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User Assessment of Low-Cost Inkjet-Printed Electrochromic Glazing

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Abstract. Rising temperatures are leading to an increase in cooling energy demand and thermal discomfort due to overheating. Despite dynamic switchable glazing being a promising solution for controlling solar radiation while preserving user access to outdoor views, their cost is currently a barrier to their widespread adoption. The recent development of low-cost inkjet-printed switchable glazing offers a cost-effective alternative; however, its performance remains uncertain concerning its contributions to energy efficiency and user satisfaction in terms of thermal comfort and visual experience. This study presents a multi-domain evaluation of the performance of a novel low-cost inkjet-printed glazing with users in terms of their satisfaction with the environment, personal control and interaction. In comparison to a conventional façade with static glazing and external roller blinds, the EC glazing performed better than the conventional façade if the shading is fully down. In this case, higher satisfaction was measured in terms of view clarity, daylight access and colour in the room with the EC glazing. When comparing the performance of the EC glazing at the clearest state with conventional glazing with blinds raised, users' satisfaction was not significantly different, except for the satisfaction with view clarity. Despite the long transition time of the EC glazing, users were not significantly dissatisfied with the speed of transition. Overall, these preliminary results show that this novel EC glazing is well-accepted by users especially as an alternative to traditional dark roller blinds, but further research is required to investigate its performance during summer.

Keywords: adaptive façade · user interaction · user comfort · smart glazing · dynamic glazing

1 Introduction

Climate change is leading to higher temperatures and, consequently, to higher cooling demand for maintaining a comfortable and healthy indoor environment [1]. The building envelope strongly influences indoor thermal conditions, especially by controlling incoming solar radiation to balance overheating and daylight access. Traditionally, solar radiation is controlled by shading devices, either as fixed louvres solutions or dynamic ones, which can be manually or automatically controlled. For the same purpose, dynamic

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switchable glazing has also been introduced in the market [2]. These technologies can dynamically vary their level of transparency (tint) to control solar radiation. The main benefit of switchable glazing technology in comparison to other shading devices is that they can maintain unobstructed access to outdoor view, even when in the dark state. Examples of these technologies are for instance electrochromic (EC) glazing or liquid-crystal dynamic technologies. Each switchable technology has a specific range in transparency along which changes in visual and solar transmittance and colour rendering are possible.

Several types of EC glazing have already been investigated in terms of user experience [3–7]. Usually, the colour rendering of the EC coating is a barrier to their adoption, since the transmitted daylight tends to have a strong shift towards the blue. Another key aspect for user experience is the time required to perform a switch in transparency state, which can be very slow and therefore frustrating for users. Lastly, the dynamic range in transparency is usually limited, either these glazing have high light transmittance, or they can be as dark as needed to mitigate glare [8]. Ultimately, the overall experience of the users is driven by multiple factors, which simultaneously affect overall user experience, such as satisfaction with personal control and interaction, visual comfort and thermal comfort [9]. The balance among these factors is key to ensure overall occupant satisfaction and environmental comfort. It was recently shown that adopting a multi-domain approach when assessing user experience with façades is necessary to capture the actual impact of a façade on users [10].

A novel electrochromic technology was recently developed through an innovative manufacturing process based on inkjet printing that abates the costs of the final product. This can support a much wider adoption of the technology in the market by reducing the cost from 500–1000 euro/m^2 to 100 euro/m^2. In addition, this new EC technology seems also to exhibit a contained shift towards the blue. However, the performance of this new EC glazing in terms of user experience is not well understood and could undermine its wider adoption.

This paper aims to perform a multi-domain assessment of user experience with this new EC technology. A field study was conducted in two different test rooms to compare the performance of the new EC technology with a benchmark façade.

2 Methodology

2.1 Glazing Characteristics

Table 1 describes the characteristics of the two facade configurations compared in user comfort and interaction. The benchmark scenario was a standard triple glazing facade with window-to-wall ratio of close to 85% and external black roller blinds. The novel inkjet EC glazing was developed by Brite and integrated into the same triple glazing unit by Si-X glass installer. As shown in Table 1, the darker state presents a shift towards the blue colour.

2.2 User Assessment Study

To assess the performance of the novel inkjet electrochromic glazing from a user perspective, a semi-controlled experiment was conducted at the living lab “Office Lab”

Table 1. Characteristics of the two façades compared in this study.

