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Effect of switching speed under overcast sky condition

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User interaction with smart glazing: Effect of switching speed under overcast sky condition

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ABSTRACT

Smart dynamic building technologies can help to significantly reduce operational energy and carbon emissions. However, human acceptance remains a significant barrier, particularly for switchable glazing used in smart windows. This study examines how users are affected by the speed and direction of transitions in the transparency of fast switchable glazing, specifically dynamic liquid crystal technology under overcast sky. Perceptual and behavioural data including facial action units, were collected through an experimental campaign in a semi-controlled environment where the glazing transparency was transitioned at two rates (1 and 10 s). It was found that user perception remained consistent regardless of transition speed or direction, but override behaviour was influenced by both factors. In the absence of glare, user overrides were primarily driven by the transition direction, with more users reacting to transitions from dark to clear. Faster transition rates led to an increase in user overrides for both transition directions. Unlike those who did not override, users who overrode the automated glazing control strategy had a negative perception of the visual environment and the window control system. Users directed their gaze more towards the glazing when this was transitioning, suggesting possible distractions. Users were clustered based on their background knowledge and reported preferences. These clusters showed a good correlation with the override delay times. However, the agreement with actual behaviour was low, indicating that a larger number of variables and clusters should be tested to predict user behaviour. Nevertheless, clustering users highlighted the importance of considering individual differences for interaction strategies.

1. Introduction

Several technologies have been deemed promising in the decarbonisation of current building stock [1]. Among these technologies, appliances, devices, and components that enable the digital and automated control of buildings are expected to play a key role. These technologies, often named smart devices or smart building technologies, such as smart windows or predictive thermostats, can significantly improve energy efficiency and lead to worldwide associated emissions reductions of 350 Mt CO_2 by 2050 [2]. Smart technologies can also drive and foster occupant behavioural changes [3], which in turn can leverage a reduction of almost 250 Mt CO_2 in 2030 [2]. This can be achieved for instance, by dynamically adjusting cooling, heating or lighting setpoints.

User acceptance of smart building technologies is a barrier to widespread adoption of these systems [4–7]. This challenge has been recently recognised by the European Union Directive with the establishment of the “Smart Readiness Indicator” [8], which among several factors related to smartness, also rates the level of perceived convenience for the users. The dynamic and automated control of building technologies, such as glazing or shading in the building envelope, or heating and lighting appliances in the indoor environment, has often been found to be disruptive to users [5,9–12]. Factors that drive this disruption are trust and privacy [13,14], the mismatch between user requirements and automated control actions [15–17], lack of information and understanding of building control rationales [18] or poor interaction and interface design [19]; for instance, disruptive frequency and mode of actuation of the smart components [20,21], or insufficient perception of personal control of the environment [14]. With the recent proliferation of artificial intelligence and cost-effective and pervasive sensing technologies, buildings will become increasingly smart, but it is essential that the technological progress is matched by advances in human-building interaction [22].

The user-centred design and operation of smart or adaptive façade

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technologies is especially challenging because these components tend to be very disruptive [23]. Changes in façade behaviour (shading position or blind angle, glazing state or vent position) can be very noticeable. In addition, users tend to place significant importance on the personal control of the façade systems (e.g. windows, shadings etc.) [16,24,25]. Smart shading devices are often disruptive because of the noise they generate in operation, while overall the speed, frequency and direction of movement can also have a detrimental impact on user acceptance or satisfaction [20,26]. For instance, Bakker et al. [20] showed that less frequent but discrete transitions in facade configurations produced higher user acceptance and satisfaction than smooth transitions at a higher frequency transitions. Unlike smart shading systems, smart glazing technologies transition from one glazing state of visual and solar transmittance to another in a silent manner. However, the speed of change (often called transition time) can be disruptive. Switchable glazing technologies such as electrochromic glazing can have slow transition time lasting several minutes, which can also result in low user acceptance [27,28]. Other smart glazing, such as those based on liquid crystal technology, change state in a few seconds, and can lead to low acceptance because of the very short transition time.

Another factor in user acceptance of dynamic, switchable or smart façade technologies is the mismatch between the preferred façade state, in terms of transparency, and the one imposed by the automated controls for energy efficiency. In this sense, the transition direction (i.e. from high to low transparency or vice versa) plays a key role in meeting user expectations. For instance, several case studies reported that in the absence of significant glare, user overrides of automated control systems are very likely when automated control lowers the blinds or switches the glazing to its darkest state [27]. Bakker et al. [20] showed that the risk of disturbance and discomfort resulting solely from the frequency of change in facade state is low, however, several experimental campaigns showed contrasting results on this topic [29,30].

It is therefore currently unclear whether the speed and direction of transition in fast switchable glazing affects user acceptance and satisfaction, and to what extent these factors should be taken into account when designing satisfactory interactions with smart façade technologies. This knowledge gap is also compounded by the fact that users may exhibit different individual preferences when interacting with smart systems [16,31] and the lack of a comprehensive approach for capturing human responses to dynamic or smart facades [32].

Previous work by the authors of the present paper focused on the combination of environmental, perceptual and behavioural data [26] to capture user response to facades. In addition to traditional behavioural measures, such as user control over the dynamic glazing, other studies have shown that the use of facial action units (FAUs) and gaze angles can provide a more comprehensive understanding of user interactions with smart facades [33]. In addition to traditional behavioural measurements, facial action units or expressions describe the movement of facial muscles, and they are considered a proxy for human emotions [34]. For instance, Allen and Overend [35] evaluated the use of facial action units for gauging user well-being, and Kim and Ham [36] used facial expressions to study individual thermal preferences. These emotional cues could then offer insights into how users perceive environmental changes [37,38] and can inform adaptive system adjustments for enhanced comfort [39]. However, it is unclear at this stage whether the use of facial expressions can positively complement other sources of data in the assessment of human-façade interaction. Similarly, the monitoring of gaze angle to assess user view direction in human-façade interaction has already been performed by previous studies investigating glare [40] or aesthetic pleasantness [41] or expert intention in façade inspections [42]. However, it is unclear if this method could also be effective in describing user interaction with automated glazing systems, in particular user distraction or attention with movement of automated facades.

This paper aims to investigate the impact of speed and direction of transitions on user satisfaction and acceptance. An experimental campaign was conducted on fast and smart switchable glazing technologies by recording perceptual data, behavioural data and facial action units. The influence of transition speed and direction on user response was collected through questionnaires and by monitoring facial expressions and behaviour of users. In this study, we also tested the use of FAUs and gaze direction to evaluate respectively: (i) whether FAUs can describe changes on user facial expression due to changes in the emotional state [43] e.g. fear or surprise feeling because an unexpected change in the luminous environment; (ii) whether the change of transparency in the glazing can attract the visual attention of users, and whether this depends on the speed of transition. From the data collected, interaction preferences were also explored in terms of individual differences and the potential of user clustering.

2. Methodology

The experiment was conducted in a mobile laboratory located in Delft, The Netherlands. The laboratory, measuring 4.1 × 2.1 × 2.2 m, featured one glazed façade oriented towards southeast fitted with a liquid crystal dynamic (LCD) glazing. This glazing can transition between dark and transparent states, with a visual transmittance ranging from 0.11 to 0.53, respectively. The transitions were actuated by an automated system, which allowed manual override by means of a switch and a slider located on the desk of the occupant. The slider provided occupants with a graduated real-time control of the glazing transparency. The LCD glazing measured 1000 × 1500 mm, the window-to-wall ratio (viewed internally) was 0.40. The laboratory, was also fitted with a 2000-watt electric convection heater, which was also manually adjustable by the volunteers through a manual dial on the radiator. Artificial lighting was provided by means of LED ceiling luminaire with LEDNED bulbs of 350 mA.

Each volunteer was seated at a desk positioned orthogonally to the LCD glazing. The desk and chair arrangement relative to the façade was fixed as shown in Fig. 1, thereby offering an unobstructed view of the outdoor environment. On the desk, a computer screen of average luminance of 300 cd/m^2 was provided to perform a reading task.

2.1. Experimental design and procedure

The experiments were conducted from December 2022 to February 2023 as repeated measures (within subjects). The sky condition was always overcast, with no direct sunlight. This was chosen to avoid glare conditions and eliminate the possible influence of visual discomfort on the preferred switching speed.

A total of 30 participants were recruited for these experiments. The volunteers were recruited by email invitation. To ensure sufficient statistical power and detect meaningful effects, we conducted a power analysis prior to the study using G*Power. The power analysis was based on the assumption of a medium effect size ($f = 0.25$), which is typical for many behavioral studies and consistent with the anticipated effect based on prior research in similar settings. The power analysis indicated that 27 participants would be sufficient to achieve the desired power of 0.80. Given the goal of achieving an adequate balance between statistical power and practicality, we rounded up to 30 participants to ensure robustness in our results. The study was approved by the Human Research Ethics Committee (HREC) at Delft University of Technology.

