The numbers in the circles are used to identify the rooms (Fig. 4a), the others numbers (Fig. 4b) are used to identify the artworks ID.

5. Conclusions

The proposed methodological approach based on integration of eyetracker techniques with spatial syntax analysis, showed that only quality and adaptive sustainable light can produce a particular emotional effect of play of shadows in the neighbourhood/ border of a picture, resulting from the control of directionality and intensity of light spectral emission; i.e. it can be an important lighting design tool oriented to quality of vision and perception, adaptive and sustainable light use just as a *parergon* i.e. the (luminous) frame of meaning and historical philological content of the artwork. A correct exposure (i.e. design for luminous climate and environmental-visit routes) and quality of vision/perception (i.e. good seeing) always involves some energy consumption. Quality and adaptive

lighting design is synonymous with energy and environmental sustainability because it involves less energy consumption, quality of vision/perception, as well as lower consumption for the conservation and maintenance of the lighting system. Results showed how the methodological approach applied in this research can enhance lighting design for museum environment, integrating dynamic with static visual fields, information content of artworks and spatial-functional areas. Findings of the method showed how light can be a fundamental guide for the project of setting up, exhibition and museography, based on quality light that everyone likes (the historian, museum exhibition curator, conservator and any visitor), because it constitutes that "common sense" that unites and communicates to all of us, and everyone has, however and wherever, experienced it.

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