Façade	Characteristics	Build-up	Shading
A .Benchmark window	Triple glazing t-vis: 73% t-sol: 48% g-value: 0.56 u-value: 0.6 W/m^{2}K	Stratobel 33.1; 15 mm Argon 90%; 4 mm Planibel Clearlite unhardened; 15 mm Argon 90%; Stratobel 33.1	External roller blind. Black colour
B. Inkjet EC glazing	Triple glazing t-vis: clear state: 35–45% dark state: 7–10% t-sol: clear state: 18% dark state: 0.4% g-value: clear state: 0.35 dark state: 0.33 peak wavelength clear state: 535 nm; darkest state: 497 nm u-value: 0.6 W/m^{2}K	EC coating is sandwiched between two 3 mm thick clear float glass sheets laminated on a thin glass sheet, replacing the glass pane of the triple glass closest to the indoor environment; in the openable window the glass sheet closest to the outdoor environment was replaced	

at the Green Village at TU Delft from December 2023 to March 2024. The living lab consists of a lightweight structure with a timber frame. The façade is reconfigurable and allows the flexible installation of façade technologies for testing. The heating system consisted of heat supplied through the mechanical ventilation system (monitored via air-flow and temperature sensors in the supply duct) and a local air-conditioning unit type Whirlpool PACW212HP with a COP for heating of 2.8. The artificial light consisted of four luminescent light tubes of 1620 lm, 16.4 W each.

The experiment was designed as a repeated measures "within subject" study. A total of 38 participants (20 males and 18 females, of which 84% were between the ages of 25 and 60 years old) spent a total of two hours in two different rooms, adjacent to each other. Participants were exposed to both room conditions in a random order. The experimental procedure is shown in Fig. 1. Participants were invited to work on a reading task at the workstation provided. For the first 30 min, participants were exposed to either clear tinted EC glazing or blind up conditions, while the sun was not in the field of view (FOV). Afterwards, when the sun was in the field of view, the glazing was tinted at the darkest state, or the blinds were lowered. After 30 min, the blinds were raised, and the glazing switched back to the clearest state. At the end of each session, participants were asked to fill in a questionnaire on their perception of the environmental conditions. Questionnaires were used to measure the following variables. Thermal sensation according to the ASHRAE 7-point scale. Then in a 5-point scale, the following variables: satisfaction with daylight, satisfaction with daylight colour,

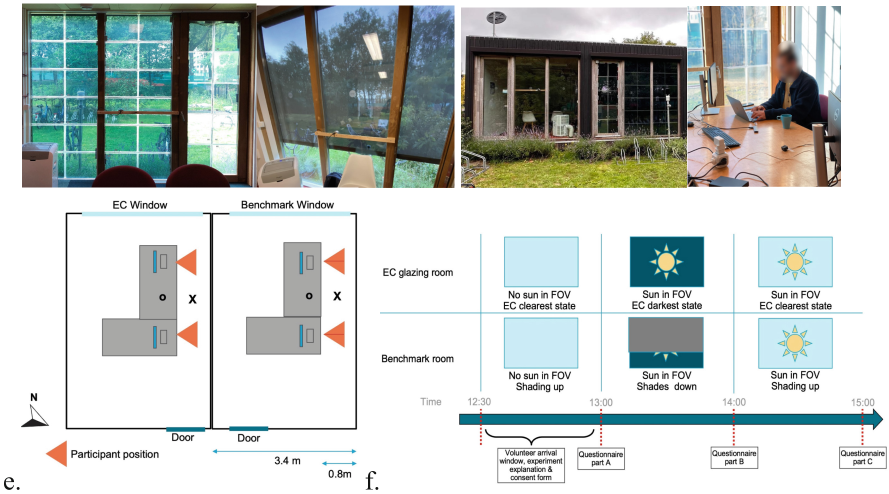


Fig. 1. Details of the living lab study: a. frontal view of the facade with EC glazing; b. View of the benchmark facade with external roller blind; c. external view of the living lab, on the right the test room with the EC glazing while on the left the benchmark test room; d. view of one participant during the experiment; e. overall plan view of the test rooms with indication of participant position and distance from window; f. overall timeline of the experimental procedure.

satisfaction with view clarity, perception of glare, satisfaction with the speed of transition. Cloudy weather was observed at 73.3% of the questionnaire data entries. For 17.8% it was partly cloudy and for the remaining 8.9% the weather was clear.

