Energy & Buildings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Virtual reality as a tool for evaluating user acceptance of view clarity through ETFE double-skin façades

Jan-F. Flor [a,*], Marina Aburas [a,b], Fedaa Abd-AlHamid [a,c], Yupeng Wu [a,*]

[a] Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom
[b] School of Architecture and Built Environment, University of Adelaide, Adelaide, South Australia 5005, Australia
[c] Department of Architecture, Faculty of Architecture and Design, Al-Zaytoonah University of Jordan, Amman, Jordan

ARTICLE INFO

Article history:
Received 6 September 2020
Revised 4 October 2020
Accepted 10 October 2020
Available online xxxx

Keywords:
View perception
Virtual reality
ETFE
Double-skin Façades

ABSTRACT

Equipping building envelopes with an additional layer is an effective measure for improving the overall thermal and daylighting performance and reducing the energy consumption of buildings. This study investigated the user acceptance of energy-saving retrofitting measures in office buildings, reporting on the view perception and emotional response towards ETFE double-skin façades (DSF). Virtual Reality (VR) and physics-based imaging techniques were used to evaluate the user experience of a window view in an office space equipped with a pneumatic ETFE cushion as a second building skin. Three DSF scenarios with different ETFE cushions, including a clear, fritted and switchable sample, were evaluated and compared to the original single-skin façade with double-glazed windows. The physical and luminous conditions of the office space were replicated in a virtual environment with a validated physically-based imaging technique and presented to a group of volunteers (N = 22) using a virtual reality headset. While immersed in the virtual environment, participants responded to a questionnaire enquiring into their view perception and emotional states. The results revealed a preference for view clarity of clear ETFE in double-skin façades (M_{dn} = 5) and less satisfaction for fritted (M_{dn} = 4) and switchable foil cushions (M_{dn} = 1.75), yet double glazing was preferred in all measured parameters (M_{dn} = 6). Statistical significance was found for fritted in comparison to switchable ETFE in terms of spatial pleasure and control. The highest ratings were given to clear glazing across all investigated parameters of view perception and emotional response. The lowest ranking in all questions was given to the sample with the switchable ETFE cushion. The study concluded that view clarity is a major aspect for the user acceptance of ETFE double-skin façades. Overall, this study provides a better understanding of the visual and emotional implications of viewing through ETFE foil and contributes to forming criteria for the design of next-generation ETFE building envelopes.

1. Introduction and background

Buildings currently consume over 40% of primary energy in developed countries and contribute significantly to the global greenhouse gas emissions responsible for climate change. According to the World Energy Outlook 2019 by the International Energy Agency, buildings account for one-quarter of the total CO_2 emissions and consume one half of the globally consumed electric energy [1]. While the goal of the Paris agreement is to limit global temperature rise below an average of 1.5–2 °C [2], the latest International Energy Outlook by the U.S. Energy Information Administration shows that energy consumption in the building sector is rising by a rate of 1.3% per year [3], a trend moving in the opposite direction to what is needed to reach global climate goals. Building energy consumption in developing countries is projected to grow even faster, with 2% annual increase due to economic growth and changing lifestyles. To close the gap between climate goal projections and realities of the built environment, building adaptation and retrofitting measures are necessary to address the twofold challenge of reducing CO_2 emission and responding to extreme weather in a changing climate [4,5]. Building concepts and standards such as the Passive House, nearly Zero Energy Building (nZEB) and Plus Energy Building (PEB) [6–9] target the building envelope as a crucial element to improve indoor comfort conditions and save or even generate energy at the same time [10]. A technical solution to achieve this objective is equipping buildings with climate adaptive and energy-saving building envelopes,

* Corresponding authors.
E-mail addresses: janflor@gmx.de (J.-F. Flor), yupeng.wu@nottingham.ac.uk (Y. Wu).

https://doi.org/10.1016/j.enbuild.2020.110554
0378-7788/

Please cite this article as: Jan-F. Flor, M. Aburas, F. Abd-AlHamid et al., Virtual reality as a tool for evaluating user acceptance of view clarity through ETFE double-skin façades, Energy & Buildings, https://doi.org/10.1016/j.enbuild.2020.110554

implementing switchable building components, with inbuilt, reversible mechanisms which change the physical properties by mechanical, chemical or electrical means [11]. When applied to the building façade and roof or assembling the entire building envelope, their capacity to adapt to climate and moderate daylighting and heat flux of buildings is fully enhanced [12]. Typical examples are phase change insulation materials, automated windows and façade shadings and electro- or photo-chromic window glazings. Previous studies suggest that integrating such elements into double-skin building façades may reduce heating and cooling loads and improve the indoor lighting conditions [13].

Lightweight constructions using tensioned fabrics and flexible foil materials offer various opportunities for the integration of climate-adaptive mechanisms and energy-saving measures in building envelopes and façades. A theoretic study calculated the energy consumption for a building with a transformable membrane double-skin façade in comparison to a standard glass façade finding an overall reduction in energy consumption between 7% and 18% across different climates [14], while another project related report predicted a 55% reduction of CO_2 emissions for a building with a switchable ETFE double-skin façade [15]. ETFE foil, a transparent, light and resistant material has been used increasingly over the past decade as a cladding material in building envelopes [16,17], either as a single-, double- or triple-layer construction [18,19]. Inflated with air, ETFE foil cushions provide structural integrity, excellent thermal and lighting performance and yet are very lightweight [20]. Equipped with reflective printing frits, switchable mechanisms, and integrated photovoltaics, truly adaptive building envelopes can be achieved [21,22], suitable for application in double-skin façades and retrofitting of outdated buildings to enhance energy performance with an additional functional layer in the building envelope [23,24]. Fig. 1 illustrates a before-and-after situation of a building where an additional layer of ETFE cushions has been applied to the façade as a retrofitting measure to increase the thermal resistance of the building envelope.

While the structural, energy and lighting performance of such advanced building envelopes is currently extensively investigated [25], the user acceptance relating to the view perception and emotional response has not received the same attention. However, the human factor is of crucial importance for the success of the implementation of such systems on a larger scale. In building practice, potential issues regarding view clarity and haze have been highlighted by designers and manufacturers. A post-occupancy study conducted in an office building in Barcelona, where adaptive ETFE foil cushions had been implemented in the façade, investigated the user satisfaction in relation to thermal comfort and natural lighting under summer and winter conditions [15]. The results of this study suggested that even though user satisfaction for the thermal and lightings conditions varied widely without a clear identifiable trend, a general issue with perceived glare and lack of natural lighting was persistent: Glare was reported by 25% of the participants during winter and 45% during summer, while 20% noted a lack of natural lighting during summer and 15% during winter. The cause of this contrary perception of lighting conditions was identified to be related to the different location of each participant within the building as well as to the slow response of the switching mechanisms of the ETFE façade to the changing solar radiation. Further limitations of the study resume to the uncontrolled survey conditions and a relatively small number of participants, of which, all were located in different spaces, and consequently reporting on different comfort and lighting conditions. View perception through the ETFE façade was not investigated at all. In general, there has been little discussion in previous studies regarding the view qualities of ETFE, mainly due to the fact that this material has been implemented in only a small number of building façades (Example projects: Beijing National Aquatics Center, PTW Architects CSCEC, CCDI and Arup, Beijing, 2007; Unilever-Haus, Behnisch Architekten, Hamburg, 2009; Media-TIC building, Architect Enric Ruiz Geli and Cloud 9 Barcelona, 2010). In consequence, exposure of the general public to such building technologies is limited and factual user experience has only been reported in one case to date. Considering this lack of knowledge together with the potential for energy savings and the benefits on health and productivity in office spaces that could be enhanced with climate-adaptive building envelopes [26–32] justifies an investigation to be carried out, to outline the limitations and challenges before implementation on a larger scale.

Conducting representative view experiments in a realistic setting to determine the ideal material for a façade project with specific requirements for natural daylighting and view clarity is difficult. Changing lighting conditions in realistic settings and the cost of fitting out a mock-up with interchangeable glazing materials represents a real challenge to repeatability and predictability of performance. Conventional glazing materials such as glass are well investigated, and view perception is assumed to be a common experience of daily life. However, the same assumption cannot be made for novel building materials such as ETFE. Especially when combined in multilayered façade assemblies with other glazing materials, view and lighting performance might have unexpected effects on space illumination and emotional response of the users. Therefore, the present study aims to investigate the user acceptance of a variety of ETFE foil façade constructions in terms of view perception and the associated emotional states with the objective to deepen the understanding of design parameters for future appli-