2.2. Each participant spent 90 min in the laboratory, during which they experienced four distinct automated control scenarios, described in Table 1

Fig. 2 shows the overall experimental procedure. Prior to the experiment, participants filled in a first questionnaire to provide background information and obtain an anonymised ID, as reported in Appendix 1. On entering the laboratory, the participants were first asked to sit in the office space for 20 min, while reading the participant information sheet and answering a second questionnaire on general background information. Participants were then informed that the

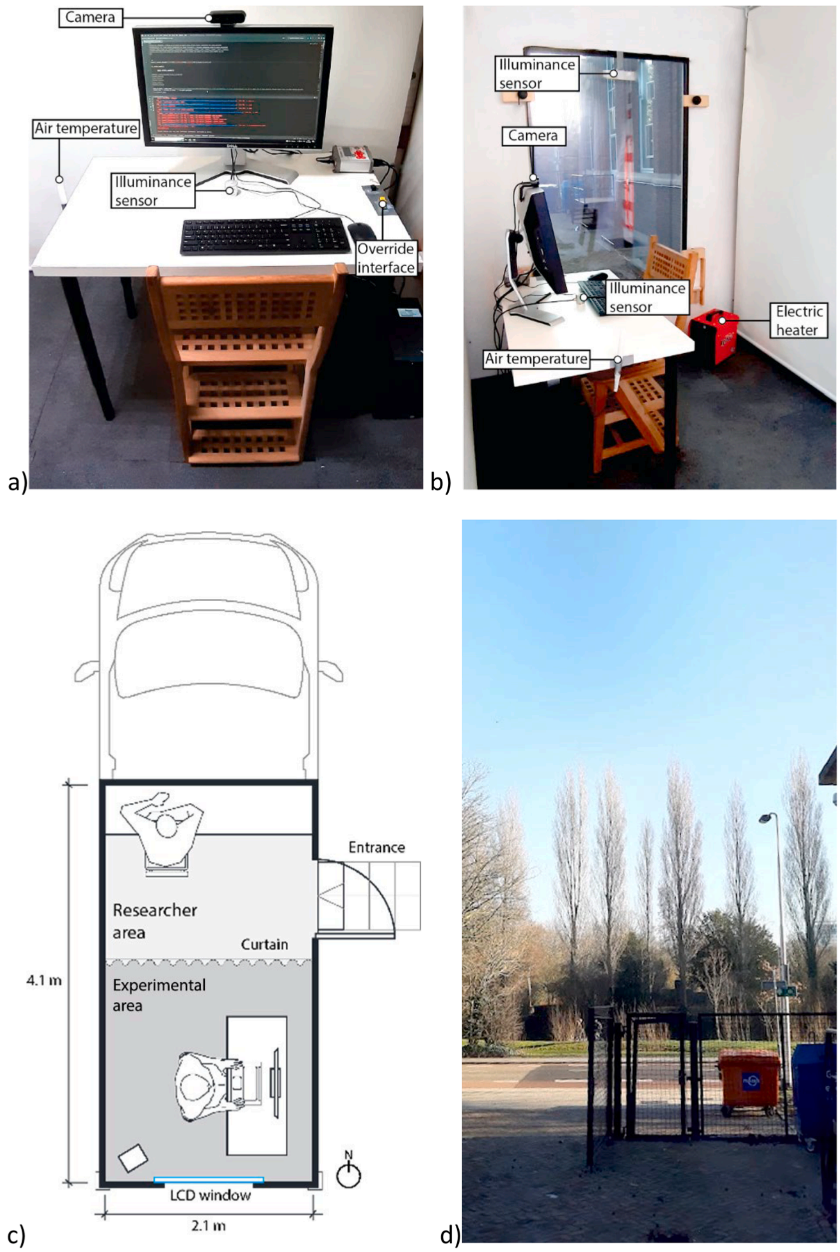

Fig. 1. View of the interior of the mobile laboratory: a) the position of the desk with respect to the façade and the location of the environmental sensors and the webcam for facial action unit recognition; b) the position of the sensors and the override interface in the desk; c) a floor plan view of the mobile laboratory; d) the view from the laboratory.

experiments involved automated control of heating, lighting and glazing, to avoid excessive focus on the operation of the glazing. After the habituation time, the participants experienced four sessions of 10 min corresponding to the four scenarios in Table 1, separated by 5 min of break, where users were asked to relax their sight and stop the reading task. During each session, automated control actions of the glazing were programmed to occur in halfway through each scenario (i.e. 5 min after the start of each scenario). After the automated control action was implemented at the start of each scenario, participants were then allowed to manually override the system. In order to not bias the perception of the participants, we did not inform the participants that the automated action had been implemented, but only that the control interface had been activated. To avoid biasing the participants' perceptions, we did not inform them when the automated action was implemented. Participants were only notified when they could override the automated action after 5 min had passed.

Additional questionnaires were then provided to capture information on participants' perception of the laboratory space, the control system for the façade, the indoor environmental quality, and familiarity with smart windows technologies (blinds or glazings). Questions were posed in terms of level of agreement. The level of agreement was indicated in a 5-point Likert scale from "strongly disagree" to "strongly agree". The questions are reported in Appendix 1.

Several measurements, reported in Table 2, were taken to describe the impact of the dynamic switching on the indoor environment and user response.

Environmental sensors were placed in the laboratory to measure indoor air temperature, desk horizontal illuminance, and vertical illuminance on the glazing. Table 3 shows a summary of the sensors used. Fig. 3 shows the distribution of the horizontal illuminance (Fig. 3 .a) and the vertical illuminance at the inner side of the window (Fig. 3.b). The indoor air temperature in the experiment was in the range of 22 °C ± 2

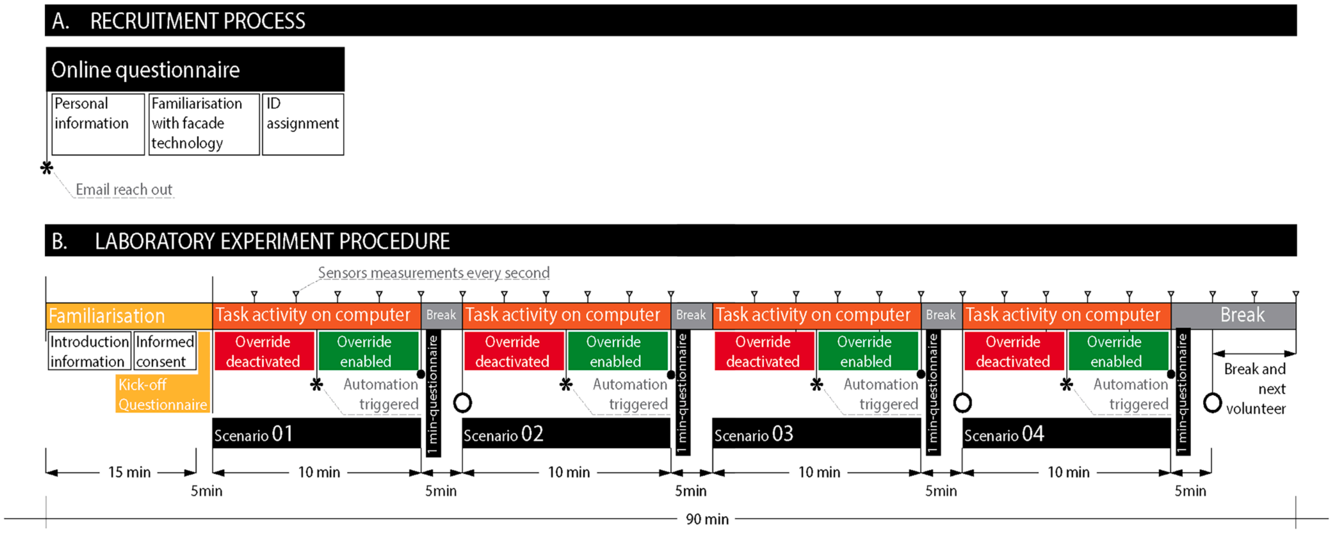

Fig. 2. Description of the experimental procedure. Every experiment lasted 90 min. Before the experiment, volunteers were asked to fill in a questionnaire. Volunteers were exposed to four control scenarios. At the end of every control scenario, they answered a survey.

Table 1
Description of the scenarios investigated in the experiment in terms of speed and direction of switching, transition time and override options.

Scenario	Speed of change	Name of the Scenario	Direction of transition	Transition duration (sec)	Override option	Behaviour during the transition
1	Fast	Fast Clear	from darker to lighter	1	Yes	Linear
2	Fast	Fast Dark	from lighter to darker	1	Yes	Linear
3	Slow	Slow Dark	from lighter to darker	10	Yes	Linear
4	Slow	Slow Clear	from darker to lighter	10	Yes	Linear

Table 2
Summary of the measurements and data collected in the experiment.

Type of measurement	**Aim**	**Methodology**
Indoor environment: illuminance and air temperature	To describe changes in the luminous and thermal indoor environment	Continuous monitoring with illuminance sensors as described in Table 3
User perception	To capture changes in perception across the scenarios	Questionnaires are provided at the end of each scenario to capture user perception
User behaviour	To capture whether a different speed of switching could affect the number of user overrides or delay potential user overrides	The interactions of the user with the glazing is tracked by logging the actions on the control interface, both in terms of time by recording the timestamp and type of action
Facial action units	To evaluate whether the speed of switching has a visible impact on user facial expression due to potential changes in emotional state	The facial action units of the participants is tracked by using a webcam and analysing these video frames with the OpenFace 2.0 software as described in Table 4
Gaze angle	To detect if the user redirects the gaze when changes in transparency are implemented at the glazing and whether this depends on the speed of switching	The gaze angle is monitored by using a webcam and analysing these video frames with the OpenFace 2.0 software

°C.

In addition, data on participant interaction with the switchable glazing was captured by a logger connected to the switch and the slider of the control interface, which recorded the instances and glazing state of users override.

