ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 26, No. 01, 2025
https://doi.org/10.69076/jomac.2025.0015

IS LIGHTING BASED ON PHOTOPIC REQUIREMENTS IN ASSEMBLY WORKSTATIONS ALSO OPTIMAL FOR NON-VISUAL PERFORMANCE IN A HUMAN-CENTRIC PERSPECTIVE? A CASE STUDY IN THE AUTOMOTIVE SECTOR

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ABSTRACT

The article explores how assembly stations in the automotive components industry are structured using Lean Production principles to minimize setup times, reduce travel distances, and ensure ergonomic arrangements of tools and materials. With the integration of Industry 4.0 technologies, companies are increasingly digitizing production processes through systematic data collection, enhancing efficiency. A key factor in optimizing workstations is proper lighting, which is also central to the emerging Industry 5.0 paradigm that prioritizes human well-being alongside productivity. The study focuses on experimental lighting analyses conducted at a plant near Turin, Italy, operated by a multinational automotive company. Researchers examined both the visual and non-visual effects of light within U- and L-shaped work cells, taking measurements at the work surfaces and eye level of the operators. To compare objective findings with subjective experience, questionnaires were administered to the workers. Results showed that the lighting met regulatory standards and provided good support for circadian rhythms. However, some employees expressed concerns about glare and wanted more control over the luminous flux and positioning of the lighting systems. The findings suggest that enhancing lighting flexibility can improve visual ergonomics and support the transition toward more adaptive and worker-centred smart workstations aligned with Industry 5.0 principles.

Keywords: Industry 4.0, Industry 5.0, Workstation 4.0, integrative lighting, Lean production

1 INTRODUCTION

Car manufacturers use specialized component suppliers to produce their cars. They can produce not only individual components, but increasingly complete modules to be assembled directly on assembly lines. Therefore, automotive component suppliers adopt Just-in-Time (JIT) and Just-in-Sequence (JIS) principles in their factories, thanks to the Lean approach developed by Toyota Motor Company to synchronize the production with the strict schedules of car manufacturers.

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The need to apply JIT and JIS has provided a strong impetus for the organization of work according to the model of lean cell production, which, thanks to their configuration and compliance with the principles of workplace ergonomics [1], allow productions to be quickly modified and adapted to customer requirements. Since 2012, with the new factory concept developed by the European Union with the introduction of Industry 4.0, cell-based production has been able to further benefit from the digitization and interconnection of production processes, improving control over the complexities of supply chains [2] and reducing the uncertainty of lead times for car manufacturers. In fact, Industry 4.0 integrates machines and devices with sensors and related software to better predict, control, and plan business [3]; besides, it acts as an enabler of lean manufacturing [4-5], thus activating increased product quality and efficiency of production processes [6].

In this regard, Cohen et al. [7] proposed a system named Workstation-Operator Interaction 4.0 (WOI 4.0) to enhance the human-machine interaction to improve operator performance, safety, wellbeing, and satisfaction, along with the production measure. In general, the manufacturing sector faces considerable challenges in a dynamic and competitive environment, and process improvement is a crucial tool to enhance competitiveness in the market and maintain long-term sustainability [8].

1.1 FROM INDUSTRY 4.0 TO INDUSTRY 5.0: A HUMAN-CENTRIC APPROACH FOR THE WELL-BEING OF WORKERS

The Industry 4.0 model emphasized the transformation of factories into intelligent structures (smart factories'). This was possible thanks to the introduction of IoT (Internet of Things) and interconnection through cloud servers, developing new business models strongly focused on efficiency and productivity. However, Bortolini et al. [9] stress that humans are one of the most adaptable elements in assembly and manufacturing systems. These must be designed to support and guide workers, rather than replacing them, by incorporating new technologies, improving their skills, and addressing any limitations they may have [10-12]. Similarly, the literature review carried out by Valette et al. [13] revealed the "great interest in human-centricity in today's industrial research". Technology is meant to be a resource to increase production efficiency, without replacing human workers, but supporting their overall wellbeing [14-15]. A 'human-centred approach' is the key factor to pursue, rather than a 'technology centre' approach: Grabowska et al. [16] evolved the concept 'Cyber-Physical Systems (CPS)' into a new 'Human Cyber-Physical Systems (H CPS)'. However, Reiman et al. [17] highlight the immaturity of Industry 4.0 from the perspective of human factors and ergonomics, as the "new technologies may also have unexpected effects in processes and cause problems to the workers". Therefore, it is essential to define and introduce clear criteria for human-centred design, increasingly relying on the integration of digital work tools [18]. In this new scenario, dominated by strong digitization and automation, the need to introduce an improvement in the cooperation between humans and machines in factories led to the creation of yet another new business model that goes by the name of "Industry 5.0" [19-20]. With this new business model, it is finally possible to speak of a "Collaborative Industry," with the ultimate goal of providing added value to production through the creation of customized products that meet consumers' needs. Therefore, since cooperation and customization are the key factors for the transition from today's Industry 4.0 toward the factory model of the future 5.0, the role of humans becomes an indispensable and determining element in production processes, in the creation of Quality in products, and in their customization [21]. Equally essential, according to recent indications from the European Community, the well-being of workers must be placed at the centre of production processes [22-23]. It was considered important to analyse the workstations of the VALEO plant in Santena (Turin) as their switches, multifunction steering wheels, touchscreen displays, and switch units are assembled for the main manufacturers of luxury cars and supercars. Assembly activities require highly professional staff with enhanced manual skills, since they carry out assembly that cannot be delegated to robots. Therefore, they represent an interesting example of a work activity in which the human factor becomes fundamental due to the high customizations introduced, also in line with the framework proposed by Industry 5.0 [24]. In addition to the electronic version a hardcopy of the complete paper including diagrams with annotations must be supplied.

1.2 TYPICAL WORKSTATION LAYOUTS IN ASSEMBLY ACTIVITIES

Within the industry involved in assembling products for the automotive sector, production by work cells is widespread. The use of this type of layout is one of the most important aspects of Lean Production. Usually, the cell layout is organized around the assembly of one product or the assembly of similar products. With this type of production layout, it is possible to increase flexibility and productivity by reducing lead time, raising Product Quality, contain equipment, and reduce the stock of semi-finished products. Depending on the configuration, workstations may feature seated or standing operators. In cell production, the most frequently used configurations are 'U'-shaped, but 'L'-shaped or 'I'-shaped layouts are also used (Figure 1). The former allows the feeding points of the components to assembly to be brought closer to the output points of the finished products, while the latter allows the use of surface area to be reduced by arranging two separate, specular cells. The workstations 4.0 analysed in this work are equipped with mechanical equipment designed ad hoc by the Valeo Group R&D team and can be replaced in about 10 minutes. The workstations 4.0 are completed by some monitors that help the operators in correctly carrying out the assembly with photographs, examples and work instructions. The assembly lines that are made up of these workstations are also configured, according to the principles of lean production, to allow operation by one or more operators at the same time, to guarantee maximum flexibility.

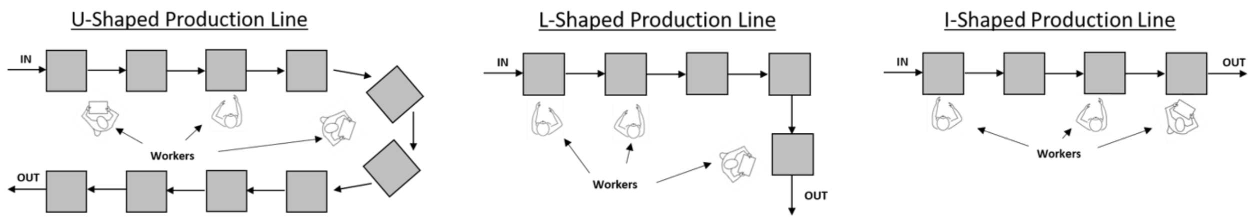


Figure 1 Typical configurations of cells.

1.3 POTENTIAL OF LIGHTING FOR THE WELL-BEING OF WORKERS IN INDUSTRIAL BUILDINGS

The International Ergonomics Association approved a definition of Visual Ergonomics, as "*the multidisciplinary science concerned with understanding human visual processes and the interactions between humans and other elements of a system. Visual ergonomics applies theories, knowledge and methods to the design and assessment of systems, optimizing human well-being and overall system performance. Relevant topics include, among others: the visual environment, such as lighting; visually demanding work and other tasks; visual function and performance; visual comfort and safety; optical corrections and other assistive tools*" [25]. In a letter to the Editor of Applied Ergonomics, Toomingas [26] reports that visual conditions can be problematic, leading to decreased performance and negative emotional reactions. This can decrease wellbeing and cause health problems, not only in the visual system, but also in other parts of the body such as neck and shoulders. On the other hand, well-adapted visual conditions can enhance system performance, health and wellbeing, and positive emotions. Models, knowledge, and methods of visual ergonomics are therefore necessary to understand how humans and elements of a system interact with each other and how systems should be designed to be optimal [27]. In recent literature, visual ergonomics encompasses the integration of the so-called visual and non-visual effects of light: the former are related to the aspects concerned with vision (performance, comfort, wellbeing etc.), the latter to aspects determining the non-forming vision effects that impact on circadian entrainment and thus on mood, alertness, sleepiness, cognitive processes, etc. According to the Industry 5.0 vision outlined by the European Commission [22-23], it is crucial to put humans back at the centre of production activities and use modern technologies to facilitate them in carrying out their tasks, such as, for example, collaborative robots (cobots). In this frame, several ergonomic devices have already been adopted to accommodate the needs of operators including, for example, by electrically adjusting the height of workbenches or tilt worktops, along with solutions for ergonomic positioning of components to be assembled. Which raises some questions: since light plays a key role in assembly activities, why, to date, isn't the same importance also attributed to lighting systems? Besides, when choosing workbench lighting, are the light sources selected also considering melanopic effects on users? Are lighting systems conceived to optimize the vertical illuminance (both photopic and melanopic) at eye-level? Visual and non-visual effects of light are addressed in more detail in the following subsections.

1.3.1 Visual effects of light

Among interventions aimed at increasing the visual ergonomics, Hemphälä and Eklund [28] evaluated the visual environment in mail sorting facilities through a before-after design (modifying the embedded lighting systems of the sorting racks) through field illuminance measurements and questionnaires. Twenty-seven participants reported that work conditions improved after the intervention, with reduced visual strain and mail sorting time. better general mood, less work induced stress. Gugliermetti et al. [29] explored sustainable lighting strategies in industrial settings by integrating natural and artificial light sources to optimize energy efficiency while maintaining visual comfort through hybrid lighting solutions tailored for industrial applications. Leccese et al. [30] analysed the lighting of some workstations used for diagnostic radiology by comparing adjustable and non-adjustable lighting settings through field measurements and questionnaire to 16 radiologists. The LED adjustable lighting resulted in reduced visual fatigue reported by the participants. Aarts et al. [31] studied the effect of lighting on errors performed by the nursing staff of different age in reading medication labels under nine lighting conditions, including three illuminances (100 lx, 500 lx, and 1000 lx) and three correlated color temperatures CCT (3000 K, 4000 K, and 6500 K). They observed a higher number of errors for older participants, with the highest impact of light conditions for the smallest font size (2.5 pt) and insufficient visual acuity of the participants. Dianat et al. [32] explored the association between objective and subjective assessments of environmental ergonomic factors including noise, lighting, and heat, through a field study in three manufacturing plants, collecting data from 130 workstations. They found that recommended noise, illuminance, and temperature levels were not met in about half of the workstations surveyed, which was consistent with the low satisfaction expressed by the operators. Similarly, Hsieh et al. [33] assessed how different lighting environments can affect people's concentration and working performance, comparing two lighting setups (task lighting and general lighting) and two attention task times (15 and 30 min, respectively). The concentration level of 60 participants was evaluated by measuring electroencephalogram (EEG) signal and cortisol secretion. Their findings indicated that concentration is influenced by the lighting conditions, with improved task performance in an environment with focused lighting for a 15-minute task duration, accompanied by activated cortisol secretion. In a different study, Juslen et al. [34] analysed the effect of illuminance on speed and percentage of errors of workers in assembling electronic devices in a factory in Holland, by comparing two horizontal illuminances at the workplace, 1200 lx or 800 lx (with a corresponding vertical illuminance of 600 lx or 400 lx, respectively). They observed a higher speed of production (+2.9% in summer and +3.1% in winter) for the 1200-lx setting. Instead, no significant effect of the illuminance on the percentage of errors was detected. In industrial spaces, Juslan and Tenner [35] showed that improving lighting conditions at work surfaces resulted in increasing visual performance, comfort, and ambience, interpersonal relationships, biological clock, stimulation, job satisfaction and problem solving. Another crucial aspect is the possibility for users to have personal controls. Studies carried out in office spaces have shown that when users can adjust the illuminance level on their desks, this has a positive effect on their satisfaction with the environmental conditions, lighting quantity and quality, mood, improved motivation and vigilance, with an indirect positive effect on their productivity [36-37]. Moreover, Despenic et al. [38] observed through two field studies that individuals chose different illuminance levels for the same task and provided a method for modelling their lighting preference profiles based on characteristics as activeness, dominance, lighting tolerance, and dimming level preference.

