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Citation for published version (APA):
Bakker, L. G., van Oeffelen, E. C. M., Loonen, R. C. G. M., & Hensen, J. L. M. (2014). User satisfaction and interaction with automated dynamic facades : a pilot study. *Building and Environment*, *78*, 44-52. https://doi.org/10.1016/j.buildenv.2014.04.007

DOI:
10.1016/j.buildenv.2014.04.007

Document status and date:
Published: 01/01/2014

Document Version:
Accepted manuscript including changes made at the peer-review stage

User satisfaction and interaction with automated dynamic facades: a pilot study

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Abstract

Automatically-operated dynamic facades can play an important role in reducing building energy consumption while maintaining high levels of indoor environmental quality. Facade automation, however, has a controversial reputation due to concerns about increased risks for occupant distraction and discomfort. This paper explores and quantifies the influence of automated facade operation on user satisfaction and interaction by presenting the results of a pilot study. In the experiment with 26 participants, multiple scenarios with varying control strategies and occupant influence options were tested, with a focus on dynamic daylight aspects and visual performance. Analysis of subject responses and data collected during experimental sessions did not directly reveal a high risk for disturbance and discomfort. We found that less frequent but discrete transitions in facade configuration are significantly better appreciated than smooth transitions at a higher frequency. Our findings also emphasize the need for further development of effective facade control algorithms and demonstrate that the ability for manual override is a requisite for high-performance operation of dynamic facades.

Keywords:

Dynamic facade, automated control, occupant satisfaction, human factors, personal control

1 Introduction

Buildings with dynamic facade components can be adjusted in response to prevailing or anticipated weather conditions and comfort preferences. Doing this adaptation in an effective way, by taking advantage of the available energy sources and sinks in the ambient environment, can lead to a significant energy saving potential compared to static design alternatives [1,2]. Dynamic facade technology can, in addition, play an important role in balancing various aspects of indoor environmental quality (IEQ), such as, discomfort glare, view to outside, privacy, thermal comfort and air quality [3–5]. Climate adaptive building shells (CABS) are therefore increasingly regarded as a promising concept for achieving high-performance building design [6], and many different adaptable facade design concepts have been proposed [7].

The way of operating CABS has a profound effect on the resulting performance in terms of occupants' comfort and energy savings. Consequently, it is an important factor to take into account in the product development of next-generation CABS concepts and their control systems. It is argued that highest performance gains can be reached when operation of the dynamic facade is appropriately integrated with occupancy detection and the control of other systems, for e.g., lighting, ventilation, heating and cooling [8]. In turn, this is best achieved when facade operation is fully automated, and coordinated by a supervisory building automation system [9].

User interaction and satisfaction are two primary factors that cannot be neglected in the development and operation of automated building systems [10–12]. Several studies in various settings have shown that the levels of perceived and exercised personal control over one's environment are important determinants of comfort, well-being and task performance [13–15]. Recent research in this field has mostly been focused on control of HVAC systems, and considers IEQ mainly in terms of thermal comfort and indoor air quality. Results from the European HOPE project nevertheless show that "satisfaction with the control of sun shading" was one of the main predictors for comfort in relation to personal control [16].

Despite its importance being acknowledged in literature, so far, only limited attention has been paid to human factors research in relation to daylighting, solar control, and the dynamics of adaptable facades [11].

Bordass et al. (1993) make the overall recommendation that "those advocating fully-automatic control of natural light and glare should proceed with caution" [17], and moreover argue that designers and modelers have "over-optimistic faith in automatic controls" [18]. In post-occupancy evaluations (POE), they identified, for example, cases of occupant frustration and hostility because automated blinds were often perceived to operate at the wrong time. In a study dedicated to automated facades, Stevens (2001) found a strong positive correlation between occupant satisfaction and their ability to overrule operation of the systems, and moreover found that in such cases a fast-responding control system is required for high performance [19]. These results are supported by studies dealing with venetian blinds [20–22], where also the risk for too frequent oscillations and noisy operation are identified as important factors for occupant satisfaction [20,23]. On a related note, Reinhart and Voss (2003) investigated occupants' tolerance towards automated blind readjustments, and found this to be "remarkably low" [24].

The type of findings presented above, contribute to the controversial reputation of automated facade systems, which may be one of the reasons why the energy-saving potential of such systems is still largely unused in practice. On the other hand, there is also research that seems to justify the growing interest in intelligent facade control systems. POE research conducted by LBNL, for example, shows that provided the systems are carefully designed, commissioned, and maintained, it is possible to develop energy-saving automated control strategies at high occupant satisfaction [25]. The preference for automated systems over manual control was furthermore also found in observational studies with automated venetian blinds [20] and electrochromic windows [26,27].

Considering this overview of literature, it is clear that there are currently no standard guidelines available to support the design of high-performance automated facade systems. Also, from the perspective of control, there are still many research questions regarding the interaction between dynamic facade components and occupant satisfaction. For example, it is currently unknown what type of adaptive control (e.g. slow vs. fast movements, or many small vs. fewer large movements) leads to higher occupant satisfaction. This lack of knowledge may inhibit the product development of next-generation CABS concepts.

In this paper, we present the results of experimental research that was designed to address several of the points raised above. More specifically, the validity of the following hypotheses was tested:

H1 Moving facade elements are a direct cause for disturbance and discomfort.

H2 Frequent but smooth facade transitions are perceived as less disturbing compared to less frequent, but more discrete transitions over a larger distance.