Data on user perception was gathered through bespoke questionnaires. Lastly, data on participants' gaze angle and facial action units (FAUs) were also collected by using OpenFace 2.0 software [44] and a webcam located in front of the participant above the screen. The camera orientation was calibrated to measure coherently the gaze angle. Table 4 shows the facial action units recorded by OpenFace 2.0. For each of the FAUs, the presence (in binary values of 0 – absent and 1 – present) and the intensity were measured. Throughout the experiment, facial expression data were recorded at a rate of one measurement per second. Specifically, at each second, the presence and intensity of the designated FAUs were registered for each participant. Only numerical data regarding the occurrence and intensity of FAUs were recorded; no images or videos of participants' faces were stored for privacy. This approach was chosen to prioritize participant privacy while still obtaining essential information about their emotional and cognitive states. In addition to the FAU data, participants' gaze angles were measured concurrently using the gaze-angle-x and gaze-angle-y variables. This allows tracking of participants' visual focus in relation to the on-screen task and correlation of their facial expressions with the automated control of the glazing.

2.3. Data analysis

User responses in the questionnaires and facial action units were analysed to evaluate whether there were significant differences in user response depending on the speed and direction of switching. For this, statistical significance was tested using linear mixed models (*LMMs*), implemented in *R* programming language [45]. *LMMs* are particularly useful when dealing with repeated measurements or hierarchical data, as they account for both fixed effects (population-level trends) and random effects (individual variability), which is common in human

Table 3
Description of the characteristics of the sensing devices included in the experiment.

Parameter	Sensor	Characteristic	Datalogger	Unit	Sampling interval
Indoor air temperature	LSI Lastem Pt100	Range: −50…70 °C Resolution: 0.01 °C Accuracy: 0.15 °C (@0 °C)	LSI Lastem Alpha Log	Degree Celsius (°C)	Every minute
Desk Horizontal illuminance	LSI Lastem ESR000	Range: 0…5000 lx Resolution: 0.5 lx Accuracy: 3 %	LSI Lastem Alpha Log	Lux (lx)	Every second
Window vertical illuminance	LSI Lastem ESR001	Range: 0…25,000 lx Resolution: 3 lx Accuracy: 3 %	LSI Lastem Alpha Log	Lux (lx)	Every second

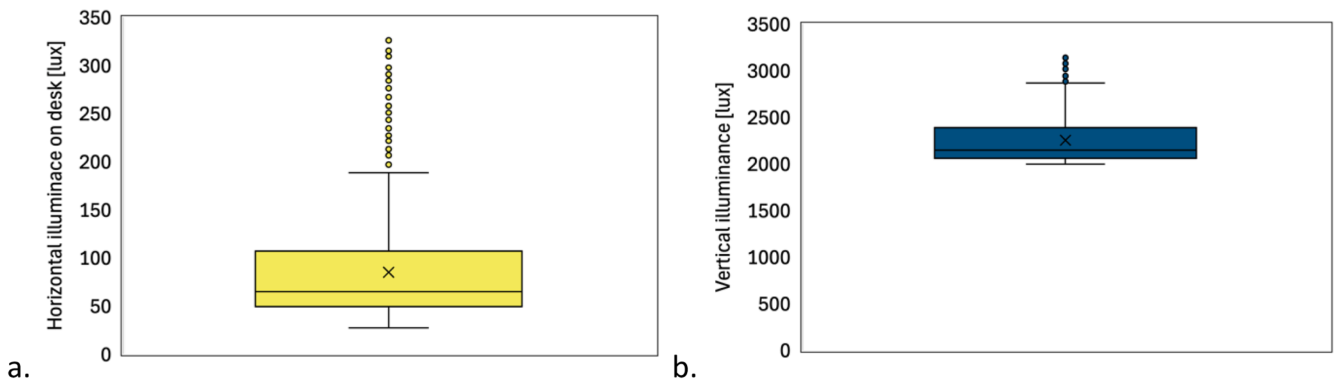

Fig. 3. Boxplots illustrating the distribution of horizontal illuminance at the desk level and the vertical illuminance during the experimental conditions. The plots provide a visual summary of the environmental parameters in which the experiment was conducted. The whiskers shows the maximum and minimum value within 1.5 times the interquartile range, while the 95 % of the data is shown in the box. Crosses indicate the means and the black horizontal line the medium.

Table 4
List of facial action units monitored by the OpenFace 2.0 software during the experiment and combination of FAU used to detect expressions related to emotions. In addition, OpenFace was used to monitor gaze angle.

FAU	Name
AU01	Inner brow raiser
AU02	Outer brow raiser
AU04	Brow lowerer
AU05	Upper lid raiser
AU06	Cheek raiser
AU07	Lid tightener
AU09	Nose wrinkler
AU10	Upper lip raiser
AU12	Lip corner puller
AU14	Dimpler
AU15	Lip corner depressor
AU17	Chin raiser
AU20	Lip stretcher
AU23	Lip tightener
AU25	Lips part
AU26	Jaw drop
AU45	Blink

subjects experiments. *Post-hoc* comparisons were performed with *Tukey's* method to assess interaction effects. In the *LMM*, both the scenario and the illuminance levels were considered as independent variables. However, no interaction between the scenario and illuminance levels was found, leading to the removal of the illuminance factor from the final model.

Data on user overrides across scenarios were analysed using the *Kruskal-Wallis test*, implemented through the *scipy.stats* library in Python. This non-parametric test was selected due to the ordinal nature of the data. Following the *Kruskal-Wallis test, Dunn's post-hoc test* with *Bonferroni* correction was applied to identify specific pairwise differences between scenarios. For this, the *scikit-posthocs* library was used to perform *Dunn's test* with *Bonferroni* adjustment, ensuring control for multiple comparisons and minimising the risk of *'false positive' errors*.

Data on gaze angles were analysed using the *Mann-Whitney test* [46], performed with the *SciPy* package in Python [47] . The choice of this non-parametric test was based on the distribution of the data. The main objective was to examine whether users directed their gaze towards the glazing during switching intervals and whether the gaze angles differed from intervals when the glazing remained static.

To analyse user personal background data, including familiarity with smart glazing or blinds, perceived importance of control, and perceived frequency of interaction, a *two-step cluster analysis* was conducted. This method was chosen due to the mixed data types (both quantitative and categorical variables) and the uncertainty about the optimal number of clusters based on the sample size. The *two-step clustering* was implemented using the *sklearn* library in Python. Additionally, pandas was used for data manipulation and organization, and *matplotlib* was utilized for visualizing the clusters. After the clusters were formed, the *Adjusted Rand Index* (*ARI*) was calculated using the *sklearn.metrics* package to assess the similarity between the clusters, taking into account chance agreement. The *ARI*, which ranges from −1 to 1, provides a measure of clustering quality, with values closer to 1 indicating better clustering and higher consistency in the detected user profiles.

Lastly, *Chi-squared tests* were conducted using the *scipy.stats* library to examine associations between the user clusters and their reported perceptions during the experiments. These tests provided insights into how user self-reported preferences and behaviors were linked to their assigned clusters, offering a deeper understanding of user interactions with dynamic facades.

3. Results

3.1. User background in relation to switchable smart glazings

The background of the users in terms of the level of familiarity, perceived level of importance and self-reported frequency of interaction with window opening and shading controls was assessed by means of questionnaires. Fig. 4 shows that all participants assigned a high importance to user control of opening of windows and controlling window shadings, with the former ranking higher than the latter. It also emerged that users were more familiar with smart blinds than smart windows, in both home and office settings. There was a large scatter of responses in self-reported frequency of user interaction with window opening or shading controls, implying that several of the participants had a tendency to be more active while others were more passive in terms of user-façade interaction.

3.2. *User perception and behaviour under different speed and direction of switching*

At the start of the experiment and at the end of each session, users were asked to fill in a short questionnaire on their perception of the environment (i.e. visual satisfaction, satisfaction with automated controls, perceived annoyance with the automated controls, self-reported perceived distraction from task) in the preceding ten minutes. The results across different switching speeds and directions show that users consistently reported a similar perception in all scenarios (with mean agreement levels close to 3 – "neither disagree or agree"). No significant differences across the responses of users were found also in comparison with the responses given at the start of the experiment. The only noticeable trend is that the distribution of reported agreement is smaller when the window was transitioning to its darkest state (scenarios "Fast dark" and "Slow Dark"), particularly for the items related to the window control, thereby indicating a lower number of people that were fully satisfied.

As shown in Fig. 5, no significant difference was found in the perceived annoyance of users with the heating (Fig. 5.a), the artificial light control (Fig. 5 .b), or the with window control (Fig. 5 .c). Since the control of the heating and the lights were unchanged across the scenarios, it was reasonably expected that to find very similar results across the scenarios.

In addition to assessing user perception, data on user overrides was collected across the four sessions, showing differences in override frequency between scenarios. In the "Fast Dark" and "Fast Clear" scenarios, 20 participants (67 %) and 10 participants (33 %) overrode the system, respectively. For the "Slow Dark" and "Slow Clear" scenarios, 17 participants (57 %) and 7 participants (23 %) overrode the system. This is consistent with the existing literature that reported higher user overrides when the blinds are lowered or the glazing is darkened [10, 48]. The result also shows that there is a small difference in overrides (approximately 10 %) induced by the speed of switching. This is explainable by the potential disruption caused to the users by fast transitions, which may not allow sufficient time for visual adaptation. Overall, the number of participants that overrode changed depending on the direction of switching. Therefore, the transition direction plays a larger role than the transition speed in inducing user overrides of the automated switching of switchable glazings.

Fig. 6 illustrates the delay between the glazing transition actuation and user interaction with the system, highlighting variations in override behavior among participants based on the scenario. As shown in Fig. 6, faster transition rates were also associated with faster responses in user overrides. Users who executed an override reacted more quickly to the 1-second glazing transitions than to the 10-second glazing transitions. In all scenarios, there was a delay between the completion of the glazing transition and when users initiated the override. A potential explanation for this effect is that when the glazing transitions slowly, users' reaction time is longer, as they may require more time to notice the changes in glazing transmittance due to the slower transition rates.