1.3.2 Non-visual effects of light

Visual ergonomics impacts on human factors through the interaction between the ambient lighting and the occupants of an indoor space. A body of literature research has demonstrated how lighting can affect the physiological, biological, and cognitive psychological aspects of humans, such as alertness, mood, working performance, hormone secretion, sleep, and circadian rhythms [39-54]. These impacts are significantly influenced by factors such as light spectral power distribution, intensity, duration, and individual circadian phases. The CIE S 026/E:2018 [55] introduced spectral sensitivity functions and metrics to assess how light affects the five photoreceptor types in the human retina that drive non-visual responses. Two metrics were introduced to quantitatively assess the non-visual effects of light: (i) the melanopic Equivalent Daylight Illuminance (mel-EDI), in [lx] to quantify the magnitude of the effects; and (ii) the melanopic Daylight Efficacy Ratio (mel-DER), which represents the melanopic content (mel-EDI) of each lx of photopic illuminance. In the second independent expert symposium organized by the CIE in Manchester in 2019 [56-57], guidelines were proposed under the motto "proper light at proper time," recommending mel-EDI ≥ 250 lx during the day, reducing to less than 10 lx three hours before bed, and less than 1 lx at night. Similar thresholds are proposed in the WELL Building Standard [58], developed by the International WELL Building Institute, which addresses both visual and circadian systems to promote health-focused lighting in buildings. The standard operates on a point-based system, making it a useful framework for integrative lighting analysis but is not tailored specifically for industrial buildings. It is worth stressing that while mel-EDI offers insights into non-visual light effects, no formal international standards exist.

Recently, several manufactures have developed the so-called tunable white LED luminaires, able to mimic daylight (the reference circadian light, particularly the skylight with a CCT of 6500K). In this regard, Cajochen et al. [59] tested a tunable LED lighting system on visual comfort, circadian physiology, daytime alertness, mood, cognitive performance, and sleep, by exposing 49 participants to a comparative test with a conventional LED light in laboratory conditions. The participants reported better visual comfort, felt more alert and happier in the morning and evening under daylight LED than conventional LED, while the diurnal melatonin profile, vigilance and working memory performance were not significantly different. In industrial buildings, particular attention has been paid to night-shift workers, who are exposed to peculiar ambient work conditions that may result in reduced cognitive performance, sleepiness, and higher possibility for human error and related incidents, due to the disruption of their circadian rhythms [60-62]. Some studies investigated whether blue-enriched white light was a practical strategy to decrease sleepiness and improve cognitive performance during night shifts. Motamedzadeh et al. [63] conducted a study through a before-after interventional design by surveying 30 control room staff members of a petrochemical industry. Every participant was exposed to two new lighting conditions (17000 K and 6500 K blue enriched white light), each lasting for a week. Through Karolinska Sleepiness Scale (KSS) and melatonin assessment using salivary and Eliza technique, their results showed that participants' sleepiness and melatonin rhythm significantly declined when they were exposed to blue-enriched white light, with positive effects on reducing memory or omission errors, and on increasing the reaction time during the attention task. Similar results were also obtained by Sletten et al. [64], while Riz à Porta et al. [65]) analysed four million behavioural responses from 1437 security officers at an international airport, comparing night shift and morning shift workers, finding no performance differences between the two shifts.

1.3.3 Integrative lighting (human-centric lighting): integration of visual and non-visual effects of light

The concept of "integrative lighting" was introduced by the International Commission on Illumination [55] to promote the balanced use of light to support both visual (photopic) and non-visual (melanopic) effects in building design. This approach, also known as "human-centric lighting" [66], combines electric and natural light to create health-supportive environments. Metrics like melanopic Equivalent Daylight Illuminance (mel-EDI) help quantify light's impact on the non-visual system. While integrative lighting has been widely investigated in offices [67-75], and classrooms [76-80], it has received less attention in industrial buildings. One of the few examples is the study by Van de Putte et al. [81]: they demonstrated that integrative lighting improved sleep and alertness in shift workers compared to standard lighting. Despite growing awareness of its benefits, current design standards still focus mainly on visual and energy efficiency requirements, often neglecting non-visual effects. There is a clear need for further guidelines to address both photopic and melanopic aspects, particularly in industrial settings where performance, attention, and safety are critical.

1.4 RESEARCH GOALS

According to the Industry 5.0 vision outlined by the European Commission [22-23], it is important to put humans back at the centre of production activities and use modern technologies to facilitate them in carrying out their activities, such as, for example, collaborative robots (cobots). In this frame, several ergonomic devices have already been adopted in recent times to accommodate the needs of operators including, for example, by electrically adjusting the height of workbenches or tilt worktops, along with solutions for ergonomic positioning of work equipment and components to be assembled. The question then arises: since light plays a fundamental role during assembly activities, why, to date, isn't the same importance also attributed to lighting systems? Besides, when choosing workbench lighting, aren't the light sources selected considering both photopic and melanopic effects on users?

The authors of the present paper already explored in the past the topic of 'factory of the future', assessing the enhancement of wellbeing of the workers by optimizing daylight amount in management offices, production/services area, and warehouse [82-83]. In this frame, the current paper presents results from a study on integrative lighting conditions in the manufacturing area of an actual factory located in the suburbs of Turin, in northern Italy (latitude: 45°N). Both electric lighting and daylighting conditions were taken into consideration, particularly focusing on lighting conditions that are produced at a sample of representative workstations, both U-shaped and L-shaped. The study therefore aims at bridging a research gap, which is the verification of the extent to which human-centric lighting (integrative lighting) conditions are achieved in real settings of industrial buildings, designed to meet photopic requirements. Such a gap is analysed in a real case-study, which is an industry in the automotive sector. In more detail, the research was conducted with the following objectives:

a) to analyse the photopic illuminance on workstations (benches and monitors) and the circadian illuminance (mel-EDI) at the eyes of the operators working at the workstations (on benches and while reading monitors) and verify if this could meet the recommendations reported in the CIE documents or in the WELL protocol
b) to investigate how the lighting conditions were perceived by the workers.

2 CASE STUDY: INDUSTRY OF ASSEMBLING INTERIOR COMPONENTS FOR LUXURY CARS NEAR TURIN (ITALY)

The study was carried out at an industrial plant, which hosts 27 assembly lines, focusing on six lines selected as the most significant from the point of view of lighting comfort analysis.

The main activity consists of assembling interior components for luxury cars ranging from infotainment controls, centre tunnels with automatic transmission, touchscreen displays, and multi-function steering wheels.

There are three shifts as follows: (i) first shift: 06:00 - 14:00; (ii) second shift: 14:00 - 22:00; and (iii) middle shift: 08:00 -16:45.

The production department staff consists of about 30 operators, ten of which employed in component receiving and storage, assembly line feeding, and finished product handling management.

2.1 CHARACTERISTICS OF THE BUILDING AND OF THE LEAN PRODUCTION LINE

The building where assembly is carried out has a rectangular area of about 1400 m^2 with a shed roof facing north-east (Figure 2). Therefore, the rectangular manufacturing area has a glazed full-height façade facing South-West SE and receives daylight mainly through the rooflighting systems (shed). The building, although inaugurated in 1974, has numerous features aimed at the well-being of the operators, with particular attention to the natural lighting of the working environment.

Furthermore, its shed roof configuration offers the possibility of integrating smart green technologies, including solar thermal collectors and photovoltaic panels, that can further contribute to the internal comfort of the operators while saving energy [84-86].

Each production line was designed according to the principles of lean production to make it possible to alternate the assembly of quantities of products belonging to the same type, but different in shape as they belong to cars of different brands. This is possible because each line is designed in a simple way, adopting layouts where it is very easy to quickly change the equipment.

Figure 2 Image of the industrial building used in the study.

In addition, for each assembly line, the work surfaces and positions of components and equipment are placed based on ergonomics principles so as not to fatigue operators and allowing assemblies with a high-quality standard throughout the work shift. Six production lines were selected across the manufacturing area, whose configurations and types of products assembled are reported in Table I.

Table I - configurations and types of products assembled in the production lines analysed in the study

Production Line	Layout configuration	Types of products
I016	L-Shaped	Instrument panel for climate, speed, lights and infotainment services control
I024	L-Shaped	Touch-screen display
I028	U-Shaped	Automatic transmission selector
I034	L-Shaped	Buttons for automatic seat memorization
I037	L-Shaped	Multi-function steering wheels, paddle-shift, etc.
I041	L-Shaped	Central tunnels with automatic transmission controls

2.2 LIGHTING CHARACTERISTICS OF WORKSTATIONS

The lighting concept of the manufacturing area relies on the combination of two systems: an arrays of pendant downlight LED lighting systems (suspended at a height of 6.74 m above the finished floor) provides general lighting to the area, especially for circulation spaces, whilst the most important contribution for the assembly tasks is provided by LED systems embedded in the structures of the cells, mounted at a height of 1.90 m above the finished floor. These are downlight systems with a diffuser to guarantee the minimum illuminance levels on the assembly benches without any glare for the workers. Figure 3 shows an example of one of the production lines that were investigated.

3 METHOD

The study relied on a combination of approaches: (i) experimental field measurements, to quantify the lighting levels at workstations where users perform their task, with respect to both visual (photopic illuminances and quantities) and non-visual effects (melanopic illuminances) of light; (ii) a short questionnaire to collect the individual perceptions of the lighting conditions as expressed by the users working at the workstations considered.

Figure 3 Image of the production line I016 (L-shaped).

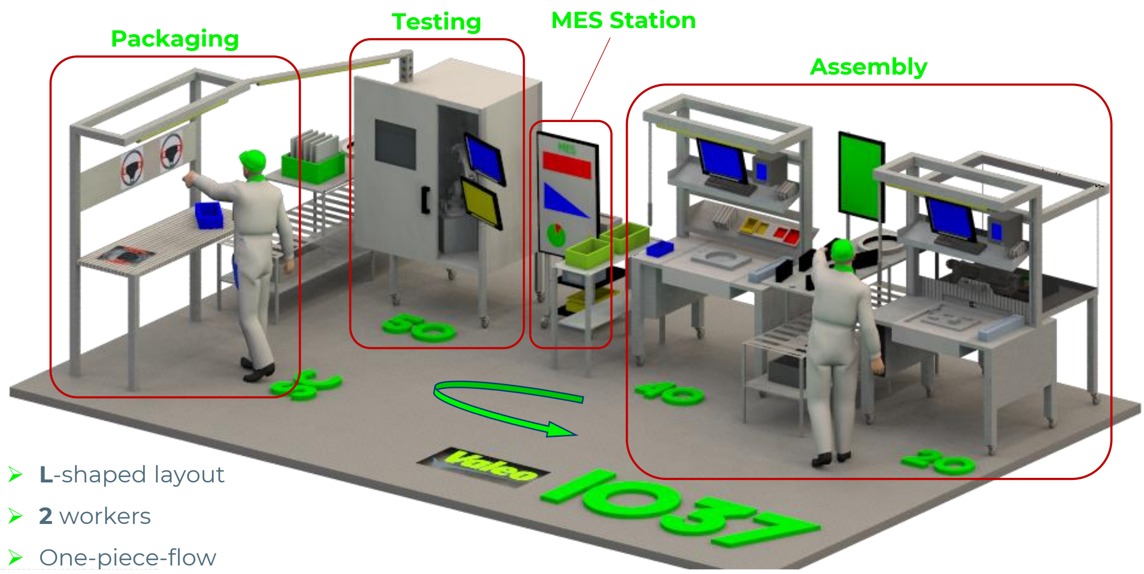


Figure 4 Schematic visualizations of two L-shaped cells, where benches, monitors and embedded lighting systems are highlighted, as well as the various tasks carried out by the workers. NOTE: MES = Manufacturing Execution System.

3.1. MEASUREMENTS

In an integrative lighting perspective, both photopic and melanopic quantities were measured. Photopic quantities were: illuminance (E), Colour Rendering Index (CRI), and Correlated Colour Temperature (CCT). The melanopic equivalent daylight illuminance (mel-EDI) was the melanopic quantity measured. All the quantities were acquired by using a spectrophotometer Gigahertz BTS256-EF (measurement range: 360–830 nm; measurement sensitivity: 10 nm; error: ±2.2%). Measurements were taken on two types of surfaces:

- *task areas*, namely: (i) benches, where workers perform tasks such as mounting, assembling, and controlling the quality of object of various size; on each bench, four measurements were taken, according to a square grid of 25 cm of size, and then assuming the average value; and (ii) monitors used by workers to read/input information on a screen: in this case, one measure was taken, positioning the instrument on the vertical (or tilted) surface of the screen. Differently, three measures were taken for the totems (e-WS), to account for the different quantity of light received due to their extension in size
- *eye-level*, positioning the instrument at a height of 1.6 m above the floor, pointing at benches and monitors, to reproduce the actual view directions of workers while performing their task.

Figure 4 shows the surfaces where measures were taken for two workstations (I-024 and I-037, L-based cells).

3.1.1. Requirements for photopic quantities

Regarding photopic quantities, the European Standard EN-12464-1:2021 [87] was taken as reference. The main parameters specified by the standard for various task activities are: (i) maintained average illuminance Em and illuminance uniformity U0; (ii) limiting unified glare rating RUGL; and (iii) colour rendering index CRI (or Ra), namely:

- rough assembly (e.g., large transformers):
  $E_m \geq 300$ lx, $U_0 \geq 0.60$ modified $E_m \geq 500$ lx
  $R_{UGL} \leq 25$ CRI = $R_a \geq 80$
- medium assembly (e.g., switchboards):
  $E_m \geq 500$ lx, $U_0 \geq 0.60$ modified $E_m \geq 750$ lx
  $R_{UGL} \leq 22$ CRI = $R_a \geq 80$
- fine assembly (e.g., IT equipment, computers):
  $E_m \geq 750$ lx, $U_0 \geq 0.70$ modified $E_m \geq 1000$ lx
  $R_{UGL} \leq 19$ CRI = $R_a \geq 80$
- precision assembly (e.g., printed circuit boards):
  $E_m \geq 1000$ lx, $U_0 \geq 0.70$ modified $E_m \geq 1500$ lx
  $R_{UGL} \leq 16$ CRI = $R_a \geq 80$

The 'modified' minimum illuminance is a 1-step increase in the minimum E_m that can be applied under any of the following conditions: critical visual work; errors costly to rectify; great importance attributed to accuracy, higher productivity or increased concentration; unusually small size or low contrast of task details; unusually long-time task; low daylight provision; visual capacity of workers below normal.