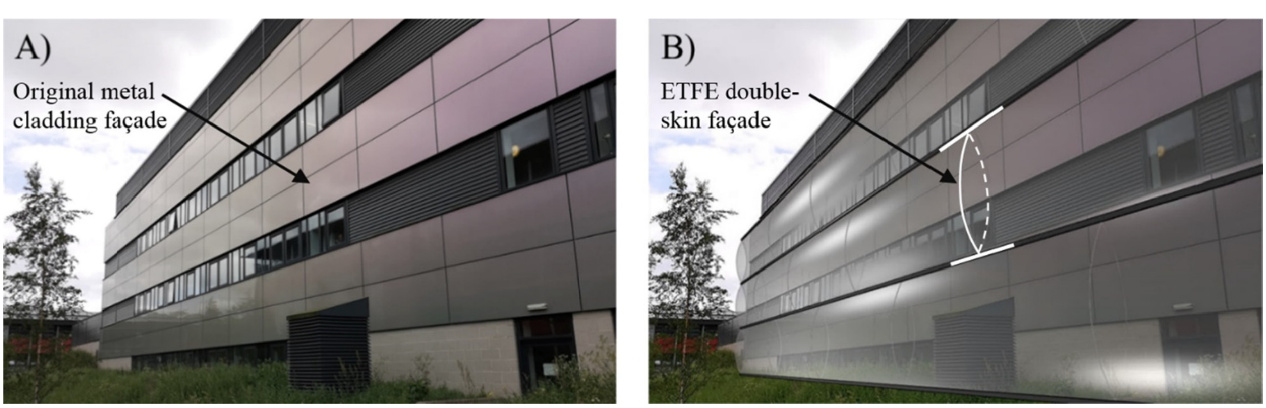

Fig. 1. Energy Technology Building at The University of Nottingham Jubilee Campus. Image A) original building with single-skin façade. Image B) artistic rendering showing the same building with an applied ETFE double-skin façade.

cations in building envelopes. Immersive virtual reality tools are used in this study as a novel methodical approach to evaluating the different ETFE foil constructions to complement the difficulty of obtaining feedback from participants under similar experimental conditions (luminous) through a validated approach [33,34]. Using virtual environments for visualisation of products and designs has been a reality for nearly fifty years now, with well-established technologies and procedures allowing the creation of virtual scenarios in which users perceive and behave as in reality [35,36]. In the automotive-, aeronautical-, medical-, and recently as well in the building-industry, immersive environments are a practical tool for design reviews before prototyping and production [37–39]. One potential benefit of virtually simulating complex façade and glazing systems, such as ETFE foil cushions, might be the reduction of overall project costs due to savings for physical prototyping [40]. Facilitating pre-build testing of innovative building solutions with virtual mock-ups might also allow for more flexibility and risk-taking within the design process, leading to higher productivity, enhanced user experience and ultimately better building performance [41]. It is hoped that the outcomes of this study inform future developments of ETFE foil constructions and trigger further improvements of the view characteristics for the implementation in building envelopes.

The contents of this paper are organised into four parts. The first part deals with the method and explains in detail the procedure of generating the virtual reality environments of the different ETFE façade systems. The second part outlines the experimental design and provides details on the sample population and testing conditions. Part three analyses the results of interviews and part four summaries the findings and concludes with a series of recommendations for future research and design developments of ETFE double-skin façades.

2. Experimental methodology

The use of virtual reality as a tool for assessing the luminous environment perception in architectural spaces is a relatively new methodological approach [42]. Commonly, physical material samples and mock-up rooms have been used to investigate the human response to novel glazing developments [43]. The method described in this study, using a virtual environment instead, is based on a previously developed method which was validated against a real environment using subjective and objective responses [34]. In this study, participants' subjective responses were collected using a verbal questionnaire to evaluate different aspects of view perception through a window in an office space with an array of different ETFE foil assemblies as seen in the virtual environment. The experimental design, facilities, equipment, and imaging technique used for this study are described in the following subsections.

2.1. Test facility and material samples

The room used in this study to assess the impact of the different ETFE foils on view perception is an office room within a three-story building located at the Jubilee Campus of The University of Nottingham, Nottingham, UK at a latitude of 52° on the northern hemisphere. The office, with three workstations, has a floor area of approximately 15 m^2, with two northward facing windows of standard double glazing. The north-facing façade has a metal cladded façade which is earth walled and greened up to the windowsill of the ground floor. In addition, the selected view which can be accessed through the window, is a neutral view with desirable features including buildings, landscaping features, trees and grass which would be considered by the green building practice guide BREEAM to be an adequate view [44]. The dimensions and spatial configuration of the room are shown in the drawings of Fig. 2.

During the experiment, four scenarios with three ETFE cushions with different material combinations plus one neutral reference without any additional ETFE layer were viewed and assessed by the participants. The reference scenario coded REF was the view through the unmodified as-built clear double pane glass window. All ETFE samples measured 1000 mm by 1000 mm with a rise of 100 mm of the main section curvature on each side of the centre plane. All samples were composed of extruded ETFE foil with a thickness of 200 μm. The cushion edges were clamped into an extruded aluminium profile and mounted on a structural wooden frame to support the cushion and withstand tension forces. The whole unit measured 1200 × 1200 mm. The cushions were air-inflated, with a nominal pressure of 300 Pa during the time the images were taken. An overview of the ETFE cushion unit, including an assembly plan showing the different components of the structure, is depicted in Fig. 3.

Sample 1, named DSF 1, was the view sample of the combined double-skin façade of the double-glazed window with the externally added inflated ETFE cushion with two layers of clear ETFE foil. Sample 2, named DSF 2, was the view sample of the combined double-skin façade of the double-glazed window with the externally added inflated ETFE cushion with two layers of clear ETFE foil. The external layer of sample DSF 2 was printed with a hexagon pattern of approximately 71% surface cover in standard silver ink with a print density of 28%. Sample 3, named DSF 3, was the view sample of the combined double-skin façade of the double-glazed window with the externally added switchable ETFE cushion in open mode. A summary of the detailed sample specifications is listed in Table 1, and a close-up view through each of the samples is shown in Fig. 4. The switchable ETFE cushion is composed of three layers, one clear and two with a square pattern of approximately 74% surface cover in standard silver ink with a print density of 28%. The printed layers are shifted in a way that the printed areas of one layer overlap with the clear areas of the other. This makes it possible to modify the light transmittance of the cushion, by controlling the air inflow into the cushion and moving the middle layer back and forth, switching from open to closed mode. However, during the experiment, the sample was only viewed in the open, transparent mode. In Fig. 5 the switching mechanisms is visualized with a diagrammatic representation of the ETFE double-skin façade in open (A) and closed mode (B).

2.2. Equipment

For the generation of the virtual environment and the experimental phase, specialised technical equipment was used. The essential instruments used in this study are described in the following section. For the image generation of the virtual environment, a Hagner S3 photometer was used to measure the luminance, and a Canon EOS 5D camera equipped with a fish-eye lens (Sigma 4.5 mm f/3.5 EX DG) and mounted on a rotating tripod. For the generation of the virtual environment, a HTC Vive virtual reality headset [45] with a computer with two 2.40 GHz processors and NVIDIA GeForce GTX 1060 graphics card were used along with Whirligig software, which supports the display of stereoscopic images, to display the immersive 360° images. The VR HTC Vive has a dual AMOLED 3.6″ diagonal screen with a resolution of 1080 × 1200 pixels per eye and has a refresh rate of 90 Hz and a 110° nominal field of view. The headset includes a gyroscope and proximity sensor to determine the location in space and update the projected images accordingly. During the experimental phase, a digital handheld voice recorder was used to record the answers given by the participant during the questionnaire. Additionally, a

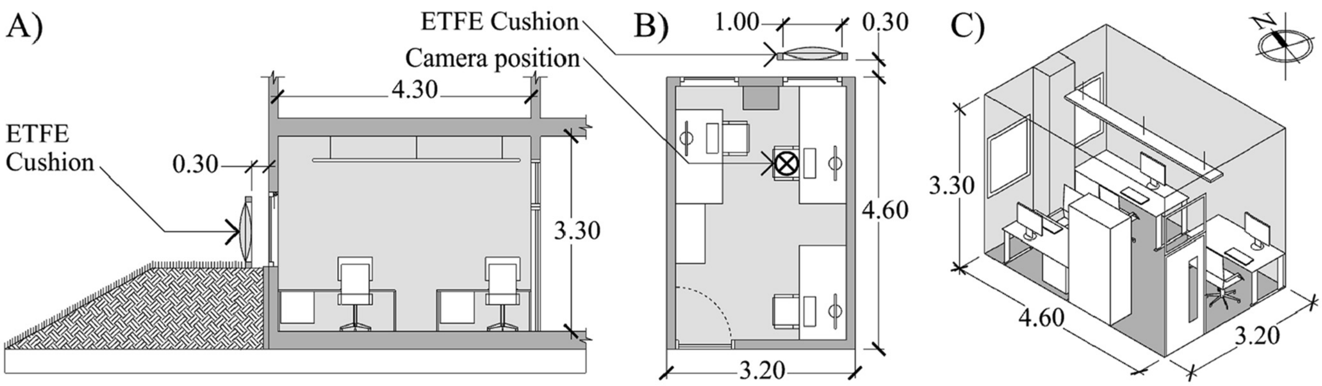

Fig. 2. Dimension and spatial configuration of the test room, showing in A) a transversal section, in B) a plan view, and in C) an isometric view.