The Kruskal-Wallis test result suggests that there is a statistically significant difference between the scenarios (H-statistic = 8.04, p-value = 0.045), indicating that at least one scenario differs from the others in terms of the measured variable. However, the Dunn's post-hoc test results with Bonferroni correction show that none of the pairwise comparisons between scenarios reach statistical significance. The p-values for all comparisons are greater than the corrected threshold (0.05/6 = 0.00833), indicating that while the Kruskal-Wallis test identified an overall significant difference, there is insufficient evidence to pinpoint which specific scenario pairs differ from each other.

When grouping participants into those that overrode the automated glazing control and those that did not, there is a clear difference in their perceived levels of satisfaction with the visual environment, the window control, the perceived distraction from reading task and the feeling of annoyance from the window control (see Fig. 7). As expected, this indicates that all the participants that override were not satisfied with these factors, however the definition of these clusters was found to be independent of the transition speed and the transition direction.

3.3. *User facial units and gaze direction under different transition rate and transition direction*

User response was also captured by means of recording Facial Action

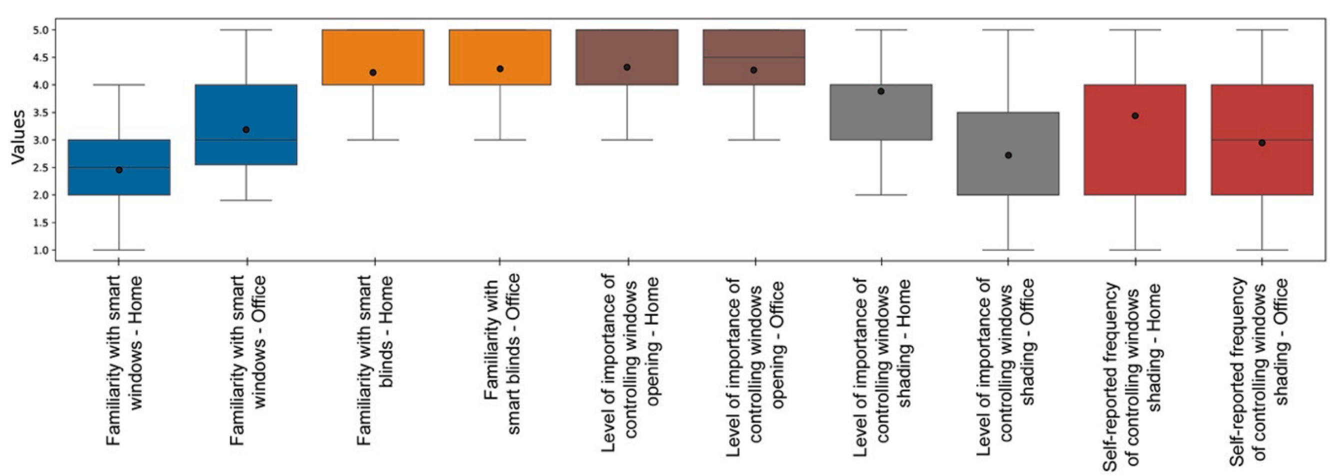

Fig. 4. Results from the background questionnaire completed by the participants at the start of the experiments. In particular, the scores (1=strongly disagree; 5=strongly agree) represent the level of agreement with statements related to their perceived level of familiarity with smart windows technologies (opening or shadings) at home and the office, the importance of personal control of window openings or shadings, and self-reported frequency of interaction with windows and shadings at home or at the office.

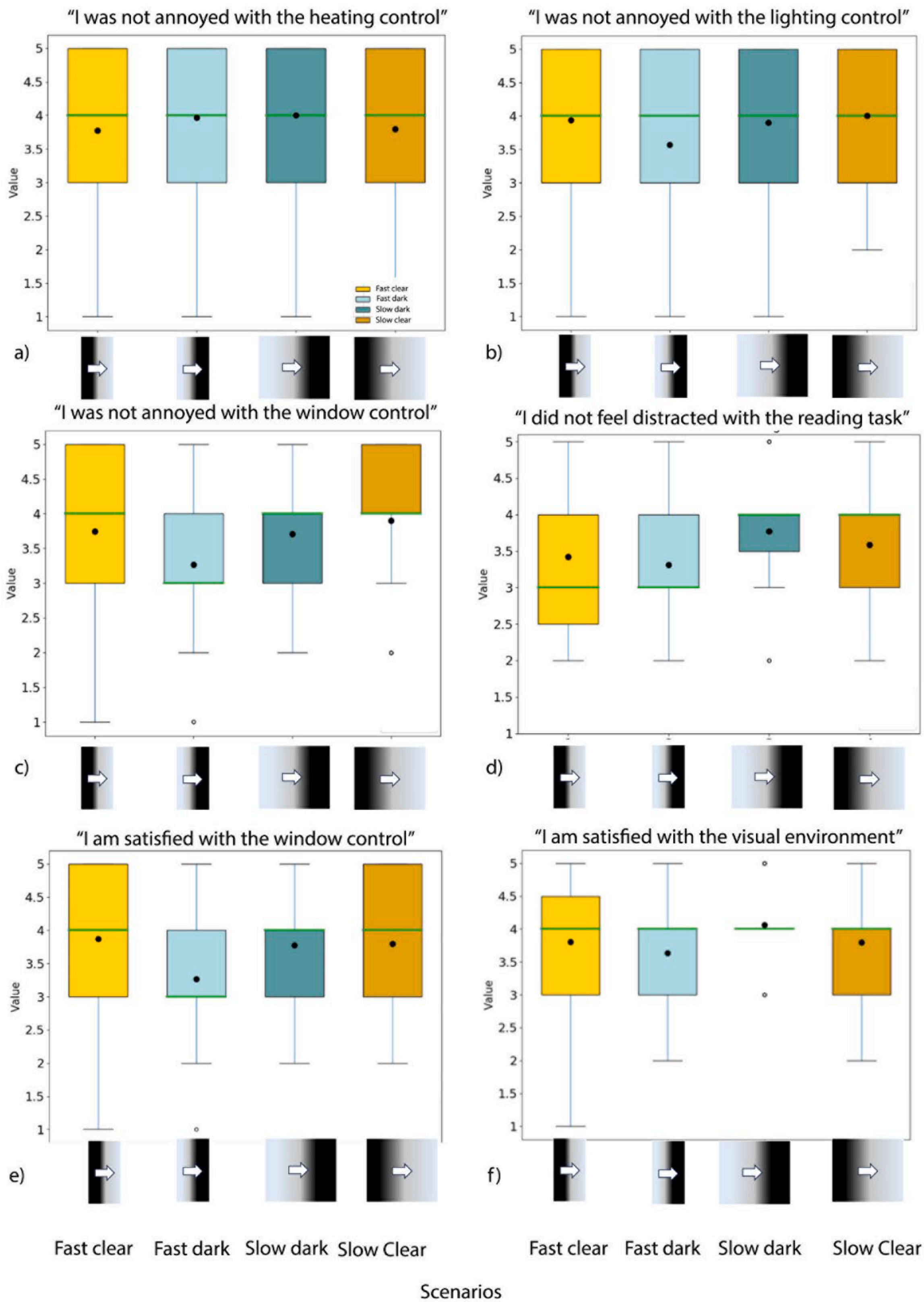

Fig. 5. User perception of annoyance with building controls and distraction with reading task. Users' level of agreement with the following statements: (a) "I was not annoyed with the heating control"; (b) "I was not annoyed with the lights control"; (c) "I was not annoyed with the window control"; (d) "I did not feel distracted from the reading task". Perceived satisfaction with the control of the window and the visual environment: (a) level of agreement with the sentence "I am satisfied with the window control"; (b) level of agreement with the sentence: "I am satisfied with the visual environment". The black dot indicates the mean value while the green line indicates the median of the data distribution.

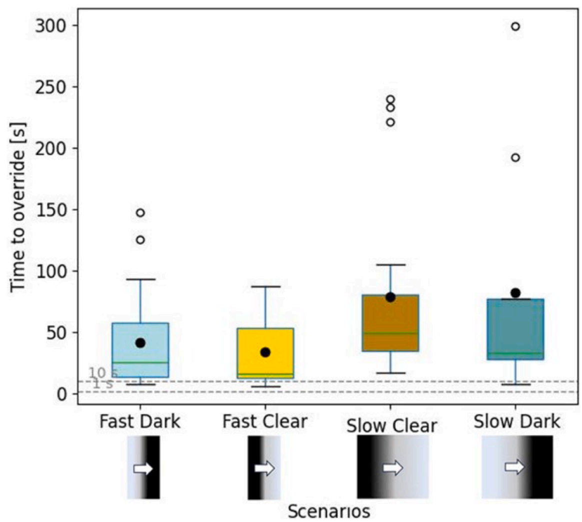

Fig. 6. Time of response of users that have overridden the façade state. The black dot indicates the mean value while the green line indicates the median of the data distribution.

Units (FAUs) and gaze angles. First, the direction of gaze was analysed to compare the intervals when the glazing was in transition versus the intervals when the glazing was static. Fig. 8 shows that there was a significant difference between the instances when the glazing was transitioning and the remaining time periods, indicating that users looked towards the glazing when the glazing was in transition. This could be potentially lead to distraction from the task. No significant difference was found between different rates or directions of the transition, indicating that users always looked towards the glazing when this was actuated, regardless of the transition rate. No significant difference was found in gaze angles on the y-plane, since the glazing was positioned on the right side of participants.

