Adaptive Façades for Activity-Specific Well-Being

Exploring emotional responses with virtual reality and machine learning

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While façades shape interior ambiance through light and shadow, architects lack evidence-based methods to tailor dynamic façades to activity-specific emotional needs. This study tests a novel framework combining Virtual Reality and unsupervised Machine Learning to identify how users configure façade's features (speed, coverage, spread, position) for distinct activities (working, relaxing, socializing). Seventy-five participants customized façades in an interactive environment and rated their emotional states using the Pleasure - Arousal - Dominance model. Analyses revealed both activity-driven preferences (slow-moving, low-coverage façades for work/relaxation vs. dynamic, highcoverage patterns for socializing) and participants' cluster specific trends. Hierarchical Clustering uncovered statistically significant subgroups related to the association between activity, architectural features and emotions. Although these findings need validation across demographics, they demonstrate that Virtual Reality experimentation and Machine Learning clustering can decode activity-specific preferences, offering architects a data-driven starting point for adaptive façade design.

Keywords: *adaptive façades, unsupervised learning, Virtual Reality, Affective Computing, Self-Assessment Manikin, PAD emotional response.*

INTRODUCTION

Architectural façades are more than static barriers between indoor and outdoor. They dynamically mediate the relationship with the environment, shaping spatial perception through their control of light, shadow, and visibility. Early works by (Ulrich, 1984) and (Boyce, 2014) established that façade design—particularly views and daylight—profoundly influences occupants' emotional states. More recently, studies such as those by (Attia et al., 2018) and (Luna-Navarro et al., 2022), suggest that adaptive facades, beyond their superior energy performances, hold potential to intentionally craft atmospheres aligned with occupants' needs (e.g., mimicking cultural motifs as in (Beatini, 2017)). However, architects lack empirical frameworks to reliably translate dynamic façade features - such as motion speed or pattern coverage - into predictable emotional outcomes tailored to specific activities. This gap stems from a disciplinary divide.

- Architectural design often prioritizes technical performance (e.g., energy efficiency, glare control, see Loosen et al. (Loonen et al., 2013)), while
- Methods common in Affective Computing (see (Marín-Morales et al., 2018)), such as Virtual Reality (VR) and Machine Learning (ML), remain underutilized in architectural contexts, particularly for adaptive façades.

In response, this study bridges these fields. Previous VR-based research has assessed the emotional impact of static sunlight-filtering façades (Chamilothori et al., 2019) cross validating responses via self-assessment survey and physiological data. (Beatini et al., 2024) introduced temporal dynamics, correlating single dynamic parameters (e.g., shadow speed) with emotional states using the Pleasure-Arousal-Dominance (PAD) affection framework by Russell & Mehrabian, (1977). However, their statistical analyses could not disentangle complex, nonlinear relationships arising from multiple simultaneous variables. Critically, neither study accounted for occupant activity - a factor central to architectural functionality, distinguishing it from purely aesthetic art.

To address these gaps, this study investigates:

- How users configure adaptive façade features (speed, spread, position, coverage) to align with activity-specific emotional needs (relaxing, working, socializing);
- Whether these configurations correlate with measurable emotional states (PAD); and
- How preferences articulate within users' groups.

By applying ML clustering to user-generated façade configurations, we uncover subgroup-specific patterns that otherwise remain hidden in aggregate analyses (Pantilimonescu et al., 2026). Pilot findings reveal that façade features such as motion speed and pattern coverage elicit divergent emotional responses across activities, with social contexts demanding markedly different configurations than work or relaxation. Demographic differences were minimal but warrant further study due to sample size limitations. These results advance evidence-based strategies for designing façades that address occupants' psychological needs, a cornerstone of human-centric adaptive architecture.

METHOD

Data collection

Experimental setting. A within-subjects design was employed, requiring all participants to configure façades for three activity scenarios: *relax, work*, and *social*.

To ensure generalizability, the study recruited a convenience sample of 75 voluntary participants (50 males, 25 females; age groups: 17 under 25, 40 aged 25–40, 18 over 40; 53 Danish nationals) from public libraries in Aarhus, Denmark. Participants were immersed in a VR environment simulating a neutral 4m × 6m x 4m room with the city's coastal view through an abstract, full-height adaptive glass façade.