3.1.2. Recommendations for melanopic quantities

Concerning the melanopic daylight illuminance (m-EDI), it was decided to refer to the two documents currently present in the literature: (i) the earlier mentioned documents from the CIE, which sets to maintain at least 250 lx of mel-EDI during daytime; (ii) the recommendations expressed in the WELL Building Standard, version 2. Both approaches converge on a minimum value of mel-EDI of 250 lx. The WELL protocol offers two options, granting different points for different targets achieved:

- mel-EDI ≥ 250 lx (consistently with the CIE recommendation) to receive 3 points
- mel-EDI ≥ 136 lx to receive 1 point.

3.2. QUESTIONNAIRE

A short questionnaire was specifically designed to investigate how the workers perceived the lighting conditions available at the various benches and monitors where they perform their tasks. The questionnaire was distributed among 11 workers and consisted of three sections (plus one section to collect free comments). Section A, on lighting conditions generally perceived at the workstation as a whole; the section contained two types of questions:

- Q1: «*overall, how do you rate the quantity of light at this workstation*?». The users could express their judgment using a 5-point scale, where: 1 = too low; 2 = low; 3 = adequate; 4= high; 5 = too high
- Q2 to Q5: the users could express their agreement on different statement, using a 4-point scale, where: 1 = totally disagree; 2 = partially disagree; 3= partially agree; 4 = totally agree; the questions were:
- Q2: «*overall, the lighting quantity at my workstation is adequate*»
- Q3: «*overall, lighting conditions at my workstation create a stimulating environment*»
- Q4: «*overall, lighting conditions at my workstation favour my concentration*»
- Q5: «*overall, lighting conditions at my workstation create a comfortable environment*».

Section B, on lighting conditions perceived regarding specific benches and monitors used to carry out the work activity (mounting, assembly, control, using a monitor – reading or inputting information on screen).

Like in Section A, the users were asked to express their agreement using a 4-point scale, where: 1 = totally disagree; 2 = partially disagree; 3= partially agree; 4 = totally agree; the following questions were asked:

- Q6: «*in this moment, lighting conditions facilitate carrying out my task*»
- Q7: «*in this moment, I perceive glare while I'm carrying out my task*».

Above questions were repeated for all the benches and monitors positioned at the workstation.

Section C, to collect information on the workers, such as gender, age, height, and the duration time of the shift («For how many hours through your shift have you worked today»?).

Comments: the participants were asked to highlight criticalities concerned with the lighting conditions that may not have been covered by the questionnaire items, as well as to express their desires for an improved and more 'visually ergonomic' workstation.

The full questionnaire is reported in Appendix A.

4 RESULTS

The following images (Figures 5-12) report the experimental results that were collected at the various workstations analysed in the study. Both the measurements and the subjective judgments expressed by the workers are shown.

It should be noted that the M/E is an alternative, more concise, symbol for the melanopic daylight efficacy ratio mel-DER. In all these figures, the symbols visualized have the following meanings:

E	photopic illuminance [lx]
M	mel-EDI = melanopic daylight equivalent illuminance [lx]
M/E	mel-DER = melanopic daylight efficacy ratio [-]
R_a	CRI = colour rendering index [-]
CCT	correlated colour temperature [K].

4.1. SYNTHETIC RESULTS: VISUAL EFFECTS OF LIGHT ON BENCHES

Figure 13 reports the average illuminance levels measured at the various workplanes. The values measured at monitors are not reported as these are self-illuminated. Illuminance was found to be above 500 lx (corresponding to medium assembly activities) on all the benches analysed; this was an expected result, as the lighting systems embedded in the cells is specifically sized to meet with this standard requirement; it can also be noted, though, that the measured illuminances are also above the 750-lx threshold (corresponding to fine assembly activities) at all workstations, excluding two cases (I028_evening and I034, in both cases on bench C, where complex tasks are carried out, such as assembling steering wheels). Moreover, all workstations also meet the minimum 1000-lx requirement, apart from two other cases (benches A and F in workstation I037 at evening, i.e. in electric lighting only), which can be associated with precision assembly activities, but also as 'modified' increased illuminances for rough and fine assembly.

4.2. SYNTHETIC RESULTS: VISUAL AND NON-VISUAL EFFECTS OF LIGHT AT EYE-LEVEL

The quantities measured at eye-level are reported in Figures 14-15: mel-EDI and mel-DER (Figure 14), and correlated colour temperature CCT (Figure 15).

The following main considerations can be drawn:

- non-visual effects of light: eye-level mel-EDI showed a wide range of values, from 53 lx to 1525 lx, with an average value of 601 lx and a standard deviation SD = 394.3 lx; referring to the target values set by CIE and in the WELL protocol, it is worth noting that 71.9% of the view directions towards benches or monitors showed values mel-EDI ≥ 250 lx (3-point WELL criterion) , with 86.0% of values mel-EDI ≥ 136 lx (1-point WELL criterion); for the same view directions, mel-DER was found to be in the range 0.58-0.89, with an average value of 0.67 (SD = 0.07)
- CCT values were in the range 3902-5600 K, with an average value of 4469 K (SD = 394.6 K); overall, the colour temperature resulting from the various spectral power distributions (electric light, daylight when present, light reflected off the workstations surfaces for the various view directions considered) is mainly in the neutral range (3300 K ≤ CCT ≤ 5300 K); the higher values above 5300 K are those of the cold light emitted by the e-WS monitors.

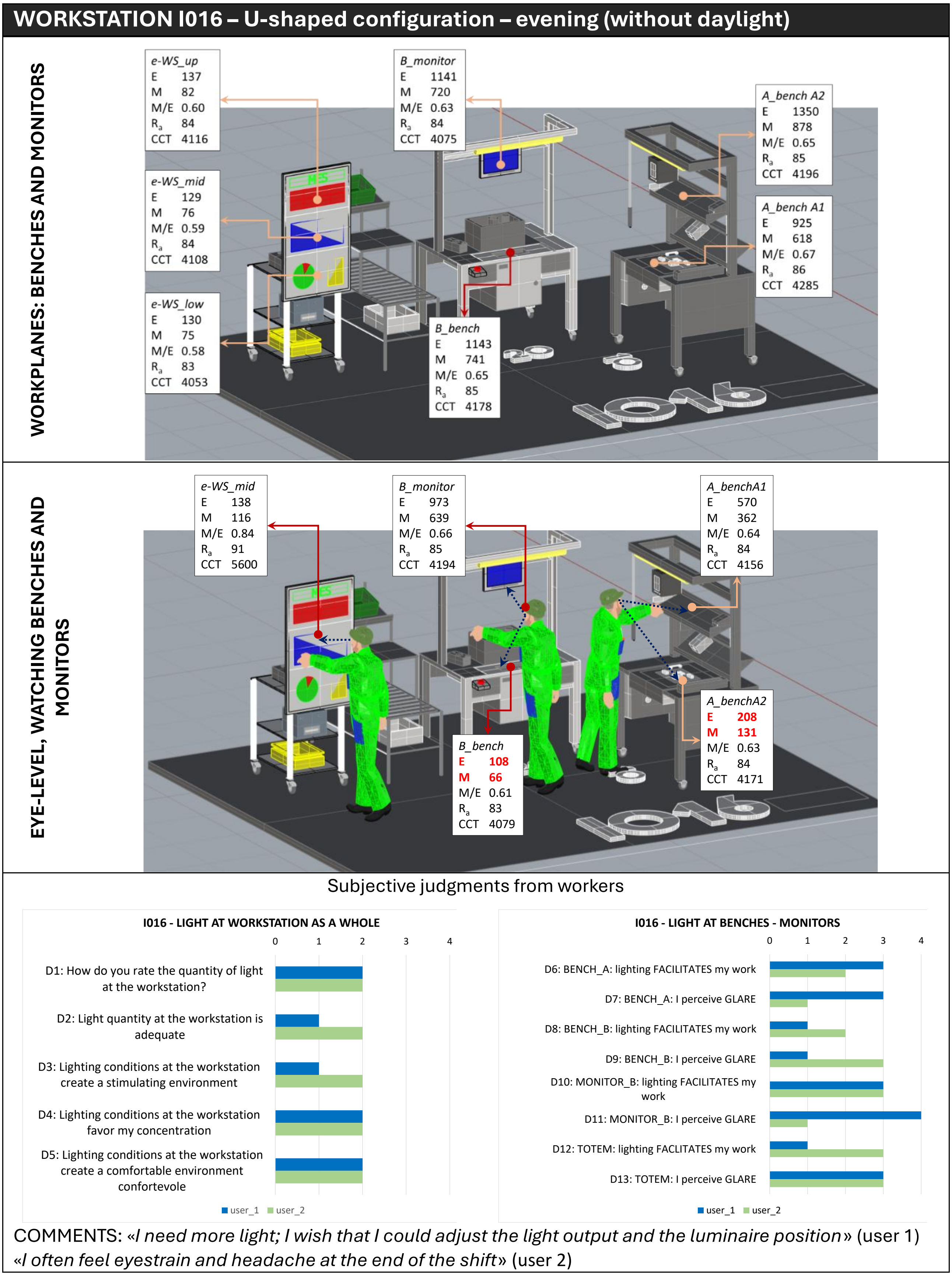


Figure 5 Lighting measurements and subjective judgments for workstation I016 (L-shaped).

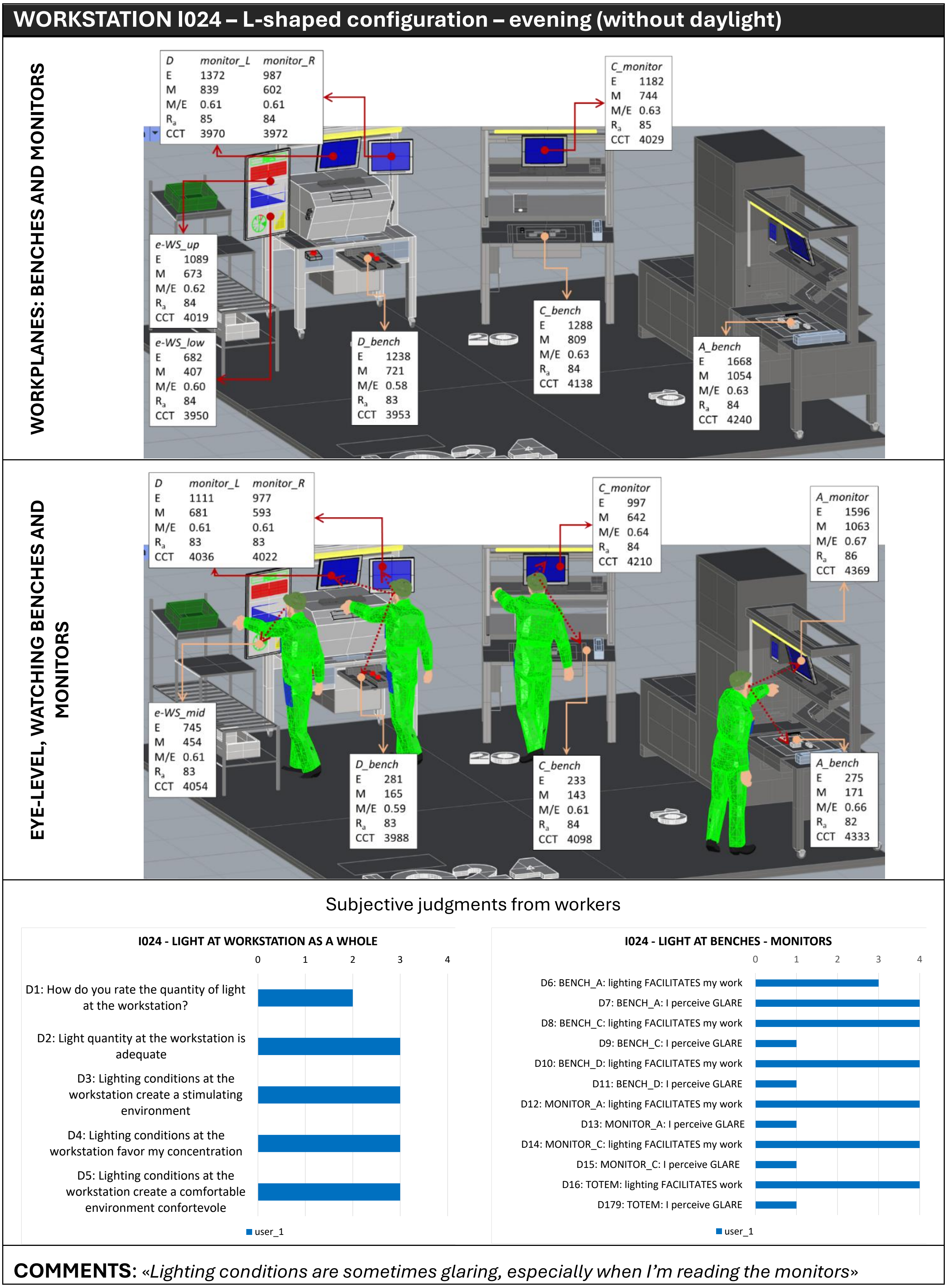


Figure 6 Lighting measurements and subjective judgments for workstation I024 (L-shaped).