Secondly, the FAUs related to the affective responses of users were analysed to investigate differences in facial actions for the same user throughout the distinct phases of the experiment. Fig. 9 shows the correlation between the facial action units and corresponding emotion expressions from the questionnaire, including information on whether the participant overrode the automated glazing control or not, coded in the variable "override". There is a positive Pearson correlation (0.47) between the perception of not being distracted and the action unit of Chin Raisers (AU17), which suggests that when reading with higher focus users would raise their chin. The action unit related to lip tightener (AU23) was also correlated with satisfaction with the visual environment (0.43). With the exception of override, all other correlations are mild and therefore are not considered meaningful. The "override" variable is correlated with satisfaction and annoyance with the window control, which confirms the results from Fig. 7. Overall, there is no strong correlation between any of the items from the questionnaire and the facial expressions.

When comparing the variations of facial action units between the intervals where the glazing remained unchanged and where it was in transition, there is a significant difference across all the facial action units and the emotion-related expressions, as shown in Fig. 10. This indicates that the facial action units did capture the effect of the glazing transitions. However, this was not sensitive to the rate or direction of glazing transitions. The facial action units associated with blinking remained unchanged during glazing transitions, indicating that the change in glazing transparency does not induce eye blinking.

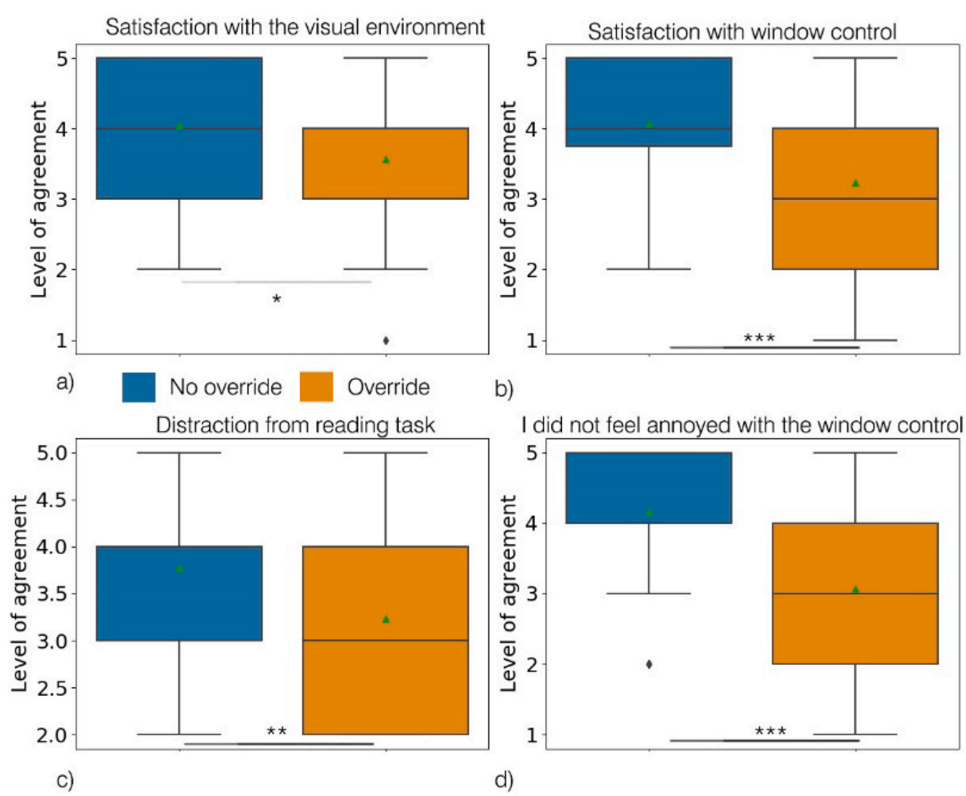

Fig. 7. Results on user perception depending on user behaviour, participants that did override and did not override are grouped separately; (a) level of agreement with the sentence "I feel satisfied with the visual environment"; (b) level of agreement with the sentence "I feel satisfied with the window control"; (c) the sentence "I did not feel distracted in the past 10 min", (d) the sentence "I did not feel annoyed by the window control". The asterisks indicate the level of significance: (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$. The black dot indicates the mean value while the green line indicates the median of the data distribution.

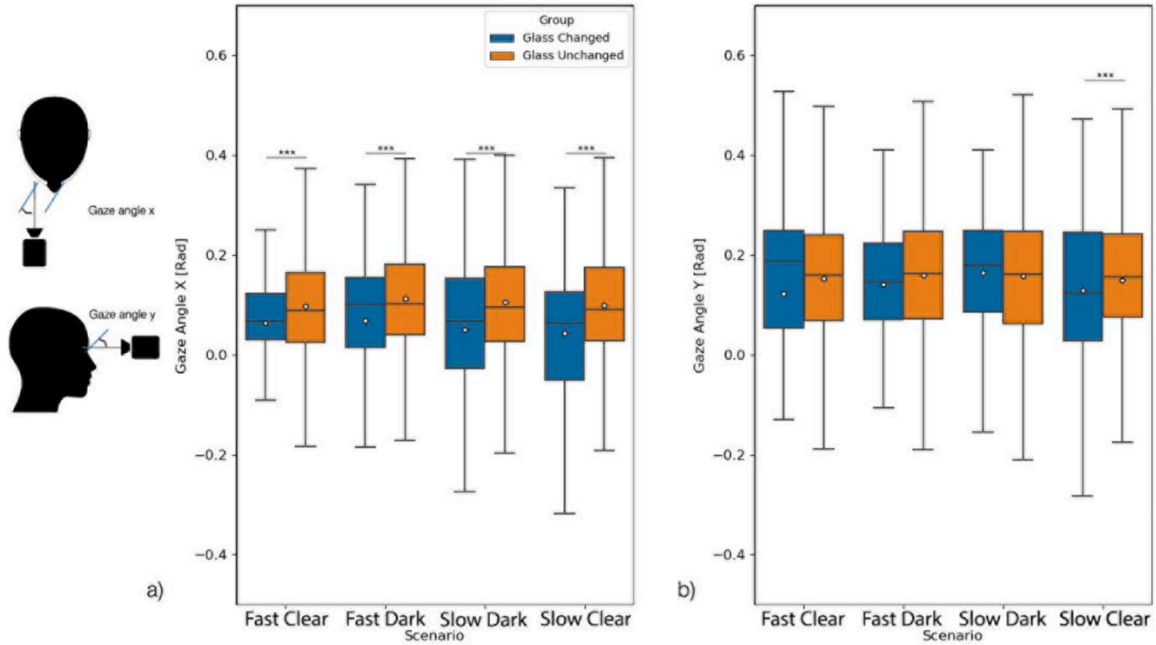

Fig. 8. Box-plots of gaze angles of the users during experiment to evaluate differences between users' gaze angle during the switching of the glaze and the rest of the time, and for different speed of switching. The box-plot shows the distribution of the gaze angles by showing the median, quartiles, and average (white-filled circle), providing insight into the central tendency, spread, and skewness of the data. a) Gaze angle on the x-plane as shown in the diagram on the left; b) gaze angles on the y-plane. The level of significance ($p < 0.05$) is shown by "***" for the sample groups connected with the line. The black dot indicates the mean value while the black horizontal line indicates the median of the data distribution.

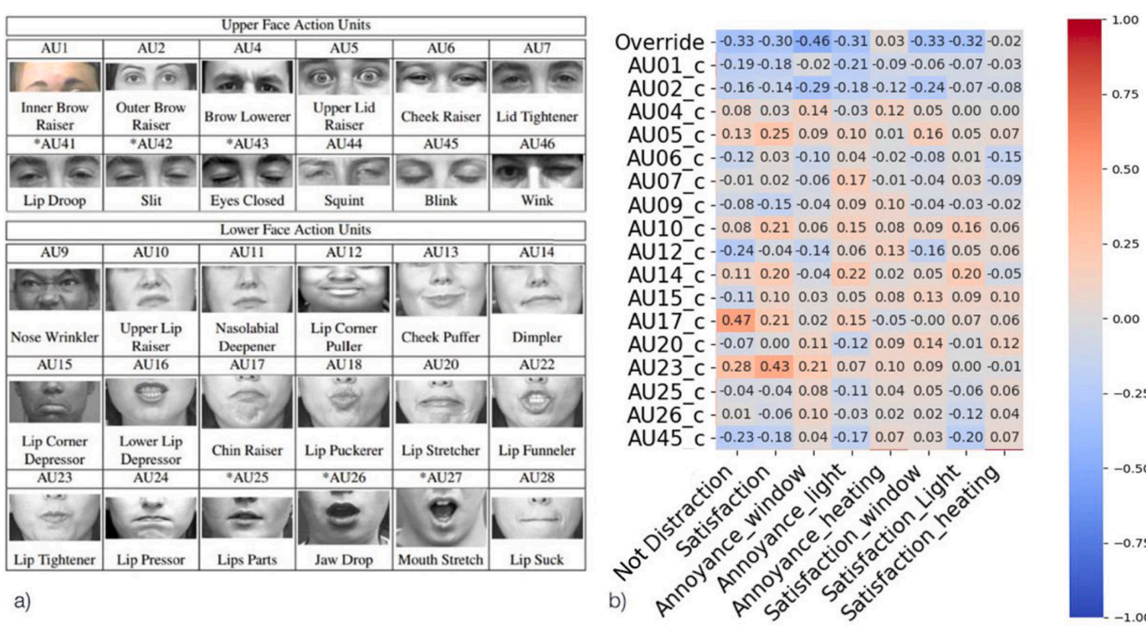

Fig. 9. Correlation matrix between participants facial expressions and perception: a) Facial action units from [49]; b) correlation between user perception and facial expression.