The analysed façade features and their range were:

- Shadow velocity, measured by *speed*: 0 cm/s – 30 cm/s
- Spatial irregularity of shadows distribution, measured by *spread*: 0.0–1.0, with 0.0 meaning uniform distribution.
- Vertical placement of patterns, measured by *position*: lower third, middle, upper third, or full façade.
- *Coverage*: 0.0 – 1.0, where 1 = fully opaque.

The first three features were selected from (Beatini et al., 2024) based on their statistically

Figure 1
Customization panel used by participants in VR to adjust the dynamic façade according to preferences and activity

Table 1 alongside the values of the underlying variables.

Concerning the technical setup, a Unity-based VR application allowed participants to control façade geometry—shadow dynamics—via Meta Oculus Quest 2 headsets and hand controllers.

Experimental protocol. After a practice session to familiarize with the interface and PAD assessment, participants received the instruction: "Adjust the façade to create a setting that you would like for [relaxing/working/socializing]. Take as much time as you need. When ready, rate the emotional state this configuration would elicit while performing the activity." To standardize interpretations of activity contexts, the design controller in VR was accompanied by different descriptive keywords for each task: Relaxing - reading, meditating, or painting; Working - focus, computer use, studying, crafting; Socializing - having dinner, hosting friends, celebrating a birthday (Figure 1).

Participants rated their emotional response using the Self-Assessment Manikin (SAM) PAD graphical model by (Bradley & Lang, 1994), embedded directly in the VR interface. The order of activities (relax, work, social) was randomised, to minimise bias linked to a particular timeline. While for the first configuration the participants allocated as much as 5 minutes, for the following two the duration lowered to 1-2 minutes. Thus, the average task duration was 2 min.

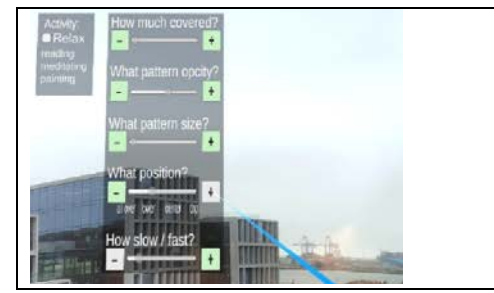


Table 1
Snapshots from the VR simulation and indication of associated features' values

Each participant generated three configurations (one per activity): yielding 225 data points. The dataset included the following.

- The façade's parameters: speed, spread, coverage and position.
- Emotional ratings: pleasure, arousal, dominance.
- Demographic metadata: gender, age and nationality.
- Any additional, oral comment made by the participant during or after the experiment (used to analyse the results)

Ethical Considerations. Participation was voluntary, with informed consent obtained prior to the experiment. Data anonymization ensured participant confidentiality.

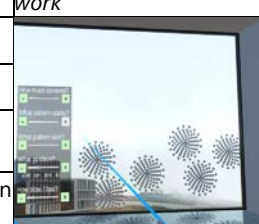
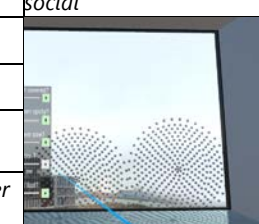
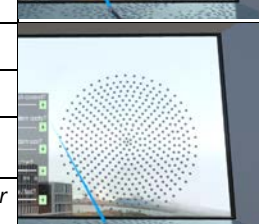
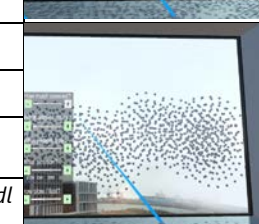
Analysis

Pattern finding with unsupervised learning.

To identify activity-specific façade preferences, a two-stage analysis was conducted:

- Complete dataset: detect broad trends in feature-activity correlations.
- Cluster-level: subgroup finding via unsupervised learning to uncover nuanced patterns (Hastie et al., 2009).

