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Literature Review On Smart Windows In Terms Of Daylight Performance, Visual Comfort and Human Perception

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***Abstract*—The glazing properties of a place affect the lighting conditions and the quality of the indoor environment. These conditions influence occupants' visual comfort and perception. Thus, the design of the glazing component becomes more of an issue. With the emerging smart window technologies, the design options have expanded. These technologies have been investigated mainly in terms of energy performance. This paper presents a literature review of smart windows and their performance on visual comfort and human perception. Experimental studies that conducted measurements or surveys in this field are evaluated. The results of the study showed that with the growing technology of smart windows, it is possible to increase visual comfort and human satisfaction indoors. However, there are performance deficiencies that create particular problems for occupants. The aim of this paper is to collect the studies on smart glazing in terms of visual comfort and human perception and bring out the potential of smart window technologies for human-centric indoors.**

Keywords—smart window, glazing technology, visual comfort, human perception

I. INTRODUCTION

People spend more time indoors compared to outdoors[1] (Fig. 1.); therefore, indoor spaces should be appropriately designed for occupants' comfort and requirements. One of the key factors that affect a person's overall comfort, health, and productivity in an indoor environment is visual comfort [2]. It is defined as a "subjective condition of visual well-being induced by the luminous environment'' in EN 12665 European Standard [3].

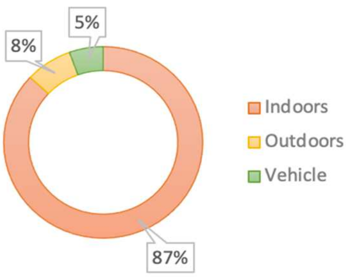

Fig. 1. Distribution of time spent by people

Indoor visual comfort is mainly associated with surface contrast and brightness variation caused by lighting [4]. Thus, the optimum way to achieve visual comfort is through the proper use of daylight. Since daylighting is one of the primary purposes of windows, their design affects the penetration of daylight [5], [6]. Windows should be designed carefully to get benefit from them in terms of visual comfort and improve indoor environment quality [7]. Window glazing types have been developed through the years by creating new opportunities and features. Recently-developed glazing types propose better performance in comparison with the traditional solutions and new light control opportunities. Technologies like smart materials have become useful for glazing options. They improve building and glazing performance regarding energy efficiency and visual comfort [8].

Researchers have completed essential studies about smart windows. Those studies from 2015 up to now have been analyzed. Most of them are review studies on energy saving [9]–[11], energy efficiency [12]–[14] of buildings, and overall performance of smart window technologies [8], [13], [15], [16]. Aburas et al. explained the energy-saving potential of thermochromic smart windows compared to plane glazing. They examined and explained materials developed for thermochromic glazing [9]. Building energy-saving potentials and operational principles of switchable smart windows are the central subjects of another study. Nundy et al. focused on sustainable low-energy for decreasing energy loads of buildings [10]. Another review study by Syrrokostas in 2022 focused on photo electrochromic devices as smart windows in energy-efficient buildings. This review study includes 25 years long progress in this glazing [12]. Two of the literature reviews explained the advantages, disadvantages, and technologies of smart glazing [8], [15]. Another review indicated the literature about smart glazing currently being researched and innovations in electrochromic glazing. The authors focused on the most recent studies about the general process of electrochromic glazing for further development [16]. Besides the literature reviews, experimental studies on smart windows have been carried out [17], [18]. These studies evaluated the possible energy saving and energy efficiency with the recent materials and technologies in smart glazing.

Despite those ongoing research on smart windows and energy performances in building environments, few attempts have been made to review studies about visual comfort and human perception of smart windows. Even though some relevant studies focused on human comfort/visual comfort in their research, they evaluated the energy efficiency together [11], [13], [14]. Thus, there is no literature review on smart windows in terms of human perception and visual comfort. This review paper aims to summarize and evaluate the literature on smart glazing/windows in terms of human perception, visual comfort, and daylight performance.