H3 Users with the ability for manual override assess automated movement of facade elements as less disturbing compared to users without override option.

H4 Movement of facade elements is perceived as less disturbing when it relates to a clear cause instead of movement without apparent reason.

2 Methodology

2.1 Test environment

Experiments were conducted in a full-scale test room (5.4 x 5.4 x 2.7 m) (Figure 1), designed as daylight laboratory at Eindhoven University of Technology, The Netherlands. The west wall of the room is fully glazed and on the interior side equipped with a prototype automated dynamic facade in the form of non-transparent movable roller shades. The position of shades is coordinated by a central control unit and actuated by Somfy Sonesse 30 DCT motors, operated at the lowest speed setting to ensure that the sound induced by the system is hardly noticeable in the center of the room. The upper and lower roller shades are operated independently and can cover a range from fully open to fully closed.

Figure 1: Overview of the experimental facility with roller shades fully opened (left). Small pictures (right) show different facade configurations.

The test subject was sitting behind a desk, at 1.5 meter from the facade (Figure 2). The direction of the chair and table relative to the facade was fixed (Figure 2), but within these constraints, users were free to adjust the layout of their workspace. Occupants had an unobstructed view to outside, which consisted of a mostly natural setting on a university campus with a pond, trees, and lawns nearby, and other buildings in the distance. The room was only occupied by the test subject. All experiments were carried out in the months April and May. Sensors were installed to monitor daylight conditions in the room and on the work plane (horizontal and vertical illuminance). Additionally, the position of the roller shades was recorded over time.

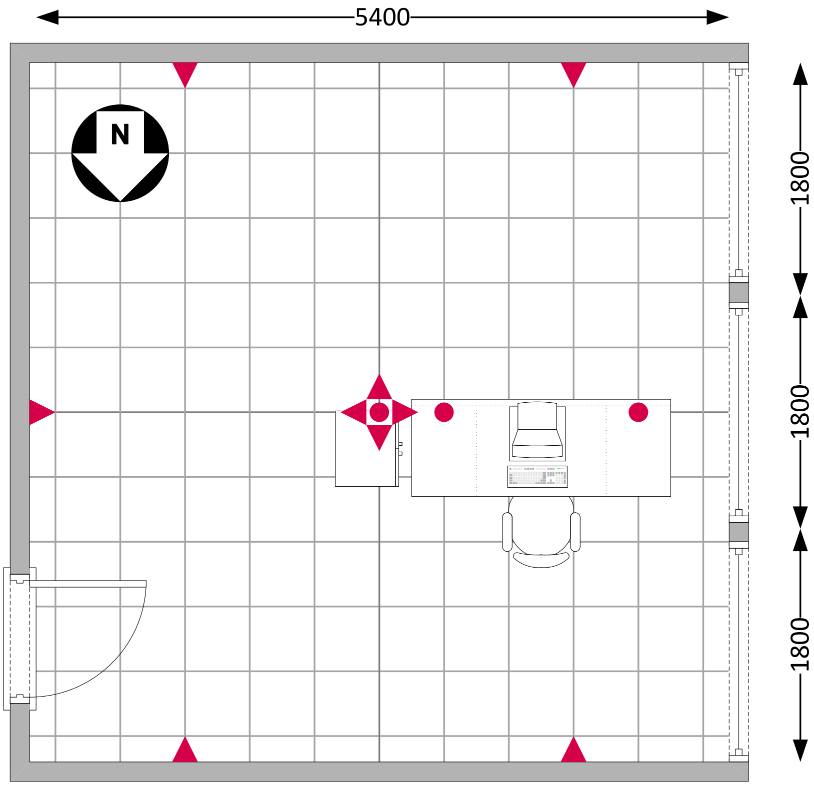

Figure 2: Floor plan of the test room, with the positions and direction of the computer screen relative to the facade. Red triangles indicate horizontal illuminance sensors; red dots indicate vertical illuminance sensors.

In some of the tested scenarios, users had the ability to override the automatically determined position of the roller shades. These override actions were controlled using a hand-held user interface (Figure 3). Users had the option to move both the upper and lower roller shade, and in this way could make the transparent window area bigger, smaller or change its position in the facade.

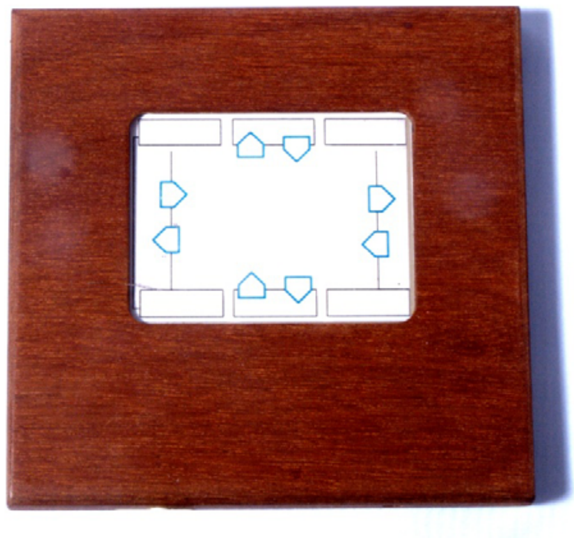

Figure 3: User-interface for overriding automated facade control.

2.2 Test subjects

In total, 26 test subjects (10 male, 16 female) participated in the experiments. The population of participants had an average age of 22.4, with a standard deviation of 3.0 years. All participants were used to work on a computer.