Clusters were derived from façade configuration preferences (PAD scores not included), prioritizing participant-driven design inputs and reflecting the design perspective of the study. Clusters were computed through hierarchical clustering (Ward's linkage, Euclidean distance) and counts were determined using linkage distances and dendrogram structures. The method, detailed in (Yim & Ramdeen, 2015), was chosen for its ability to reveal natural subgroups in small-to-medium datasets while preserving interpretability through dendrograms.

	work		*relax*		*social*	
Spread		*0.20*		*0.43*		*0*
speed		*6*		*6*		*6*
Coverage		*0.21*		*0.01*		*0.10*
position		*lower*		*lower*		*lower*
Spread		*0*		*0.05*		*0*
Speed		*2*		*4*		*10*
Coverage		*0.23*		*0.23*		*0.28*
Position		*all over*		*all over*		*all over*
Spread		*0*		*0*		*0*
Speed		*0*		*4*		*20*
Coverage		*0.12*		*0.12*		*0.12*
Position		*upper*		*middle*		*middle*

Correlation between facade's features and activities.

To identify the existence and strength of associations between activity type (independent categorical variable) and the façade's features (dependent variables: speed, spread, position, coverage), statistical analyses were performed on the whole dataset and on the clustered ones. The analysis workflow comprises Hypothesis Testing, Post Hoc analyses and Effect Size.

In Hypothesis Testing, the null hypothesis H_0 states that a given façade feature's values exhibits no difference across activities. H_0 is rejected for p-values less than 0.05, though values up to 0.15 are also considered relevant to capture marginal trends ((Arias-Castro, 2022)). Kruskal-Wallis tests compared median differences in continuous features (speed, spread, coverage) across activities. Chi-square tests assessed the distribution differences on the categorical variable (position). The resulting p-values were adjusted through the Benjamini–Hochberg correction for multiple comparisons, detailed in (Glueck et al., 2008), to control false discovery rates. Dunn's post hoc tests identified pairwise differences between activity types (work vs. relax, work vs. social, relax vs. social).

The Effect Size (ES) evaluated the strength of the so identified association between activity type and façade features. The resulting η^2 (eta squared) statistic quantified variance in the dependent variable that is explained by an independent variable (Kahn, 2017). According to (Cohen, 2013, p. 285), the thresholds for interpreting η^2 are as follow: large ES for $\eta^2 > 0.137$, medium ES for $\eta^2 \in (0.058, 0.137]$, and low ES for $\eta^2 \in (0.009,\ 0.058]$.

Demographics and emotional expectations.

To examine how these configurations correlate with occupant emotional states, demographic patterns (age, nationality, gender) within each cluster were analysed using frequency distributions. ANOVA with Benjamini–Hochberg correction was used to test for significant differences in emotional responses (PAD) across clusters.

Features patterns within participants subgroups.

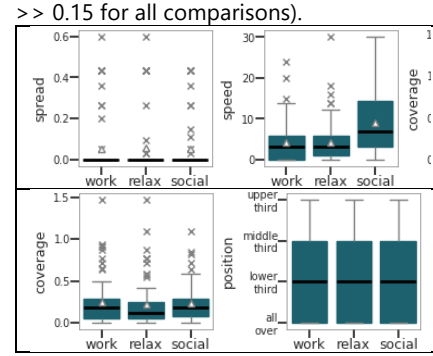
To visualize how preferences articulate within users' groups, Spearman's Rank Correlation explored associations between continuous or ordinal variables such as PAD scores, demographics, and façade features. Synthesizing these analyses identified activity-specific design preferences unique to subgroups, illustrated in correlation graphs and 2D histograms.

Software. The following Python libraries were used: SciPy (correlations), Scikit-posthocs (post hoc tests), Matplotlib and Seaborn (visualisation), Statsmodels (ANOVA) and NetworkX (correlation graphs).

RESULTS

Full dataset analysis

Analysis of the full dataset (n = 225 observations) revealed limited associations between activity type and façade features. Speed was the only variable showing a statistically significant association with activity type (p-value = 0.00, Kruskal-Wa llis test / Chi-square test), Table 2. Position, spread, and coverage exhibited no significant differences across activities (p-value >> 0.15 for all comparisons).



Social activities elicited higher median speeds (7 cm/s) compared to work and relaxation (both 4 cm/s). Effect sizes for these associations were uniformly small ($\eta^2 < 0.06$), indicating that activity type explained minimal variance in façade preferences at the aggregate level. This trend is visualized in Figure 2, where similar interquartile ranges across activities underscore the weak discriminative power of most features.