II. Methodology

Authors should consider the previous literature before starting new research. Determining the targets and significant outcomes of prior studies help recent authors to analyze gaps and assess unquestioned research problems. Literature review studies are beneficial during the evaluation of a certain topic or theory. The process of a literature review starts with the design and continues with the conduct, analysis, and structuring, and writing the review phases [19].

The authors searched the databases such as Science Direct, Web of Science, and Google Scholar during this literature review to find out the published studies earlier. The keywords are determined as; smart window, smart glazing, visual comfort, daylight performance, occupant perception, and human perception. More terms were included to reach wider literature during the search process, such as electrochromic, thermochromic, satisfaction, and preference. Most recent studies from 2009 up to now have been examined.

Afterward, the studies were sorted out according to the focus points, and they are listed due to some parameters in Table 1. Each of them is analyzed in terms of the information given during the study and the results at the end. The analyzed literature is structured and reported according to the motivation of the study.

III. Smart Glazing Technologies and Their Performances

By utilization of smart materials, advanced glazing types emerged in the industry. Smart materials and window technologies progressed through time. These materials are applied to the glass and create smart glazing, primarily for energy efficiency, indoor comfort, and direct solar radiation control [14]. Smart windows are categorized according to their light transmission features. These categories are called passive and active technologies. Passive technologies can change with surrounding parameters (such as temperature or light intensity alteration), while active technologies are adjustable according to user preferences (Fig. 2.).

TABLE I. Studies between 2009-2023

Reference	Sorting Parameters				
	Year	***Focus***	***Window type***	***Building Type***	***Methodology***
[23]	2009	Daylight Performance	Electrochromic Windows	Scaled test-cell	Measurements
[24]	2015	Daylight Performance	Electrochromic Windows	Office room	Survey and measurements
[25]	2015	Thermal and Visual Comfort	Electrochromic Windows	Scale models	Measurements
[26]	2018	Energy and Comfort Performance	Electrochromic Windows	Office building	Measurements
[27]	2013	Visual and Thermal Comfort	Electrochromic Windows	Office room	Simulations, surveys, measurements
[28]	2017	Glare Control Performance	Electrochromic Windows	Varied Simulated Environments	Simulation
[29]	2018	Daylight Performance	Thermochromic Windows	Simulated office room	Simulation
[30]	2020	Daylight Performance	Thermochromic Windows	Simulated office buildings	Simulation
[31]	2022	Visual Performance	Photochromic Windows	Simulated laboratory	Simulation
[32]	2022	Visual Performance	Smart Colored Windows	Simulated office room	Simulation
[33]	2021	Energy Efficiency And Comfort	Electrochromic Windows	Test-cells	Simulation and physical model measurements
[34]	2013	Visual Comfort	Photovoltachromic Windows	Simulated office rooms	Simulation and measurements
[35]	2023	Indoor Daylight Environment and Visual Comfort	Cadmium Telluride Photovoltaic Window	Experimental rooms	Measurements
[36]	2022	Visual Comfort	PDLC Smart Switchable Window	Scaled test-cell and simulated office building	Simulation and experimental measurements
[37]	2021	Daylight Performance	Smart Window	Office spaces and simulations	Simulation
[38]	2015	Daylight Control Performance	Electrochromic Windows	Meeting rooms	Survey and measurements
[39]	2021	Daylight Performance	Electrochromic Windows	Office building	Survey and measurements
[40]	2021	Visual Comfort	Electrochromic Windows	Office test-room	Survey
[41]	2019	Occupant Responses to Smart Glazing	Smart Windows	Office building	Survey
[42]	2019	Human Response to Chromatic Glazing	Chromatic Smart Windows	Test-room	Survey
[43]	2022	Glare Perception of Users	Electrochromic Windows	Office test-room	Survey and measurements
[44]	2015	Performance Requirements for Electrochromic Window	Electrochromic Windows	Laboratory controlled conditions	Experimental comparison

To give brief examples, thermochromic and photochromic glazing are known types of passive systems. The electrochromic, gasochromic, and PDLC glazing are devices that can be samples of active smart glazing systems [8], [15], [16].