3 Results

3.1 Environmental Conditions

Figure 2 shows the results of the environmental monitoring during the experiment. In terms of operative temperature, the two conditions did not significantly differ, with average operative temperature of 21.5 °C. In terms of vertical illuminance, the two rooms show different values when the sun is in the field of view (Fig. 2b at 13:00–14:00 and 14:00–15:00). The darker state of the EC glazing produced a small reduction of the range of illuminance (see Fig. 2b 13:00–14:00 in comparison to 14:00–15:00) in comparison with the bleached state, while when the blinds are lowered in the benchmark room, the level of vertical illuminance is lower than in the room with the EC glazing. When the sun is in the field of view and the facades are at highest transparency level (Fig. 2b at 14:00–15:00, blinds are raised in the benchmark facade and the EC glazing is in the bleached state), both rooms have similar extreme values of vertical illuminance. In terms of horizontal illuminance measured at the desk, the room with the EC glazing shows much higher value when in darkest state than the benchmark room with the blinds lowered.

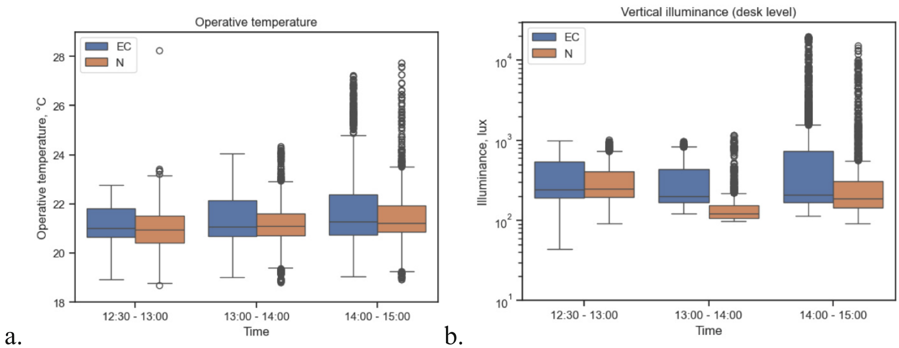


Fig. 2. Results from the environmental monitoring during the three scenarios: 12:30–13:00 blinds up or bleached state, no sun in the field of view, 13:00–14:00 sun in the field of view, blinds down or glazing in darkest state; 14:00–15:00 sun in the field of view, blinds up or glazing in bleached state. Parameters monitored: a. operative temperature in the room; b. vertical illuminance in proximity of the eye of the occupant at 1.2 m from the floor.

3.2 User Perception

Figure 3 shows the results from the user assessment during the experiment. Despite similar values in operative temperature, the participants felt significantly cooler in the benchmark room, especially in the first two parts of the experiments.

The thermal conditions were however still perceived as comfortable. In terms of satisfaction with daylight colour, participants had a lower satisfaction when in the EC room. Indicating that the blue colour is generally dissatisfactory. The only exception was in the scenario where the blinds were fully lowered in the benchmark room, during the second part of the experiment, at 13:00–14:00 h. In this condition, participants were significantly more satisfied with the daylight colour in the EC glazing than in the benchmark room where the access to daylight was significantly reduced. In terms of view clarity, the satisfaction of the participants was higher in the benchmark room where the glazing did not exhibit any haze and presented largest transparency. Similarly to the daylight colour conditions, participants prefered the view through the darkest state of the glazing to the condition to fully lowered blinds.

In terms of glare perception, the level of glare was always between imperceptible and noticeable and the participants' responses were not significantly different. Only a few users perceived the level of glare disturbing. As expected, when the blinds were fully lowered in the benchmark room, no participants perceived glare. This indicates that the overall performance for glare mitigation of the EC glazing in its darkest state may be sufficient, if the sun is the peripheral view. However, this may be due to the fact that glare conditions were not severe, therefore further studies should be conducted to evaluate this aspect. In terms of satisfaction with daylight amount, as shown in Fig. 4, the two room conditions were significantly different only in the scenario where the blinds were fully lowered in the benchmark scenario. Finally, user satisfaction with interaction was overall comparable in the two rooms.