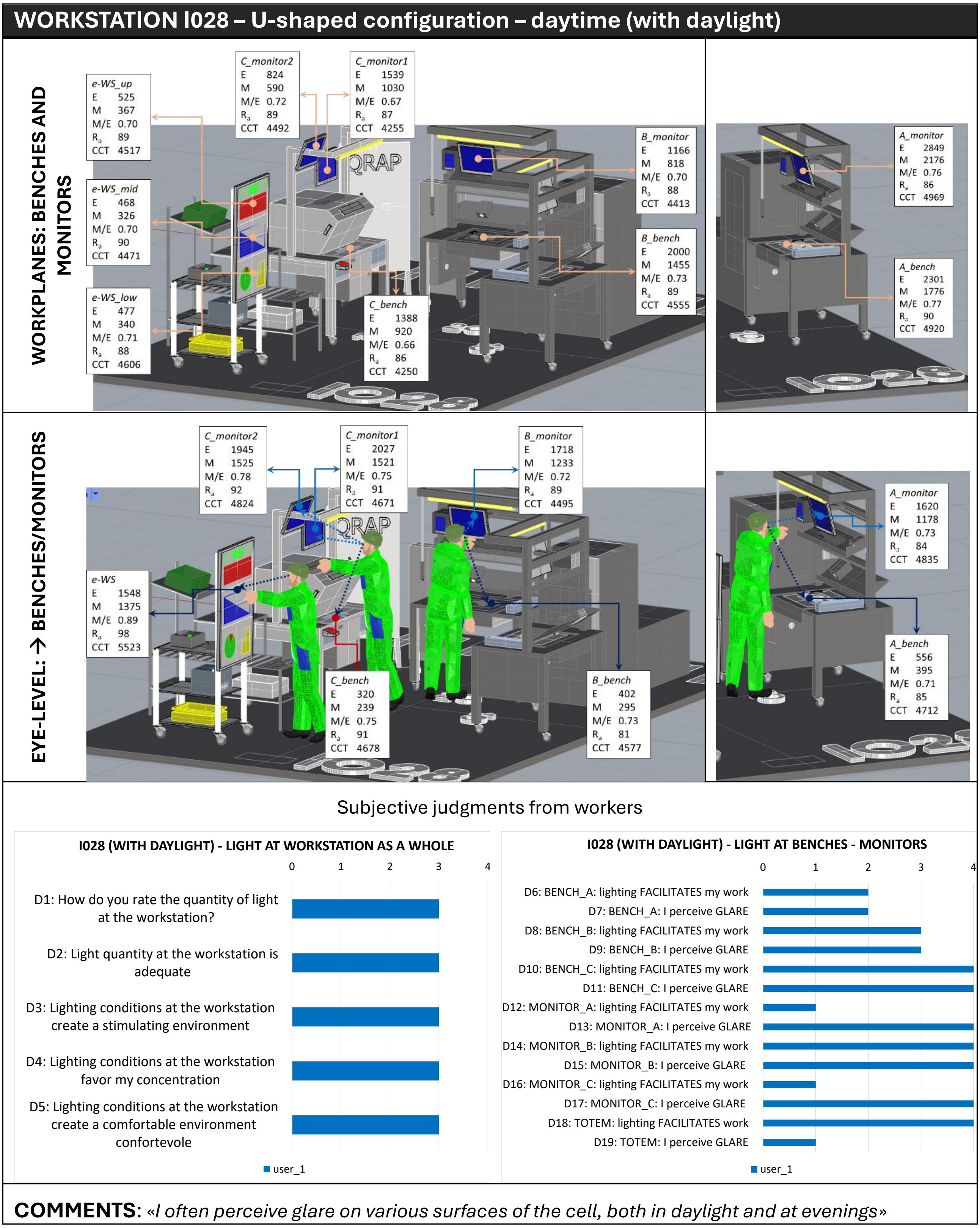


Figure 7 Lighting measurements and subjective judgments for workstation I028 (U-shaped, with daylighting).

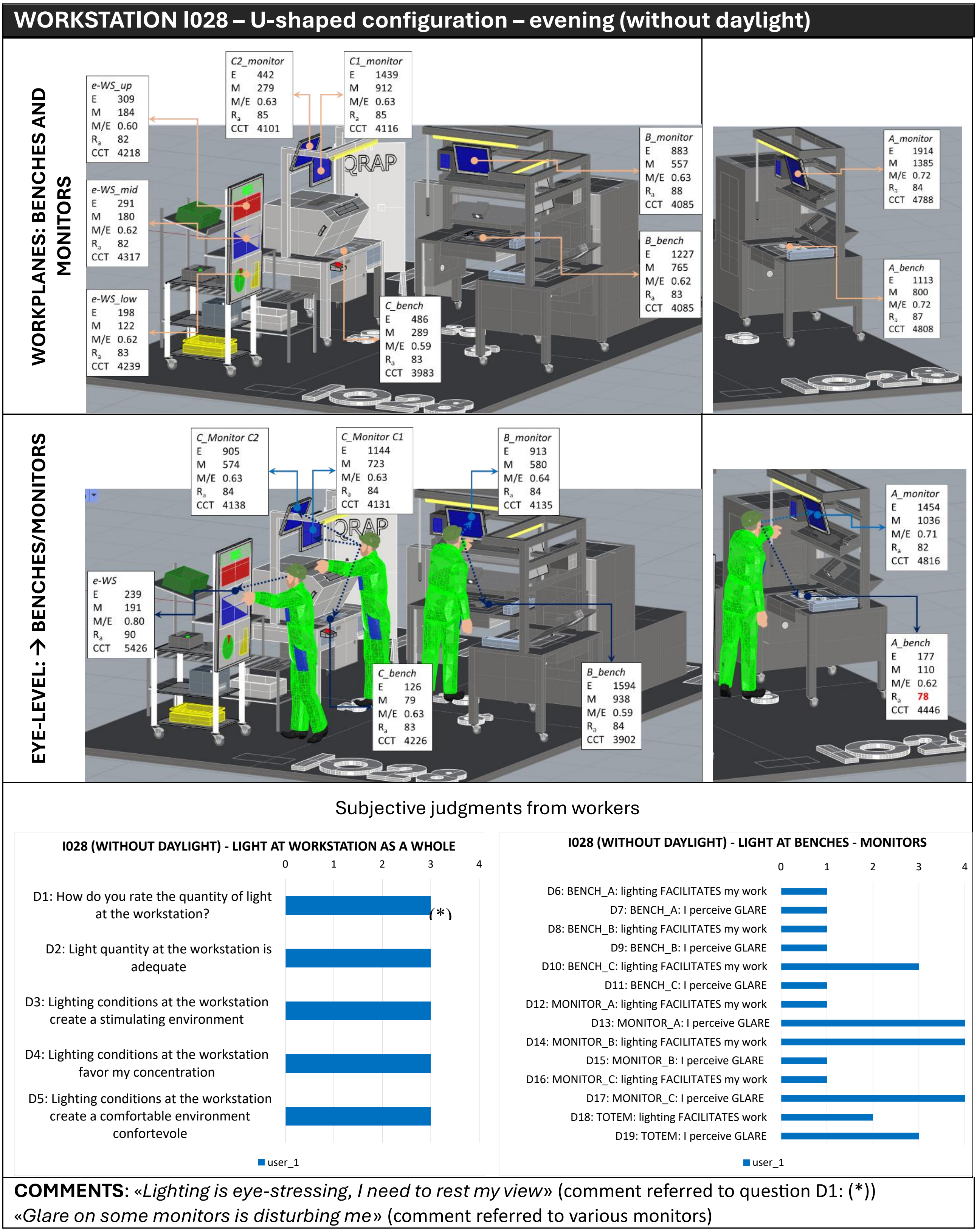
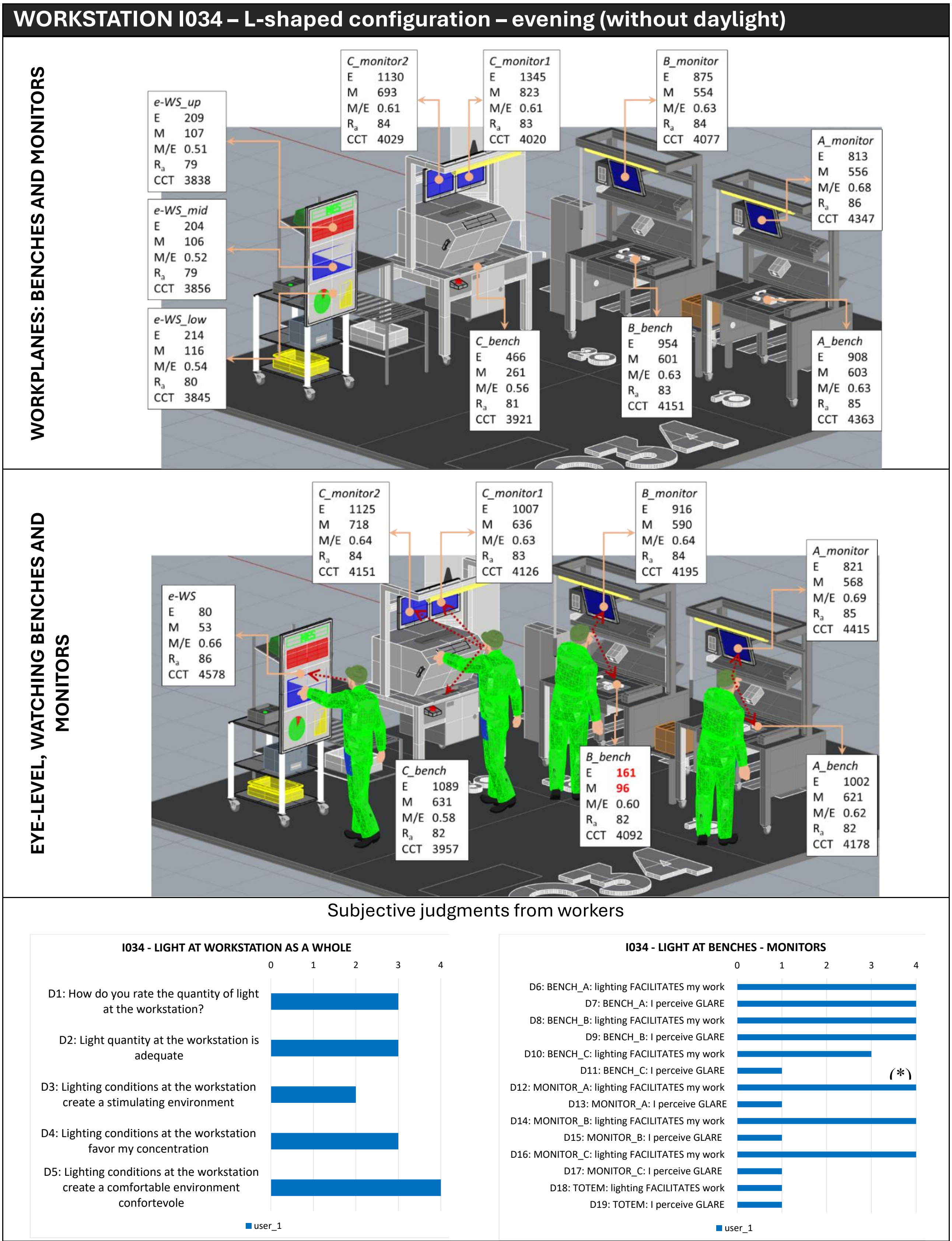
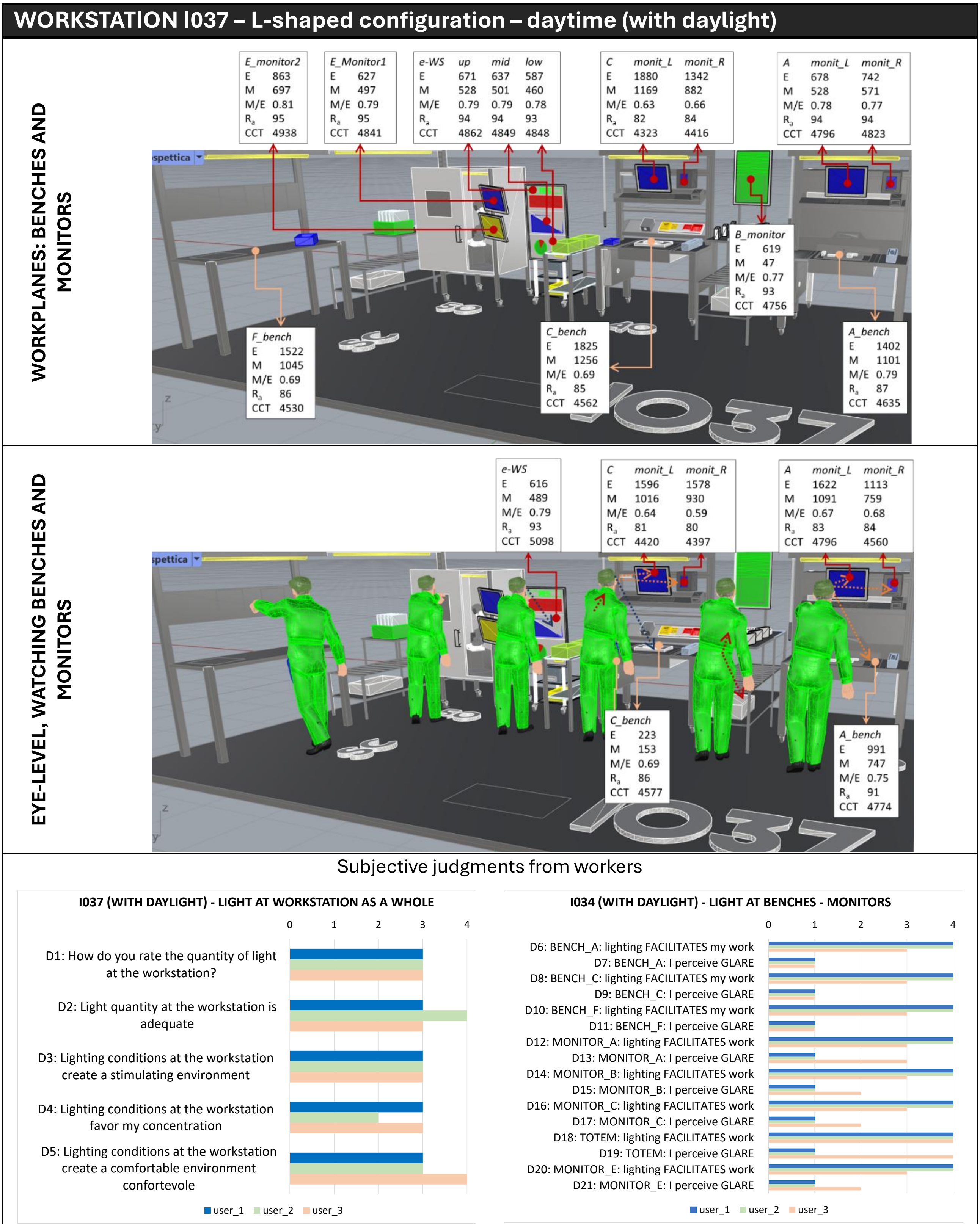