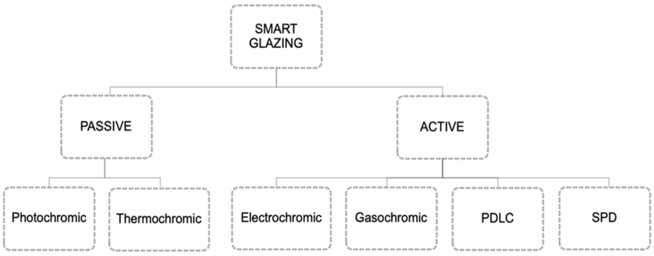

Fig. 2. Smart glazing technologies categorization

As mentioned above, a wide variety of smart window technologies have emerged in the glazing industry. A passive glazing example is thermochromic windows which have thermal responsive ingredients and response to temperature shifts. Another one, photochromic glazing, changes color when there is a particular wavelength [15]. Electrochromic materials and the devices produced with them are examples of evolving smart glazing technologies. These devices work with the application of electrical current [14], [20]. Electrochromic glazing is seen as the most advanced and efficient active glazing technology. Later on, gasochromic windows are evaluated within these glazing types. Also, these windows are cheaper and have a more basic producing process. PDLC is the short version of polymer-dispersed liquid crystal, and these windows change between opaque and clear conditions [8], [15]. In this regard, common types of glazing technologies have been explained briefly.

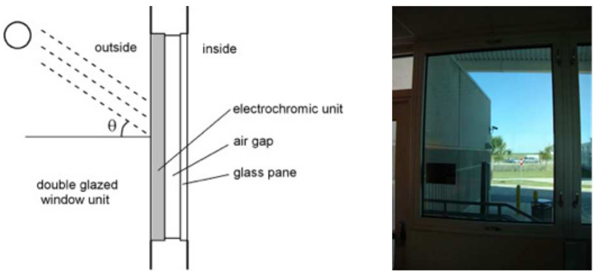

Fig. 3. Schematic layout of the EC double-glazed unit [23] (left) and installed EC window in a vehicle inspection point booth [24] (right)

Most common smart glazing types were represented under this subtitle. In Fig. 3, the schematic layout of EC glazing and an application example is shown. Hence the main function of smart windows is to help organize the natural light penetration into the buildings. Smart window technologies decrease the energy loads of the building and help provide thermal and visual comfort for the occupants at the same time [16]. Besides, a significant benefit of switchable glazing is that it makes it easy to keep a comfortable amount of light in space and control the daylight by adjusting transparency [21].

A. *Smart Glazing Technologies for Visual Comfort*

The sample of experimental studies about smart glazing technologies for visual comfort is collected under this subtitle. Different parameters and metrics are considered for visual comfort evaluation. Varying illuminance values of the indoor environment daylight glare, and luminance are identified as some of these metrics that help researchers investigate visual comfort [22]. However, there is no mutually acknowledged measurement of lighting quality that can guess how a luminous environment affects humans since visual comfort is highly complicated [23].