All participants performed regular office work during the experiments. A desktop computer was available for use by participants during the tests, but users could also work on their own laptop computer. Users received a small compensation for their participation in the experiment.

2.3 Scenarios and sessions

Each subject participated in the experiment for a period of 4.5 hours. During the experiment, the test subjects were exposed to multiple test scenarios in which the effects of different options for control strategies and user interaction were evaluated. All experiments took place at the same time period during the afternoon, because direct sunlight at the facade was needed for the experiments.

The subjects started the experiment at 12:30 p.m. with an initial trial period of 15 minutes. In this period, users were given the time to settle down and get used to the laboratory environment, facade operation, questionnaire system, etc. In this 15 minutes period, participants also had the opportunity to get familiar with the manual override option of the roller shades via the user interface. The test subjects were not informed about the specific purpose of the test.

After this introduction, four different scenarios of one hour each were tested (Figure 4):

Scenario 1: The roller shades are operated automatically. Position of the roller shades is pre-determined. The shades move every ten minutes over a distance of 20 cm.

Scenario 2: The roller shades are operated automatically. Position of the roller shades is pre-determined. The shades move every two minutes over a distance of 5 cm.

Scenario 3: The roller shades are operated automatically. The control strategy responds to daylight conditions. Position of the lower roller shade is fixed. Position of the upper roller shade is continuously adjusted to avoid glare (based on vertical window luminance), while keeping work plane illuminance between 500 and 2000 lux.

Scenario 4: The roller shades are operated automatically. Position of the roller shades is pre-determined. Only the upper shades move, every ten minutes over a distance of 20 cm.

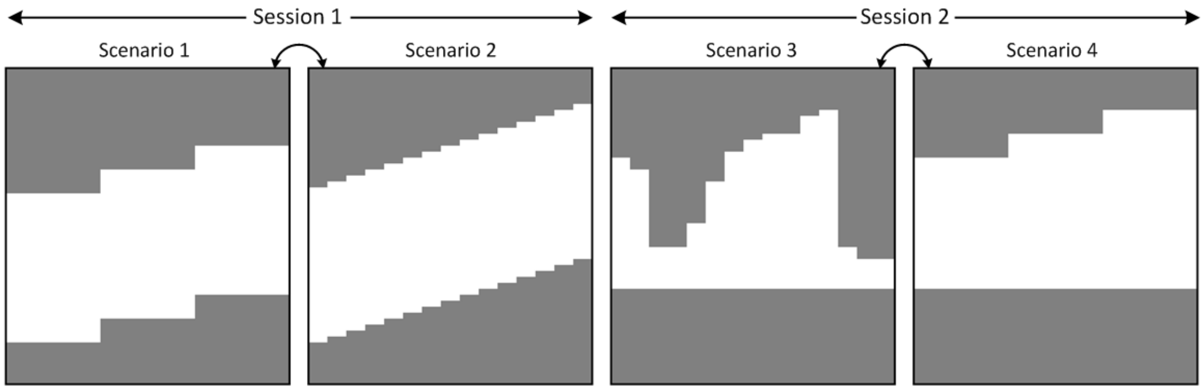

Figure 4: Overview of experimental procedure in two sessions and four scenarios. Each of the scenarios was tested with and without the option for manual override. Roller shade positions in scenario 3 depended on daylight conditions and were therefore different in each experiment.

Each of these scenarios was tested with and without manual override option (30 minutes each), so in total eight different test scenarios were carried out. The order of these test scenarios was counterbalanced across the test subjects to avoid order effects. However, scenarios 1 and 2 were always tested in the first session of the experiment and the scenarios with manual override option were always tested in the second part of each session.

Test subjects were allowed to leave the test room for a short break after each scenario in the experiment. They left the test room for a longer break halfway through the experiment (between session 1 and 2).

2.4 Questionnaire

Test subjects were asked for their subjective feedback by completing a web-based questionnaire three times during each scenario. Most questions were answered on a visual analog scale, while some others required the choice for one of predefined options (Table 1). Depending on scenario and users' response, each questionnaire consisted of 7 up to 17 questions. In the case of a positive answer to question QA7, i.e. roller shade movement was observed, an additional set of seven questions was asked to inquire about the user's perception regarding the movement (QB1-7). Only in situations with manual override, users were asked about their perception regarding this feature (QC1-3). Results analysis was done by taking the average of the three questionnaires per scenario.

Table 1: Overview of questions in the questionnaire. A-questions were asked in each scenario. B-questions were asked only if users had noticed movement of the automated facade. C-questions were only asked in scenarios with user override. D-questions were only asked at the end of the whole experiment.

