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Azin Akbarzadeh

Islamic Azad University

Javad Asadpoor

s.ja.1075@gmail.com

Islamic Azad University

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A Review of the Impacts of Façade Features on UNI and Occupants' Perceptual Reactions in Apartment Housing

Azin Akbarzadeh¹, Javad Asad Poor^{1,*}

1. Department of Architecture, Ma. C., Islamic Azad University, Mashhad, Iran

*. Corresponding Author, Email: sja.1075@gmail.com

Abstract

Urban Noise Islands (UNI) has become a crucial issue to face, especially by considering the impacts of apartment building facade properties on energy consumption due to occupants' UNI-related perceptual reactions. In this view, UNI is able to produce serious threats at apartment buildings scale on occupants' perceptual reactions. There is any comprehensive approach to mitigate UNI especially in apartment housing architectural scale, and in relation to its impacts on energy consumption. The main objective of this article is to explain the impact of facade architectural properties of apartment buildings on mitigating UNI effects on occupants' perceptual reactions through a cross comparison of the previous studies. Apartment building facade has a moderator role in the correlations between residents' perceptual reactions and noise. According to literature facade architectural properties can reduce noise levels into tolerable and acceptable levels. The façade properties influence the propagation and reflection of sound waves. Sound reflection can be tuned by modifying the facade geometry. Some studies reported the correlation between wall diffraction, opening position, and mitigation in sound pressure level. The review of selected studies resulted in the classification of the UNI-related façade features into four main architectural categories, including façade geometry, surface properties, add-on elements, neighborhood quality. These findings suggest the ability of apartment building facade properties to mitigate noise levels and improving occupants' perceptual reactions especially in relation to use AC/NV as the key-criterion for reducing the overall energy consumption, and UHI.

Keywords: Apartment housing, UNI, Façade features, Occupants' perceptual reactions, Energy, UHI.

Introduction

Urban Noise Islands (UNI) has significant impacts on occupants' perceptual reactions [1-3]. Given the UNI negative effects on occupants' perceptions, they prefer to stay indoor areas of their dwelling units, which in turn lead to more frequent use of Air conditioning (AC) [4-5]. Using AC leads to the increase in Urban Heat Island (UHI) effects, and hence,

more AC demands in return [2-3]. Although, UNI is not a well-documented phenomenon, it is known as a harmful urban issue [1]. It is indicated that a 10 dB noise mitigation measure improve natural ventilation (NV), which could reduce summer temperature between 2.0°C and 3.4° C [3].

Many people across the world are living in noise levels higher than WHO standards (53 dB day, 45 dB night) [6]. In 2013, 65% of the total the European Union (EU) population was reported as exposed to traffic noise levels exceeding the upper standard levels [1]. 32% of over 30000 Europeans In, 2016_2017, experienced noise problems near their home close neighborhoods [7]. The local noise islands that form deteriorate noise comfort in the outdoor environment, negatively affect indoor comfort [1-2, 4]. There is a positive correlation between noise exposure and stress [8], insomnia [9], anxiety symptoms [10], depressive symptoms [11], mental health [12-13], cardiovascular disease [14], premature deaths [15]. According to European Environment Agency (EEA) [16] report, 66,000 premature deaths annually in Europe, 50,000 new cardiovascular disease cases and 22,000 cases of type 2 diabetes are related to chronic exposure urban noise.

Rapid development and densification of apartment housing types in urban living areas caused noise problems from multiple sources e.g. motor vehicle, construction, etc. [17]. Apartment housing has been introduced in urban areas to meet the needs of industrialization since the 1970's [18]. Reasons such as increase in buildings density, alongside increase in construction areas which means the growth in the use of cement, concrete and asphalt and motor vehicle in urban neighborhoods are also some another reasons contributed to the UNI increase [4, 19]. The majority of studies have focused on traffic noise mitigation [1], e.g. low noise engines, reduction of traffic density, development of public transportation for offsetting UNI. The actual traffic noise level depends on apartment building facade features and neighborhood quality e.g. density, height, and road width [20].

Apartment building facade as one of the most important components of UNI intensification, mitigation, and control, could also impact UNI-related buildings energy performance [21]. For instance, facade features could mitigate UNI and facilitate natural ventilation (NV) [1-2, 21-22]. In apartment buildings NV, as passive cooling, can quickly reduce the temperatures up to 9 °C [23-24]. This is particularly important in densely populated apartment buildings with a hard reflective facade built from glass, stone, and metal [6, 25-26]. Appropriate facade features can possibly decrease the UNI effect and hence, moderate occupants 'perceptual reactions [2-3, 22, 27].

While insightful, the evidence on UNI mitigation confronts serious limitations [28]. Apartment Building facade can function as a sound reflector or absorber in urban noise islands dependent on their geometry and materials, which were not gained proper paid attention so far [25]. There is not any comprehensive approach to the correlations between UNI mitigation and the urban geometry and the buildings [1, 19, 29], especially the impacts of this correlation on occupants 'perceptual reactions [22]. Therefore, the

previous studies have seldom paid proper attention to the role of buildings, and particularly the role of apartment housing façade features in UNI mitigation, which needs special consideration in the future studies.

The main objective of this review paper is to explain the impacts of UNI-related facade features on UNI and occupants' perceptual reactions based on previously conducted studies to respond to the following research questions:

What features of facades and their surrounding neighborhoods are involved in the generation of the UNI effects, and its impacts on the occupants' perceptual reactions?

What are the effects of facades features on the UNI, and the occupants' perceptual reactions?

The required data were gathered from the previously conducted studies on the effects of apartment buildings facades on the UNI and/ or the occupants' perceptual reactions (prefer NV/ AC). This study first describes the methods and materials adopted in searching, identifying, and selecting the previous works, alongside the software and analysis techniques that are employed to analyze the gathered row data. The study presents the result of the analysis in different tables to explain the role of different facade features and neighborhoods parameters in impacting UNI and occupants' perceptual reactions. Finally, a brief discussion on the results and conclusion of the study are the last parts of the paper.

2. Methods and materials

Since the creation of the decibel unit in the 1920s, measurements of the sound pressure level have been continuously used to concretely assess the noise level [30]. Urban Noise Islands (UNI) which is defined as the higher level of noise in urban centers with high traffic density compared to the surrounding rural areas [1-2] is an indicator of noise level pressure in urban environment. A wide range of studies has been conducted to assess the interplay between UNI and the different aspects of urban environment, e.g. people, buildings, and climate (e.g. [1-3]). Given the main objective of this paper, this section addresses the methods and materials employed to review the interplay between UNI and apartment housing facade, occupants' perceptual reactions, and energy and urban heat island (UHI) as some of the most important aspects of the urban environment.