Preventing discomfort glare and controlling illuminance provide more comfortable indoor environments for the occupants. Luis et al. investigated electrochromic glazing and whether they have an impact on visual comfort improvement. An experimental study was conducted in a port of entry with an existing glare problem. A survey and physical measurements were performed to evaluate visual comfort through installed glazing. The results indicated that the electrochromic glazing contributed to glare control due to the ability to adjust the glazing tint according to the environment. Thus, glare control benefits for providing visual comfort to occupants [24]. During the transmission adjusting, it is substantial to provide quality daylight autonomy without causing darkness or discomfort glare. Ajaji and Andre assessed both the visual and thermal comfort of office occupants with electrochromic glazing. The researchers conducted the experiments in Belgium with south-facing room scale models equipped with electrochromic and clear glazing. Illuminance and luminance measurements have been made to evaluate the visual comfort of the users. The results showed that electrochromic glazing could remove over-illumination while keeping decent daylight autonomy except for summer days with overcast sky [25]. Electrochromic glazing technology is used with the automated lighting control system for a study. According to measurements by researchers, in an office building, in California, the glazing systems are very effective at decreasing glare when it's fully tinted, but, these fully tinted conditions resulted being very dark environments [26]. Prior research in 2009 worked on electrochromic glazing and investigated its performance in decreasing visual discomfort due to the negative effects of glare from the outdoor environment. A 1:10 scale model equipped with a prototype of electrochromic glazing was used under real weather conditions. The research concluded that even though switchable glazing cannot completely prevent glare from the sun, it can be able to decrease discomfort glare effects due to high brightness levels of diffuse daylight from the south-facing windows. The glazing was able to provide acceptable visual comfort requirements with the improved daylight control system without additional devices such as blinds, curtains, etc. Besides, given that the electrochromic glazing does not have a negative impact on the color rendering of the objects. However, the west and east-facing windows produced glare effects that are more challenging to control without additional shading devices [23]. Another study aimed to create a visually comfortable environment for the users while decreasing energy consumption while comparing electrochromic glazing, blinds, and artificial lights. The electrochromic windows with automatic control (between transmittance range of 15%-50%), blinds, and dimmable fluorescent lights were installed in a south-facing window of an office in Switzerland. The simulation results emerged that electrochromic glazing creates better visual comfort conditions than a glazing with blinds. According to the evaluations of occupants in the study, the electrochromic windows created unnatural color rendering on the view outside, and the need for blinding emerged due to glare problems. However, compared to the blinding control system, most people preferred electrochromic glazing [27]. A simulation study by Ardakan et al. was conducted to assess the daylight performance of electrochromic glazing and fritted glass. The Low-E glass with frit was not enough to control the direct sunlight glare; on the contrary, electrochromic glazing was able to provide better performance on glare control [28].

There is various literature that is investigating smart glazing rather than electrochromic windows. Liang et al. simulated a room with five types of thermochromic glazing and explored the daylight effects. The study's results revealed that compared to double glazing 15.5% better daylighting performance was achieved. To clarify, a rise in the intended range of illumination, which is in the UDI500-2000, was described as better daylighting performance in this study [29]. Salamati et al. evaluated thermochromic glazing in terms of visual comfort, color quality of light, and non-visual effects. The glazing created a positive impact by decreasing both daylight glare probability (by 10%) and glare occurrence probability (by 20%) in comparison with blue and clear tinted. The useful daylight illuminance percentage increased in the area closer to the window; however, the area far from the window, useful daylight illuminance was affected adversely. Besides, thermochromic glazing had higher performance in higher latitudes with regard to glare and useful daylight illuminance [30]. Several scientists have attempted to determine the performance of the photochromic window (PCWs), comparing the usual solutions (clear glazing and Low-E window). The study is conducted with the software in the virtual environment. As can be derived from this study's results, photochromic glazing is more advantageous than clear glazing in terms of illuminance conditions. The useful daylight illuminance has improved by up to 2% with the photochromic window. Despite the fact that PCWs are preferred daylight when possible, the risk of glare is decreased [31]. Smart photochromic color-coated glazing with colors of red, blue, and yellow and their combinations were used in the study design. According to the results, the utilization of multi-color glazing instead of no-coating, daylight glare probability, and useful daylight illuminance is improved [32].