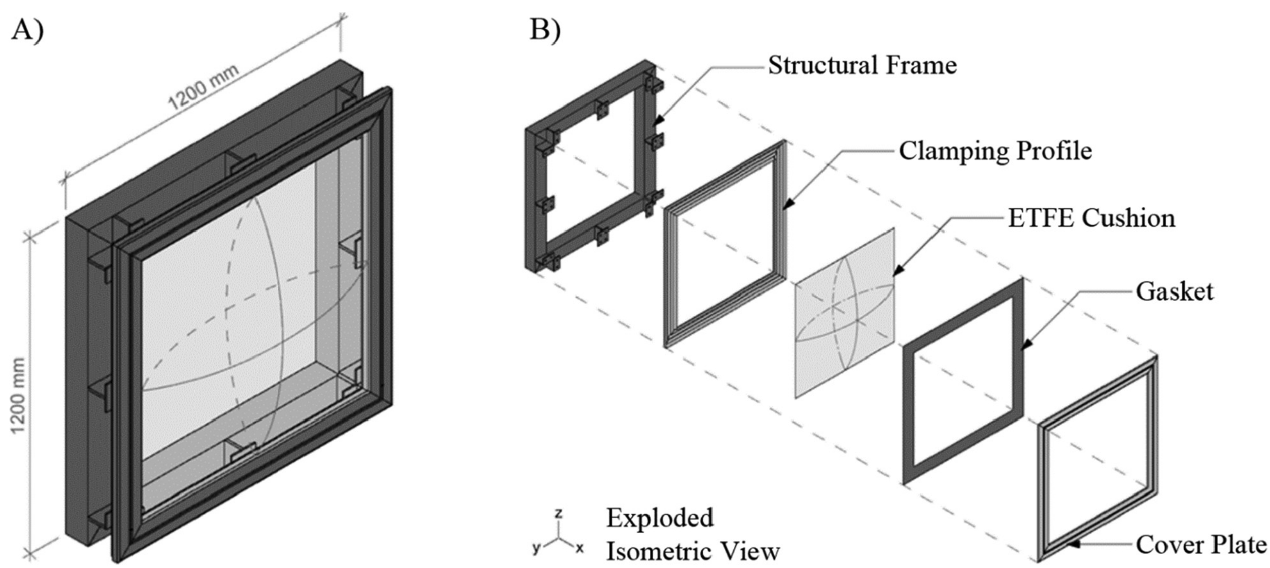

Fig. 3. Isometric view of the test frame and ETFE cushion (A). Exploded view of the test frame showing main system components (B).

Table 1
Material description and layer composition of ETFE double-skin façades used in the experiment.

ID	Description	Configuration
REF	Double Glazing (DG)	14 mm Double Glazed Window
DSF 1	DG + Clear ETFE Cushion	14 mm Double Glazed Window/300 mm Air Gap/ 250 μm clear ETFE foil/200 mm Air Gap/250 μm clear ETFE foil
DSF 2	DG + Fritted ETFE Cushion	14 mm Double Glazed Window/300 mm Air Gap/ 250 μm clear ETFE foil/200 mm Air Gap/250 μm silver fritted (71%) ETFE foil
DSF 3	DG + Switchable ETFE Cushion	14 mm Double Glazed Window/300 mm Air Gap/ 250 μm clear ETFE foil/200 mm Air Gap/250 μm silver fritted (74%) ETFE foil/250 μm silver fritted (74%) ETFE foil

digital timer was used to control the view time in the virtual environment and the time reserved for applying the questionnaire.

2.3. Generation of the physically based virtual environment

To recreate the view experience of a double-skin building façade in a virtual environment, a physically-based 360° virtual environment that replicates the physical and luminous conditions of the actual office was generated to represent the four scenarios following a validated methodology [34]. To create the physical test scene, the mock-up of the ETFE façade unit , shown in Fig. 3, was installed with 0.3 m distance from the building façade, as can be seen in Fig. 5 A). The mock-up frame developed during a previous stage [46], allowed the installation and exchange of the inflatable ETFE foil cushions with different print designs and layer configurations specified in section 2.1. The upper part of the window was blocked internally with matt white paper and a solar lamella shading screen in order to only observe the view through the double-skin façade. Additionally, the second window in the room was entirely covered with a lamella screen to avoid any possibility of accidental reference views to the outside without the ETFE cushion, and to limit the interior luminous conditions to be occurred by the light coming through ETFE cushion. Inside the test room, the camera was mounted on a tripod at 1.65 m from the floor (corresponding to the approximate eye position of the participants in standing position) located 1 m from the window and used to capture high dynamic range images (HDRI) created by combing seven low dynamic range images (LDRI) with different exposure values. The lowest sensitivity (ISO) 100 was used to reduce the noise in the HDRI with fixed white balance (i.e., correct colour temperature (CCT)) to maintain consistent colour space transitions [47]. A white balance of 5500 K was used, which was the CCT in the room measured using the Chroma-meter CL-200 (accuracy ± 0.02%) at the camera position.

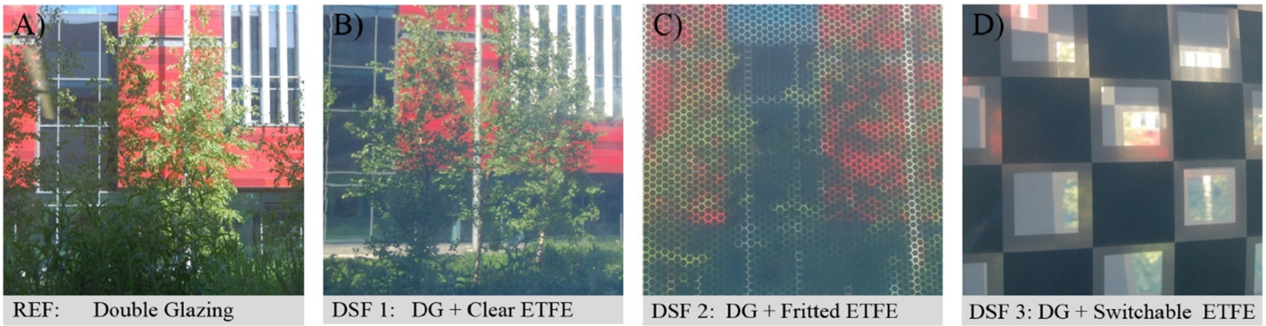

Fig. 4. Views as seen from the window, A) REF Double Glazing, B) DSF 1, Double Glazing + Clear ETFE, C) DSF 2, Double Glazing + Fritted ETFE, D) DSF 3, Double Glazing + Switchable ETFE.

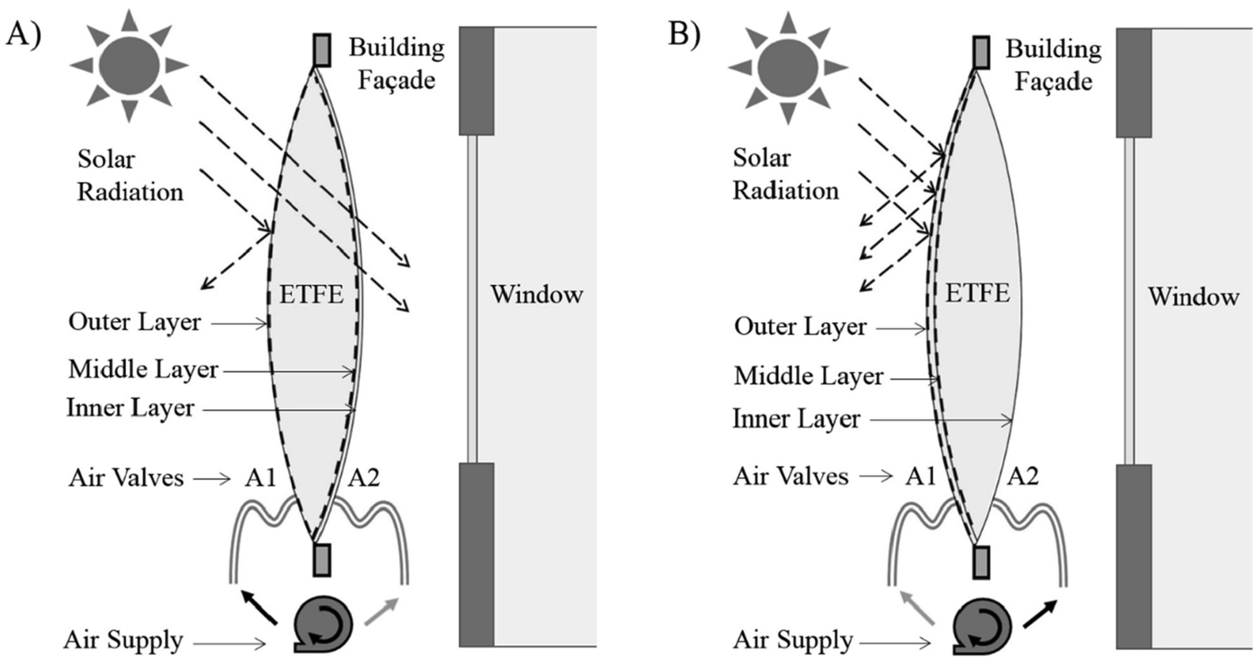

Fig. 5. Visualization of the switching mechanisms showing the ETFE double-skin façade in open (A) and closed mode (B).

The images were taken on a summer day in June during a time period of 1 h and 40 min from 11:50 AM to 13:30 PM under sunny and clear sky conditions to reduce changes in illuminance conditions. The average horizontal illuminance measured at 0.8 m from the floor was 200 l×. The camera was rotated in 360° around the room, and six 180° HDRI images to cover the room were taken for each of the three ETFE samples and the reference sample. The HDRI images were taken aligning the entrance pupil axis to the rotation axis, minimising the differences between the various pictures composing the 360° view [48]. The HDRI images were calibrated with point luminance measurements and were tone-mapped with 2.2 gamma value [49]. The procedure was repeated to take one set for the left and one for the right eye at 65 mm horizontally apart positions to account for the human binocular vision [50]. The pictures in Fig. 6A) and B) illustrates the imaging process of the test scenarios.