Clustering appraisal

Cluster Identification. Hierarchical clustering revealed four subgroups of participants (Figure 3). With reference to Figure 4the participants distributed as follows:

- Cluster 0: no discernible demographic trends (10 participants).
- Cluster 1: no discernible demographic trends (10 participants).
- Cluster 2: mostly Danish, aged 25–40 (29 participants).
- Cluster 3: mixed age (26 participants).

Demographic trends were largely inconclusive due to sample homogeneity: 67% of participants were male and 71% were Danish. While Cluster 2 hinted at nationality/age correlations, the overrepresentation of Danish males precluded the possibility to reliably characterize the clusters' demographics.

Table 2
p-values indicating the statistical significance of associations between activities and façade's features.

Façade feature	p-values across activities
spread	0.89
speed	0.0
coverage	0.89
position	0.89

Figure 2
Boxplots computed across the full dataset, describing the preferred values of the façade's features for different type of activity.

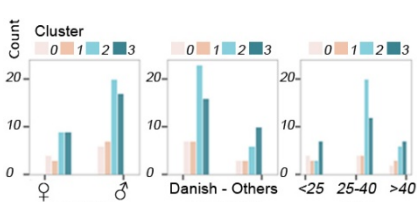


Figure 3
The clustering dendrogram suggests the presence of four clusters

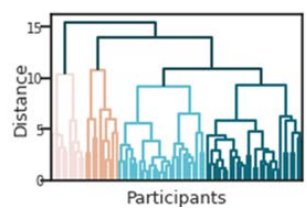


Figure 4
The demographics across clusters was scattered, with the exclusion of Cluster 2.

Façade Feature-Activity Associations. Clustering by façade preferences significantly enhanced the discernibility of activity-specific patterns.

As reported in Table 3, Clusters 0, 2, and 3 exhibited statistically significant associations between activity type and façade features, with p-value < 0.05, (Kruskal-Wallis / Chi-square tests with Benjamini-Hochberg correction), alongside high ($\eta^2 > 0.137$) or medium size effect ($\eta^2 \in (0.058, 0.137]$). Spread and speed showed meaningful size effect in two out of the four clusters, suggesting their critical role in activity-driven preferences. Coverage has a significant association with the

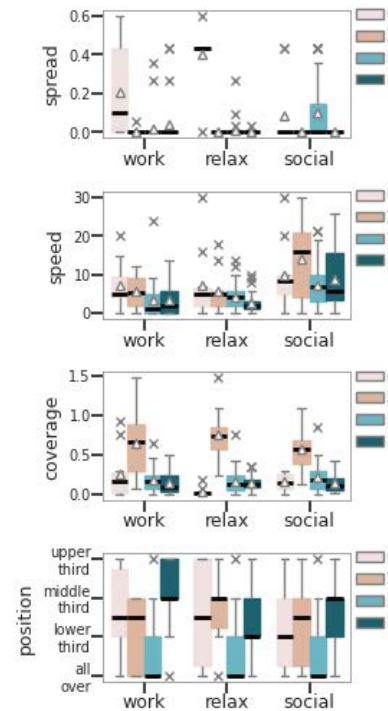
preferences of Cluster 0, albeit with medium size effect.

Social scenarios consistently diverged from work/relaxation, reporting high or medium differences in all the façade features early identified as significant for the clusters (Table 4, Dunn's post hoc tests). This suggests that certain design decisions may be appropriate for both working and relaxing contexts but could prove unsuitable for social scenarios.

cluster		0	1	2	3
No. of participants		10	10	29	26
spread	p	0.03		0.00	0.23
	η^2	0.26		0.11	0.02
speed	p			0.00	0.00
	η^2			0.11	0.17
coverage	p	0.04			
	η^2	0.19			
position	p				0.11
	η^2				0.10

cluster		0	1	2	3
spread	w-r				
	w-s	0.00		0.00	
	r-s	0.10		0.00	
speed	w-r			0.11	
	w-s			0.10	0.00
	r-s			0.00	0.00
coverage	w-r				
	w-s	0.03			
	r-s	0.04			
position	w-r				0.01
	w-s				0.02
	r-s				
*w=work; r=relax; s=social					

Emotional Response Trends. To understand whether the facade configurations link with measurable emotional states (PAD), the Anova test for mean differences was conducted -Table 5. When changing activity type, arousal was the only PAD dimension showing significant differences. Arousal showed significant correlation in cluster 2 (p-value=0.02) and cluster 3 (p-value=0.00), and marginal correlation in cluster 0 (p-value=0.08).