ID	Question	Score	
A1	How do you assess the current illuminance level on the work plane?	-100 Too low	100 Too high
A2	How satisfied are you with the current illuminance level on the work plane?	-100 Very dissatisfied	100 Very satisfied
A3	How do you assess the current illuminance level of the room in general?	-100 Too low	100 Too high
A4	How satisfied are you with the current illuminance level of the room in general?	-100 Very dissatisfied	100 Very satisfied
A5	Were you disturbed by glare (e.g. by direct sunlight, bright sky, or bright walls) in the previous period?	0 Not at all	100 Very much
A6	How satisfied are you with the current view to outside?	-100 Very dissatisfied	100 Very satisfied
A7	Have you noticed movement of the automated facade in the previous period?	Yes / No	
B1	To what extent did you observe facade movement?	0 Not at all	100 Very obvious
B2	How did you experience the movement of the facade in the previous period?	-100 Very annoying	100 Absolutely not annoying
B3	How did you experience the sound induced by the automated facade in the previous period?	-100 Very annoying	100 Absolutely not annoying
B4	Were you distracted from your work due to the movement of the facade in the previous period?	0 Not at all	100 Very much
B5	How do you assess the fact that the shape and position of the window are now different (not considering view)?	-100 Very unpleasant	100 Very pleasant
B6	How do you assess the fact that the view to the outside is now different?	-100 Very unpleasant	100 Very pleasant
B7	Do you assess the changed facade configuration as an improvement?	0 Not at all	100 Very much
C1	What type of adaptation did you do?	Increase window size / Decrease window size / Shifted window / Other	
C2	What was your reason for overruling the position of the roller shades?	View / Daylight / Sunlight / Other	
C2*	What is the reason that you decided not to overrule the position of the roller shades?	I don't know / Too much effort / Not needed / Other	
C3	How satisfied are you with having the ability for overruling the position of the roller shades?	-100 Very dissatisfied	100 Very satisfied
D1	Overall, did you experience discomfort due to too low temperatures?	0 Not at all	100 Very much
D2	Overall, did you experience discomfort due to too high temperatures?	0 Not at all	100 Very much
D3	Overall, did you experience discomfort due to draught?	0 Not at all	100 Very much
D4	Overall, did you experience discomfort due to stuffiness of the air?	0 Not at all	100 Very much
D5	Overall, did you experience discomfort due to smell?	0 Not at all	100 Very much
D6	Overall, did you experience discomfort due to noise?	0 Not at all	100 Very much
D7	Overall, how did you experience the fact that the view to outside changed over time?	-100 Very unpleasant	100 Very pleasant
D8	Overall, how did you experience the fact that the position of the roller shades changed over time?	-100 Very unpleasant	100 Very pleasant
D9	Would you like to have this office as your daily working environment? Why (not)?	(open question)	

After completing the last scenario of the second session, users were additionally asked to give an overall evaluation of the conditions in the test room throughout the entire measurement period (QD1-9). Questions asked for users' overall satisfaction regarding temperature, draught, smell, freshness/stuffiness, acoustic environment, view to outside and the changing facade.

2.5 Hypothesis testing

The scenarios described in Section 2.3 were devised to enable testing of the four hypotheses that are examined in this paper. Figure 5 presents a schematic overview of the relationships between the different scenarios, and how these scenarios are used to test the hypotheses. H1 aims at assessing the overall subjective perceptions about the dynamic facade. This is done by analyzing descriptive statistics for all four scenarios. For testing H2, the results from scenario 1 are contrasted to the results from scenario 2. The direct comparisons are done by performing paired t-tests. H3 evaluates the effects of manual override. Because all four scenarios are measured with and without manual override possibilities, they are all included in the analysis. Finally, H4 tests the impact of control strategy. This test is done by directly comparing the differences in results between daylight-based (scenario 3) and pre-programmed control (scenario 4).

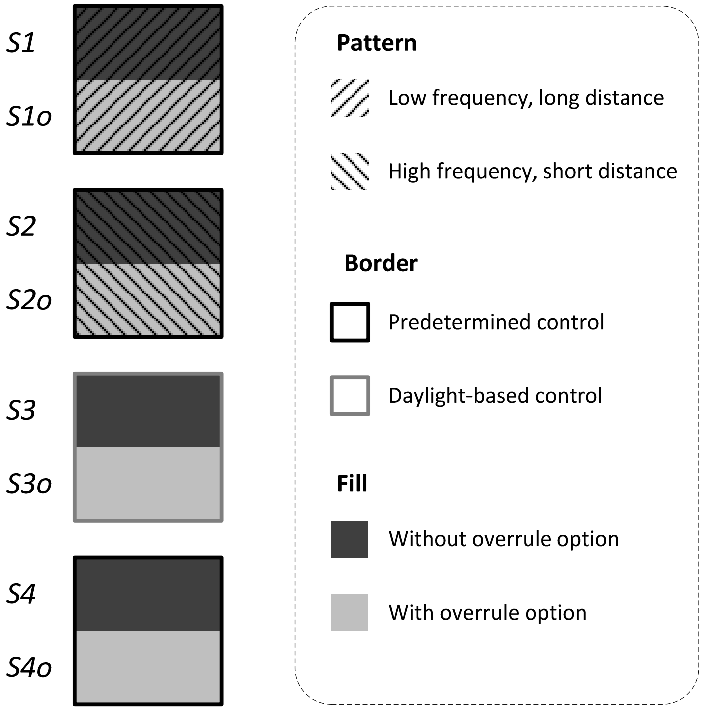

Figure 5: Schematic overview of the relationships between experimental scenarios and testing of hypotheses. The different patterns, fills and border styles are used to illustrate the translation from scenarios to hypothesis testing.

3 Results and analysis of hypotheses

In this section, we present and analyze the outcomes of the experiments in relation to the hypotheses as they are formulated in the Introduction. Each hypothesis is described in a following sub-section, but first we focus on some general observations and findings from the questionnaires.