The obtained images were then combined using a specialised 'stitching' software to obtain two 360° panoramas of the room in two dimensions (for left and right eye) and were converted to a stereoscopic image to be used in the VR equipment. In the following step, the image was projected onto a three-dimensional sphere with the viewpoint of the user in the centre of the sphere. In the final step, the three-dimensional stereographic image was projected onto the Fresnel lenses equipped imaging screens of the virtual reality headset. The steps of the above-described procedure can be seen in a diagrammatic flowchart in Fig. 7, steps one to four. An impression of one of the researchers wearing the virtual reality headset can be seen in Fig. 8A), a view of the user's perspective on the inner side of the virtual reality headset is shown in Fig. 8B). An example of the stereographic images projected through the lenses of the headset is depicted in Fig. 9.

2.4. Evaluation parameters

The developed questionnaire was based on previous studies relating to lighting, the view clarity index, and emotional responses on a view [51–53]. The questionnaire is composed of rating scales developed around view clarity through window shades, based mainly on the work of Kostantzos [54]. With adaptations made to fit the purpose of this study, the questionnaire included responding to visual tasks, recognising and counting elements outside the room, as well as assessing the view appearance and the corresponding emotional state, with the goal to identify the participants' acceptance of the different ETFE samples. The evaluation

Fig. 6. External view of the building façade showing the installed ETFE cushion mock-up with the switchable sample DSF 3 (A). Interior view of the office space showing the camera in the view position for the 360° stereographic imaging (B).

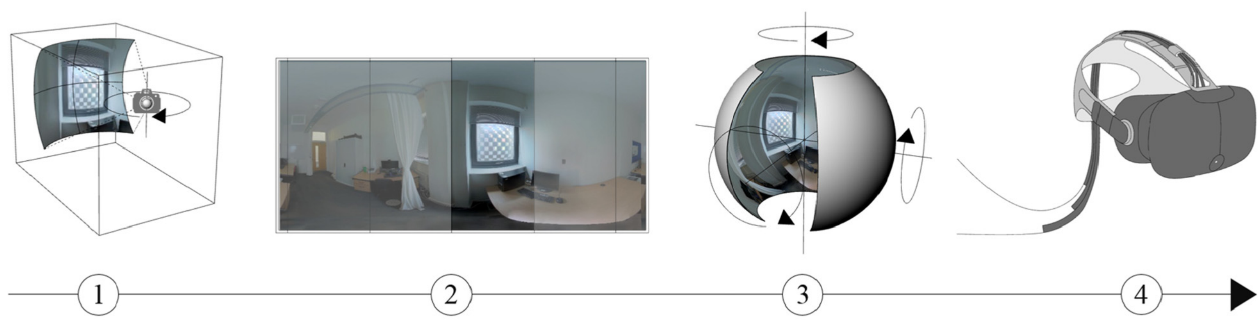

Fig. 7. Process of VR image generation, 1. HDRI photography of test room, 2. Stitching of images, 3. Post-processing and projection of images to spherical geometry, 4. Projection of imagery to VR headset as a stereoscopic environment.

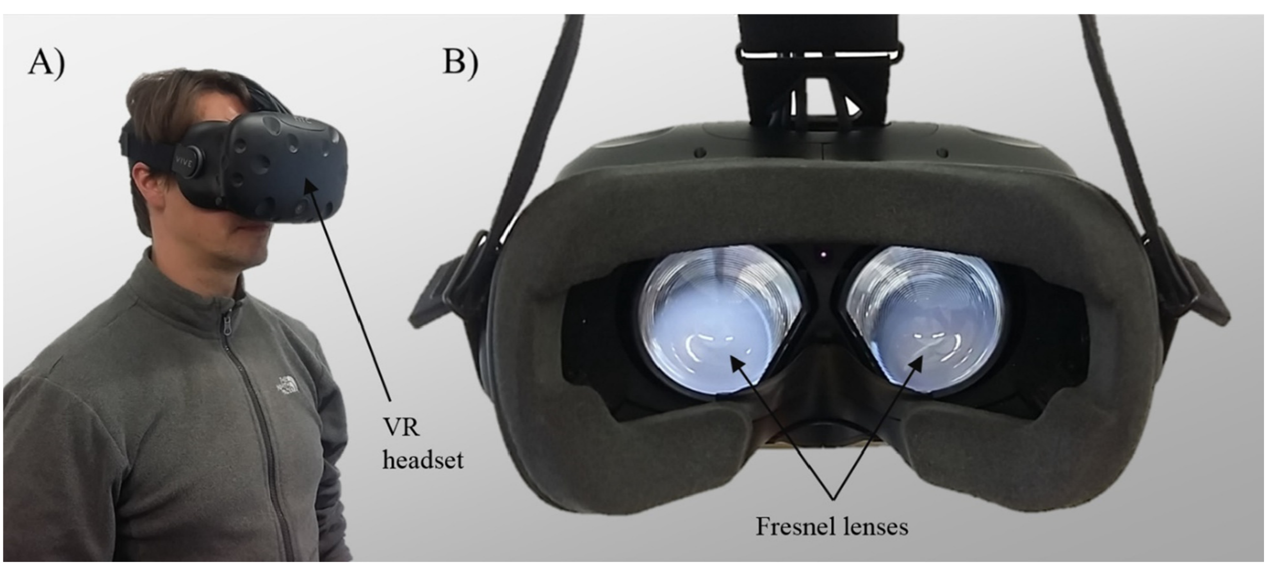

Fig. 8. Researcher equipped with the Virtual Reality (VR) headset as used during the experimental sessions (A). Close-up view of the VR headset from the participant's perspective, showing the two Fresnel lenses through which, the stereoscopic image of the room is projected (B).

included parameters such as view clarity, amount of view, view appearance and emotional states of pleasure, arousal and dominance. The parameters were assessed with questions derived from previous research studies [26,28,30,42,51,52,55,56]. All questions were measured on a continuous scale ranging from, "Not at all" (=0) to "Very much" (=7). The scale type (continuous) was

Fig. 9. An example of the stereographic images projected through the lenses of the virtual reality headset for the left and right eye.

explained to the participants during the experiment demonstration. The questions were randomised across the three conditions to eliminate any bias in subjective responses [57]. The full catalogue of questions and parameters addressed with the questionnaire is listed in Table 2.

2.5. Experimental procedure

Prior to undertaking the investigation, ethical clearance was obtained from The University of Nottingham Faculty Research Ethics Committee. Participants were recruited via a poster advertisement for the study, followed by invitation through an e-mail request. A total of 22 participants were recruited for this virtual reality experiment, 8 female and 14 male, with a mean age of 29 (SD = 4), from a range of different ethnic backgrounds. None of the participants reported any colour vision problems and participants wore corrective glasses during the experiment. No other eye problems were reported by any other participant.

After confirming their interest and ability to participate, potential participants received an information sheet with an overview of the process. A one-hour time slot was then scheduled for the test, with the agreement of the participant. The experiment took place at the University of Nottingham facilities at the Energy Technology Building, on Jubilee Campus. Following a brief introduction and check on their well-being, participants were asked for their written consent to take part in the study. This included providing basic personal information and checking on VR related simulator sickness symptoms before the test. The immersed virtual environment test took place in a neutral test room, containing all the VR equipment, headset, computer and a desk for the researcher conducting the experiment. The participants were familiarised with the head-mounted VR equipment and given instructions for the VR viewing and questionnaire. Participants were asked to stay during the test within a colour-marked floor of 1 m × 1 m. This zone was covered by the VR spatial location sensors communicating with the VR headset. Within this zone, participants could freely rotate in 360° but would be guided back by the experimenter in case of stepping accidentally out of the zone. After the introduction, the four different test scenarios (REF, DSF 1, DSF 2, and DSF 3) were shown to the participants. The scenarios were assigned in a random order to counterbalance the presentation order effect. Each immersive environment session was timed to not exceed 5 min with a 5 min recovery break between each session. At the beginning of each VR session participants were allowed 2 min to familiarise with and visually adjust to the environment. Participants were then asked questions by the researcher on the view seen within the immersive virtual environment. The questions were read out loud by the researcher from a 10-item questionnaire and were randomised for each condition. The participants' answers were noted down by the researcher on individual questionnaire forms and audio recorded with the consent of the participants for later verification. After completing the virtual reality test followed by a recovery period, participants were assessed again on any motion sickness symptoms through a questionnaire. All test participants volunteered for the experiment without receiving any benefits. Participants signed an informed consent form before and after taking part in this study and were made aware that they could abandon the experiment procedure at any point in time. All collected information was processed and stored according to the standards established by the ethics committee of the University of Nottingham. A summary flowchart of the experimental procedure can be seen in Fig. 10.

3. Results and discussion

The first set of analyses examined the ratings on the different view samples given by the participants during the questionnaire. The response of the participants to the questionnaire was given during the virtual environment experience in which they were immersed, reflecting their real-time response to the perceived visual stimulus. The scores of the 22 participants were analysed in order to determine differences and preferences in the view perception of the 3 ETFE samples (DSF 1, DSF 2, DSF 3) as well as the double-glazed reference sample (REF). The first question at the

Table 2
Evaluated Parameters in the questionnaire.