Participants configured façades to elicit progressively higher arousal from relaxation scenarios, work, and social activities, with specific values differing from cluster to cluster (Figure 5). Pleasure and dominance showed minimal variation across activities: pleasure remained high overall, likely due to participant control over façade customization. Dominance scores were skewed upward, with a slight dip for cluster 1, reflecting the empowerment inherent in user-driven design, as well as a desire to feel in control of the surrounding constructed environment.

	Cl. 0	Cl.1	Cl.2	Cl 3
Pleasure	0.95	0.69	0.48	0.94
Arousal	0.08	0.51	0.02	0.00
Dominance	0.95	0.69	0.91	0.94

Cluster-level insights

Figure 5 reports the cluster-based boxplots describing the preferred values of the façade features for different type of activity. As expected, the complex nature of interaction between façade features makes it difficult to gain insights on how different features interact in determining groups' preferences. For this scope, two visual tools were employed. Correlation Graphs (Table 6) illustrate monotonic relationships (Spearman's Rank non-parametric correlation) between variables (e.g., "Does higher speed correlate with lower coverage?"), alongside the p-value (correlation significance) and r-value (correlation strength and direction). Line thickness indicates correlation strength. 2D Histograms (Table 7) map frequency of co-occurring variable values (e.g., "How often do high speed and low coverage appear together?"), reported by an increased colour density. Variables deemed non-significant according to medians (Figure 5) were included for improved visual understanding.

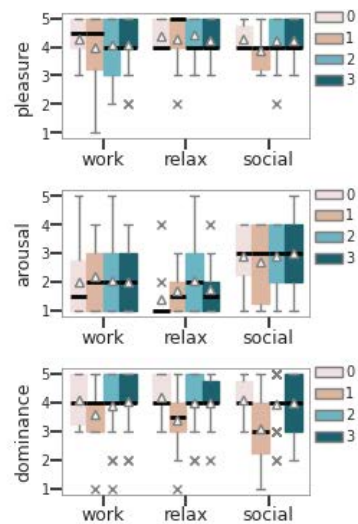
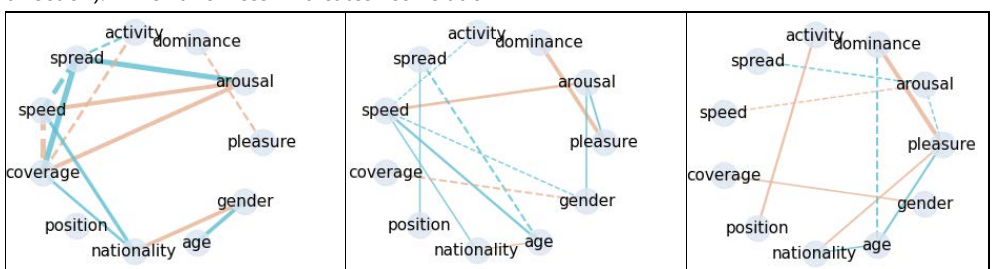


Figure 5
Cluster-based boxplots describing the preferred values of the façade features for different type of activity.

Table 3
Statistically significant correlation (p-values) and effect size (η^2) between clusters and façade features were identified.

Table 4
Post hoc Dunn's test for pairwise comparison between activity pairs (w: work; r: relax; s: social) shows that social scenarios differ in at least one feature across all significant clusters.



Cluster 0, $r \in [-0.78, 0.58]$	Cluster 2, $r \in [-0.33, 0.53]$	Cluster 3, $r \in [-0.29, 0.58]$
p-values $\in [0.00, 0.15)$, dashed line where p>0.05, r indicates widths of the connections		

Table 5
Association between PAD dimensions and clusters when changing activity type.

Figure 6
Cluster-based boxplots describing the elicited emotional PAD dimensions for different type of activity.