Overall, 69% of the test subjects responded positively to the question if they would like to work in the pilot office on a daily basis (QD9). Even though users were not asked to base their opinion on the facade system specifically, several replies showed a direct link:

- *It is nice to be able to adjust window size, and, as a result light intensity. This is useful, especially under bright sky conditions;*
- *The facade system provides personal control over the amount of light that enters the room and it is also useful if you don't want to be distracted by what happens outside;*
- *It is good for my concentration when entrance of daylight changes from time to time;*
- *Having the ability to change window position is useful to avoid discomfort due to direct sunlight;*
- *It is convenient to be able to adjust the size of the window yourself.*

Some of the positive replies, however, were more related to the users' overall experience during the tests instead of the facade, and included comments about e.g. the room's spaciousness, lightness and quietness, large window opening, interior design, and the scenic view in general.

Facade-related reasons expressed by the remaining 31% of respondents who indicated they would not prefer the pilot office room as their everyday workplace, included:

- *Too much discomfort from daylight. It is annoying to work when there is too much sunlight entering the room;*

- *I prefer to have ample daylight that does not change all the time, and a large window area for looking outside.*

Indirect negative comments were made about the lack of atmosphere, decoration and color in the room (6 times), and the fact that windows could not be opened.

Results in Figure 6 show the overall perception regarding eight indoor environmental aspects on the basis of questions in the final questionnaire (QD1-8). In general, users felt slightly uncomfortable with the thermal environment (QD1-2) and the acoustical environment (QD6). Users were slightly positive about the dynamic facade (QD7-8). Especially for the changing view to outside, the spread in results is relatively large. This may be due to individual differences, expectations compared to their regular work environment, but also the fact that weather conditions were different in each experiment.

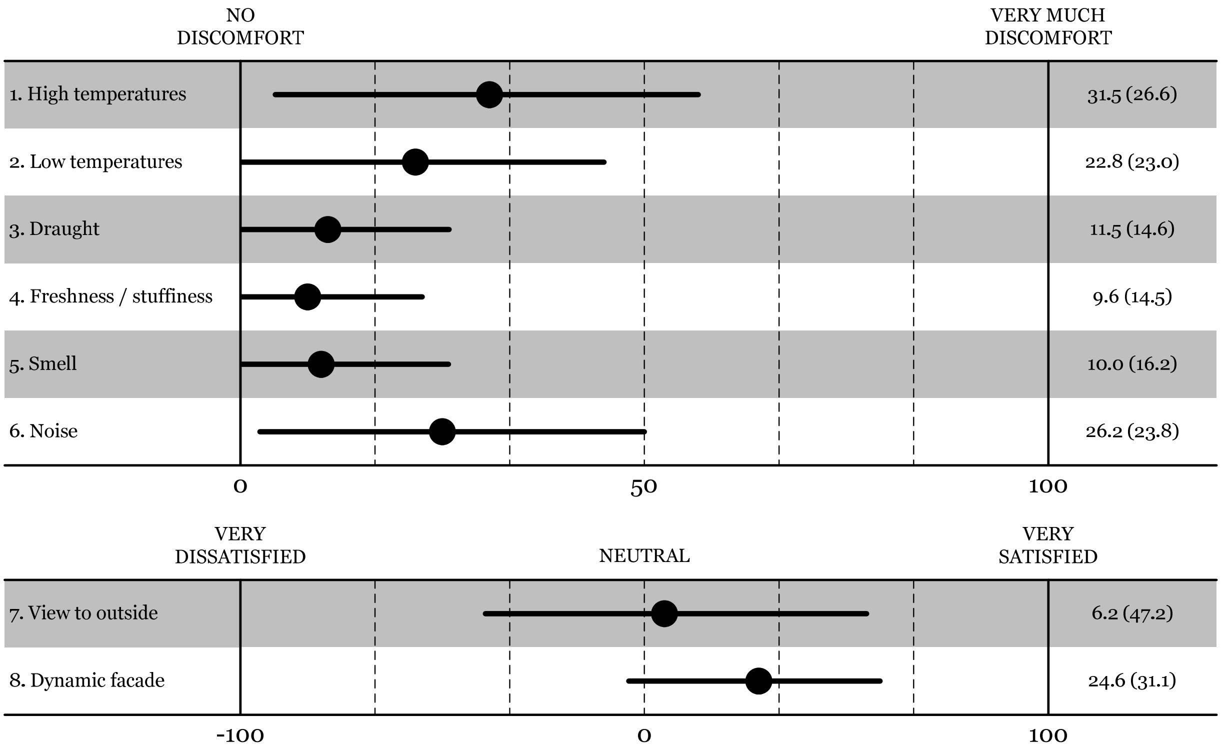

Figure 6: Overall evaluation with respect to eight indoor environmental aspects (mean and standard deviation). Scores for question 1 to question 6 range from “no discomfort” (0) to “very much discomfort” (100). Scores for questions 7 and 8 range from “very dissatisfied” (-100) to “very satisfied” (100). Numbers on the right indicate the mean values with standard deviations in parentheses. Five subjects were excluded from this analysis, because of too extreme oscillations during scenario 3 and 4.

3.1 Hypothesis 1

H1: Moving facade elements are a direct cause for disturbance and discomfort

The number of times that a change in position of the roller shades was not noticed by the test subjects (Table 2), provides a good first indicator of the level of disturbance. Throughout all the analyses, we assume that users who were not conscious of the changes were neither disturbed nor distracted by the facade movement in that period. From the results presented in Table 2, it can be concluded that the majority of changes were detected by the test subjects. The results indicate a decreasing trend. Changes are most often noticed in scenarios 1 and 2; the two scenarios which were always tested in the first session of the experiment, before testing scenarios 3 and 4. One can argue that in the beginning of each experimental session, users were relatively more aware of their surroundings, and therefore more receptive to environmental stimuli. Our results may reveal the process of habituation [28], i.e. users getting accustomed to the automated facade system and the accompanying increase in tolerance. As such, this finding may contribute to justifying the acceptance of CABS in practice. It is difficult, however, to demonstrate such an effect in a laboratory setting. The validity of this effect should be examined in future research with in-situ experiments over a longer period of time.