Parameter	Question	Bipolar description			Reference
Engagement	Which outside objects can you distinguish from the following?	Columns/Trees/W.Shades			[Konstanzos 2017]
View clarity	How clear is your outside view through the glazing?	Not Clear	–	Very Clear	[Konstanzos 2017]
View satisfaction	How satisfied are you with the view from the window?	Dissatisfied	–	Satisfied	[Masoudinej.2009]
View amount	How satisfied are you with the amount of view?	Dissatisfied	–	Satisfied	[Cetegen 2008]
View appearance	How clear is the weather outside?	Hazy	–	Clear	[Bülow-H. 1995]
View perception	How sunny is the weather outdoor?	Grey	–	Sunny	[Bülow-H. 1995]
View vividness	How would you grade the vividness of the outside colours?	Faded	–	Strong	[Konstanzos 2017]
Spatial pleasure	How pleasant do you feel about the space?	Unpleasant	–	Pleasant	[Bakker 2014]
Spatial arousal	How energised or drowsy you feel due to the space?	Drowsy	–	Energized	[Bakker 2014]
Spatial dominance	How controlling versus controlled you feel due to the space?	Submissive	–	Dominant	[Bakker 2014]

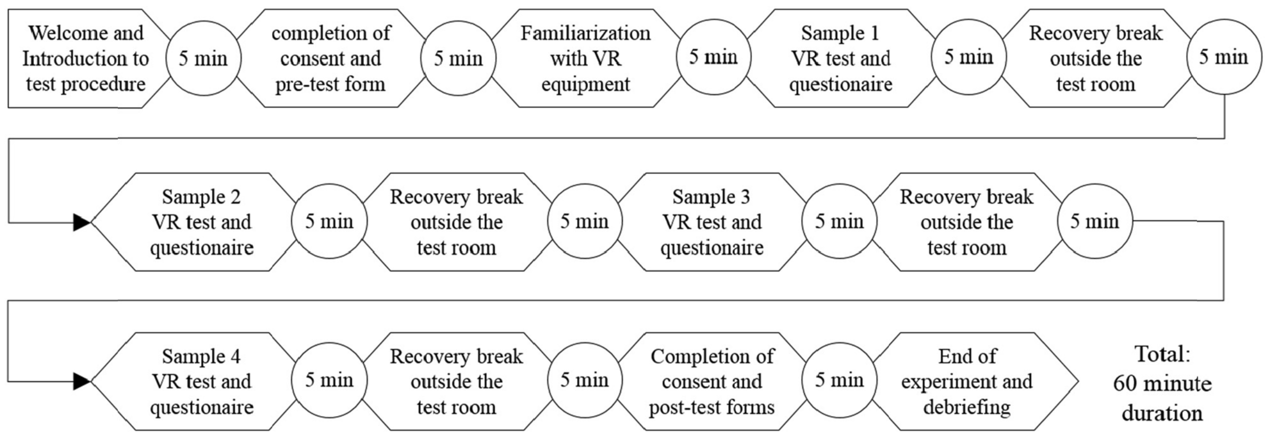

Fig. 10. Flowchart of the experimental procedure.

beginning of each virtual reality session was always "Which outside object can you distinguish from the following?", asking the participants to recognise and count three types of objects (columns, trees, window shades) visible in the outside view. The answers to this question were not included in the analysis of the results, since the question was only intended to make the participants engage with the virtual environment and focus their attention on the window view before initiating the questions which would rate the participants' viewing experience. It was possible for the experimenter to simultaneously observe an on-screen projection of the view the participant was looking at through the virtual reality headset to ensure the participant was viewing the correct virtual ETFE environment. The results demonstrated in the following sections showed across all investigated parameters that the highest ratings were given to the reference sample REF with the clear glazing. The DSF 3 sample with the switchable ETFE cushion was the lowest ranking in all questions.

3.1. Statistical analysis

Data analysis was carried out using SPSS Statistics 26 to analyse the experimental data in this study. To determine whether the mean values were a reliable indicator of the data distribution (i.e., normal distribution), the Shapiro-Wilk test was used as the sample size was less than 50 (N = 22) [57]. Non-parametric tests were used as the normality assumption if the data was violated. Friedman's ANOVA was applied to analyse the differences in the participants' questionnaire responses across the independent variable (DSF conditions) to determine whether there was a significant difference between the four conditions. The statistically significant difference was found for all questions, as can be seen in Table 3 below.

As the assumption of the normal distribution of the data was violated, a non-parametric Wilcoxon Signed-Rank Test was used to further analyse the data and isolate the main effect by performing pairwise comparative tests [57]. The effect size *r* was reported along with statistically significant values to provide a standardised measure of the differences across the conditions to specify the magnitude of the effect of the DSF ETFE conditions [57]. The interpretation of effect sizes was derived from thresholds ranging from small ($0.20 \leq r < 0.50$), to moderate ($0.5 \leq r < 0.80$), to large ($r \geq 0.80$), respectively as recommended by Ferguson [58]. In order to control the experimental-wise error rate, Bonferroni corrections were applied to determine the significance for pairwise comparisons (i.e., a modified Bonferroni-corrected significance level value ($p \leq 0.008$) for six comparative pairs was applied) [57]. Table 4 presents the results of the Wilcoxon Signed-Rank Test and effect sizes. All questions were found to have statistically significant differences between at least two environments for a particular parameter. The parameters of view clarity, satisfaction, amount, appearance, perception and vividness were related to the visual-quality perception of the scene. Other perceptual aspects of the luminous environment included perception and feeling within the space: spatial pleasure, arousal and control.

3.1.1. Visual-quality perception of the scene

The attributes of the visual quality of the scene were collected using a continuous scale, and the statistically significant pairs for the visual-quality perception of the scene are highlighted in Table 4. These results, along with bar chart plots of the results, show participants' tendencies across the ETFE façade types, indicated in Fig. 11. There was always statistical significance found between a double-glazed unit reference REF unit and DSF 3. This implies that there was enough of a difference for participants to visually notice between these two types. The larger effect sizes were found when making a comparison to DSF 3, implying that this condition had the largest influence on the participants' visual perception of the scene in the VR environment.

3.1.2. View clarity

View clarity asked of the participant to rate how clear they felt the view to the outside was through the glazing from *Not clear* (1) to *Very clear* (7). Participants perceived view clarity slightly higher for the double-glazed reference sample REF in comparison to DSF 1 ($p < 0.041, r = 0.31$). View clarity was significantly perceived lower for DSF 2 compared to REF with relative magnitude ($p < 0.000, r = -0.56$). There was also a statistical significance perceived for view clarity between DSF 1 and DSF 3: $\Delta M_{dn} = 3.25$, $p < 0.008$, $r = -0.62$ (moderate effect size), and DSF 2 compared to DSF 3: $\Delta M_{dn} = 2.25$, $p < 0.008$, $r = -0.60$ (moderate effect size), with relative magnitude. In general terms, view clarity of clear ETFE was preferred, followed by fritted, and last, switchable ETFE cushions.

3.1.3. View satisfaction

View satisfaction asked the participant to rank how satisfied they were with the view from the window from *Dissatisfied* (1) to *Satisfied* (7). View satisfaction was perceived with a statistical difference between REF and DSF 2 conditions: $\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.53$ (moderate effect size) as well as DSF 1 varying with statistical significance in comparison to DSF 3: $\Delta M_{dn} = 4$, $p < 0.008$, $r = -0.62$ (moderate effect size). Satisfaction was also significantly noted viewing from DSF 2 in comparison to DSF 3: $\Delta M_{dn} = 3$, $p < 0.08$, $r = -0.61$ (moderate effect size) with relative

Table 3
Friedman test results for all questions.

Question	Condition	Mean Rank	N	χ^2	*p*-value
View clarity	REF	3.52	22	43.87	0.000*
	DSF 1	3.00			
	DSF 2	2.32			
	DSF 3	1.16			
View satisfaction	REF	3.50	22	50.18	0.000*
	DSF 1	3.05			
	DSF 2	2.41			
	DSF 3	1.05			
View amount	REF	3.50		49.96	0.000*
	DSF 1	3.02	22		
	DSF 2	2.45			
	DSF 3	1.05			
View appearance	REF	3.25	22	22.28	0.000*
	DSF 1	2.68			
	DSF 2	2.30			
	DSF 3	1.77			
View perception	REF	3.18	22	27.46	0.000*
	DSF 1	2.91			
	DSF 2	2.20			
	DSF 3	1.70			
View vividness	REF	3.34	22	26.56	0.000*
	DSF 1	2.77			
	DSF 2	2.32			
	DSF 3	1.57			
Spatial pleasure	REF	3.07	22	15.91	0.001*
	DSF 1	2.57			
	DSF 2	2.68			
	DSF 3	1.68			
Spatial arousal	REF	2.93	22	13.57	0.004*
	DSF 1	2.82			
	DSF 2	2.50			
	DSF 3	1.75			
Spatial dominance	REF	3.18	22	17.27	0.001*
	DSF 1	2.48			
	DSF 2	2.57			
	DSF 3	1.77			

p-values: *statistically significant.

magnitude. This indicated that participants view satisfaction levels differed distinctly between REF and DSF 2/DSF 3 and DSF 3 and DSF 1/DSF 2. Overall participants were more satisfied with the view through the clear ETFE, followed by the fritted ETFE. The view through the switchable ETFE was ranked less satisfying than clear and fritted ETFE.