Figure 8 Lighting measurements and subjective judgments for workstation I028 (U-shaped, without daylighting).



COMMENTS: «*I switch off lighting on bench C*» (comment referred to bench C, (*))
«*Lighting is too scarce on monitors*» (comment referred various monitors)

Figure 9 Lighting measurements and subjective judgments for workstation I034 (L-shaped). NOTE: the e-WS was off.



COMMENTS: user 1: «*I feel eye strain, especially towards the end of the shift and especially in the evening, when I'm working without daylighting (electric light only)*»
user 2: «*lighting conditions do not favor my concentration as there are discrepancies among the various surfaces*»
user 3: «*I wish I could adjust the amount of light and the position of the luminaire to match my needs*»

Figure 10 Lighting measurements and subjective judgments for workstation I037 (L-shaped), with daylight.

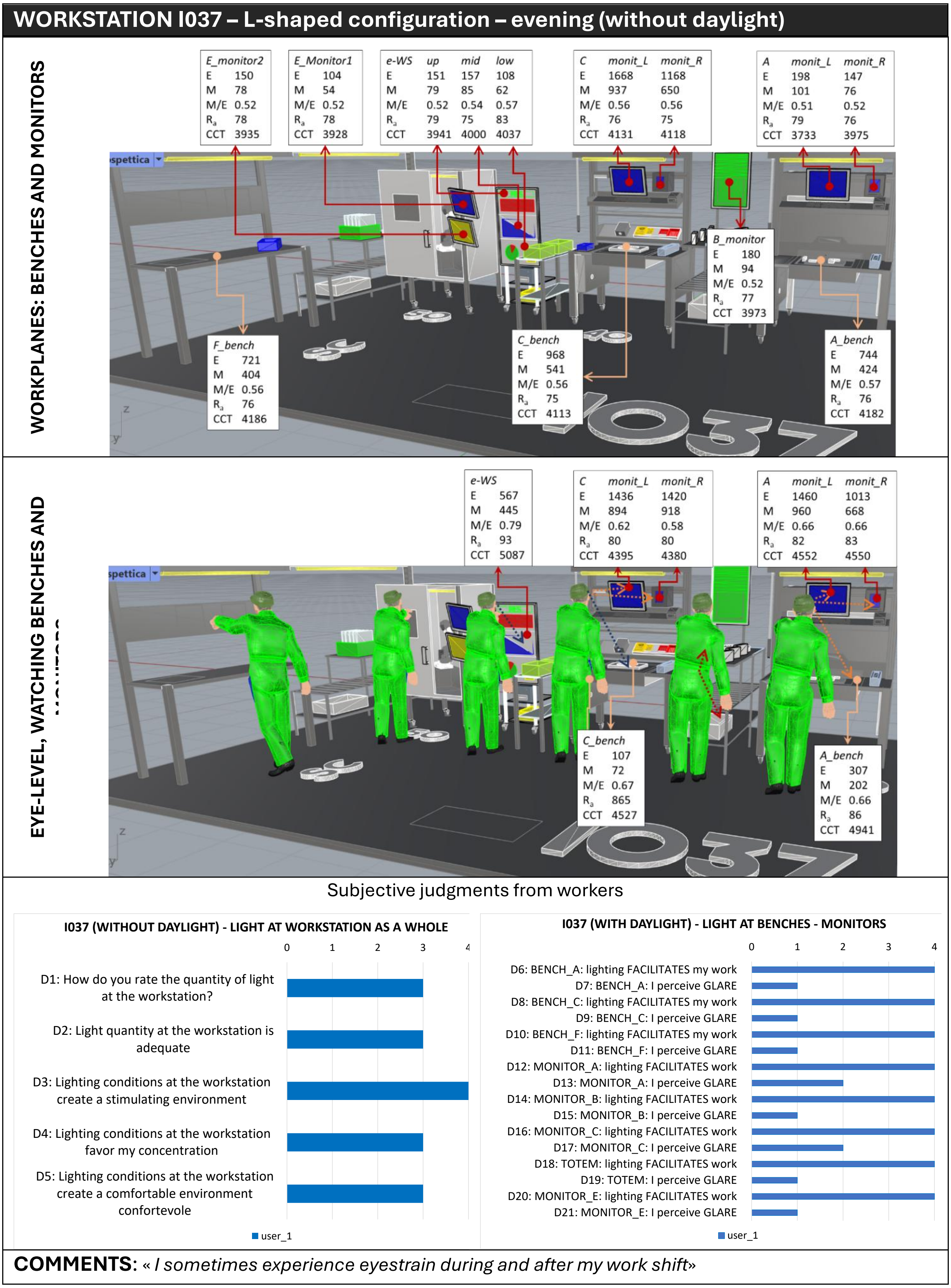
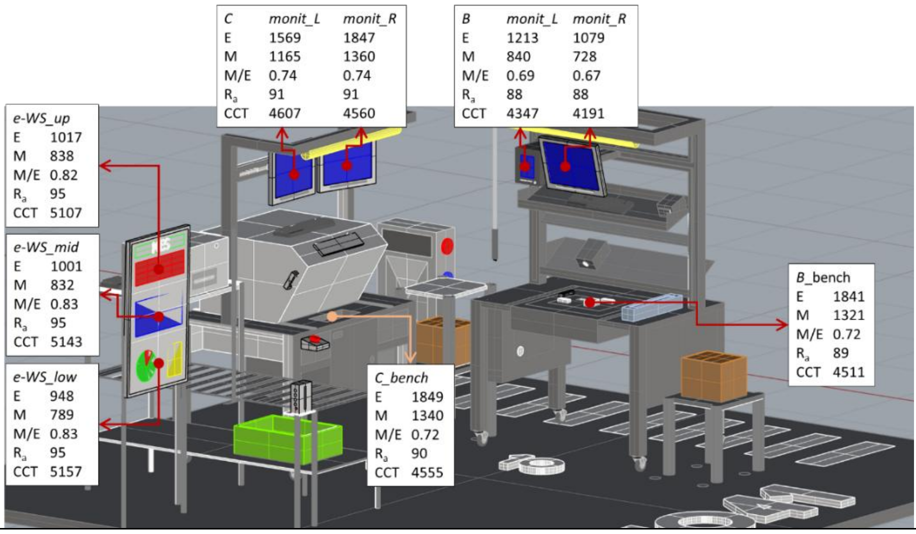


Figure 11 Lighting measurements and subjective judgments for workstation I037 (L-shaped), without daylight.

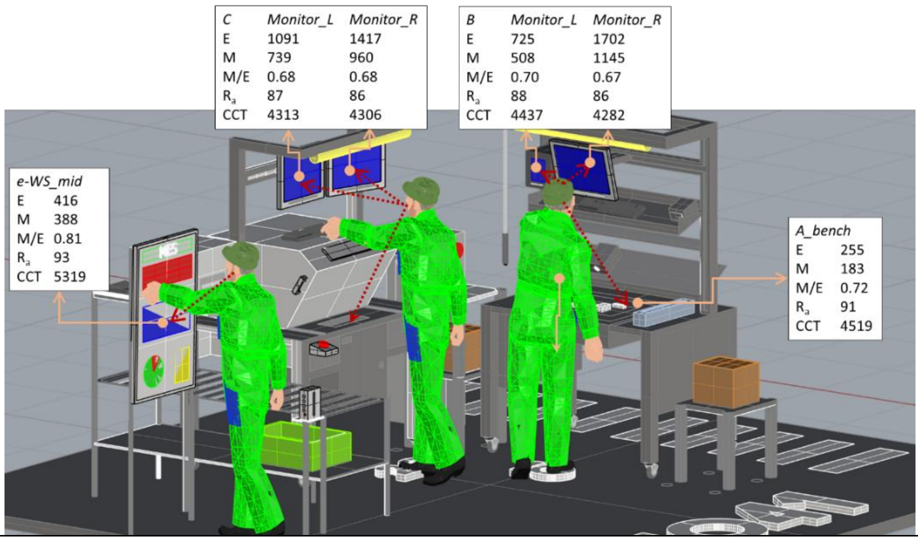
ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 26, No. 01, 2025

WORKSTATION I041 – L-shaped configuration – evening (without daylight)

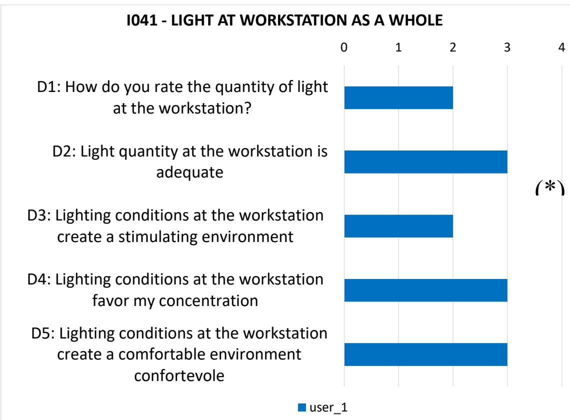
WORKPLANES: BENCHES AND MONITORS

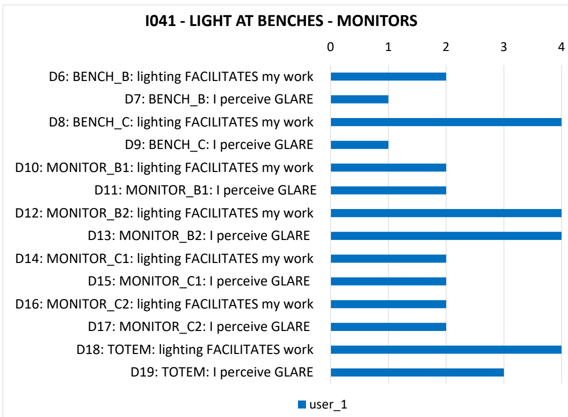


EYE-LEVEL, WATCHING BENCHES AND MONITORS



Subjective judgments from workers





COMMENTS: «*I would need more light to carry out the assembly of small objects, especially those that have black symbols against a black background*» (comment referred to question D2: *) »
«*In the presence of daylight, especially when sunlight is hitting the workstation, reading the information displayed on the screen becomes difficult*» (comment referred to various monitors) »

Figure 12 Lighting measurements and subjective judgments for workstation I041 (L-shaped).

4.3. EFFECT OF DAYLIGHT

For two workstations (namely I028 and I037), measurements were repeated during daytime, in the presence of daylight, and in the evening, in electric light only. The following considerations can be drawn by comparing data:

For illuminance values on benches:

- workstation I028: the average illuminance on the 3 benches (A, B, C) was 1896 lx in daylit conditions and 952 lx in electrical lighting conditions only, thus with a relative increment of +99.2% due to daylight
- workstation I037: the average illuminance on the 3 benches (A, B, C) was 1583 lx in daylit conditions and 844 lx in electrical lighting conditions only (relative increment of +87.5% due to daylight)
- at both workstations, illuminance values on the various benches were over 1300 lx, which is consistent with the strictest illuminance requirements of precision assembly ($E \geq 1000$ lx)

For mel-EDI and mel-DER:

- workstation I028: the average mel-EDI for all the view directions was 970 lx in daylit conditions and 527 lx in electrical lighting conditions only, thus with a relative increment of +83.9% due to daylight; the corresponding average m-DER increased from 0.66 to 0.76 in daylight condition (15.4%)
- workstation I037: the average mel-EDI for all the view directions was 741 lx in daylit conditions and 580 lx in electrical lighting conditions only (relative increment of +27.7% due to daylight); the corresponding average m-DER increased from 0.66 to 0.69 in daylight condition (+4.0%)
- at both workstations, thanks to the increment in the mel-EDI values at eye-level, all view directions comply with the 1-point WELL criterion as well as, apart from one case, with the 3-point WELL criterion

For CCT:

- workstation I028: the average CCT for all view directions increased from 4403 K in daylit conditions to 4789 K (+8.8%)
- workstation I037: a different trend was observed, as the average CCT for all the view directions remains unchanged (4628 K in daylit conditions and 4633 K in electrical lighting conditions only).