3.4. Clustering of users based on behaviour with switchable glazing

Information on users' self-reported familiarity with smart glazing or blinds, and their perceived importance of controlling the glazing was analysed to evaluate whether it was possible to cluster users based on these two features. In addition, data on the frequency of interaction with the switchable glazing was also analysed for the purpose of clustering.

Fig. 11 shows the results from the two-step cluster analysis. Two distinct cluster of users were identified. In terms of familiarity with smart glazing or blinds, users can be grouped in: (i) individuals with a self-reported high familiarity (Cluster 1), and (ii) individuals with a self-reported low familiarity with these technologies (Cluster 2), as shown in Fig. 11 .a. In terms of the perceived importance of controlling window openings and shading (Fig. 11 .b), two clusters were also identified. Cluster 1 exhibited strong importance of personal control, whereas Cluster 2 showed a lower perceived importance for controlling façade devices.

Lastly, in terms of the self-reported frequency of interaction with

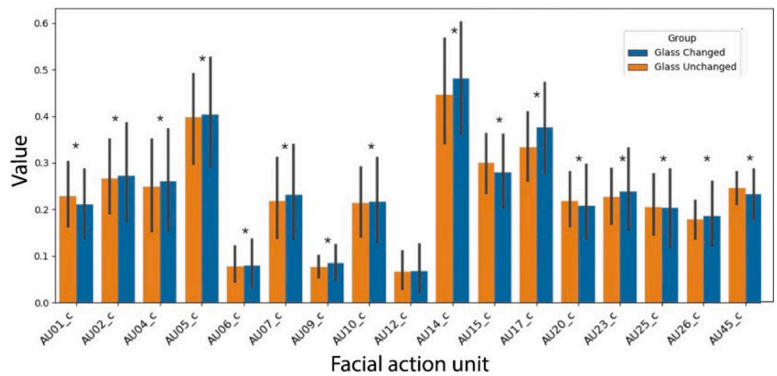

Fig. 10. Facial action units during the intervals where the glass remained unchanged, and the glass was changed. The asterisks indicate that the differences are statistically significant.

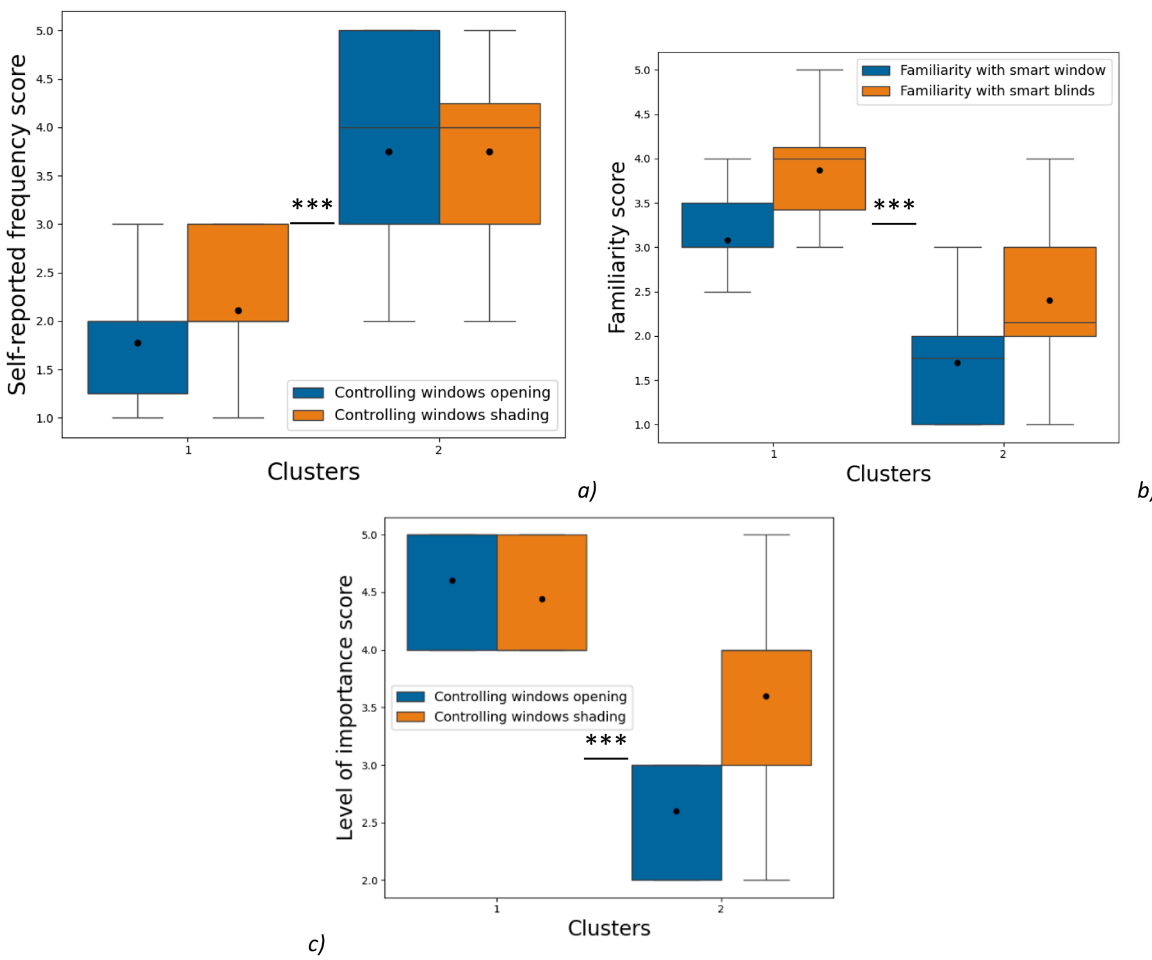

Fig. 11. Boxplots of the results of three cluster analysis performed regarding (a) level of familiarity with smart windows and smart blinds, (b) level of importance of controlling window's opening and window's shading, and (c) self-reported frequency of interaction on controlling window's opening and window's shading. Each analysis provided two clusters of users. All the analysis were validated by using the silhouette measure of cohesion and separation, scoring 0.6 for each of them. The black dot indicates the mean value while the black line indicates the median of the data distribution. The asterisks indicate the level of significance: (***) $p < 0.001$.

window openings and shading (Fig. 11 .c), two clusters were identified as well, where Cluster 1 represented users reporting a low frequency of interaction, while Cluster 2 was composed of users who interacted with window devices frequently. Each of these analyses achieved a silhouette score of 0.6 for cohesion and separation. This score indicates that the data points within each cluster are well-separated from other clusters and are significant in their grouping.

When examining participant behavior with the switchable glazing, particularly in response to automated control actions, two distinct user clusters emerged (Fig. 12), demonstrating statistically significant differences in behavior (Mann-Whitney U, $p = 0.017$). The first cluster consisted of users who tended to override the controls predominantly when the glazing transitioned to a clear state, irrespective of whether the transition occurred at a fast or slow rate. These participants generally exhibited longer reaction times, indicating a more gradual response to the automation. In contrast, the second cluster comprised users who

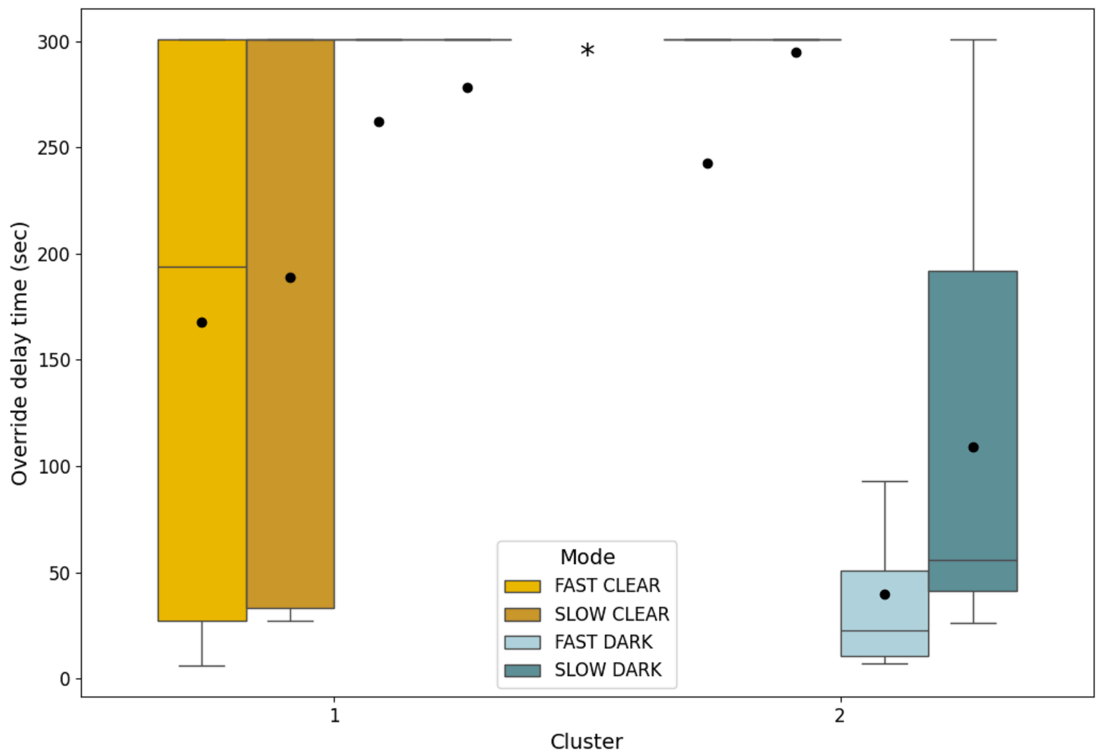

Fig. 12. Boxplot of the cluster analysis of users override delay time of users with the switchable glazing. This analysis provided two clusters of users: Cluster 1 represent users that override the automated control only when the glazing was turned at the darkest state; while Cluster 2 represent users that override the automated control only when the glazing was turned clear. The analysis was validated by using the silhouette measure of cohesion and separation, scoring 0.5. The black dot indicates the mean value while the black horizontal line indicates the median of the data distribution. The asterisks indicate the level of significance: (*) $p < 0.05$.

frequently overrode the controls when the glazing transitioned to a dark state, with much shorter reaction times. These patterns reveal each cluster's consistency and likelihood of overriding under particular transition conditions, suggesting that user preferences are closely tied to both the state of the glazing and the timing of control actions.