With the integration of advanced materials and devices into the windows, the visual comfort of the occupants may reach better conditions [33]–[37]. Cannavale et al. created a simulation environment with photovoltachromic devices integrated into the windows. This integration resulted in higher visual comfort and lower intolerable glare levels in indoor environments [34]. Current research by Hu et al. investigated photovoltaic windows from the perspective of humans. A Cadmium Telluride Photovoltaic window integrated room and clear glazing integrated room were examined. The results underlined that the illuminance levels of the working surface are lower in the room with photovoltaic glazing, which is between 500-2200 lx and adequate for visual comfort requirements. Regarding the color rendering index, both rooms have the appropriate visual comfort conditions [35]. Smart switchable glazing windows and their benefits on energy efficiency and visual comfort are researched in Saudi Arabia with a scale model of Polymer-Dispersed Liquid Crystal (PDLC) smart window. When the data and simulation results are compared, it has been seen that visual comfort conditions are provided [36]. Besides another improvement for smart glazing, the hybrid model predictive control strategy is proposed by researchers. A simulation study was conducted to investigate the control method for the online operation optimization of electrochromic glazing. According to the study, with the proposed strategy, the percentage of discomfort hours decreased [33]. Sun et al. conducted a study about providing advanced indoor luminous environments by using transparent insulation material in windows. These windows provided an increase in daylight performance with better values than UDI 500-2000 lux when it is compared to the traditional double-glazed window [37].

B. *Occupant Perception in Indoor Environments with Smart Glazing*

Creating an indoor environment by using smart glazing components may have influences on the overall satisfaction of occupants and perception of the indoor environment. In a study conducted in meeting rooms in Shangai, electrochromic and Low-E glass windows were compared. Subjects evaluated the meeting rooms with types of glazing through a survey about their overall satisfaction. The study concluded that light level control and glare control have positive impacts on satisfaction with electrochromic windows. Even though this electrochromic glazing decreased indoor illuminance values, occupants were comfortable [38]. Similarly, another study is focused on the subjective experience and perception of occupants over electrochromic glazing. A survey is conducted in an office building in Raleigh, NC. Four transmittance levels (1%, 6%, 40%, 58%) of electrochromic glazing are installed in the conference room in this building. The study concluded that occupants prefer un-tinted or slightly tinted conditions. They were satisfied with the glare control due to tinted electrochromic glazing and found the place visually comfortable. However, tinted glazing caused unnatural color rendering in both indoor and outdoor environments [39]. Thus, people tend to be more satisfied with the conditions if they have control over them. Likewise, Jain et al. evaluated the visual comfort and quality aspects in a workplace. Twenty participants attended the study in Switzerland in an office-like test room with electrochromic glass. Occupants were able to control the transmittance of this glazing individually. According to the results, they preferred blue-tinted electrochromic glazing with a minimum of 0.6% to avoid discomfort glare and visual discomfort (if the sun is in the peripheral field of view). Nonetheless, most of the participants tend to use additional shading devices due to discomfort glare. Thus, the study concluded that human perception should be taken into consideration to achieve visually comfortable spaces with glazing control technologies and façade design [40]. Although there are circumstances in that occupants need manual shading or blinding [23], [40], there are other studies which the application of the smart glazing performance is more appreciated [27], [41]. Choi et al. conducted a survey study to evaluate human responses to smart windows and manual shading. It was performed with 17 occupants in an office building in Canada. The results revealed significant information about environmental satisfaction, perceived health, perceived productivity, and emotional responses. The environmental satisfaction of occupants in an office with dynamic smart glazing was 33.8% higher than the ones with manual blinds. Besides, occupants in an office with dynamic smart glazing had fewer syndromes such as headaches, stress, visual discomfort, glare problems, etc. Another study result was increased relaxation, happiness, comfort, calmness, energy and less tiredness, darkness, sadness, etc., thanks to better daylight and glare control performance of dynamic glazing. The survey ended up with general indoor environmental satisfaction and visual comfort with dynamic glazing instead of manual shading [41].