To summarize, the presence of daylight increased the light levels at the two workstations considered, but more significantly for the illuminance values on the benches and to a lower extent for the vertical planes at eye-level (mel-EDI, mel-DER, CCT).

4.4. SUBJECTIVE EVALUATIONS

Eleven workers answered the questionnaires, five men and six women, whose age was in the range 31-57 years (average: 49.3 years; SD: 6.86 years). The height of the participants ranged from 153 cm to 180 cm (average: 168.4; SD: 9.8 cm). Splitting the sample and analysing separately the groups of men and women, some differences emerged: men had a lower age (average: 47.2 years; SD: 10.1 years) than woman (average: 51.2 years; SD: 2.1 years); as for the height, men showed a higher height, with an average of 176.8 cm (SD: 3.42 cm) than women (average: 161.3 cm; SD: 7.34 cm). As for the question «*For how many hours through your shift have you worked today?*», 9 workers answered that they had been working for more than 6 hours, while one woman for 2-4 hours and one man for less than 2 hours. Therefore, most operators filled in the survey towards the end of their shift. Figs. 16-17 summarize the subjective judgments expressed by the sample of workers.

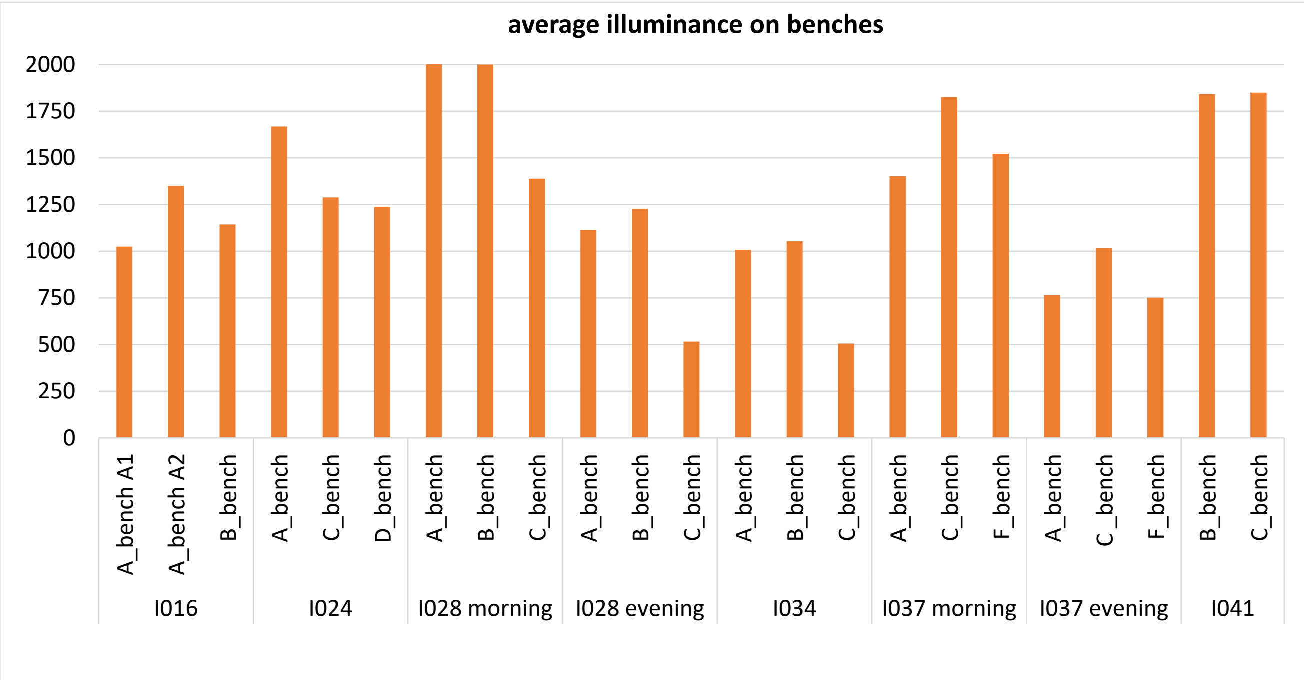
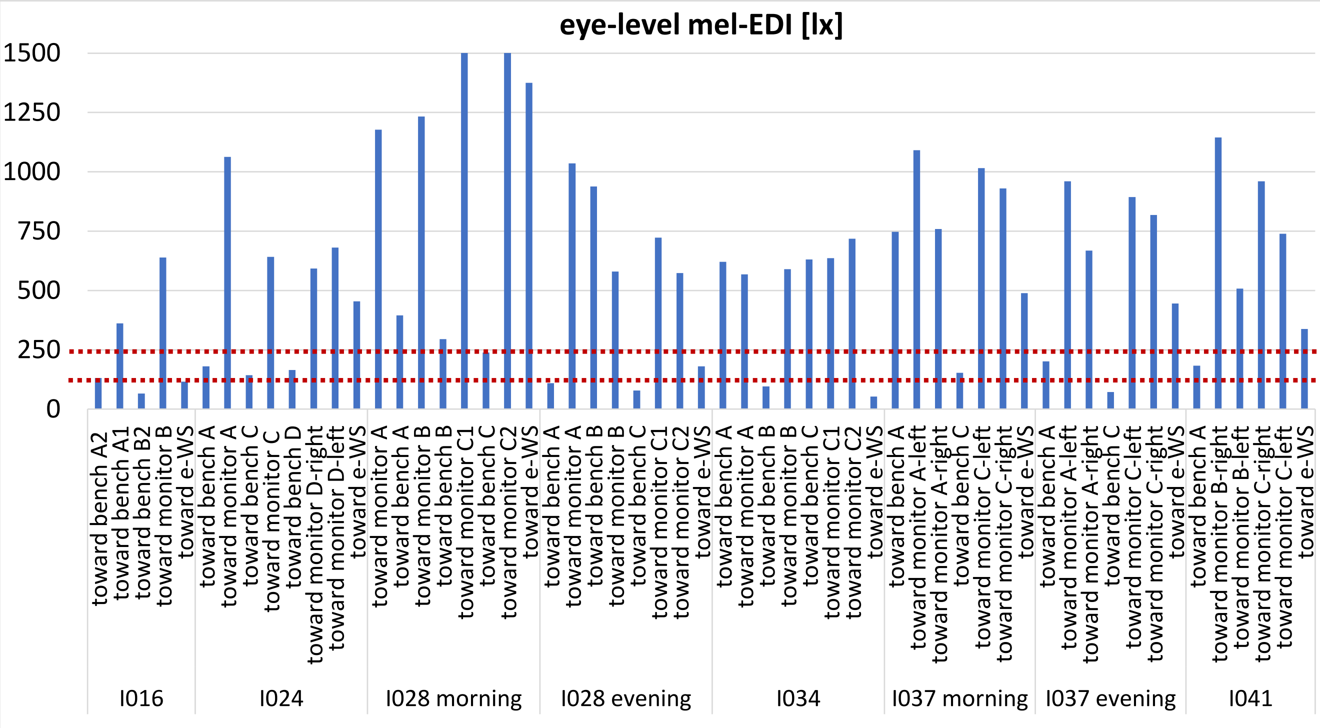


Figure 13 Average illuminance values measured on the various benches analysed.



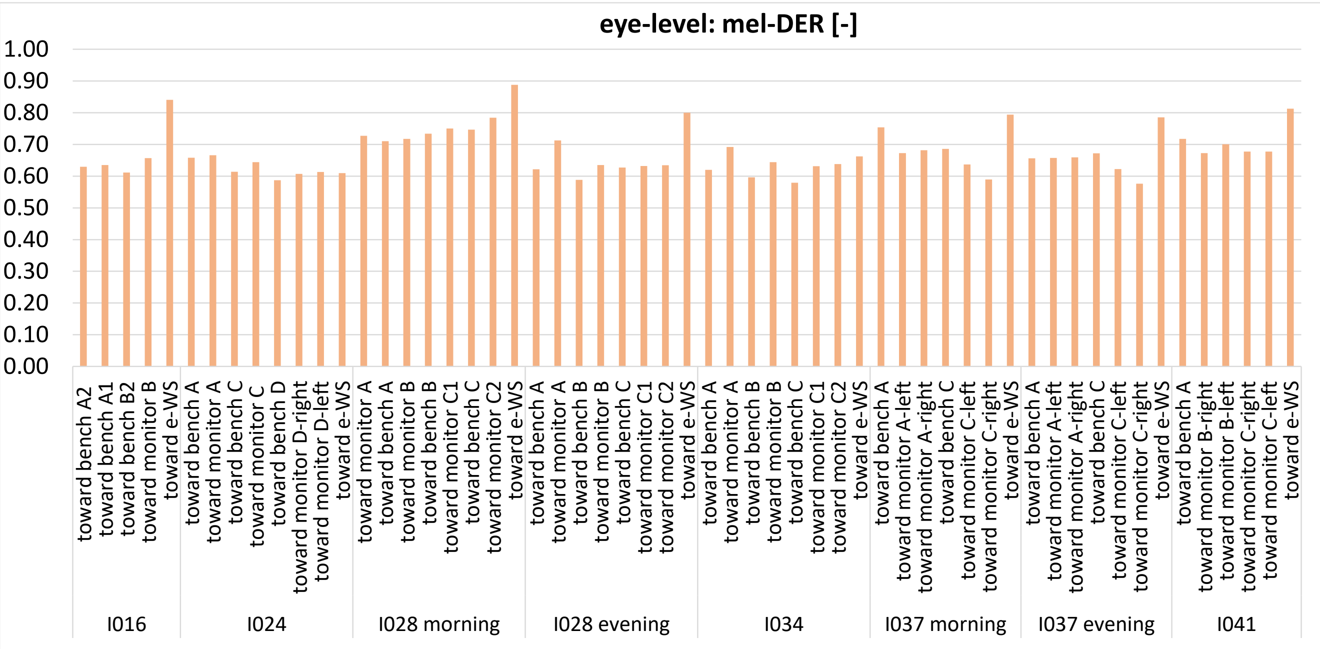


Figure 14 Melanopic results from measurements at eye-level: mel-EDI and mel-DER.

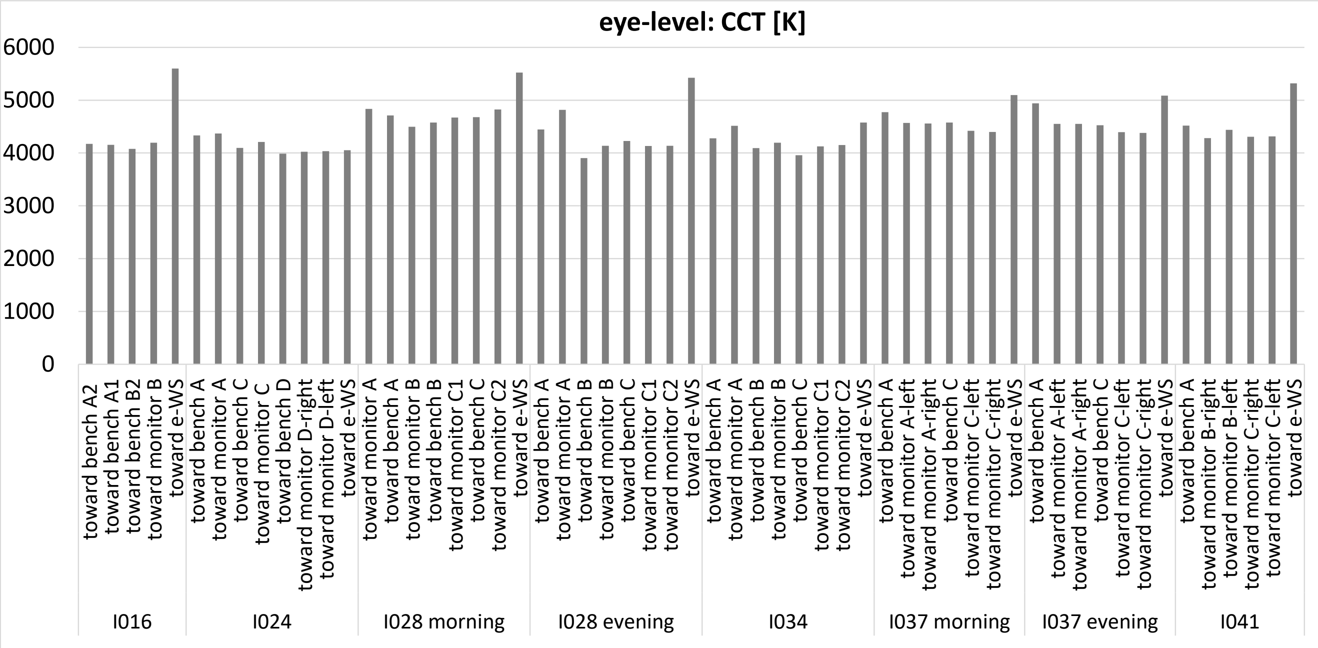


Figure 15 Photopic results from measurements at eye-level: correlated colour temperature CCT.