Table 2: Overview of changes that were not consciously detected by the subjects (N=19). Seven subjects were excluded from this analysis, because of too extreme oscillations during scenario 3 and 4 (5 subjects) or the settings of the facade were not correct (2 subjects).

Scenario	Changes not detected [%]	Persons who did not detect any change
1	20	1
2	26	1
3	34	3
4	39	6

Of the users who did notice the changing facade configurations, the majority was *neutral* to *moderately satisfied* (QB5-6) with the changes. In none of the sessions, users perceived the changing facade configurations as *very pleasant*. Only in a small number of situations, users assessed the changes as *very unpleasant.*

Self-reported distraction from work (QB4) is another important performance indicator for assessing the level of disturbance. In this study, distraction was found to be strong in only a limited number of cases. On average, users felt moderately distracted, with a spread in results that is relatively large. Potential factors that explain this wide variability, such as the influence of control algorithms and type of roller shade movement, are explored later in this paper.

The majority of users indicated that the movement in itself (QB2) and sound level during transitions (QB3) were not perceived as disturbing. We emphasize that in our experiments, special care was taken to make facade operation as quiet as possible.

A few exceptions aside, users experienced the automated facade in a neutral to positive way. The results from this experiment do nevertheless not provide sufficient basis for rejecting the hypothesis that moving facade elements easily lead to disturbance and discomfort. Various factors can cause the occurring complaints, and the tests were performed under a range of different circumstances. This needs further analysis, which is presented in the next subsections.

3.2 Hypothesis 2

H2 Frequent but smooth facade transitions are perceived as less disturbing compared to less frequent, but more discrete transitions over a larger distance

The differences in user perception for these two modes of facade adaptation are evaluated by making a comparative analysis of user feedback between scenarios 1 and 2. Table 2 shows that there is a small difference in the number of non-detected facade changes between the two scenarios, but in a paired t-test, this effect was found to be non-significant. Table 3 shows the average results on all questions between scenarios 1 and 2 (N=24). Significant differences between scenarios 1 and 2 were found for:

- The extent at which movements of the roller shades are perceived as disturbing (QB2). On average, the movements in scenario 1 were perceived as less disturbing compared to scenario 2 ($t(24)=-2.37$, $p=.027$).
- The extent at which test subjects are distracted from their task (QB4). In scenario 1, self-reported levels of distraction were on average lower than in scenario 2 ($t(24)=-2.99$, $p=.007$).

For none of the performance aspects, scenario 2 was perceived significantly more positive than scenario 1 (Table 3). Therefore hypothesis 2 was rejected.

Table 3: Comparison of results (mean and standard deviation) between scenarios with roller shade movement over large and small distances (N=24). Lines in bold indicate a significant difference. In this analysis two subjects were excluded, because one of the subjects did not complete the questionnaire and in one case the setting of the facade was not correct.

Q	Large distance (scenario 1)		Small distance (scenario 2)		Q	Large distance (scenario 1)		Small distance (scenario 2)	
	μ	σ	μ	σ		μ	σ	μ	σ
A1	-5.1	27.7	-5.0	22.7	B1	40.6	21.9	50.5	20.3
A2	23.3	41.6	23.1	32.6	**B2**	**54.0**	**32.6**	**36.7**	**36.6**
A3	-6.2	25.3	-7.4	22.8	B3	42.0	39.6	27.5	41.0
A4	21.9	38.4	19.6	35.1	**B4**	**25.1**	**16.9**	**37.3**	**17.4**
A5	16.7	20.4	14.3	20.6	B5	-12.6	26.6	-9.6	25.7
A6	-8.9	29.2	-2.8	34.5	B6	-12.9	29.2	-13.2	35.4
					B7	35.2	17.2	33.4	16.5

3.3 Hypothesis 3

H3 Users with the ability for manual override assess automated movement of facade elements as less disturbing compared to users without override option

Throughout all experiments, in 54% of the scenarios (143 instances) manual override actions, taken in response to automated adjustments of the roller shades, were recorded (Table 4). Most of the time (64%), users adjusted the roller shades to increase the size of the window. In 21% of the cases, users shifted the position of the window, and in 17% of the cases, users requested a smaller window-to-wall ratio (QC1).

Table 4: Number of manual interventions, sorted per scenario and type of adaptation (multiple types of adaptation are possible in one intervention). N indicates the total number of test subjects considered in the statistical analyses for each scenario. Values in parentheses indicate the number of test subjects that performed a particular action.

Scenario	N	Number of interventions	Type of adaptation (number of instances (number of persons))			
			Bigger	Smaller	Shifted	Other
S1o	24	38 (22)	27 (18)	4 (4)	7 (4)	2 (2)
S2o	24	41 (21)	28 (16)	5 (4)	9 (6)	5 (2)
S3o	20	34 (17)	23 (14)	7 (5)	5 (4)	0 (0)
S4o	21	30 (17)	13 (10)	9 (7)	9 (6)	0 (0)

Different reasons were indicated as the trigger for these interventions (QC2, Table 5). The most common reason for adaptation was to enhance views to outside (66%) and/or daylight entrance (57%). This is consistent with the fact that most users adjusted the window size to make it bigger. Exposure to direct sunlight was only mentioned as the reason for intervention in a limited number of cases. In such cases, the user either decided (i) to limit entrance of solar gains, or (ii) to avoid the occurrence of glare discomfort.