2.1. Search strategy and Criteria

This paper was conducted on the basis of in depth review of a number of peer-reviewed publications including journal papers, book chapters, and thesis published in English published in the period of 2003-2025. The initial selection criteria of the publications were their relationships with the central keywords of this paper including apartment housing façade features, urban noise island (UNI), and occupants' perceptual reactions. The selection of studies was carried out using a number of well-known academic and scientific online databases, e.g. Pub Med, Scopus, Science Direct, and web of science, by manually searching the keywords in engine search of these databases.

The search keywords intend to intersect the fields of apartment housing facade (“facade” or “apartment housing envelope”), outdoor urban environment (“urban” or “city” or “outdoor”), UNI (“noise” or “sound” or “acoustic”), and indoor occupants perceptual reactions (“health” or “well-being” or “behavior”). After initial identification of a publication, a first round of review was made on the content of the paper, to select the most reliable and deeply related studies. Eventually, 36 articles out of 167 initially screened publications were considered as the most suitable research works for the further considerations, and selected as the main sources of the database of this study.

2.2. Data extraction

Information was extracted from each of the selected study on: (1) noise measure(s); (2) UNI-related facade features measure(s); (3) sound levels and corresponding metrics, and then considered to define exposure conditions and levels; and the lateral positive/negative effect(s) of UNI on occupants’ health, wellbeing, and behavior.

Considering the differences in the metrics across the different studies, a quality assessment and quantitative meta-analysis were not possible [31]. Therefore, a qualitative approach to data synthesis was adopted to answer the review question.

2.3. Synthesis of extracted data

The extracted articles were analyzed on the basis of the publication year and UNI-related facade features: Geometry, Surface Properties, Add-on Elements, and Neighborhood Quality [25]. The following is a definition of each the main areas of façade features.

Given the literature:

- Façade geometry (FG) is the building facade three-dimensional surface shape and formal features that often acts as sound reflecting and/or scattering, and specifically related to building facade architecture [25, 32-33].
- Surface properties (SP) are the appearances of the facade surface materials that have sound absorbing or reflective impacts on UNI [32, 34]. In other word SP is related to Cladding Elements which is defined as the outer covering of a building’s facade (e.g. stone, brick, metal, glass, composite panels) [1-2, 32-33].
- Add-on elements (AE) can be categorized into three main groups including natural elements (e.g. Green walls, vegetated low screens at roof edges, etc.), ornaments (e.g. louvers, eaves, etc.), and functional elements (sound absorber shielding, Muffler, etc.) that add to the building envelope other than geometry and appearance features and have effects on UNI mitigation [34].
- Neighborhood quality (NQ) refers to the impacts of materiality and shape of surrounding environment surfaces on UNI-related facade features [33, 35-36].

The reviewed articles could be categorized into two areas including studies related to UNI-related façade features and studies related to UNI-related occupants’ reactions, which will be addressed in the next sections.

2.3.1. Studies related to UNI-related housing façade features

A wide range of studies have been done in the area of UNI-related facade features [37]. An initial screening of these research works and given the outputs of these studies in relation to the UNI-related façade features made it possible to develop an overall categorization, which can be categorized into four different groups including: studies looking at façade geometry [e.g. 3, 20, 25-27, 30, 38-42], studies related to surface properties [e.g. 1-3, 17, 25, 27, 30, 38, 40, 42-45], studies looking at add-on elements [e.g. 3, 25, 39, 42, 46], and studies related to neighborhood quality [e.g. 3, 17, 19, 29, 35, 40, 45, 47]. Table 1 provides a summary of the studies conducted on the four architectural categories of UNI-related façade features (Geometry, Surface Properties, Add-on Elements, and Neighborhood Quality).

Table 1. Studies related to four architectural categories of UNI-related façade feature

Architectural Categories	Year	Ref.	Doi.
FG	2007	[38]	doi:10.1016/j.buildenv.2006.10.044
	2012	[3]	uk.bl.ethos.577350
	2013	[39]	https://doi.org/10.1016/j.buildenv.2012.12.001
	2015	[40]	https://doi.org/10.1016/j.egypro.2015.11.246
	2017	[20]	https://doi.org/10.1080/23744731.2016.1262708
	2017	[26]	https://doi.org/10.7480/jfde.2017.1.1422
	2020	[25]	https://doi.org/10.1016/j.buildenv.2020.107121
	2020	[41]	https://doi.org/10.1016/j.buildenv.2020.106733
	2022	[30]	https://doi.org/10.3390/su14159670
	2024	[42]	https://doi.org/10.1177/14780771241260852
	2024	[27]	https://doi.org/10.3390/su16177855
SP	2012	[3]	uk.bl.ethos.577350
	2015	[40]	https://doi.org/10.1016/j.egypro.2015.11.246
	2018	[43]	https://doi.org/10.1016/j.matdes.2017.10.016
	2018	[44]	https://doi.org/10.1016/j.coco.2018.05.001
	2020	[25]	https://doi.org/10.1016/j.buildenv.2020.107121
	2020	[1]	https://doi.org/10.1088/1748-9326/abaa0d
	2020	[45]	https://doi.org/10.3389/fpsyg.2020.00344
	2022	[30]	https://doi.org/10.3390/su14159670
	2022	[17]	https://doi.org/10.1016/j.buildenv.2022.109526
	2024	[42]	https://doi.org/10.1177/14780771241260852
AE	2012	[3]	uk.bl.ethos.577350
	2013	[39]	https://doi.org/10.1016/j.buildenv.2012.12.001
	2015	[46]	https://doi.org/10.1016/j.buildenv.2015.05.015
	2020	[25]	https://doi.org/10.1016/j.buildenv.2020.107121
	2024	[42]	https://doi.org/10.1177/14780771241260852
NQ	2012	[3]	uk.bl.ethos.577350
	2013	[47]	https://doi.org/10.3813/AAA.918619
	2015	[40]	https://doi.org/10.1016/j.egypro.2015.11.246
	2019	[35]	https://doi.org/10.1080/23748834.2019.1624332
	2020	[45]	https://doi.org/10.3389/fpsyg.2020.00344
	2022	[30]	https://doi.org/10.3390/su14159670
	2022	[17]	https://doi.org/10.1016/j.buildenv.2022.109526

Source(s): Author's own creation

Table 2 also represents a number of researchers and scholars studying the different areas of UNI-related facade features (e.g. geometry, surface properties, add-on elements, neighborhood quality).

Table 2. Different UNI-related Facade Architectural Categories mentioned by the different researchers. (+ Mentioned 0 Not Mentioned).