The clustering of users based on their perceived familiarity with the technologies, their importance of user control of glazing, and self-reported frequency of interaction were compared to the clustering from their behaviour during the experiment. The Adjusted Rand Index (ARI) was used to assess the degree of similarity between the clustering assignments based on self-reported information and those resulting from the analysis of override delay times, as shown in Table 5. A moderate ARI of 0.08 for clustering based on familiarity with smart facades indicates a reasonable alignment with actual behavioural patterns measured in the experiment. This means that users that reported high familiarity with the technology were also the users that override the façade with a longer reaction time. This could potentially be explained by the lower disruption perceived when familiar with the technology.

Table 5
The Adjusted Rand Index (ARI) between the clusters on users' self-reported information (level of familiarity, importance and frequency of interaction) to cluster on users' behaviour (override delay time) is displayed, showing that the level of importance clustering has the least agreement while level of familiarity shows the most higher alignment.

	Clustering on the level of familiarity with smart facade	Clustering on the level of importance for controlling facade	Clustering on the self-reported frequency of interaction with facade
Clustering on the Override delay time	ARI = 0.08	ARI = −0.02	ARI = 0.01

Conversely, the negative ARI of −0.02 for clustering on the level of importance for controlling facades suggests a divergence from the override delay time clustering structure, indicating less agreement. Additionally, the low positive ARI of 0.01 in the clustering based on self-reported frequency of interaction with facades implies only a slight agreement between the derived clusters and the override reaction time clustering.

Finally, users self-reported perception was compared to the behavioural clusters, as shown in Table 6. Chi-square tests were used to statistically assess whether there is a significant association between the clusters and the perception of users during the glazing operations on users.

Clusters related to the level of familiarity with the technology, self-reported frequency of interaction with the facade, and behaviour with switchable glazing were significantly associated with user satisfaction with the visual environment, with corresponding p-values of 0.039, 0.014, and 0.002, respectively. Thus, the cluster of users with high level of familiarity with smart glazing is also characterised by users that expressed dissatisfaction with the visual environment. Clusters associated with high levels of interaction with the façade (both self-reporting and observed behaviour with switchable glazing) exhibited also a greater satisfaction with the visual environment compared to the users in the cluster described by a low frequency of interaction.

Differences among clusters can also be explained by differences in user perception. For example, the cluster demonstrating a high level of familiarity with smart windows is correlated with a greater number of users expressing annoyance with window control (p-value = 0.017). Similarly, higher levels of self-reported interaction with facades are linked to a higher prevalence of dissatisfaction with window control. Conversely, a low measured frequency of overriding automated controls corresponded to a higher number of users not noticing changes in the window state (p-value = 0.002). In contrast, the cluster associated with the importance of controlling facades stands out as the most dissimilar

Table 6
Correlation between the user clusters, based on self-reported familiarity, importance, frequency of interaction and delay in users response with user perception. The chi-square test was used to test the correlation between the clusters and the perception reported by users.

Perception of users	Clusters	Level of familiarity		Level of importance		Self-reported frequency of interaction		Override delay time	
		High fam. Cluster 1 $n = 48$	Low fam. Cluster 2 $n = 72$	High imp. Cluster 1 $n = 100$	Low imp. Cluster 2 $n = 20$	High int. Cluster 1 $n = 73$	Low int. Cluster 2 $n = 47$	Low int. Cluster 1 $n = 120$	High int Cluster 2 $n = 192$
Perceived change on the glazing state	Yes	96 %	92 %	92 %	100 %	93 %	92 %	85 %	99 %
	No	4 %	8 %	8 %	0 %	7 %	8 %	15 %	1 %
	p-value	*0,0258*		*0,163*		*0,295*		***0,002****	
Distraction perceived	Agree	17 %	18 %	20 %	5 %	19 %	15 %	63 %	50 %
	Neutral	33 %	22 %	28 %	20 %	26 %	28 %	19 %	32 %
	Disagree	50 %	58 %	51 %	75 %	53 %	57 %	17 %	18 %
	p-value	*0,583*		*0,213*		*0,917*		*0,289*	
Satisfaction with the visual environment	Agree	50 %	58 %	67 %	75 %	71 %	64 %	79 %	61 %
	Neutral	33 %	22 %	28 %	20 %	29 %	23 %	17 %	33 %
	Disagree	17 %	18 %	5 %	5 %	0 %	13 %	4 %	6 %
	p-value	***0,039****		*0,45*		***0,014****		***0,002****	
Window's control annoyance	Agree	31 %	11 %	18 %	25 %	21 %	17 %	67 %	58 %
	Neutral	17 %	18 %	21 %	0 %	19 %	15 %	13 %	24 %
	Disagree	50 %	69 %	59 %	75 %	58 %	68 %	21 %	15 %
	p-value	***0,017****		***0,020****		*0,386*		*0,449*	
Lighting control annoyance	Agree	6 %	7 %	6 %	10 %	5 %	9 %	65 %	46 %
	Neutral	19 %	14 %	18 %	5 %	14 %	19 %	15 %	17 %
	Disagree	46 %	58 %	50 %	70 %	58 %	47 %	2 %	10 %
	p-value	*0,706*		***0,022****		*0,176*		*0,285*	
Heating control annoyance	Agree	13 %	17 %	13 %	25 %	21 %	6 %	13 %	17 %
	Neutral	21 %	11 %	17 %	5 %	11 %	21 %	17 %	14 %
	Disagree	67 %	63 %	64 %	65 %	60 %	70 %	60 %	67 %
	p-value	*0,555*		*0,108*		*0,104*		*0,533*	
Satisfaction with windows	Agree	46 %	65 %	56 %	65 %	42 %	81 %	65 %	53 %
	Neutral	29 %	19 %	24 %	20 %	33 %	9 %	19 %	26 %
	Disagree	25 %	11 %	17 %	15 %	21 %	11 %	17 %	17 %
	p-value	*0,078*		*0,631*		***0,002****		*0,552*	
Satisfaction with the lighting	Agree	38 %	47 %	42 %	50 %	49 %	34 %	52 %	38 %
	Neutral	27 %	17 %	21 %	20 %	19 %	23 %	15 %	25 %
	Disagree	2 %	11 %	8 %	5 %	5 %	11 %	10 %	6 %
	p-value	*0,209*		*0,09*		*0,183*		*0,462*	
Satisfaction with the heating	Agree	65 %	63 %	63 %	65 %	59 %	70 %	63 %	64 %
	Neutral	15 %	11 %	14 %	5 %	8 %	19 %	15 %	11 %
	Disagree	21 %	19 %	18 %	30 %	26 %	11 %	15 %	24 %
	p-value	*0,732*		*0,634*		*0,13*		*0,569*	

* indicate significance at p-value < 0.05.

from the others (ARI = −0.02). Table 6 shows a higher frequency of neutral votes for window control annoyance in the high-importance cluster (p-value = 0.020), while the low-interaction cluster concentrates votes indicating no annoyance with lighting control.

4. Discussion

The perceptual data from this study shows that there was no significant difference in perception across the scenarios. Therefore, both the speed (1 or 10 s) and direction of glazing transition seem to have a low impact on user satisfaction with the visual environment and window control.

The analysis of behavioural data provides further important insights, highlighting the importance of considering both sources of data when assessing user-façade interaction. As shown in Fig. 6, approximately half of the participants overrode the glazing change of state, especially when the glazing was turned to its dark state (17 out of 30 for the lower transition rate, 20 out of 30 for the faster transition rate). Faster transition rates triggered a larger number of overrides in both transition directions. As expected, the slower the glazing transitions, the longer it takes for users to react to the glazing change, since the reaction time between glazing transition and user response was larger. The perception of participants who opted to override the glazing control was also significantly different and worse than those who did not override, confirming that overriding the control is induced by dissatisfaction with the visual environment or the window control (Fig. 7). Thus, overriding of controls is a good proxy for user satisfaction with the automated control strategy.

The examination of facial expressions emerged as a valuable approach for gathering further insights when combined with perceptual and behavioural data. Notably, there was no significant variance in gaze angles observed across various glazing transition rates or directions. However, it is noteworthy that, during the transitions of the glazing, participants consistently directed their gaze towards the glazing, irrespective of the transition rate (Fig. 8). This was also confirmed by the analysis of the facial expressions, which differed significantly between the intervals when the glazing remained unchanged and the periods when the glazing was transitioning (Fig. 10).