Table 5: Number of manual interventions, sorted per scenario and reason for (no) adaptation (multiple reasons are possible for each adaptation). N indicates the total number of test subjects considered in the statistical analyses for each scenario. Values in parentheses indicate the number of test subjects that performed a particular action.

Scenario	N	Manual adjustment				No manual adjustment			
		View	Daylight	Sunlight	Other	Not aware	Too much effort	Not needed	Other
S1o	24	31 (19)	18 (11)	4 (3)	1 (1)	0 (0)	3 (2)	25 (16)	9 (8)
S2o	24	28 (15)	22 (15)	6 (3)	3 (2)	0 (0)	2 (2)	21 (13)	10 (9)
S3o	20	20 (13)	24 (15)	5 (4)	1 (1)	0 (0)	5 (3)	22 (13)	2 (1)
S4o	21	15 (10)	18 (12)	9 (5)	0 (0)	0 (0)	4 (3)	26 (16)	4 (4)

In cases where automated facade operation was not adjusted by the user, most of the time, user feedback indicated that in their opinion, there was no need for it (76%), because the automated strategy was in line with their comfort preferences. Only a few test subjects never did a manual intervention.

On average, users were *satisfied* to *very satisfied* when given the ability to adjust facade operation (the average score for QC3 was >+50 in all scenarios). This situation is also reflected in satisfaction levels regarding the luminous environment. In scenarios where users had the ability for manual override, they were significantly more satisfied with the light levels on their desk (QA2: $\mu=36.5$, $\sigma=25.2$), compared to cases with fully automated control (QA2: $\mu=24.4$, $\sigma=25.2$, $t(18)=2.37$, $p=.029$). Significant differences favoring manual override were also found for user satisfaction with light levels in the entire test room (QA4, $t(18)=3.30$, $p=.004$), and satisfaction with the view to outside (QA6, $t(18)=5.80$, $p<.001$). Although the differences in satisfaction were significant, no significant differences were found for the perceived illuminance levels (QA1, QA3). Manual override further had a positive influence on users' perception considering the dynamic facade, as a significant difference was found for the satisfaction regarding window shape (QB5, $t(18) = 2.24$, $p = .038$). Such an effect was expected because users deliberately decided to change the facade to match their preferences at that moment. A positive, but non-significant difference was found for satisfaction with the changing view (QB6).

The fact that users were not able to override automated decisions did, opposite to our initial expectations, not lead to additional distraction. In contrast, in cases with override capability, users indicated significantly higher levels of distraction (QB4, $t(18)=-2.70$, $p=.015$). This result may be explained by the fact that users may pay more attention to the facade when having the ability to overrule. This finding seems to contradict with conclusions from other research which shows the positive effects of personal control [29]. However, our findings further emphasize the complexity in psychological interactions between perceived and exercised control [13].

3.4 Hypothesis 4

H4 Movement of dynamic facade elements is perceived as less disturbing when it relates to a clear cause instead of movement without apparent reason

The differences in perception regarding movement of the automated facade between daylight-based (scenario 3) and pre-programmed control (scenario 4) are relatively small (Table 6). It was hypothesized that daylight-based control would lead to less disturbance, because in those cases the movement of the roller shades is based on environmental conditions with the aim of preventing discomfort. On the basis of our experiments, we can neither accept nor reject this hypothesis. No significant differences between the two scenarios were found for disturbance-related questions regarding user-awareness of changes (QB1), movements (QB2), noise (QB3) and distraction (QB4). However, it should be noted that in the daylight-based control scenario, both the frequency and magnitude of facade changes was higher than in the pre-programmed control scenario. Therefore the results related to the changes of the facade can hardly be compared.

Table 6: Comparison of results (mean and standard deviation) between scenarios with daylight-based and pre-programmed roller shade movement (N=20). Lines in bold indicate a significant difference. Six subjects were excluded from this analysis, because of too extreme oscillations during scenario 3 and 4 (5 subjects) or an incorrect settings of the control algorithm (1 subject).

Q	Daylight-based (scenario 3)		Pre-programmed (scenario 4)		Q	Daylight-based (scenario 3)		Pre-programmed (scenario 4)	
	μ	σ	μ	σ		μ	σ	μ	σ
A1	**-15.1**	**21.3**	**1.3**	**27.7**	B1	29.0	22.5	23.5	18.9
A2	18.8	37.4	20.2	34.6	B2	70.4	27.6	77.4	22.0
A3	**-19.6**	**23.4**	**0.5**	**28.7**	B3	69.4	28.0	74.3	25.3
A4	15.7	38.8	22.2	38.3	B4	19.8	21.4	15.3	15.6
A5	**14.2**	**16.8**	**25.5**	**28.1**	B5	7.6	32.8	12.3	41.7
A6	**-1.0**	**30.9**	**20.8**	**40.3**	B6	12.2	33.4	2.2	41.0
					B7	34.6	13.0	39.7	25.1