Ref.	FG	SP	AE	NQ
[38]	+	o	o	o
[3]				+
[39]				o
[47]				+
[40]				+
[46]				o
[20]				o
[26]				o
[43]				o
[44]				o
[35]				+
[1]				o
[25]				o
[45]				+
[41]				o
[30]				+
[17]				+
[42]				o
[27]				o
[2]				o

Source(s): Author's own creation

2.3.2. Studies related to UNI-related occupants' reactions

Table 3 also provides a brief classification of the extracted articles on the basis of publication year and UNI-related occupants' perceptual reactions, i.e. wellbeing, health, and behavior.

Table 3. 3 categories of UNI-related occupants' perceptual reaction studies

Occupants perceptual reactions	Year	Ref.	Doi.
Well being	2003	[5]	https://doi.org/10.1016/S0378-7788(02)00075-0
	2015	[66]	https://doi.org/10.1007/s40572-015-0069-5
	2019	[65]	http://dx.doi.org/10.1016/j.cacint.2020.100021
	2019	[73]	https://doi.org/10.1016/j.scs.2019.101647
	2019	[4]	https://pmc.ncbi.nlm.nih.gov/articles/PMC7183564/
	2021	[60]	https://doi.org/10.3389/frsc.2021.644418
Health	2018	[8]	https://doi.org/10.1016/j.envpol.2018.07.022
	2019	[11]	https://doi.org/10.1146/annurev-publhealth-040218-044106
	2020	[9]	https://doi.org/10.3390/ijerph17186621
	2020	[10]	https://doi.org/10.1016/j.envres.2020.110118
	2021	[14]	https://doi.org/10.1038/s41569-021-00532-5
	2021	[13]	https://doi.org/10.1016/s0140-6736(21)02629-5
	2022	[12]	https://doi.org/10.3390/ijerph19052809
Behavior	2019	[73]	https://doi.org/10.1016/j.scs.2019.101647
	2019	[4]	https://pmc.ncbi.nlm.nih.gov/articles/PMC7183564/
	2021	[69]	https://doi.org/10.3390/earth2030038
	2024	[68]	https://doi.org/10.5772/intechopen.1006205
	2026	[75]	https://doi.org/10.1016/j.eiar.2025.108100

Source(s): Author's own creation

3. Results

3.1. Summary

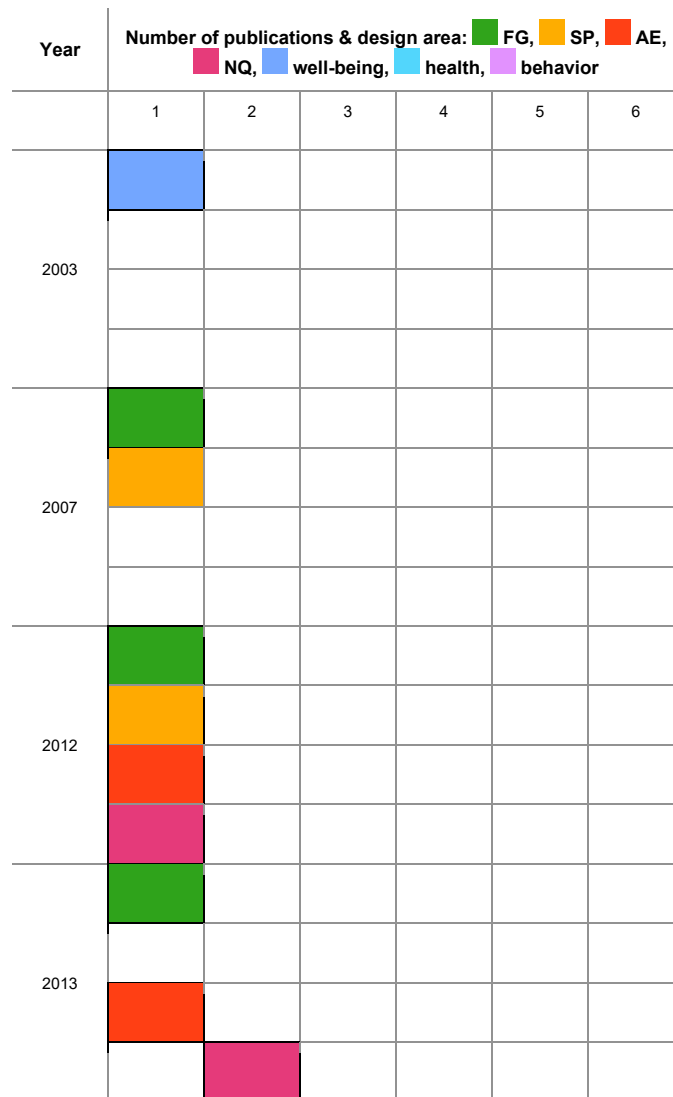
In the case of UNI-related facade features 20 out of 36 studies including journal articles, book chapters, and thesis were published 2007 upward. Given the architectural categories, the Geometry (FG), Surface Properties (SP), Add-on Elements (AE), and Neighborhood Quality (NQ) were considered for further investigations. Each architectural category comprised different components/features [25].