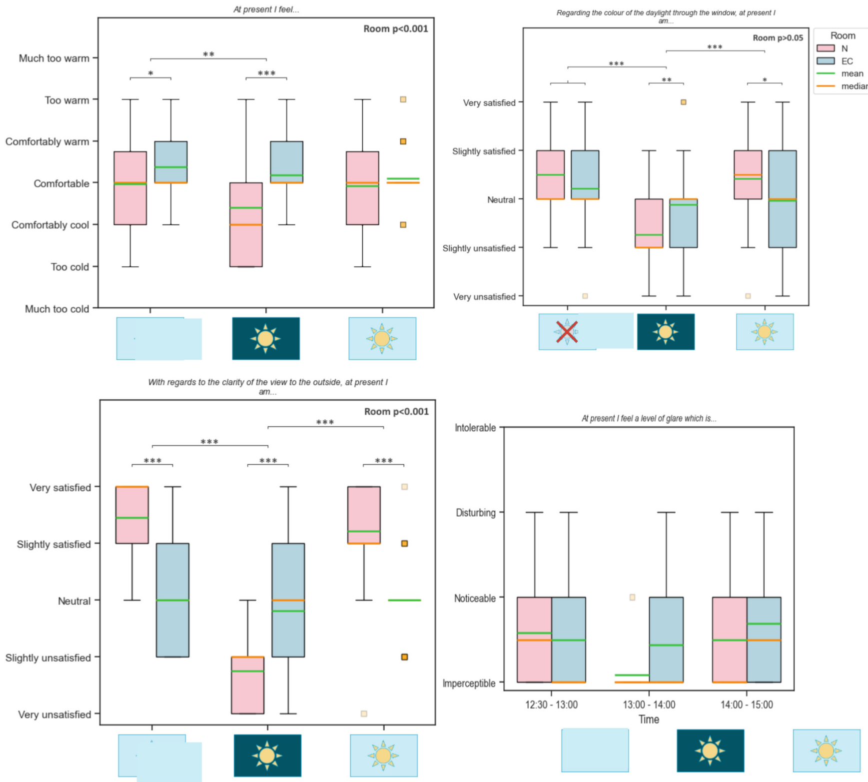
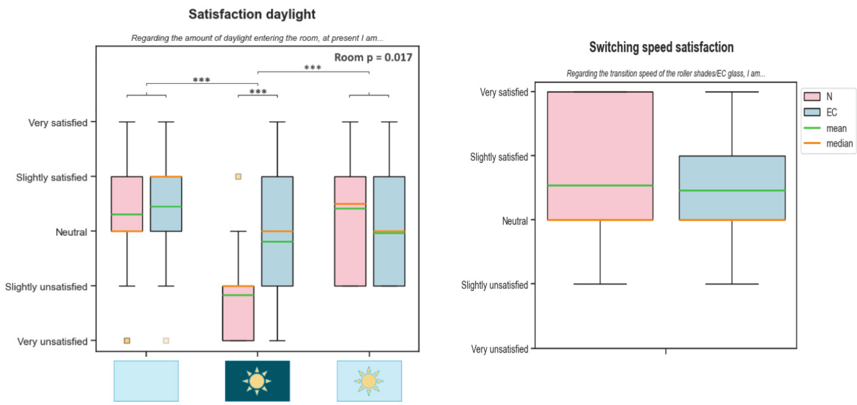


Fig. 3. Results from the assessment of the user satisfaction with thermal and visual domain during the experiment. a. Thermal sensation of the participants; b. Satisfaction with the daylight colour in the room; c. Satisfaction with view clarity; d. Perception of glare. The level of significance is expressed as: * = p-value < 0.05; ** = p-value < 0.01; *** = p-value < 0.001.

The satisfaction with speed of transition was higher in the benchmark room, where the actuation of the roller blind was faster than the transition speed of the EC technology. However, participants were in the large majority still satisfied with the speed of transition. Conversely, the EC technology being silent when transitioning between state, gave a much higher satisfaction in terms of the sound/noise related to changes in façade transparency. Still the majority of users felt neutral in terms of the roller blind’s noise.



a. b.

Fig. 4. a. satisfaction with the amount of daylight entering in the room; b. satisfaction with daylight sufficiency; b. User satisfaction with interaction: satisfaction with speed of change.

4 Conclusion

This study compared a novel EC glazing technology with a conventional static glazing with external roller blind from a multi-domain perspective. When blinds were lowered in the conventional façade, satisfaction with view clarity, daylight colour and daylight availability was higher. When the EC was in the clearest state and the blinds were raised in the benchmark facade no difference was perceived, except for view clarity. Users were not significantly dissatisfied with the speed of transition of the EC even if it would take between 3–5 min to switch. Overall, the EC glazing provided to participants with a better alternative to dark roller blinds, thus has the potential to increase user acceptance when façade are controlled for mitigating solar gains in summer. Future work is required to assess the performance for thermal comfort in summer and evaluate view clarity in large-scale application.

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