3.1.4. View amount

Participants were asked how satisfied they were with the amount of view from *Dissatisfied* (1) to *Satisfied* (7). A statistical significance was found in the participants' rating of the amount of view between REF and DSF 2 conditions: $\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.50$ (moderate effect size) as well as statistical difference from null hypothesis between REF and DSF 1 conditions, with relative magnitude. View amount was significantly perceived differently for REF compared to DSF 3: $\Delta M_{dn} = 4$, $p < 0.008$, $r = -0.62$ (moderate effect size), DSF 1 and DSF 3: $\Delta M_{dn} = 3.75$, $p < 0.008$, $r = -0.62$ (moderate effect size), and DSF 2 and DSF 3: $\Delta M_{dn} = 3$, $p < 0.008$, $r = -0.62$ (moderate effect size) conditions with relative magnitude. The participants rating is not surprising as the view through the overlapping squared printing pattern of the foil layers of the switchable cushion is limiting the view through the window considerably as can be observed in Fig. 3D). Participants reported much higher scores for REF, DSF 1 and DSF 2 stating a general satisfaction with the view through those conditions, and less satisfaction with the view amount of switchable ETFE cushions.

3.1.5. View appearance

View appearance investigated the clearness of the weather from *Hazy* (1) to *Clear* (7). View appearance was statistically perceived different for DSF 2 compared to REF: $\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.48$ (small effect size), DSF 3 compared to REF: $\Delta M_{dn} = 1.25$, $p < 0.008$, $r = -0.50$ (moderate effect size) as well as DSF 1 compared to DSF 3: $\Delta M_{dn} = 1.25$, $p < 0.008$, $r = -0.41$ (small effect size) conditions with relative magnitude. Unlike the response to questions on view clarity, satisfaction and amount, no significant difference was noted for these elements for DSF 2 compared to DSF 3. Not surprisingly, participants rated the view through the ETFE cushion without any frit prints as the clearest among the ETFE samples.

3.1.6. View perception

View perception asked the participants to determine how sunny the weather was outdoors from *Grey* (1) to *Sunny* (7). View perception was significantly perceived differently between DSF 2 compared to REF: $\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.48$ (small effect size), DSF 3 compared to REF: $\Delta M_{dn} = 1.25$, $p < 0.008$, $r = -0.50$ (moderate effect size) as well as DSF 1 compared to DSF 3: $\Delta M_{dn} = 1.25$, $p < 0.008$, $r = -0.41$ (small effect size) conditions with relative magnitude. Participants perceived the weather to be sunnier when viewed through the clear ETFE, followed by the fritted, and last, the switchable ETFE. It is noted that the highest rating for all ETFE types was found for this question, meaning that regardless of the visibility, participants were still able to perceive with statistical

Table 4
Results of the Wilcoxon Signed-Rank test for responses to questions on view clarity.

Parameter	Conditions (M1 vs. M2)	M_{1dn}	M_{2dn}	*p*-value	Positive	Negative	Ties	Z_{score}	Effect size *r*
View clarity	REF vs. DSF 1	6	5	0.041	5	14	3	−2.048	−0.31*
	REF vs. DSF 2	6	4	0.000*	1	17	4	−3.727	−0.56**
	REF vs. DSF 3	6	1.75	0.000*	1	21	0	−4.069	−0.61**
	DSF 1 vs. DSF 2	5	1.75	0.011	3	14	5	−2.536	−0.38*
	DSF 1 vs. DSF 3	5	1.75	0.000*	1	21	0	−4.091	−0.62**
	DSF 2 vs. DSF 3	4	1.75	0.000*	1	20	1	−3.957	−0.60**
View satisfaction	REF vs. DSF 1	6	6	0.060	4	10	8	1.882	0.28*
	REF vs. DSF 2	6	5	0.000*	0	16	6	−3.532	−0.53**
	REF vs. DSF 3	6	2	0.000*	0	22	0	−4.133	−0.62**
	DSF 1 vs. DSF 2	6	5	0.016	5	13	4	−2.405	−0.36*
	DSF 1 vs. DSF 3	6	2	0.000*	0	22	0	−4.141	−0.62**
	DSF 2 vs. DSF 3	5	2	0.000*	1	21	0	−4.079	−0.61**
View amount	REF vs. DSF 1	6	5.75	0.041	3	10	9	−2.046	−0.31*
	REF vs. DSF 2	6	5	0.001*	2	17	3	−3.287	−0.50**
	REF vs. DSF 3	6	2	0.000*	0	22	0	−4.131	−0.62**
	DSF 1 vs. DSF 2	5.75	5	0.034	5	13	4	−2.122	−0.32*
	DSF 1 vs. DSF 3	5.75	2	0.000*	0	22	0	−4.125	−0.62**
	DSF 2 vs. DSF 3	5	2	0.000*	0	21	1	−4.053	−0.61**
View appearance	REF vs. DSF 1	7	6	0.046	3	10	9	−1.997	−0.30*
	REF vs. DSF 2	7	6	0.001*	1	13	8	−3.197	−0.48*
	REF vs. DSF 3	7	5.75	0.001*	0	14	8	−3.330	−0.50**
	DSF 1 vs. DSF 2	6	6	0.054	3	9	10	−1.925	−0.29*
	DSF 1 vs. DSF 3	6	5.75	0.007*	4	13	5	−2.718	−0.41*
	DSF 2 vs. DSF 3	6	5.75	0.078	2	11	9	−1.761	−0.27*
View perception	REF vs. DSF 1	7	6.75	0.103	3	6	13	−1.630	−0.25*
	REF vs. DSF 2	7	6.25	0.005*	0	10	12	−2.818	−0.42*
	REF vs. DSF 3	7	5.75	0.000*	0	17	5	−3.657	−0.55**
	DSF 1 vs. DSF 2	6.75	6.25	0.011	1	10	11	−2.550	−0.38*
	DSF 1 vs. DSF 3	6.75	5.75	0.002*	2	14	6	−3.100	−0.47*
	DSF 2 vs. DSF 3	6.25	5.75	0.205	4	10	8	−1.266	−0.19*
View vividness	REF vs. DSF 1	6	5.5	0.012	3	13	6	−2.525	−0.38*
	REF vs. DSF 2	6	5	0.002*	2	13	7	−3.035	−0.46*
	REF vs. DSF 3	6	4	0.000*	2	18	2	−3.712	−0.56**
	DSF 1 vs. DSF 2	5.5	5	0.027	5	12	5	−2.210	−0.33*
	DSF 1 vs. DSF 3	5.5	4	0.003*	1	16	5	−2.973	−0.45*
	DSF 2 vs. DSF 3	5	4	0.041	4	14	4	−2.042	−0.31*

p-values: *statistically significant.
Effect size: *** Large; ** Moderate; *Small.

confidence the outside weather condition and judge if it is sunny or not.

3.1.7. View vividness

View vividness asked participants to grade the vividness of the outside colours from *Faded* (1) to *Strong* (7). The overall lowest rating for the questionnaire was scored by sample DSF 3. View perception was significantly perceived differently for DSF 2 compared to REF: $\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.46$ (small effect size), DSF 3 compared to REF: $\Delta M_{dn} = 2$, $p < 0.008$, $r = -0.56$ (moderate effect size) as well as DSF 1 compared to DSF 3: $\Delta M_{dn} = 1.5$, $p < 0.008$, $r = -0.45$ (small effect size) conditions with relative magnitude. The visibility of the different view samples had only a limited influence on the participants' perception of outside environmental conditions, but showing again a clear preference for REF, followed by DSF 1, DSF 2 and the least preferred DSF 3.

3.2. Reported emotional perception of the space

In addition to visual-quality of the scene, emotional response was analysed through the investigation of participants' spatial pleasure, arousal and control within each of the four proposed spaces using a 7-point continuous scale. In the final part of the questionnaire, participants were asked about their emotional state during the view experience within the virtual environment using the dimensions of pleasure, arousal and dominance (PAD), developed by Mehrabian and Russel [55]. Pleasure, arousal and dominance (control) have been inferred as three independent emotional dimensions to describe a person's state of feeling within the space. The statistical results are shown in Table 5.

3.2.1. Spatial pleasure

Spatial pleasure defines a participant's level of pleasure from *Unpleasant* (1) to *Pleasant* (7). Looking at spatial pleasure, it was significantly perceived differently for REF compared to DSF 3: $\Delta M_{dn} = 2$, $p < 0.008$, $r = -0.53$ (small effect size), and DSF 2 compared to DSF 3: $\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.45$ (small effect size). Participants noted expressively less of a difference in their pleasance within the environment than claimed for what they could see outside of the DSF view. There was always statistical significance found between a double-glazed unit reference REF unit and DSF 3. In terms of spatial pleasure, participants reported higher ranking for the clear ETFE, fritted and switchable ETFE, in decreasing order respectively.