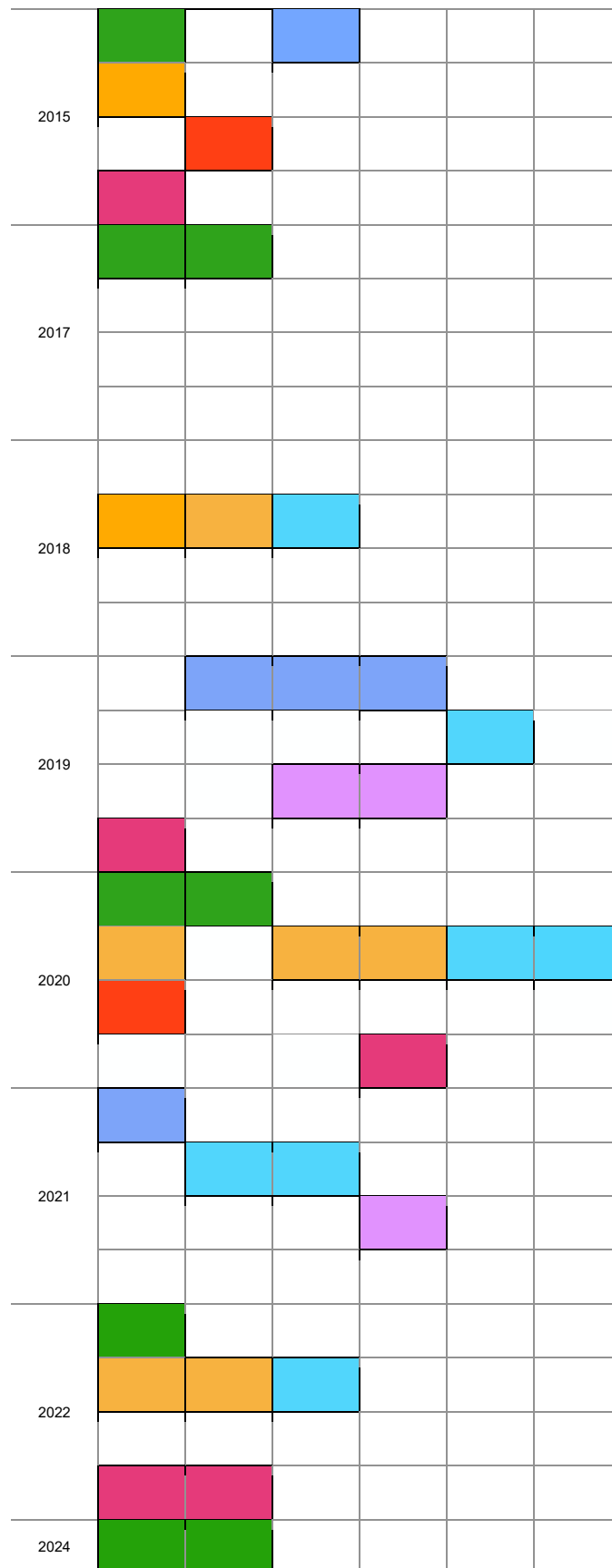
In the case of occupants' perceptual reactions 16 out of 36 studies including journal articles, book chapters, and thesis were published 2003 upward. Occupants' perceptual reactions include three core-concepts, i.e. health, well-being, and behavior. Given the concept of health the definition provided by WHO definition which is "a state of complete physical, mental and social well-being and not merely the absence of a disease or infirmity" provides a suitable platform for the study [4].

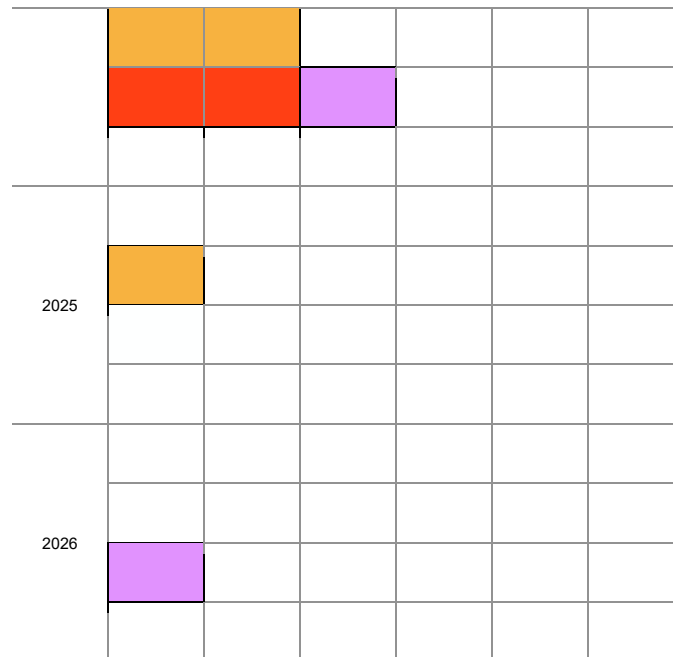
Figure 1 presents the number of publications published per year from 2003 to 2026 (n = 36) with differentiating the studies that focused on the role of façade features in noise mitigation in which the decibel level is the main descriptor (n = 20) and studies that focused on the occupants' perceptual reactions in which residents reported reactions of the UNI is the main descriptor (n = 16).

In the UNI-related facade features studies, 8/11 in FG, 8/12 in SP, 3/6 in AE, and 6/7 in NQ aimed to improve occupants' perceptual reactions (health, wellbeing, and behavior). In other words, 14 of the 20 studies overlapped with occupants' perceptual related articles. This number is a strong indication of the importance of housing facade features in reducing UNI-related effects and the need to examine their correlation.

Fig 1. Number of selected publications per year in four façade architectural categories and three occupants' perceptual reaction categories







Source(s): Author's own creation

3.2. UNI-Related Housing Facade Features

In this section, UNI-related façade features are explained on the basis of the conducted literature review. The features are addressed in four architectural categories including FG, SP, AE, and NQ.

3.2.1. Facade Geometric Features

[38] investigated the effect of apartment housing facade design on the reduction of UNI. They measured the noise from traffic at an apartment near the road side. They result indicated that balcony's inclined ceiling and parapet by adding absorbing surfaces provide noise reduction between 10-16 dB. Incidence Angels have correlation with noise mitigation [38].

[3] studied the interaction between energy use, ventilation, and urban noise. He calculated the sound transmission through the ventilation openings. This study revealed that opening geometry is important in the level of noise transmitted through the building façade [3, 20]. The acoustic requirements of building can interact with the natural ventilation (NV) of building and impact directly the cooling energy demands [3]. Cooling energy consumption for a building located in a relatively quiet place with lower noise level can reduces between 22% and 45% [3]. This study indicated that the untreated apertures would give the façade a Sound Reduction Index (SRI) of 20dB, whereas the same airflow could be provided with double louvers that gave the façade an SRI of 31dB.

Likewise, [20] also emphasized the significance of NV in using outdoor air to improve the air quality of the indoor environment, and hence in reducing building energy consumption.

However, NV systems can create an acoustical problem due to the direct exposure of the indoor environment to the outside. The study of [20] showed that the wall diffraction and opening position mitigate the traffic noise level due to path differences between direct and indirect sound. In particular, high-frequency noise is significantly reduced by the effects of these two objects. Their study also described the noise mitigation effects of various façade elements, such as building envelope, location of openings, opening ratio, and indoor boundary conditions.

[27]' Study have found that upward horizontal tilting in louvers and a higher repetition of eaves also contribute to noise reduction, and reported a correlation between protruding elements in a façade and a reduction in sound pressure levels.

In the study of [39] building geometry was addressed for its impacts on sound reflection and propagation. According to this study, the use of concave and triangular shapes in the facade geometry causes an almost 8.4 dB reduction in noise levels on the upper floors of an apartment building.

According to the [40] the façade with balconies change the UNI effects near the facade for all the widths of the road. Balconies can influence the noise field and their appropriate design could contribute to the effective noise control.