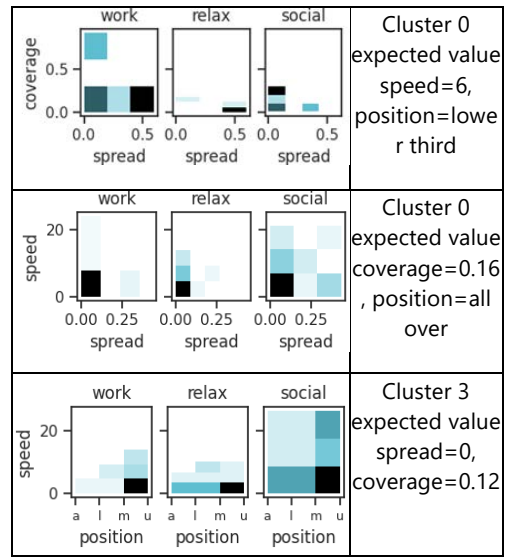
Table 6
Spearman's rank correlation graphs for clusters 0, 2, and 3, illustrating relationships between emotional responses, façade features, activity and demographic data. Orange connections indicate positive correlations, while blue connections represent negative correlations between nodes.

Cluster 0. This cluster preferred vertical positioning of opaque elements below eye level and non-overlapping, predictable shadow patterns (as in Table 1, Row 1).

From Tables 3-4, spread (η^2 = 0.26, p-value = 0.03) and coverage (η^2 = 0.19, p-value = 0.04) differed significantly across activities. Looking at the 2D histograms (Table 7), the facades they designed for relaxation scenarios were sharply defined, with high spread and low coverage (transparent façades). Facades designed for social activities were also well defined and presented uniform shadows (spread ≈ 0) and high opacity (coverage = 0.4) (Table 7). In work contexts they showed flexibility, but still tended to prefer non-uniform shadows (Table 7) (spread > 0.2 with low coverage.

The correlation graph (Table 6) showed spread inversely correlating with coverage (r= -0.78, p-value < 0.01) and speed (r= -0.64, p-value < 0.01). Also, uniform shadows (spread ≈ 0) linked to higher arousal (r= -0.72,p-value < 0.01). Overall, this group prefer thereof intimate, enclosed settings for social activities, perceiving it as more arousing, but preferred open settings for working and especially relaxing.

Cluster 1. Here, as mentioned, no significant activity-related differences emerged (Table 3 reports p-value > 0.15 for all features), suggesting either inconsistent feature sensitivity or misalignment between measured variables and subjective preferences.



Cluster 2. Participants in cluster 2 designed tendentially uniform, organic shadow patterns across the façade, as those exemplified by row 2 in Table 1.

Figure 6). They had more flexibility both in terms of speed and spread for socializing, welcoming some irregularities in shadows (spread ≤ 0.4) and higher speeds (median = 7 cm/s).

The correlation graph (Table 6) indicated that dominance was key to a feeling of pleasure, and certain preferences were based on gender. Females under 25 preferred higher speeds (r= -0.33, p-value = 0.01), while males tended to favour higher coverage (r = -0.2, p-value= 0.13), a trend also observed in Cluster 3.

Cluster 3. This cluster tended to prefer medium-to-low coverage façades emphasizing connection to the outdoors and higher levels of speed (row 3 Table 1).

From the previous results, speed (η^2 = 0.17, p-value < 0.01) and position (η^2 = 0.10, p-value = 0.01) were the variables with meaningful variation across activities (Table 3 and 4). Looking at the 2D histogram (Table 7), preferences for relaxing and working activities were the most well-defined, albeit not as sharply as in the other groups. In work scenarios, the preferred position was upper-third coverage, and speed was medium-low (≤5 cm/s) (Figure 5), suggesting a need for visual shielding without dynamic distraction. In relaxation scenarios, speed was low but accompanied by a slightly increased flexibility in position – still in the medium-upper part of the façade. On the contrary, for social activities, they selected also particularly high speeds (15–25 cm/s), alongside variable façade coverage. Higher speed was accepted in social contexts only if upper coverage maintained a sense of enclosure (Figure 5).

This indicates that, while members of this cluster are open to dynamic façade behaviour, it is contingent on maintaining a sense of enclosure from above, with minimal distraction at eye level. This is confirmed by the correlation graph (Table 6), which links dominance with pleasure, (as in cluster 2), further inversely correlating dominance and age. The same gender -based trend observed in cluster 2 was reported here.