3.2.2. Spatial arousal

Spatial arousal defined the state of feeling from *Drowsy* (1) to *Energised* (7). Differences in spatial arousal were only significantly noted between REF and DSF 3: $\Delta M_{dn} = 1.25$, $p < 0.008$, $r = -0.47$ (small effect size) conditions. It should be noted that, though no statistical significance was inferred, there was a large effect size found between the spatial arousal values between REF compared to DSF 1 conditions. This can be understood to mean that, though a large effect can be seen, it is not certain at a 95% confidence level

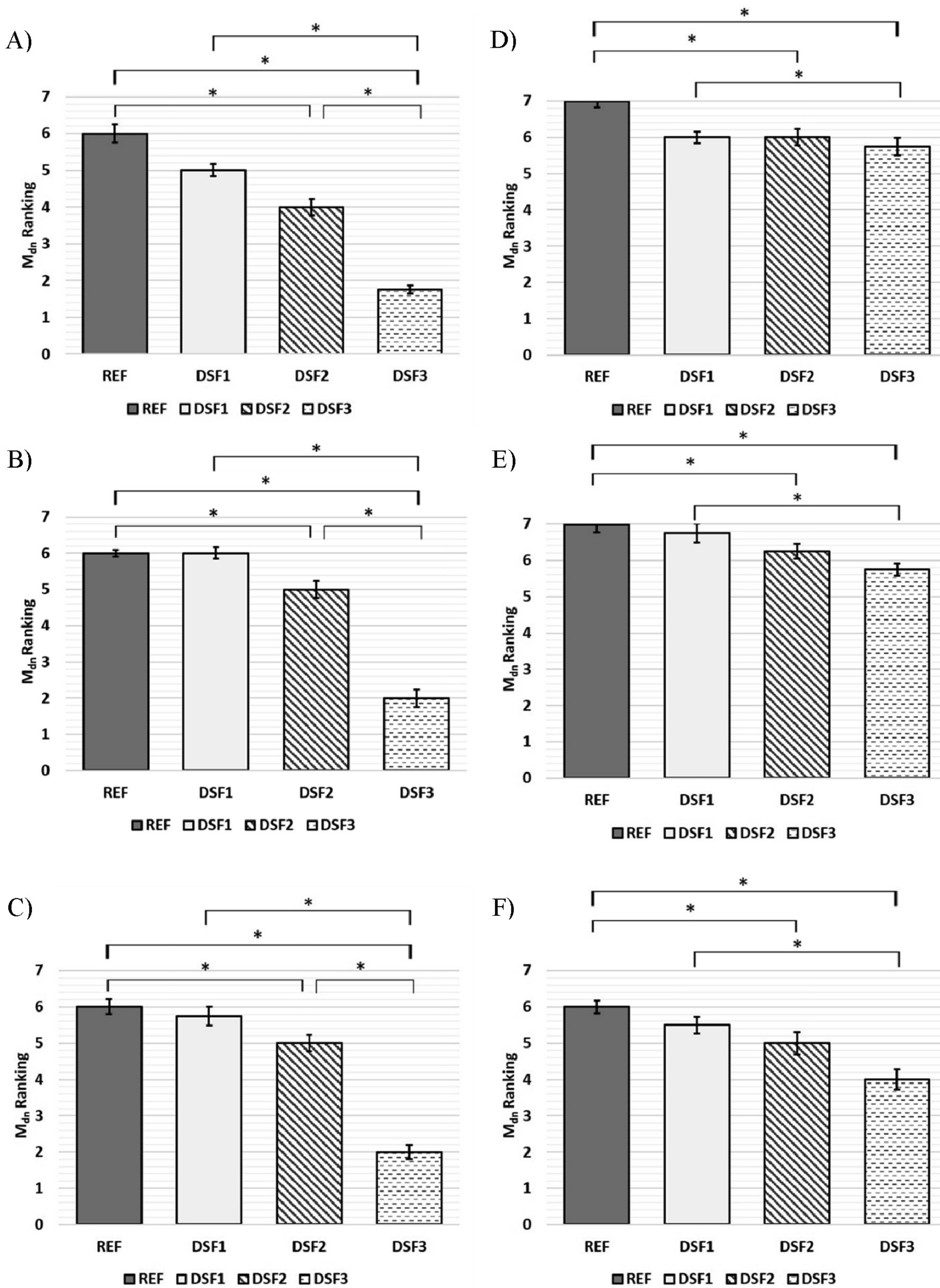

Fig. 11. Results of the responses to questions regarding view (A) clarity, (B) satisfaction, (C) amount, (D) appearance, (E) perception and (F) vividness.

that what is seen is not due to fluctuation as a result of having a smaller sample size. This effect was not noted when comparing any other condition pairs.

As is customary when interpreting PAD data, a plot of pleasure in comparison to arousal can be seen in Fig. 12. When visualised in this manner, the correlation between the variables is made more distinct. Values for DSF 3 stand out to cluster at both low pleasure and arousal levels, DSF 2 had the highest pleasure, and arousal levels whilst REF and DSF 1 ETFE façades showed a large amount of overlap in participant rankings.

3.2.3. Spatial dominance

Spatial dominance was related to feelings of control and extent to which participants felt restricted in their spatial behaviour from

Table 5
Results of the Wilcoxon Signed-Rank test for responses to questions on emotional perception of the space.

Parameter	Conditions (M1 vs M2)	M_{1dn}	M_{2dn}	*p*-value	Positive	Negative	Ties	Z_{score}	Effect size *r*
Spatial pleasure	REF vs. DSF 1	6	5	0.059	4	12	6	−1.886	−0.28*
	REF vs. DSF 2	6	5	0.040	6	10	6	−2.049	−0.31*
	REF vs. DSF 3	6	4	0.000*	3	16	3	−3.527	−0.53*
	DSF 1 vs. DSF 2	5	5	0.655	8	8	6	−0.446	−0.07
	DSF 1 vs. DSF 3	5	4	0.029	5	16	1	−2.179	−0.33*
	DSF 2 vs. DSF 3	5	4	0.003*	2	14	6	−2.982	−0.45*
Spatial arousal	REF vs. DSF 1	5.25	5	0.671	6	7	9	−4.240	−0.64**
	REF vs. DSF 2	5.25	5	0.030	4	10	8	−2.170	−0.33*
	REF vs. DSF 3	5.25	4	0.002*	3	15	4	−3.100	−0.47*
	DSF 1 vs. DSF 2	5	5	0.095	4	9	9	−1.667	−0.25*
	DSF 1 vs. DSF 3	5	4	0.012	6	16	0	−2.523	−0.38*
	DSF 2 vs. DSF 3	5	4	0.016	4	15	3	−2.406	−0.36*
Spatial dominance	REF vs. DSF 1	5.25	5	0.173	4	10	8	−1.363	−0.21*
	REF vs. DSF 2	5.25	5	0.055	3	10	9	−1.921	−0.29*
	REF vs. DSF 3	5.25	4.25	0.000*	1	18	3	−3.549	−0.54*
	DSF 1 vs. DSF 2	5	5	0.973	7	5	10	−0.160	−0.02
	DSF 1 vs. DSF 3	5	4.25	0.030	6	13	3	−2.171	−0.33*
	DSF 2 vs. DSF 3	5	4.25	0.008*	3	11	8	−2.663	−0.40*

p-values: *statistically significant.
Effect size: *** Large; ** Moderate; *Small.

Submissive (1) to *Dominant* (7). Spatial control was significantly perceived lower for REF compared to DSF 3: $\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.54$ (small effect size), and DSF 2 compared to DSF 3: $\Delta M_{dn} = 0.75$, $p < 0.008$, $r = -0.40$ (small effect size) conditions with relative magnitude. As per spatial pleasure, participants noted expressively less of a difference in their control within the environment than claimed for what they could see outside of the DSF view and there was always statistical significance found between a double-glazed unit reference REF unit and DSF 3.

3.3. Summary

From the findings for this research, the design of ETFE projects based on users' perceptive feedback can simultaneously lead to higher performing infrastructure design and end-user satisfaction. The main findings to emerge from this study summarise as follows:

- The highest ratings were given to the reference sample REF with the clear glazing across all investigated parameters of view perception and emotional response. The lowest ranking in all questions was given to the DSF 3 sample with the switchable ETFE cushion.
- Statistical significance was found for DSF 2 in comparison to DSF 3 in terms of spatial pleasure ($\Delta M_{dn} = 1$, $p < 0.008$, $r = -0.45$) and control ($\Delta M_{dn} = 0.75$, $p < 0.008$, $r = -0.40$).
- DSF 1 and DSF 2 were rated similarly in terms of both sets of questionnaire responses, with no statistical significance found between them regarding view clarity, satisfaction, amount, appearance, perception or vividness.

Though applying ETFE as a building material in building façades is a relatively new development, parallels to the findings of this study can be found in previous investigations on more traditional window control systems. A study on window blinds, which also create a patterned obstruction through a view, reported 60–70% of respondents suggested keeping blinds open as long as possible [59,60], expressing a preference of obstructed views over blocked views when solar shading in workspaces is negotiated. ETFE double-skin façades with printed reflective frit patterns represent a similar situation, where the retrofitting measure of improving the thermal and lighting performance of the building envelope with an additional layer compromises the visibility through the windows, which has an effect on view perception and emotional response of the space occupants, as this study has shown. The more the view clarity of the ETFE samples was compromising the perception of colours, weather and restricting the amount of the available view extent, the lower the samples were rated by the participants. This trend was especially noticeable for the switchable sample (DSF 3). Despite the climate adaptive capability, the switchable frit pattern limited considerably the view through the glazing and the subjective perception of the reduced visual quality of the view was coherently reflected by the participants' ratings. The lowest ranking in all questions was given to the DSF 3 sample with the switchable ETFE cushion, as shown in the results outlined in Tables 4 and 5. The highest ratings were given to the reference sample REF with the clear glazing across all investigated parameters. The sample ranking maintained persistently within the emotional response categories; however, it was not as pronounced as in the view perception rating. The emotional response towards samples with an obstructed view (DSF 2 and DSF 3) was more positively rated by the participants in comparison to the perceived view qualities. This finding relates well to a more recent study, which investigated subjective and physiological responses to façade and sunlight patterns seen in VR [61]. Irregular façade geometry variation was evaluated here as more pleasant, interesting and exciting than the regular façade variation, demonstrating the influence of the spatial distribution of façade openings.