Regarding Geometric features. [26] investigated the effect of the facade surface modification on noise reflection.

The study of [41] quantified acoustic reflection from facades of three buildings, each of which has an array of concave rectangular shapes (deep rectangular balconies, sawtooth façade with corner cubes, and recessed retroreflective windows). They found that facades with concave right-angles have acoustic retroreflection. Their reflections are stronger than flat facades and some facades focus acoustic energy [41].

Finally, [42] described the sound scattering performance of certain types of facade geometries. Putting such findings together provides a suitable platform for a continuous improvement of facade quality during pre-design and design stages, which leads to a more efficient and sustainable performance of building during operation stages and the whole lifecycle of building.

3.2.2. Facade Surface Properties

The potentials of façade materials in both types of natural or artificial in the UNI mitigation have been also addressed by some researchers [43-44]. Noise absorbent materials can be divided into two categories: porous absorbers with a wide frequency absorbing and resonance absorbers with a low frequency absorbing [1-2]. Porous materials are an ideal solution for noise absorption in building facades because of their wide frequency sound absorption, cost-effectiveness, and low environmental impacts [1-2].

[43] studied sound absorption nickel-based superalloy open-cell foams. This foams which have a high sound absorption with coefficient of up to 0.95 at 1728 HZ can be effective in UNI mitigation.

[44] studied porous materials noise absorption qualities. They clearly demonstrated that physical factors e.g. thickness, density, and porosity have significant contribution on sound absorbing.

[1] presented the previous mitigation techniques of UNI by surface properties and described the innovative solutions for dealing with UNI. They analyzed sound absorbing materials under three main headings (porous, resonant, and meta materials). According to [43] Porous absorbers perform well in medium to high frequency e.g. traffic noise, while resonant absorbers perform well in low frequency e.g. indoor sounds.

3.2.3. Facade Add-on Elements

The study of [39] investigated the potential of 3 types of add-on elements (green roof, green wall, and vegetated low-height noise barriers/screens positioned near roof edges) for the mitigation of UNI. For instance, inclined screens reflect the sound outward from the surrounding surface of the building. Green walls as add-on elements could reduce facade noise reflections in urban areas [39].

[42] indicated the facade ornaments as add-on elements category. [46] also studied the impacts of some other add-on elements of the building façade, e.g. eaves/louvers as on the UNI effects mitigation. The study of [48] revealed that solar panels on green roofs attenuated sound pressure up to 5 dB at the shielded building facade.

3.2.4. Neighborhood Quality

[40], investigated the influence of ground absorption (green areas and absorbent paving) in the UNI level close to a building facade. They found out lower facade levels influenced by the ground absorption effects more than higher levels. Green lands and absorbent paving don't have significantly effect on the UNI close to the facade (probably due to the small ground surfaces compared to the façade surfaces) [40]. Their study revealed that the controls of the average speeds of the vehicles resulted on 10 dB(A) attenuation of the average UNI levels (from 85 to 75 dB), even for the highest facade levels.

Environmental quality of neighborhood, e.g. streets surface and building facade, leads to strong amplification of the noise and increases UNI [39]. [17] studied the relationship between facade characteristics and building orientation on noise perceived effects [17]. [19] examined the relationship between noise and high-density high-rise urban areas.

In the case of neighborhood quality, [45] indicated that acoustical parameters would be able to predict the perceived acoustic comfort in outside spaces (i.e., courtyards, balconies). Regarding the interplay between building geometry and neighborhood quality, facade complex geometries*** could increase the UNI effects rather than decrease the effects [45, 49]. This could be happened if the façade architecture do not consider the surrounding buildings, or if the façade geometry scatter the noises rather than focally reflect them [45, 49].

The use of sound barriers e.g. reflective and inclined surfaces is also related to neighborhood quality, which was studied by [50]. Their study on the effects of sound barriers reported a traffic noise reduction of 8.8 dB [50].

In the neighborhood quality field, one of the important long-term actions to deal with the UNI is the land-use planning especially with considering the location/direction of future developments [51, 52]. Detecting noise-sensitive (e.g. residential apartments) and noise-insensitive (e.g. green space) buildings and using noise insensitive buildings as barriers between noise sources (e.g. streets) and noise receivers (low-income apartments) could mitigate UNI effects [51, 52]. With the latter in mind, placing a noise-insensitive building e.g. green space between residential buildings and the noise source, for example, a street with a lot of traffic, can be a low-cost and high performance solution [51, 52].

Table 4. UNI-related facades features derived from reviewed studies

Façade Architectural Categories	Facade Features	Definition of UNI-Related Facade Features derived	Ref.
FG	<u>vertical composition</u>	the vertical arrangement of floors	[3], [20], [25-27], [30], [39], [40-42]
	<u>bay division</u>	the visual separation of the facade	
	<u>Aperture</u>	the arrangement, design, and placement of windows, doors, and other openings in a facade	
	<u>Cladding ornament</u>	the outer covering of a building's facade design (texture/ pattern)	
	<u>Shapes</u>	Articulation/ Concave and convex areas/ Inclined surface/ Triangular shapes/ Round or Curve shapes/ Protrusion and Indentation/ fragmented surface/	
	<u>facade composition</u>	translation, rotation, scale and mirror	
	<u>Orientation</u>	Parallel/ Nonparallel	
	<u>the spatial relationships of a facade element</u>	window frames, lodges, or cladding elements (initial position, width, height, thickness, complexity***), Diffraction/ position/ orientation of the facade	
	<u>The balcony</u>	one of the protrusions/indentations on the façade that occupied by occupants (floor, ceiling, parapet)	
SP	<u>Cladding Elements features</u>	the outer layer of a building's facade that described as reflective or absorptive (up to 10dB reduction absorbing facade cladding compared to reflecting cladding)	[1-3], [17], [25], [27], [30], [40], [42-45]

	<u>sound reflecting cladding</u>	the materials identified in the studies were classified as “reflective”, including concrete, glass, masonry, stone, brick, wood, and etc	
	<u>Sound absorbing cladding</u>	solid materials with special sound absorbing structures (e.g. Porous Materials*, Resonant sound absorbers**, Metamaterials***)	
AE	<u>Green screens/ Green walls</u>	vegetated low-height noise barriers positioned near roof edges/ A growing substrate is placed in front of the façade	
	<u>Shielding/ sound absorbing devices</u>	Noise shields/ attenuators (e.g. Blinds, Acoustic Plenum, Quarter-Wave Resonator, and Muffler)	[3], [25], [27], [39], [42], [46]
	<u>Fins/eaves/louvre</u>	architectural features as a noise shielding device attached on the building facade to reduce excessive environmental loads	
NQ	<u>road width</u>	As road geometry related to road traffic noise level	
	<u>surrounding elements</u>	green space/ water body/inner yards of housing complexes/ buildings density	[3], [17], [30], [35], [40], [45], [47]
	<u>surrounding building characteristics</u>	Building height, nonparallel/ parallel wall	