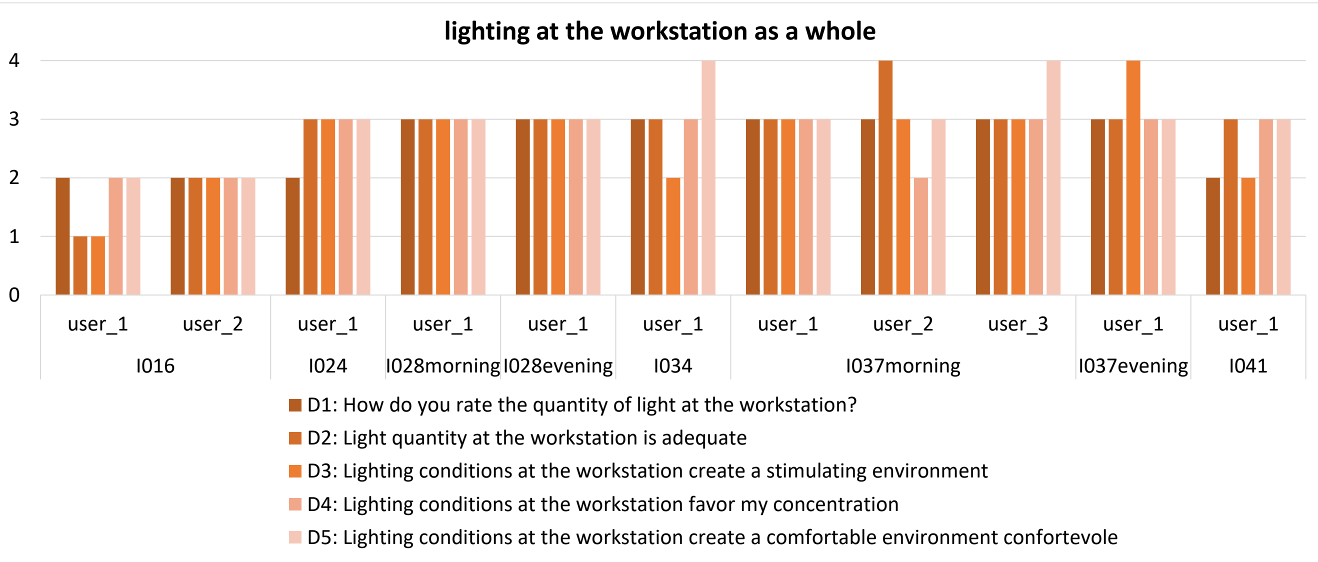


Figure 16 Synthesis of subjective judgments expressed by the workers on the lighting conditions globally perceived at the workstation.

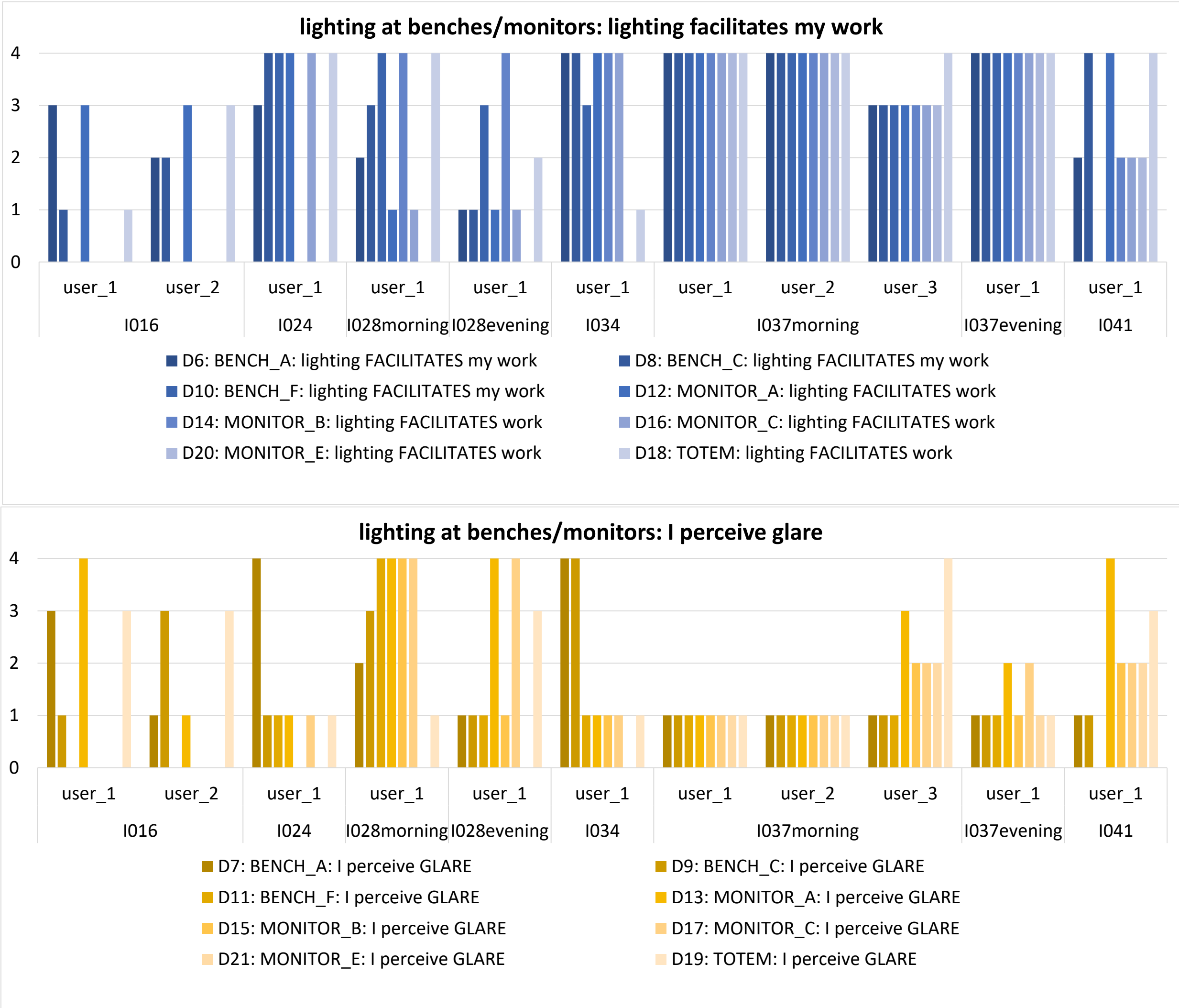


Figure 17 Synthesis of subjective judgments expressed by the workers on the lighting conditions perceived at specific benches and monitors.

Besides the subjective scores, interesting findings emerged from the open comments. The following considerations can be drawn from the results shown in the figures:

- for lighting conditions on the workstation as a whole: the workers expressed satisfaction with the overall lighting conditions for most workstations, with an average scores ≥ 3 (questions D1-D5); slightly lower score were expressed by the worker of workstations I024 (average score of 2.80), particularly for the quantity of light, and by the worker of workstation I041 (average score of 2.60), who reported a low quantity of light and a low stimulating lighting scenario; however, the lowest scores were expressed by the 2 workers of workstation I016 (average score: 1.60 and 1.80, respectively), with lowest scores on the quantity of light and on the stimulating ambient light. Particularly, these workers complained about the fatigue and eyestrain they perceive and would like to have a flexible lighting system
- for the lighting conditions at each specific bench/monitor, regarding the questions on «lighting facilitates my work»: a lower number of high scores was observed compared to the assessment on the whole workstations. Four workstations received high scores (average score ≥ 3). Average scores < 3 were observed for workstations I016 (average: 2.33 for both workers), consistently with the low scores expressed on the overall workstation, and I041 (average score: 2.67). The lowest scores were expressed for workstation I028 during the evening (average: 1.83), while the scores resulted higher (average: 2.50) but still not satisfactory during the daytime, thanks to the presence of daylight; however, complaints about eyestrain were expressed by the evening worker and on glare during the daytime (see next point)
- for the lighting conditions at each specific bench/monitor, regarding the questions on «I perceive glare»: complaints about glare were raised for some surfaces (bench/monitors) at workstations I016 (however, the average score was 2.67), I024 (average: 1.60), I034 (average: 2.00), and I041 (average: 2.00). The most critical workstation was I028, especially during daytime: complaints about glare concerned all the surfaces, thus resulting in a quite high average score of 3.50

- some complaints about the lighting systems were expressed in terms of visual fatigue and eyestrain, especially by the evening workers (electric light only)
- a higher flexibility of the lighting systems available at the workstations is demanded, for what concerns both the amount and the color of the light emitted and the position of the luminaire; both aspects should be adjusted and controlled by each worker in a customized way.

5 DISCUSSION

The photopic illuminances measured on benches were compliant with the minimum requirements set by the reference European standard EN 12464-1:2021 for medium precision tasks ($E_{wp} \geq 500$ lx), and for most benches also for fine and high-precision tasks ($E_{wp} \geq 750$ lx and $E_{wp} \geq 1000$ lx, respectively). This is an expected result, as the lighting systems were designed just to guarantee compliance with the minimum maintained illuminance requirements of the standard, along with avoidance of glare. Accordingly, the various benches are equipped with embedded anti-glare lighting systems. For this reason, glare measurements were excluded from the analyses. Even though the compliance of illuminance values is a somewhat expected result, this is not always the case. There is literature evidence of non-compliant illuminance values at workstation workplanes. For instance, Giovannini et al. [75] observed through field measurements some illuminance values below standard in office spaces with fluorescent luminaires in Turin (Italy), while Lo Verso et al. [88-89] found several incompliances regarding both daylighting and electric lighting in health care spaces and in university classrooms, and Almarez and Nawang [90] highlighted that only 3 out of 23 classrooms were compliant with the standard illuminance value of 300 lx in a high school in the Philippines. Examples of non-compliant illuminances in industrial buildings were not found, but it is also possible that the company management did not disclose such data for publication.

On the circadian lighting side, 71.9% of view directions towards benches and monitors showed mel-EDI ≥ 250 lx, thus meeting the CIE recommendation and the 3-point WELL criterion. The percentage increased to 86.0% when focusing on mel-EDI values ≥ 136 lx, as per the 1-point WELL criterion. For the same view directions, an average CCT of around 4500 K was detected. Considering that the lighting systems were designed to comply with photopic requirements and not specifically with circadian recommendations, this can be considered a very good result. Such performance seems to be due to a combination of the following factors: (i) illuminance values significantly higher than 500 lx for most workstations; (ii) mel-DER values in the range 0.59-0.89; (iii) presence of daylight, which contributes to increasing both photopic and melanopic quantities. Conversely, it is worth noting that the melanopic performance is not linked to lighting systems with cold CCT (above 5300 K), as light reaching the eyes of the operator is mostly in the neutral range. However, several melanopic non-compliances remain, and are equally distributed among the various types of surfaces that workers observe during their task (benches, monitors, e-WS - totems). Possible solutions may involve the use of new generation lighting systems, including tunable white luminaires, able to modify their spectral power distribution (SPD) during the day to mimic the dynamic variation of the SPD of daylight (sunlight and skylight). Besides, it is possible to consider the installation of dedicated task lights with a cold CCT to be used at the best operator convenience, following up the study from Figueiro et al. [91], who optimized the lighting systems to support visual and non-visual lighting design without increasing discomfort glare or lighting power density. They considered four ceiling lighting setups, incorporating various combinations of direct and indirect lighting, plus one additional design that employed blue task lighting (with a high mel-DER value), all providing participants with an equally high level of circadian-effective lighting. They found out that most participants preferred the task lighting over the ceiling-mounted lighting. Similarly, in the industrial sector, it would be worth developing lighting systems embedded in the assembly workstation, able to optimize the photometric curve to favour the melanopic illuminance at eye-level, as well as the light output and the variation of the colour temperature. Concerning similar studies, Van de Putte et al. [81] exposed 80 shift workers in an assembly plant to integrative lighting with mel-EDI of 192 lux, characterized by bright light with a high fraction of short wavelengths. Their results indicated improved sleep efficiency, reduced sleep latency, and enhanced alertness during the morning shift compared to the control group. Kindt et al. [92] exposed 71 shift workers in a truck factory to a Human-Centric Lighting (HCL) condition with a vertical mel-EDI of 250 lx and a CCT of 5000 K. Compared to the control group (44 lx, 4000 K), the HCL group showed significant improvements in sleep quality and attention, with lower amounts of errors. Nie et al. [93] engaged three subjects in 38 consecutive days of shift work in a semi-isolated, controlled environment with dynamic daylight-like lighting. The lighting system featured tunable illuminance (226 to 678 photopic lx, and 170 to 650 melanopic lx, simulating daylight dynamics), CCT (2680 to 7314 K), demonstrating stable circadian rhythms, improved alertness at night hours and cognitive performance, with a maintained mood status, through proper tuning of the lighting systems. Similar results were also obtained by He and Yan [94]. Zauner and Plischke [95] applied non-visual lighting design principles in an industrial production line to support the circadian health of night shift workers. They designed a new luminaire that allows for a large melanopic stimulus range between 412 and 73 lx mel-EDI vertically at eye level, while maintaining a neutral white illuminance at task level between 1250 and 900 lx. Their findings demonstrated that the designed lighting system successfully increased night-time alertness, with workers reporting better adaptation to night shifts. It seems that different approaches can be applied to enhance non-visual effects of light and circadian entrainment: tunable systems, modified spectral power distribution (and CCT), increased melanopic illuminance levels over 250 lx, in combination with increased photopic illuminance on workplanes.