DISCUSSION

The cluster-based analysis reveals critical nuances in how users associate façade features with activity-specific emotional needs. Three overarching themes emerge.

Social contexts (e.g., hosting friends) consistently demanded dynamic, enclosed façades (high speed/coverage in Clusters 0, 3). Work/relaxation activities favoured calm, predictable patterns (low speed, semi-transparency in Clusters 0, 2), reflecting a need for focus or serenity. From a design perspective, it can be derived that adaptive façades should prioritize adjustable speed/coverage for social zones, while work/relaxation areas benefit from static or slow-moving, semi-transparent designs.

The cluster insights indicated personalization potentials. Cluster 0 preference for enclosed social spaces vs. open work/relaxation settings suggests a subgroup sensitive to privacy-connectivity trade-offs. The gender/age trends (e.g., younger females preferring higher speeds) that emerged in clusters 2 and 3 highlight the potential for demographic-driven personalization in adaptive façades. Finally, the appreciation by Cluster 3 for high-speed façades only with upper coverage (to maintain enclosure) underscores the importance of perceived control in dynamic environments. As a design takeaway, it emerges the potential for facades to integrate user profiles (age, gender, activity) to auto-adjust features like speed or coverage, balancing stimulation and comfort.

From a methodological viewpoint, the interplay between spread, speed, and coverage (e.g., inverse correlations in Cluster 0) would remain masked in conventional analyses. ML clustering exposed hidden subgroup preferences, demonstrating its value for occupant-centric design. Early-stage VR simulations paired with ML can identify user-specific design priorities, reducing reliance on intuition or one-size-fits-all solutions.

It was also noted that most clusters aimed for high dominance across activities, whereas Cluster 1 in social settings felt comfortable with lower dominance and preferred more dynamic, fast-

Table 7
2*D* histograms illustrating the distribution of significant façade features within each cluster.

moving façades. This pattern suggests an opportunity to enhance perceived control for socially anxious individuals by carefully adjusting façade features to balance stimulation and comfort.

LIMITATIONS

The minimalistic VR setting may not fully replicate real-world perceptual complexity, reducing ecological validity. To avoid noise, the study intentionally presented a simplified façade, which does not connect to a specific cultural context.

It is well - known that spatial appraisal relates to culture (Pantilimonescu, 2020). The abstract façade (Cluster 0's "intimate" social settings) may not translate to contexts where cultural motifs shape spatial perception (e.g., Middle Eastern latticework).

Concerning the emotional assessment, PAD ratings were collected on an ordinal, 5-point scale, treating subjective interpretations as discrete intervals rather than continuous measures.

The convenience sample (75 participants, predominantly Danish male) limits generalizability to broader demographics and cultural groups. Gender/age trends in Clusters 2/3 are suggestive but require validation in balanced, diverse samples.

CONCLUSION

This study positions façades as emotional interfaces, dynamically modulating occupants' pleasure, arousal, and dominance. A pilot method was employed in which data collected through a VR-based self-assessment survey were statistically analysed at both the aggregate and cluster levels, with the latter identified through unsupervised ML.

By framing findings against H_0 (no activity differences), the study proves façades require activity-specific tuning. A notable takeaway is that social activities require distinct façade settings compared to work or relaxation scenarios.

Coupling VR-based emotional assessment with ML clustering bridges the gap between architectural intuition and data-driven design, uncovering patterns obscured in aggregate analyses. ML clustering revealed three subgroups with divergent preferences involving speed, spread, and position.

From a designer's viewpoint, social activities demand distinct façade configurations (higher speed, coverage) compared to work/relaxation, which favour slower, semi-transparent designs. The study suggests using speed thresholds (e.g., ≤5 cm/s for work) to preconfigure façades for generic activities while allowing user customisation for subgroups (e.g., Cluster 3's high-speed social façades).

Future studies should replicate the experiment with larger, culturally diverse cohorts to test the robustness of observed trends. Eventually, it would be worth comparing the VR findings with extended reality or physical prototypes to assess perceptual gaps between simulated and built environments and extend the study to more nuanced façade variables, such as pattern texture or transient light effects.

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