The dispersion in participants' results shows that individual preferences may differ, and personalised interaction can be considered, in particular when designing transition to clear glazing states. For instance, if participants are grouped depending on whether they override or not the automated switching, there is a clear and significant difference in participants' satisfaction with the visual environment and the window control, perceived distraction from the reading task and perceived annoyance with the window control. The overriding behaviours are strongly associated with low levels of satisfaction, high levels of annoyance and perceived distraction from the reading task, as also shown in the correlation matrix (Fig. 9).

Users exhibited a range of backgrounds and preferences. Interestingly, the majority emphasized the importance of controlling both window openings and shading, particularly in home environments

(Fig. 4). Clustering analysis revealed two distinct user profiles based on self-reported information on the level of familiarity with the technology, the importance of personal control of the glazing, frequency of interaction and override reaction times. However, the Adjusted Rand Index (ARI) values indicated random agreement between these profiles and actual user behaviour (Table 5). This suggests that while self-reported data provide insights into user background and perceived preferences, they do not consistently align with user behaviour when interacting with the glazing system.

Although clusters on users' backgrounds and preferences do not align with their actual behaviour, they were shown to be associated with specific perceptual response regarding the level of distraction, annoyance, and satisfaction of smart glazing operation (Table 6). Consequently, the cluster of high familiarity exhibits a strong correlation with visual satisfaction and annoyance with window control. The cluster of low self-reported interaction shows a higher correlation with the satisfaction with window control. The low-importance-of-façade-operation cluster exhibits low correlation with visual dissatisfaction with lighting and window control. In contrast, the cluster of high actual users' interaction shows good association with noticing changes in window states. Overall, the clustering reveals the importance of considering personal preferences when designing automated control strategies.

5. Conclusion

This study investigated the influence of speed and direction of transparency change in switchable glazings on user satisfaction and acceptance. An experimental campaign involving 30 participants was conducted in a controlled environment, wherein perceptual and behavioural data were collected and complemented with the analysis of facial action units. Clustering analysis was also employed to explore the relationships between users' backgrounds, preferences, and behavioural drivers.

It was found that:

- No significant difference exists in user perception across the scenarios, while a noticeable difference in user behaviour emerged from the variations in the direction and speed of transitioning;
- User overrides are mainly driven by the direction of the glazing transition. A larger amount of users overrode the automated glazing control when transitioning towards the dark state. Approximately 10 % more users overrode the glazing in response to faster transitions, in both directions of transition. When considering users that overrode the automated control system, they exhibited low satisfaction with the visual environment and the control of the window.
- Capturing data with facial action units and gaze orientation revealed some further patterns in user response to the glazing transition rate, such as differences in response between users that override and do not override.
- Users can be clustered based on their background knowledge and reported preferences. These clusters showed good correlation with the override delay times. However, the agreement with actual behaviour was low, indicating that a larger number of variables and clusters should be tested to predict user behaviour based on self-reported preferences.
- Clustering analysis on users' backgrounds and preferences has the potential to inform the distribution of certain behavioural drivers and perceptual responses when interacting with smart glazing, such as level of perception of glass changing state, distraction, annoyance, and satisfaction with the smart glazing operation.

This study has some limitations that merit investigation in future work. First, the participants were never exposed to glare conditions, which may have an effect on the satisfaction with the speed of switching. Users tend to prefer swift automated controls when experiencing visual discomfort to promptly restore comfort levels. However, it is important to highlight that this study specifically focused on the transition rate during automated glazing operations. In these instances, the control of glazings to mitigate glare risk typically aims to anticipate discomfort [50], posing more challenges in terms of acceptance.

Secondly, participants were positioned very close to the glazing and in a space with a large window-to-wall ratio. Therefore, the impact of the glazing transition rate could be larger than in real office environments, where users may be sitting further from the façade and exposed to a stronger artificially lit environment. It is also expected that the impact of the glazing transition rate can vary depending on the outside luminous conditions, so further assessments with larger daylight variance are recommended to expand the results beyond the overcast sky conditions.

Thirdly, this study tested only two transition rates, both of which were perceptible to the occupants, as indicated by the FAUs. Further research on longer, potentially imperceptible transition times may be valuable, especially since longer transitions can be implemented without compromising building energy performance. This experiment focused on very fast transition times (1 second and 10 s), reflecting the capabilities of current glazing technologies and typical real-world applications. However, the ability to operate these technologies at such rapid rates raises an important question: what is the optimal balance between the shortest and most effective transition time to maintain both energy efficiency and occupant acceptance of the automated control action.

Finally, for evaluating the impact of additional factors on user response to changes in dynamic glazings, a larger group of people would have been required. The sample size was chosen on the basis of the main experimental scenarios, but aggregating additional variables e.g. likelihood of overriding behaviour and other personal attitudes, would require a larger sample size."

CRediT authorship contribution statement

P. de la Barra: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **A. Luna-Navarro:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **E. Brembilla:** Writing – review & editing, Methodology, Investigation, Conceptualization. **M. Allen:** Writing – review & editing, Validation, Conceptualization. **U. Knaack:** Writing – review & editing, Supervision, Funding acquisition. **M. Overend:** Writing – review & editing, Validation, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported. The authors are not part of the Editorial board of the journal and they are not involved in any decision regarding the publication of this manuscript.

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Appendix 1. Questionnaires

Table 7
Questionnaire Sent via Email for Recruitment Purposes. The questionnaire was designed to gather demographic information about participants, assess their familiarity with smart facade technologies, and record their self-reported frequency of interaction with facade devices. Upon completion, participants were assigned a random ID number, which was used to anonymize their data during the experiment.

Question	Alternative / answer
Please indicate your age:	[]
Please select your gender:	Male / Female / Other
Please select your highest level of education from the list below:	- Primary or secondary school - Completed Bachelor - Completed Master - Doctorate - Professional education
From which country are you from?	[]
How familiar are you with smart windows? For example: smart switchable glazings	1= "Not familiar at all" 2 = "Slightly familiar" 3 = "Moderately familiar" 4 = "Familiar" 5 = "Very familiar"
How familiar are you with smart blinds or shadings? For example: automated roller blinds	1 = "Not familiar at all" 2 = "Slightly familiar" 3 = "Moderately familiar" 4 = "Familiar" 5 = "Very familiar"
How important is for you to have control of the window (blinds and shadings) at home?	1 = "Not important at all" 2 = "Slightly not important" 3 = "Neither important or not important" 4 = "Slightly important" 5 = "Very important"
How important is for you to have control of the window (blinds and shadings) at the office?	1 = "Not important at all" 2 = "Slightly not important" 3 = "Neither important or not important" 4 = "Slightly important" 5 = "Very important"
How important is for you to have control of the window (opening or closing) at home?	1 = "Not important at all" 2 = "Slightly not important" 3 = "Neither important or not important" 4 = "Slightly important" 5 = "Very important"
How important is for you to have control of the window (opening or closing) at the office?	1 = "Not important at all" 2 = "Slightly not important" 3 = "Neither important or not important" 4 = "Slightly important" 5 = "Very important"
How often do you usually open or close the window at home or at your usual office space?	1 = "Never" 2 = "Rarely" 3 = "Occasionally" 4 = "Frequently" 5 = "More than once a day"
How often do you usually interact with shadings or blinds at home or at your usual office space?	1 = "Never" 2 = "Rarely" 3 = "Occasionally" 4 = "Frequently" 5 = "More than once a day"
Random ID generation	[]

Table 8
Kick-off questionnaire. Starting with a briefing on the existing systems and their functionalities, participants were guided through signing the informed consent form. Subsequently, they were asked to complete a questionnaire assessing their familiarity with the laboratory environment in which the experiment was conducted.

Question	Alternative / answer
If you have an ID code, please type it down:	[]
To what extent, do you agree to these statements:	
" I like this office space" "I find the thermal environment in the office satisfactory" "I find the daylight in the office satisfactory"	1 = Strongly disagree 2 = Somewhat disagree 3 = Neither agree nor disagree 4 = Somewhat agree 5 = Strongly agree
Do you feel glare? i.e. feeling of excessive brightness	Yes No

(*continued on next page*)

Table 8 (*continued*)

Question	Alternative / answer
To what extent, do you agree to these statements:	
"I am satisfied with the outdoor view from my desk"	1 = Strongly disagree
"I find the control of the window in the office satisfactory"	2 = Somewhat disagree
"I find the control of the indoor temperature satisfactory"	3 = Neither agree nor disagree
"I find the acoustic environment in the office satisfactory"	4 = Somewhat agree
"I find the indoor air quality in the office satisfactory"	5 = Strongly agree
"I feel calm"	
"I feel well rested"	
" I feel familiar with this office space"	
Do you have any visual impairment?	Yes - Please describe which No
Would you like to give any additional feedback? If yes, please feel free to comment below	[]

Table 9

After each automated scenario, participants completed a brief 1–2-minute questionnaire. The aim was to gauge their perception of the automated control scenarios, their level of distraction, satisfaction, annoyance, and to understand any reasons behind overriding actions taken, if applicable.

Question	Alternative / answer
In the past 10 min, did you notice any change in the state of the window, the lights, or the heating?	Yes - Please describe which of these changed No
To what extent do you agree to these sentences:	
"In the past 10 min, I did not feel distracted from the reading task"	1 = Strongly disagree
"In the past 10 min, I felt satisfied with the visual environment"	2 = Somewhat disagree
"In the past 10 min, I was not annoyed with the automated control of the windows, the lights, and the heating"	3 = Neither agree nor disagree
"In the past 10 min, I felt satisfied with the automated control of the window, the lights, and the heating"	4 = Somewhat agree
	5 = Strongly agree
If you have overridden the automated control of the window, lights, or heating, why did you do so?	[]

Data availability

Data will be made available on request.

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