In the case-study used in the research, the lighting systems embedded in the cells were not tunable, with a constant neutral CCT. However, they produced good circadian light levels at the workers' eyes by increasing the illuminance level, which resulted in mel-EDI values over 250 lx at most view directions. Clearly, increased illuminance level may lead to increased energy consumption, but it's also true that the lighting systems are embedded in the bench structure, thus minimizing the distance between the source and the workplanes. On the other hand, glare issues may arise and need to be addressed through an optimized design of the luminaire photometry and position. About the view directions considered for melanopic measurement, it is worth noting that no formal indication is specified in the CIE documents, nor in the WELL protocol. It is evident that a user can assume different view observation while performing a task, particularly when working in production cells in an industrial setting. However, to the best of the Authors' knowledge, there is currently no established rule governing the selection of weighting factors to achieve a balance among different view observations that an occupant may encounter while working. Consequently, it was decided to adhere to the actual working conditions and to refer to the main directions that workers assume towards benches and monitors. It seems that more research is needed on this aspect, as well as about how to apply the circadian recommendations in industrial workspaces, especially considering how strategic the comfort and wellbeing of the workers and the human-machine interaction has become in the industry 5.0 protocol.

Another aspect of interest emerged from the comments expressed by the workers involved in the survey: most of them expressed satisfaction with the lighting conditions, but complaints about low lighting levels on certain benches or monitors were expressed, as well as glare issues; wishes were expressed about having the possibility of controlling several aspects:

1) dimming the light output; this suggests the possibility of installing lighting systems with higher light output and let the workers dim it based on their preferences; for instance, Safranek et al. [96] monitored five patient rooms in a neonatal intensive care unit (NICU) where an automatic tunable lighting system was installed, with manual override options, and found that giving occupants control over the lighting system resulted in optimized light levels without a considerable increase in energy use
2) changing the colour of the light emitted by the lighting systems, in terms of correlated colour temperature; this can also be beneficial in melanopic terms, as highlighted above
3) adjusting the position of the lighting systems: this involves both vertical and horizontal shifting and possible tilt; this wish was particularly expressed by the group of women involved in the study, who had an average height lower than the counterparts of men (161.3 cm versus 176.8 cm): the lower height may expose the group of women to higher discomfort (in terms of glare, for instance). The electric lighting luminaires are embedded in the structure of the cells and thus in a fixed position, but it seems that more flexibility is desired in this aspect
4) having supplementary lighting systems close to the least lit surfaces, shaded by the specific shape of the equipment.

It is worth noting that beneficial effects of controlling lights are well documented in the literature (for instance in Kompier et al. [97]), as already shown in the introduction section, particularly for what concerns the possibility of adjusting the workplane illuminance [37-38; 98-99].

In the building used as case-study, the operators work on different shifts, from 6 am until 10 pm, which means that there isn't an overnight shift. Workers in factories are exposed to longer periods of electric lighting, in the absence of daylight, than other categories of workers (such as in office or educational buildings). The quantity and the spectral quality of electric lighting becomes a key factor in their wellbeing and performance, like it is for night-shift workers. In this regard, it is worth stressing that most current circadian lighting recommendations (like those from WELL Building Standard or guidelines inspired by CIE and academic research) are designed around the "typical" daytime worker, i.e., people active during the day and sleeping at night. These standards aim to strengthen the natural light-dark cycle, supporting high melanopic stimulation in the morning (bright, blue-enriched light) to boost alertness, and low stimulation in the evening (warm, dim light) to promote melatonin secretion and healthy sleep. On the other hand, shift workers are an entirely different case, as their activity-rest rhythms are inverted or irregular (e.g., awake and working at night, trying to sleep during daylight). Non-visual needs for them are not yet clearly defined in the standards, so simply applying 'normal' circadian lighting strategies could increase circadian disruption, lead to worse sleep quality, higher risk of health problems (e.g., metabolic disorders, cardiovascular issues). It seems therefore that need for targeted, evidence-based lighting recommendations that address their specific chronobiological risks, able to clarify the following aspects: addressing how to artificially shift circadian rhythms using light timing, intensity, spectrum; how to protect shift workers from "wrong-time" light exposure (like bright light when they need to sleep after work); and how designing dynamic lighting profiles for night workers, different from daytime workers.

5.1. MERITS AND LIMITS

The innovation of the study lies in analysing integrative lighting conditions in an actual industrial building as one of the vectors to rely on for the transition from Industry 4.0 to Industry 5.0 paradigms. The study therefore combined the Industry 5.0 principles with human-centric lighting. Among non-residential buildings, the integrative lighting approach has been explored in office, educational, and healthcare buildings, but to a significantly lower extent to industrial and manufacturing spaces. The study from Van de Putte et al. (2022) is one of the few studies what specifically analysed circadian lighting conditions in an industrial setting. The present study aimed at bridging this gap, by assessing and verifying if the proposed melanopic recommendations in terms of mel-EDI values could be met in an existing industrial context. Besides the merits, there are some limitations that need to be acknowledged.

The first limitation is the fact the survey was conducted in a single automotive manufacturing plant. It would have been useful to carry out, for example, experimental testing in other companies in the automotive industry that perform assemblies that require the presence of highly skilled operators, so that comparisons could be made. In justification of this lack, it should be mentioned that it is difficult to get authorizations for lighting tests in production environments since the analyses/field campaigns and surveys interrupt the activities of employees or be limited by the secrecy policies of certain processes. Another limitation concerns the low number of participants in the subjective questionnaires (n=11): this was due to the number of workers who worked at the workstations selected for the study, all of them involved in the questionnaire. Considering the reduced sample of participants, no statistical analyses were performed to sustain the measurements results: however, the subjective assessments were useful to highlight some trends, such as the occurrence of glare perceived at various workstations during tasks, especially (but not only) when the workers assumed a view direction towards the suspended monitors. Besides the subjective scores, useful information was collected from the open comments: in short, these highlighted inadequate light levels and glare problems in some cases, and raised some interesting requests, such as the need to adjust the light output, in terms of light intensity and spectral power distribution, and the position of the lighting systems. Besides, dedicated task lights in the proximity of the worst lit work surfaces were also desired. To summarize, the need for more flexibility in the lighting systems emerged.

6 CONCLUSIONS

The study focused on experimental integrative lighting analyses that were carried out at a plant of a multinational company operating in the luxury automotive sector, under natural and electric light, in central and evening shifts, on U- and L-shaped conformed work cells. The analyses consisted of campaigns of experimental measurements on the work surfaces of the benches and at eye-level of the operators, measuring both visual and non-visual effects of light. In addition, questionnaires were administered to workers to compare subjective perceptions with measured data. Both photopic illuminances on benches and monitors of sample workstations and eye-level melanopic quantities (mel-EDI and mel-DER) were measured in-the-field to verify if photopic and circadian recommendation can be met in actual industrial settings, typically designed to comply with photopic targets, especially in terms of workplane photopic illuminance. As industries evolve from Industry 4.0 to Industry 5.0, the focus increasingly shifts towards the wellbeing of workers, through a human-centred approach. In this new industrial paradigm, lighting emerges as a critical factor in supporting operators' well-being, directly impacting not only their health but also their overall work performance. Proper lighting is essential to ensure optimal working conditions, as it influences both visual comfort and the non-visual effects of light on the human body.

The main findings from the experimental study results indicated that:

- visual effects of light: all workstations were generally well lit and met current standards in terms of average maintained illuminance, as one could expect considering that lighting systems are designed to meet such criterion as for the standard EN 12464-1:2021 non-visual effects of light: eye-level mel-EDI measurements ranged from 53 lx to 1525 lx, with an average of 601 lx (SD: 394.3 lx); with regard to the target set by the CIE and the WELL protocol, 71.9% of view directions toward benches or monitors showed mel-EDI ≥ 250 lx, meeting the 3-point WELL criterion; while 86.0% of them showed mel-EDI ≥ 136 lx, meeting the 1-point WELL criterion. Although current lighting systems are designed to meet photopic standards (which primarily address visual requirements), melanopic measurements reveal important nuances. These measurements assess how lighting affects non-visual functions, such as circadian rhythms, which are crucial for maintaining energy levels, alertness, and sleep quality. Despite compliance with photopic guidelines, some lighting environments may still fail to fully support the broader spectrum of human health needs, particularly in terms of circadian regulation
- feedback from workers indicates general satisfaction with the lighting conditions, yet many expressed a desire for improvements. Specifically, they emphasized the need for more flexible and adjustable lighting systems that could be customized to suit individual preferences and work requirements. Such flexibility could allow workers to adjust light intensity or quality based on the task at hand or personal comfort, fostering a more adaptive and health-supportive work environment.

This highlights the growing need for further research into integrative, human-centric lighting, which seeks to harmonize both visual and non-visual effects of light. Integrative lighting accounts for not only the brightness and colour of light but also its impact on human circadian rhythms and overall well-being. While significant progress has been made in understanding and applying this concept in tertiary environments such as offices, schools, and hospitals, there has been limited attention paid to industrial spaces. Yet, industrial environments stand to benefit greatly from human-centric lighting solutions, as they are often characterized by long working hours and conditions that demand sustained attention and alertness. To fully embrace the potential of Industry 5.0, where technology and human-centric design converge, it is crucial to expand the application of integrative lighting principles to industrial settings. By doing so, industries can create environments that not only enhance productivity but also prioritize the health and well-being of their workers, ensuring a more sustainable and human-focused approach to industrial design. For this reason, the authors plan to evaluate in the future the possibility for each operator to independently set the lighting of the various workstations and to memorize them automatically, so that every time an employee logs in to the work cell, the settings saved are loaded and the cell sets the customized lighting conditions [7, 28, 100].

This option would also allow as successive assemblies of different products which may require specific lighting levels for each operator, the different needs to be satisfied in an extremely fast way, precisely according to the flexibility, productivity [7, 37-38, 101] and speed established by the lean approach.

ACKNOWLEDGMENTS

The authors wish to express their sincere gratitude to Valeo ISC Italia (Santena plant), and notably to Davide Cino, for supporting the research.

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APPENDIX A: QUESTIONNAIRE SUBMITTED TO WORKERS

Politecnico di Torino

Valerio R.M. Lo Verso, Department of Energy DENERG 'Galileo Ferraris'
Antonio Carlin, Department of management and production engineering DIGEP
Research activity "LIGHTING IN PRODUCTION CELLS 4.0"
Experimental measures and questionnaires to assess lighting conditions at workplaces in Valeo – Santena campus

QUESTIONNAIRE FOR WORKERS

SECTION A: QUESTIONS ADDRESSING THE WORKSTATION AS A WHOLE

Question 1:
Overall, how do you rate the quantity of light at this workstation?
- Too low
- Low
- Adequate
- High
- Too high

Questions 2-5:
Indichi il suo grado di accordo con le seguenti affermazioni riferite alle **condizioni di illuminazione sulla sua postazione di lavoro nel complesso:**

Questions 2:
- Nel complesso, la **quantità di luce** sulla mia postazione di lavoro è **adeguata**
  - totally disagree
  - disagree
  - agree
  - totally agree

Question 3:
- Nel complesso, le **condizioni di illuminazione** presenti sulla mia postazione di lavoro **creano un ambiente stimolante**
  - totally disagree
  - disagree
  - agree
  - totally agree

Question 4:
- Nel complesso, le **condizioni di illuminazione** presenti sulla mia postazione di lavoro **mi aiutano a concentrarmi**
  - totally disagree
  - disagree
  - agree
  - totally agree

Question 5:
- Nel complesso, **le condizioni di illuminazioni** presenti sulla mia postazione di lavoro **creano un ambiente confortevole**
  - totally disagree
  - disagree
  - agree
  - totally agree

Politecnico di Torino

Valerio R.M. Lo Verso, Department of Energy DENERG 'Galileo Ferraris'
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Research activity "LIGHTING IN PRODUCTION CELLS 4.0"
Experimental measures and questionnaires to assess lighting conditions at workplaces in Valeo – Santena campus

SECTION B: QUESTIONS ADDRESSING SPECIFIC WORKING AREAS (BENCHES AND MONITORS)

Rate your agreemtn on the following questions concerningn the specific lighting conditions on **benches and monitors:**

Benches (mounting, assembly, control):

Question 6:
In this moment, lighting conditions are ADEQUATE to carry out my task (mounting, assembly, control):
- totally disagree
- disagree
- agree
- totally agree

Question 7:
In this moment, I perceive GLARE while I'm carrying out my task (mounting, assembly, control):
- totally disagree
- disagree
- agree
- totally agree

Monitors:

Question 8:
In this moment, lighting conditions are ADEQUATE to carry out my task (reading or inputting information on screen):
- totally disagree
- disagree
- agree
- totally agree

Question 9:
In this moment, I perceive GLARE while I'm carrying out my task (reading or inputting information on screen):
- totally disagree
- disagree
- agree
- totally agree

SECTION C: GENERAL QUESTIONS

Question 10:
Gender: ☐ Man
☐ Woman
☐ Prefer not say

Question 11: Age: ____________________; Height: ____________________;

Question 12:
For how many hours through your shift have you worked today?
- less than 2 hours
- between 2 and 4 hours
- between 4 e 6 hours
- over 6 ore.