Color change in smart windows can shape the indoor environment and cause visual improvements. Thus they can be used instead of traditional glazing systems. Liang et al. conducted a study to investigate the effects of thermochromic windows on visual comfort and performance. A test room of an office was designed and illuminated with blue-tinted and bronze-tinted glazing. A questionnaire was conducted with subjects. They preferred to work and stay under bronze glazing conditions when compared to clear and blue glazing conditions. Researchers pointed out that subjects chose the bronze window since it provides a warm tint and natural rendering of indoors [42]. In order to assess the impact of the spectrum, Jain et al. investigated the perceived discomfort glare under blue-tinted electrochromic glazing and neutral-color electrochromic glazing of varying transmittances. To create an experimental environment, an office-like test room was used. The participants of the research were able to tolerate glare more under neutral-color glazing. Neutral color created higher values of predicted glare metrics compared to blue-tinted glazing. However, participants reported equal or lower levels of discomfort under neutral-color glazing conditions. The study demonstrated that people's perception of glare is significantly influenced by the spectrum of a glare source [43]. The color of the smart glazing and its effects on visual comfort was investigated by another research as well. Aste et al. conducted a study with the aim of analyzing the visual performance of the LSC smart windows. A 1:10 scale model of the room and glazing was prepared. The different fanlight component of the smart windows was analyzed, and according to visual comfort parameters, yellow and orange colored ones helped the luminous efficiency improvement and visual comfort increase. Thus, yellow fanlights for LSC smart windows are the most appropriate ones in buildings in terms of visual comfort[20]. Findings on color rendering properties of electrochromic windows showed that the colors are not perceived as natural. Therefore the necessity for better color rendering improvements is expected by the occupants [39], [40].

People benefit from smart window applications in many areas and take advantage of better visual comfort conditions; however, certain disadvantages have been revealed. A study focused on the performance requirements of smart windows in terms of energy performance and indoor comfort discusses specific improvements needed in electrochromic glazing performance such as faster switching speed, higher visible transmittances in the bleached state, and higher neutral color level in the darkened state for maximizing building integration, visual comfort, and sufficient color perception [44]. Other literature confirmed that switching speed is essential for occupant comfort [26], [38] Although most of the occupants preferred electrochromic glazing instead of conventional windows, during the switching period, occupants encountered extreme glare according to tests [26].

IV. Conclusion

Designing and creating indoor environments according to occupants' comfort and requirements is essential. This paper provides a review of smart windows and their performance on daylight, visual comfort, and occupants' perception. It examines the human-centric studies that benefit from smart window technologies rather than their energy performance. The experimental studies in this field were described and analyzed. Based on the literature, smart window technologies offer many advantages in better daylight performance, better illuminance conditions, visual comfort, and indoor quality. These glazing have the potential to enhance indoor environmental quality and satisfy occupants' requirements. From this review, some additional points can be summarized as follows:

- The literature shows that smart glazing technologies are preferred to standard clear glazing due to their performance.
- People are more likely to be satisfied when they are able to control the glazing transmission in terms of their desire.
- Smart windows revealed good performance in preventing glare and over-illumination, and they are advantageous for human visual comfort. However, the drawbacks should be considered during the integration, such as the tinted state of the glazing led to unnatural color rendering for both indoor environment and outdoor views [39]. Moreover, switching speed is another disadvantage of glazing, according to studies [44]. Therefore, the color rendering performance of tinted glazing should be improved for more natural environment perception, and the switching speed should be increased with regard to their daylight performance.
- The perception and satisfaction of the occupants indoors and their visual comfort can be instructive for further designs of the glazing types of a building, and benefiting from the given advantages and disadvantages can present options that are suitable for varied indoors.
- The most common building types were office buildings in the analyzed literature. These types can be expanded and include educational facilities and studies conducted on human well-being [45] can be enhanced with smart glazing technologies, or other building types such as housing design, can be developed with the help of these technologies.
- Analyzing the current studies that used survey, simulation, and experimental measurements helped to evaluate both the human-centric approach to smart glazing and objective calculation for daylight measurements indoors.

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