Source(s): Author’s own creation

3.3. Trends and Impacts of Apartment Housing

More than 50% of the world’s population lives in urban areas, and this number is expected to increase to 85% by 2100 [1]. Cities are responsible for two thirds of the global energy consumption, and over 60% of greenhouse gas emissions [53]. Urbanization unlike its aim at improving health, social, and economic conditions for inhabitants, caused serious environmental problems that not only threaten ecosystems but also population health and energy consumption [54-55]. Apartment housing is the most common housing style in Korea (among 40% of occupants) [19]. In high-rise apartment housing, the noise level is more severe in the upper floors, where noise barriers have limitations for noise mitigation [19]. In higher-density communities, inadequate size and uncontrolled noise could hurt residents’ health and energy use [56]. For instance Micro apartments are becoming increasingly common due to the housing affordability crisis in Australia [57]. The study of [58] stressed that building characteristics are more significantly correlated with the energy consumption patterns. A number of recent apartment projects exhibit several design issues related to noise and ventilation [57]. The style of modern architectures along with the dense urban planning, together with the urban population needs for transportation resulted in UNI increase [1]. Apartment houses have been introduced to meet the

urbanization needs since the 1970's [18]. In particular, densely populated high-rise buildings with a hard reflective façade built from glass, stone, and metal are one of the main reasons of increased ambient noise levels [25]. The role of good housing design in alleviating energy use and dependency to cooling energy has been previously well recognized in practical and academic experiences [59-60]. The noise exposure of a building can be complex and can vary from a building surface to another surface, from opening to opening with additional variation through time [3]. Including measurements of this as part of a large survey becomes a substantial task [3].

Given the reviewed articles, the UNI-related facade features can be categorized at apartment housing scale (Table 5).

Table 5. The main architectural categories, sub-categories, and façade features related to UNI at apartment housing scale (Source: 19 out of 35 selected studies related to UNI-related façade features).

Main Categories	Sub-Categories	Features
FG	Vertical Composition	Height
	Bay Division	Width
	Aperture	Height—Depth—Composition—Orientation—Shapes—Spatial Relationship
	Cladding geometry	Fragmentation—Pattern—Texture
	Shapes	Convex—Concave—Articulation—recessions—protrusions—Indentation—Round—Curve—Fragmentation—Triangular—Inclination—Diffraction—orientation
	Composition	Translation—Rotation—Scale and Mirror-Complexity***S
	Orientation	Parallel—Nonparallel
	The Spatial Relationship	initial Position—Width—Height—Thickness
	The balcony	width, depth, parapet shape and height, side configuration, ceiling shape
SP	Cladding materials	thickness—density—porosity
	Porous Fibrous* (natural, inorganic or synthetic)	thickness—density—pore structure
	Porous Foams*	interconnected cellular structures—pore structure
	Membrane Panel**	perforated structures—different cross-section
	Helmholtz Resonator**	extended neck—air gap
	Meta Surfaces***	compact—lightweight
	Meta Porous***	compact—lightweight
AE	Green Walls	Depth—Area—highly porous and low-weight materials

	vegetated low screens at roof edges	multiple screens—Inclination—absorbing faces
	Fins/Eaves/ Louvers	Inclination—Angle—Repetition
	Shading Devices, Blinds	Depth-Inclination-Angle
	Acoustic Plenum Quarter-Wave Resonator, Muffler	Position
NQ	Road width	Width—Porous Asphalt—Speed Control
	Noise Barriers/ screens	green elements—artificial barriers
	Noise Insensitive Buildings as Noise Barriers	Green Areas
	Pedestrian Traffic Areas	Surface Properties
	Buildings geometry	Height—Orientation—Rotation—Diffraction

Source(s): Author's own creation

3.4. UNI-related Occupants' Perceptual Reactions

Aside from physical measurement of the sound, the assessment of UNI-related occupants' perceptual reactions is also crucial [30]. Therefore, it is very urgent and important to study the impacts of UNI on occupants' perceptual reactions. This is especially important for occupants of apartment housing in densely populated urban districts, because they are severely affected by UNI in both health and well-being issues [61].

UNI as an environmental problems have chronic effects for occupants' health that lead to widespread long-term consequences [62]. Given recent studies, there is a positive correlations between noise exposure and stress [8], insomnia [9], anxiety [10], depression [11], mental health [12-13], cardiovascular disease [14], and premature deaths [15].

In the study of [9], about 25% of European residents have well-being issues due to UNI, and 5–15% of the total European residents struggle with insomnia related to noise effects. According to [4], the increase in the UNI restricts residents from remaining outdoors and leads them to stay inside their housing units, resulting in the increased cooling demands and more AC usage. According to the [63] and International Energy Agency [64] low-income, substandard housing, and lack of access to cooling devices in summer expose residents to overheating conditions. Exposure to extreme temperatures (hot/cold) causes cognitive disorders and health problems [4]. [60] and [65] stated that low-income people should manage their living costs and expenditures to survive, and so these affordability concerns restrict their ability to consume proper amount of energy. They indicated that low-income occupants living in substandard dwelling units are not able to consume proper amount of energy, and are not protected against urban environmental challenges e.g. UNI and UHI. The [66] revealed that the burden of noise pollution is upon those most

vulnerable and socio-economically unprivileged, and according to [67] this issue is robustly associated with income. According to the [68] living in substandard, poorly designed, and poorly constructed housing especially at facade scale put low-income people in higher pressure and discomfort due to the impacts of environmental challenges, e.g. UHI and UNI. The study of [3] demonstrated that increasing the noise tolerance results in more windows being open on the facade. [69] stressed that the improvement of people awareness and availability of proper information could increase the environmental challenges tolerance of the people. [68] also indicate the role of people's socio-demographic characteristics and cultural background in promoting their pro-environmental behaviors, which in turn leads to their higher tolerance on the environmental challenges.

[70] calculated the financial cost of UNI in Tehran, which were about 56 million EURs per year. The calculated cost economically justifies the use of noise reduction measures, e.g. improvement of facade features in pre-design stages [2].

Therefore, it is worth mentioning that in apartment housing, facade architecture beside occupants' socio-demographics, and their awareness and information, could moderate UNI-related occupants' perceptual reactions.