Together these results provide important insights into the view perception and emotional response towards DSF with ETFE foils, suggesting that there is a strong association between user satisfaction and view clarity, where a DSF with higher clarity and less obstruction through reflective fritted prints are preferred and provoke a more positive emotional response in users towards the spaces they are working in. These results might appear as a negative indicator for the use of fritted ETFE foils in façade constructions, where visibility and view clarity is of importance to the user. This is especially true when considering switchable ETFE cushions (DSF 3), with double-layered prominent frit prints. However, the results are not a negative outcome, per se, for the question of the feasibility of applying printed and switchable ETFE foils in double-skin façades, but rather suggest that the frit prints must be carefully designed to fulfil the users' need to interact with the external environment visually. For spaces where no direct visual interaction with the external environment is expected, and

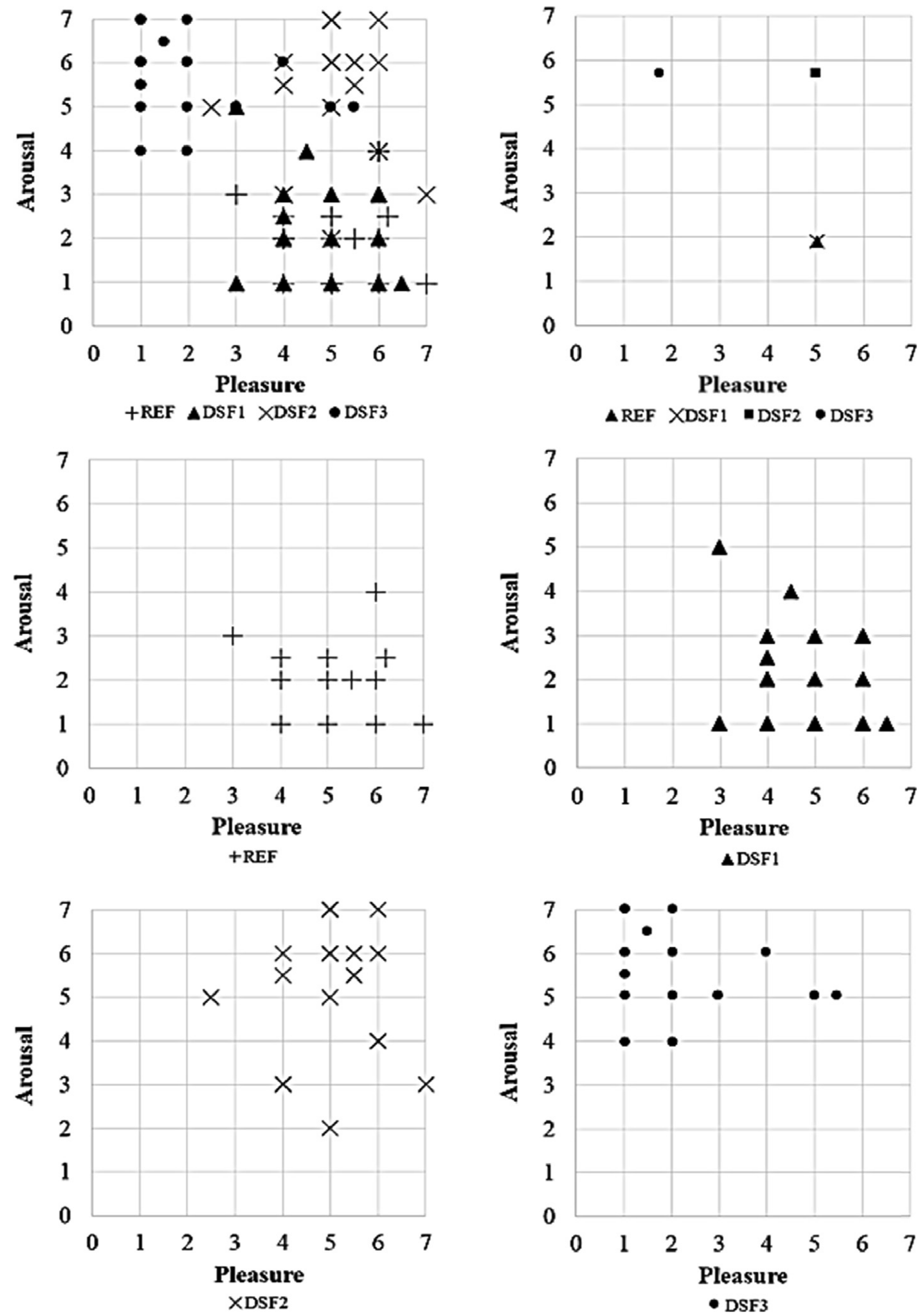

Fig. 12. Mdn plots of the responses to questions regarding spatial pleasure (i.e. valence) and arousal.

window functions are limited to provide natural daylight only, view clarity of ETFE double-skin façades might be of less importance for user acceptance in buildings. Future developments of novel material and surface treatments for ETFE might overcome the technical dilemma of having to choose between climate-adaptive performance and view clarity, providing comprehensive building solutions for lightweight façades [62].

Overall, the results were statistically relevant and interpreted based on a conservative approach, reporting effect sizes as an additional measure for significant difference alongside *p*-values. However, caution should be acknowledged when attempting to generalise these findings beyond the constraints of this research recommending ETFE for future application as a building material for façades.

4. Conclusions

This study set out to investigate the viewing experience and emotional response to different ETFE materials in climate-adaptive double-skin façades which may play an important role as an effective measure in energy retrofitting office buildings, making them more resilient in a changing global climate. The goal was to determine the user acceptance towards the different design options of future applications, simulating the viewing experience in immersive environments with physically correct imagery using virtual reality equipment. The method had been validated previously and was used in this case for a practical application of investigating the view clarity of energy-saving building envelopes. Virtual reality and immersive environments have been demonstrated within this study to be a practical and reliant tool to experience in advance the view and feeling of being in a room with an innovative and novel façade system without incurring the costs of a large size mock or running the risk of exposing future users to work for decades in an unsatisfying environment. The relevance of using virtual reality for the early design evaluation and user feedback is clearly supported by the current findings.

One of the more significant findings to emerge from this study is that participants preferred window views with clear ETFE facades over fritted foil constructions. This outcome is, at first sight, unsatisfactory, considering the fact that fritted ETFE foils with reflective prints provide better energy and daylighting performance. However, the study also showed that the categorical preference for unobstructed views was less pronounced in the emotional response, were participants spatial perception did not appear to be affected in the same intensity by the different façade samples as their view perception through the window. This finding is of interest for the consideration of material choices in future projects. Fritted ETFE facades, with an obstructed window view, might therefore still be acceptable to building occupants in spaces where window views are not required by the spatial program or where a reflective and insulating ETFE façade is necessary to improve the environmental performance of the building envelope.

Nevertheless, the development of better foil frit prints, coatings, inks and less obstructive print patterns with a higher view clarity for the application in novel ETFE façades should be prioritised. The findings suggest that this is especially true for the switchable ETFE cushions which on one side offer many opportunities for energy savings and enhanced daylight performance, but on the other side were not well accepted by the participants of this study due to its limited view clarity and amount of clear view to the outside environment. This outcome is of significance for the future application of switchable ETFE cushion in its current form and reinforces the intuitive impression that the view satisfaction and related user acceptance of switchable ETFE foils in building façades are directly linked to the proportional amount and grade of clear view through the window. Further research regarding the role of the switching process itself of the adaptive ETFE cushion would be worthwhile, especially under different environmental conditions. Future studies might also investigate other parameters which influence the view perception and emotional response to a window view, such as: viewing scenarios (e.g. urban vs rural), different window orientations (north vs south), alternative sun angles and solar radiation intensity (direct vs indirect) and varying outdoor viewing weather conditions (e.g. cloudy or rainy sky). The development and validation of a method which would allow to change the virtual scenery and modify the window materials and façade design digitally would, therefore, be of much interest for future research.

In addition to this, factors outside the scope of this paper include the effect of ETFE on the luminous indoor environment and also building energy performance, which will be investigated in future work.

CRediT authorship contribution statement

Jan-F. Flor: Methodology, Project administration, Investigation, Data curation, Writing - original draft. **Marina Aburas:** Methodology, Investigation, Data curation, Formal analysis, Writing - review & editing. **Fedaa Abd-AlHamid:** Methodology, Software, Investigation, Validation, Writing - review & editing. **Yupeng Wu:** Resources, Funding acquisition, Supervision, Methodology, Writing - review & editing.

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 in this paper.

Acknowledgements

This work was supported by the Faculty of Engineering at the University of Nottingham through a PhD studentship awarded to Jan-Frederik Flor. This work was also supported by the Engineering and Physical Sciences Research Council, UK [grant number EP/S030786/1]. All ETFE cushion samples and the manufacturing of the mock-up was generously provided by Architen Landrell. The authors thank their industry partner and all participants of the experiment for their voluntary support. A special thanks to Xiao Liu for the technical assistance during the experimental procedures.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2020.110554.

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