The mode of operation did lead to differences in average perceived comfort levels. Although in both cases users reported they did not frequently experience glare discomfort, in the case of daylight-based control, the average glare discomfort levels (QA5) were significantly lower ($t(19)=2.09$, $p=.050$). We therefore observe that the implemented control strategy works effectively for preventing glare, but that in doing so, it also gives rise to negative consequences. Scores for perceived light levels on the desk

(QA1) and in the room (QA3), and view to outside (QA6) were significantly lower in the case of daylight-based control. These findings are characteristic for the type of trade-offs that need to be made in multi-criteria control of shading systems [30,31], and show that the development of such algorithms is not straightforward. In our experiments, the control strategy worked well for preventing glare from direct sunlight. However, the strategy may have been overly conservative in closing roller shades, at times when daylight admission and view to outside could have been perceived as valuable. It is evident that the specific type of daylight-based control implementation has an effect on user satisfaction and interaction. At this point, it is unclear to what extent the test subjects in our experiment perceived the daylight-based control strategy as 'logical' or 'relating to a clear cause'. In any case, the participants in our experiment did not assess the daylight-based control for changing facade configuration as a big improvement (QB7).

4 Conclusions and recommendations

This paper presented the results of experimental research in a pilot study setting, that aimed at gaining a better understanding of the relationships between automated dynamic facades and human factors. With reference to the hypotheses set out at the beginning of this article, the data from our experiments supports several conclusions.

We found no clear link between automated facade operation and a high risk for disturbance and discomfort. On average, most users reported to have a moderately positive experience regarding the automated dynamic facade. None of the test subjects perceived the changes in daylight aperture and view as *very pleasant*. On the other hand, few respondents evaluated these changes as negative, but in those cases the complaints could be coupled to a clear reason for discomfort or annoyance.

Less frequent, discrete transitions in facade configuration are better appreciated than smooth transitions at higher frequency. In the former case, test subjects found the movement of the facade significantly less disturbing, and reported significantly lower rates of distraction from their work. Additionally, in this scenario more facade adaptations were not consciously detected, which gives further indication of limited disturbance.

The type of control is an important consideration in the design and development process of CABS. Having the opportunity to manually overrule the automated facade leads to significantly higher satisfaction with light levels on the work plane and in the room in general. In addition, with override option, test subjects were more satisfied with the view to outside. This study therefore provides further evidence that the ability for personal control is a basic requirement for enabling successful operation of CABS. The ways of human-technology interaction for these interventions is still a point of attention. This also applies to the development of new algorithms for high performance dynamic facade operation. Results from our experiments do not provide sufficient evidence to conclude that daylight-based facade changes are better appreciated than pre-programmed actions. It was hard to assess in which cases users would understand and appreciate the reason for adaptation, mainly because preventing one type of discomfort sometimes reduces the comfort on other aspects. The balance between preventing glare discomfort and providing enough daylight in the room and a view to outside is an important issue in the control strategy.

Future research should verify the validity of our findings in a wider context with respect to e.g. different orientations, climates, view types and directions, or time of the year. More work is also needed to test the robustness or need for refinement of our findings in subgroups of the population defined by e.g. gender or age. Based on the subjective responses to our questionnaire and observations during the experiments, we recommend the following points of attention for further research and technology development of automated dynamic facades.

Noisy operation tends to be seen as a precarious factor that has the potential to undermine the success of dynamic facade systems as a whole. Our study shows that the sound levels induced by dynamic facades' movement need not to be a problem, on the condition that special care is taken to ensure quiet operation.

Better control algorithms are needed to harmonize the energy-saving potential of CABS with the ambition to improve IEQ in many aspects. Ideally, automated control strategies should more closely resemble occupants' preferences, to help reduce the need for manual interventions and associated disturbance. Future research should focus at developing (i) better control algorithms that limit the number of overrule actions, and (ii) better user interfaces to increase the ease at which manual interventions can be done.

Even though our results are based on an experimental set-up with internal roller shades, the results can be applied in a wider context. The diffusion into practice of other sorts of CABS technology, such as various types of kinetic facade elements, and emerging technologies like electrochromic glazing, will face similar challenges in terms of user interaction and occupant perception.

Acknowledgements

This research project was funded by Agentschap-NL EOS-LT project: FACET (www.eosfacet.nl). This support is gratefully acknowledged. We also thank Somfy Nederland B.V. and Verosol Nederland B.V. for their contributions to the experimental set-up.

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Figure captions

Figure 1: Overview of the experimental facility with roller shades fully opened (left). Small pictures (right) show different facade configurations.

Figure 2: Floor plan of the test room, with the positions and direction of the computer screen relative to the facade. Red triangles indicate horizontal illuminance sensors; red dots indicate vertical illuminance sensors.

Figure 3: User-interface for overriding automated facade control .

Figure 4: Overview of experimental procedure in two sessions and four scenarios. Each of the scenarios was tested with and without the option for manual override. Roller shade positions in scenario 3 depended on daylight conditions and were therefore different in each experiment.

Figure 5: : Schematic overview of the relationships between experimental scenarios and testing of hypotheses. The different patterns, fills and border styles are used to illustrate the translation from scenarios to hypothesis testing.

Figure 6: Overall evaluation with respect to eight indoor environmental aspects (mean and standard deviation). Scores for question 1 to question 6 range from “no discomfort” (0) to “very much discomfort” (100). Scores for questions 7 and 8 range from “very dissatisfied” (-100) to “very satisfied” (100). Numbers on the right indicate the mean values with standard deviations in parentheses. Five subjects were excluded from this analysis, because of too extreme oscillations during scenario 3 and 4.