Table 6 shows the occupants' perceptual issues in three sub-categories that derived from 16 out of 35 reviewed articles.

Table 6. UNI effects on Occupants Perceptual Reaction (well-being, Health, and behavior).

Well being	energy consumption/AC cost/ low-quality housing/ substandard construction material/ substandard architectural design/ high level of thermal transfer/ energy waste
Health	Death/ illness/ stress/ insomnia/ anxiety symptoms/ depressive symptoms/ mental health/ cardiovascular disease/ hearing loss/ premature deaths
Behavior	use of Air conditioning frequently (AC)/stay more in indoor spaces/lack of comfort & more stress in outdoor spaces

Source(s): Author's own creation

3.5. The impacts of UNI on Energy Consumption and UHI Effects

Appropriate apartment facade features in the first stages could notably decrease a building's energy consumption due to mitigation of UNI effects [2, 27], and potentially lead to less global energy consumption, carbon emissions, and global warming [3, 22]. Barclay studied the relationship between building energy consumption and UNI [3], and stressed

that UNI has serious impacts on building energy consumption [3]. By integrating noise mapping techniques with buildings thermal modeling, this study showed that 10 dB mitigation of noise level leads to 44.8% decrease in cooling energy consumption.

According to the [24], in apartment buildings, natural ventilation can quickly reduce the temperature of indoor spaces up to 9 °C. As investigated by [71], Natural ventilation (NV) is one of the low-cost and initial methods to enhance air quality, and to reduce cooling demand. [20] identified that UNI reduces the possibility of natural ventilation. According to the [63] and [64] low-income, substandard apartment housing, and lack of access to cooling devices in summer cause occupants to experience overheating conditions. Exposure to extreme temperatures (hot/cold) causes cognitive effects and health problems [4]. According to the [4] and [2] studies, the increase in the UNI effects restrict residents from remaining outdoors and lead them to stay inside their dwelling units, which in turn results in more AC usage. Residents' more frequent usage of AC leads to the UHI increase, which in turn results in more energy consumption.

4. Discussion

The information provided by the selected literature regarding the interplay between effects, UIN, and occupants' perceptual reactions can be classified into two main areas including UNI-related façade features, and UNI-related occupants' perceptual reactions (Table 4). This classification is proposed with data obtained from the 35 selected publications. Looking at the content of review articles makes it possible to identify similarities, contrasts, and patterns among the studies, and to organize the findings into a more practical level. These effects are classified into two groups:

- 1- Effects of facades on the UNI (sound reflection and sound absorption)
- 2- Effects of facades on the Occupants' perceptual reactions (select to use AC and/or NV)

4.1.1. Sound reflecting effects

Sound reflecting effect is refer to the increase in sound pressure level (dB(A)) due to ground and facades sound reflections on urban environment [30]. This phenomenon is very significant in the conditions that the receiver is close to the buildings (not important when receiver is more than 20m far from buildings) [30].

Sound reflection by concave and triangular shapes was studied by [39], who demonstrated a reduction up to 8.4 dB in upper floors of an apartment building.

The reflection effect of balconies was studied by [27], who identified a reduction sound pressure level up to 3 decibel at the third-floor level. Upward facing reflective surfaces are useful for noise mitigation in pedestrian level of building but have the potential to make discomfort for the mid to high building floors [27].

Attached eaves and louvers effects on noise mitigation were studied by [46], who found out that the inclined eaves are effective for noise reduction through noise diffractions and noise reflection outward from the facade. This effect becomes stronger by moving up the higher floor levels [46]. The intensity of the incident noise to the facade becomes weak due to eaves ability in sound scattering. At the high stories, the noise reduction effects becomes maximum (among 10-15 dB) by making the eaves inclination angle 20° upward. Given the length of the inclined eaves, shorter length decreases the noise reduction effects.

Retroreflection studied by [41]. They indicated that Corner cubes retroreflection are more energetic than flat facades, and they can concentrate acoustic energy. Beyond the implications of the outputs of this study in UNI effect mitigation, this work has the potential to inform architectural design where retroreflection could be intentionally used in indoor environments to support human sources of sound (lecturers and musicians) [41].

Attention to the facade acoustic parameters is needed in order to deal with UNI [26]. The exposure of a facade to UNI depends on the neighborhood quality [3]. The arrangement of the different constituent elements of neighborhood (e.g. buildings, trees) can decrease the UNI effects due to the sound shielding effect, or can increase the UNI due to the sound reflection effect [3].

At the last, it is worth mentioning that despite the influence of facade geometric on UNI, the impacts of architectural facade parameters on UNI have not been transferred into architectural design of the facade [26].

4.1.2. Sound absorbing effects

Architectural acoustics is concerned with noise absorption rather than its reflection and scattering [42].

The main contested facade properties are absorptivity and reflectivity in façade finishing [27]. Absorptive surfaces are the most effective strategy for urban noise mitigation, and upward-facing reflective surfaces are more effective for reducing noise pollution at the pedestrian building level, although their design would need to account for the possible discomfort happened for upper building floor levels [27]. Given the sound absorbing strategies, traditional sound absorbing materials are not properly efficient for absorbing low frequency sounds, and hence the adoption of the developed meta-materials is highly recommended [1]. However, these types of materials cannot be used currently because of the lack of suitable and low-cost mass-production technologies [72]. In general, in the future, with developing new mass-production technologies, it is necessary to reduce the costs, and also to improve the long-term efficiency, and effectiveness of met-materials for large scale use [1]. In sum, proper materials played a significant role in mitigation of the UNI effects.

4.1.3. Occupants' perceptual reactions to use AC and/or NV

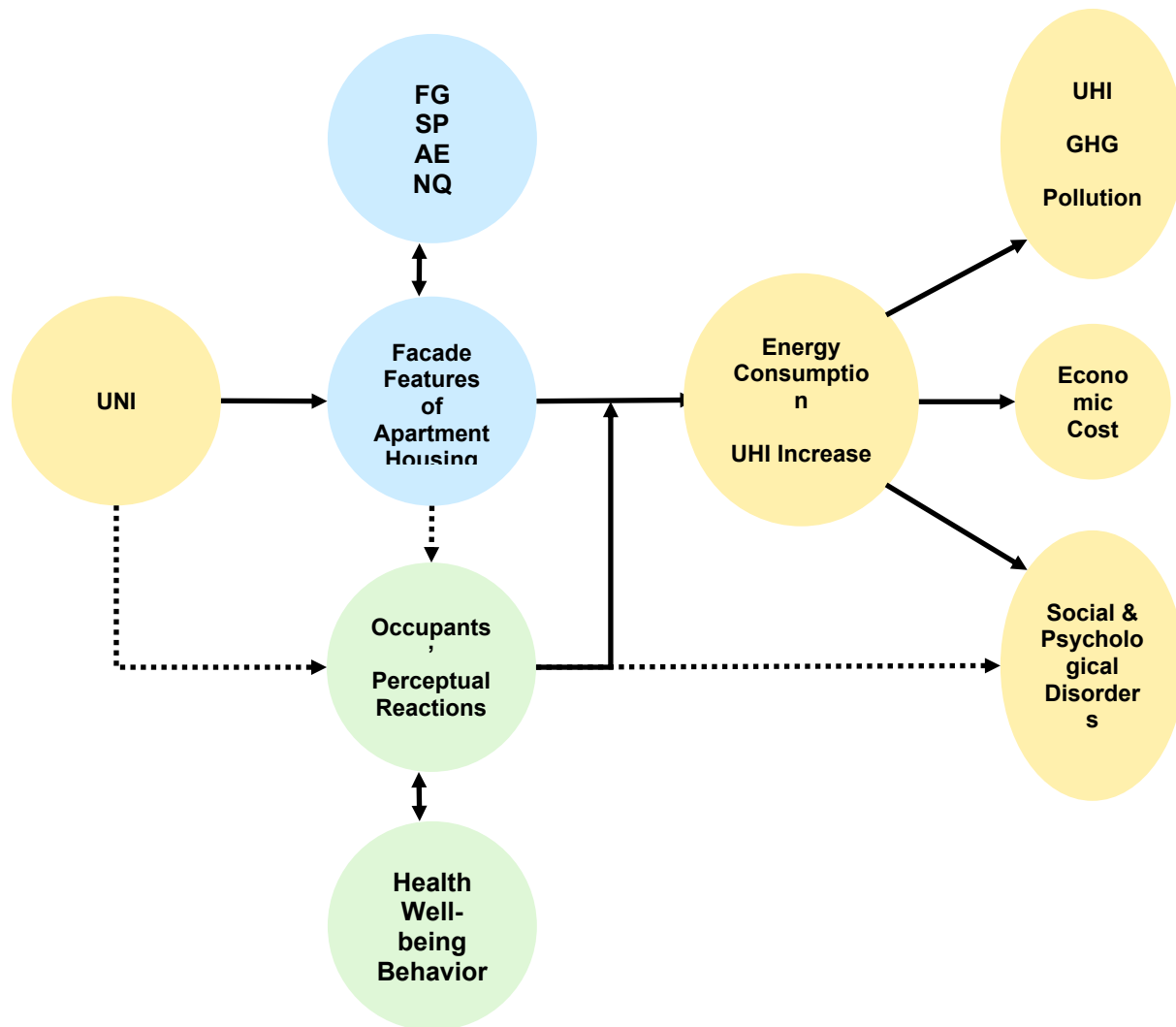
UNI generate negative impacts on occupants' perceptions, and threaten their health, well-being, and behavior's. These negative impacts lead to some perceptual reaction, e.g. stress [8], insomnia [9], anxiety [10], depression [11], One of the main behavioral consequences of UNI is the more usage of AC devices in summer, which leads to higher energy consumption and UHI. UNI mitigation has the potential to prevent occupants from these perceptual reactions by letting them to stay outside of their dwelling units, and to use NV while staying inside their houses. NV as the most effective and low-cost heat reduction action, can reduce the operation time of AC device, and hence can reduce energy consumption and UHI.

Given the UNI reduction actions, therefore, the optimization of natural ventilation (NV) as the most cost-effective heat reduction technique in summer is highly necessary. This is especially necessary to achieve affordable housing for low-income residential apartments. For example, air conditioning (AC) systems release a large amount of heat to the outside, leading to the UHI formation and in turn higher energy consumption [73-74]. The AC is responsible for an average $0.5^{\circ}\text{--}2^{\circ}\text{C}$ air temperature increase due to the release of the indoor heat to the outdoor.

UNI mitigation allows more natural ventilation, as larger openings with longer time can be used before noise entry exceeds acceptable levels (53dB day- 45dB night) [3]. This level of natural ventilation and airflow reduces the operation time of AC devices [3].

Figure 2 provides a brief explanation of the interplay between UNI, façade features of apartment housing, and perceptual reactions of occupants.

Fig 2. The interplay between UNI, façade features of apartment housing, and perceptual reactions of occupants



Source(s): Author's own creation

5. Conclusion

This paper presented a cross comparison review of the interplay between facade features, UNI, and occupants' perceptual reactions. Data from 36 articles were extracted to answer the research objectives, which are (1) identification UNI-related facade features, and UNI-related occupants' perceptual reactions (2) the effects of facades features on the correlations between UNI and the occupants' perceptual reactions in apartment housing.

In the first stage, the effects of apartment housing façade features on UNI have studied by reviewing 36 studies conducted from 2003 to 2026. As a result, the UNI-related façade features were classified into 4 architectural categories, including FG, SP, ad-on elements, NQ. The findings provide a comprehensive insight of façade features influencing the UNI effects through sound reflection/absorb. In the second stage, the effects of UNI-related facade features on the occupants perceptual reactions have studied, and classified in three categories, including well-being (energy use), health (psychological/ physiological), and behavior sections with emphasis on NV/AC use.

This study results further clarified the structure of impacting facade features on UNI and occupants reactions. The findings showed that apartment housing energy use is vary across socio-demographic groups and different facade features, that expectations and concerns differ according to users' motivation (e.g. psychological, social, cultural).

A central finding of the study is that apartment housing facade features play significant mediating roles between UNI and occupants' behavioral reactions. This finding suggests that the facade UNI-related features impacts are associated not only with the design of FG, SP, AE, and NQ, but also with the extent to which these features are perceived by occupants, which can promote their positive behavioral actions (NV and/or AC use). In the future, conducting a field based study is necessary to develop this research into a more practical and concrete level.

In the step of facade design, the compatibility of facade properties with urban and neighborhood requirements should be assessing carefully to reach a UNI conscious façade design, which has the potential to decrease the UNI effects [27, 75]. Such an appropriate architectural design of apartment housing facade can significantly reduce the noise level acoustically, improving occupant's perceptual and behavioral reactions especially in using NV while staying inside their dwelling units.

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Data Availability

Not applicable

Consent to Participate

Not applicable

Consent to Publish

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Competing Interests

The authors declare no competing interests.

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Ethical Declaration

The study was approved by the Research Ethics Committee of Islamic Azad University-Mashhad Branch, Iran. It is further certified that the study was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki, and its later amendments or comparable ethical standards.

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