

Research Article

Effect of Personal Space Invasion on Passenger Comfort and Comfort Design of an Aircraft Cabin

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Received 31 March 2021; Revised 11 June 2021; Accepted 17 June 2021; Published 27 June 2021

Academic Editor: Peter Dabnichki

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Passenger comfort is becoming an important issue with the recent increase in air travel. A common cause of passenger discomfort and distress is the invasion of the passenger's personal space. This paper presents the results of two studies addressing the environmental psychological characteristics of passengers during personal space invasion (PSI) and how PSI affects cabin comfort design. In study 1, our survey shows that PSI has different effects on the comfort of passengers with different genders, ages, education levels, and interpersonal relationships. From these survey data, we extracted 14 factors of PSI. In study 2, a Decision-Making Trial and Evaluation Laboratory (DEMATEL) model was established, with passenger comfort as the target layer, to determine the interrelation between 14 PSI factors. The causal relationships between the 14 factors were visualized by a causal diagram. We established a priority ranking of the 14 aircraft interior design indexes based on the corresponding relationships between the indexes and PSI factors. The findings of this study contribute to the understanding of how PSI impacts passenger comfort and offer strategies to improve the comfort design of aircraft cabins.

1. Introduction

Individuals choose to travel by aircraft for various reasons, including leisure, family visits, and business. Traveling by aircraft is a growing industry, providing business opportunities for airlines [1]. Some research data [2, 3] show that passengers' choice of flight is closely related to the comfort of their flight experience. This means that comfort attracts passengers. Therefore, with the increase in the number of aircraft passengers, it is important to consider passenger comfort during flights.

Comfort has many concepts, as Vink [1] wrote. In Dutch dictionaries, such as in the Van Dale 2000, comfort is described as "freedom from pain, well-being". There are many definitions of comfort, but one point is undisputed: comfort is a subjective experience [4]. Comfort can be a pleasant state of physical, psychological, and physiological harmony between a human and their environment, or a subjective state of well-being [1]. The term aircraft passenger comfort was

first proposed by Richards and Jacobson in 1975 [3], but very limited research has been published on this issue. Generally, aircraft passenger comfort is a subjective feeling that passengers experience during their flight. The subjective comfort feeling of aircraft passengers is affected by various aspects of the entire cabin environment system, such as seats, illumination, noise, and cabin crew service [3, 5, 6]. As aircraft passenger comfort research has progressed, many achievements have been made in seat comfort design and other research areas [7–9]. Previous literature [10] shows that many studies have examined factors in aircraft seat comfort design such as seat height, seat pitch, seat width, seat pan length, and legroom [5, 11, 12]. Other areas of research include the physical comfort of aircraft passengers, such as seat posture, human-body load, seat and foot pressure measurements, vibration, noise, temperature, and air quality [13–15]. Few of these studies have proposed a framework for combining these physical factors with passengers' psychological feelings. A pleasant psychological feeling is also an

important part of a passenger's objective comfort experience [16]. Having personal space that is not invaded by others can promote pleasant feelings in aircraft passengers [17].

The theory of "personal space" originates from Environmental Psychology, as proposed by Sommer [18] on the basis of a large number of observations. Sommer [18] described personal space as an "emotionally tinged zone" around the body that can vary in dimensions at any given time and context. Some scholars describe personal space as "the area immediately surrounding the individual in which the majority of his interactions with others takes place" [17] and "a space over where individuals feel a sense of ownership" [18]. Generally speaking, personal space is the minimum space that people require, psychologically. Uninvited intrusion of this space can lead to discomfort [19], stress, avoidance, or withdrawal [20]. Personal space has boundaries, which are affected by several factors including demographics, interpersonal relationships, personality, context, and cultural and background factors. People's gender and age affect the scope of their personal space [21–23]. Different interpersonal relationships between two people, such as friends, colleagues, or strangers, influence their comfortable interaction distances [23]. For example, cheerful people are more willing to interact with others at a closer distance than introverts [24, 25]. People with higher educational background prefer to keep a greater distance from strangers [17, 18]. Different contexts also affect the interaction distance between people [26–28].

Scholars describe personal space as an invisible bubble around the human body (see Figure 1) that is cylindrical from the waist up, conical below the waist, and the thinnest around the feet [27]. The bubble moves with the human body and shrinks and expands according to different situations [27, 29, 30]. It is well known that many contextual factors (e.g., spatial density, illumination, size of the room, vertical space, and whether the setting is indoor or outdoor) affect the distances between people and their comfortable interactions with each other [16, 17, 20, 23, 24, 26, 31–33]. Within a broad context, the ways in which people cope with personal space invasion (PSI) are known [25]. However, the aircraft cabin is a special environment that presents some unusual characteristics, including an enclosed space, interpersonal distance that is too close, limited adjustment space, and sometimes a long flight duration. Most travelers fly in economy class [34], and thus it is significant to study how comfortable passengers are in economy class. The space in economy class cabins is very limited compared with first and business class. Economy class passengers must share a space with other people of different genders, ages, and educational backgrounds for the duration of the flight [16]. Thus, the personal space of passengers in economy class will be more vulnerable to invasion than other cabin classes. It is therefore important to study the phenomenon of passenger's personal space invasion (PSI) in economy class specifically. Until recently, there have been few studies examining how passengers interact with each other with regard to their perception of personal space and comfort. In Ahmadpour et al.'s [35–37] study, the term "proxemics" was defined as one of the themes that influence aircraft passenger comfort. However, they did not specifically focus on the passengers'

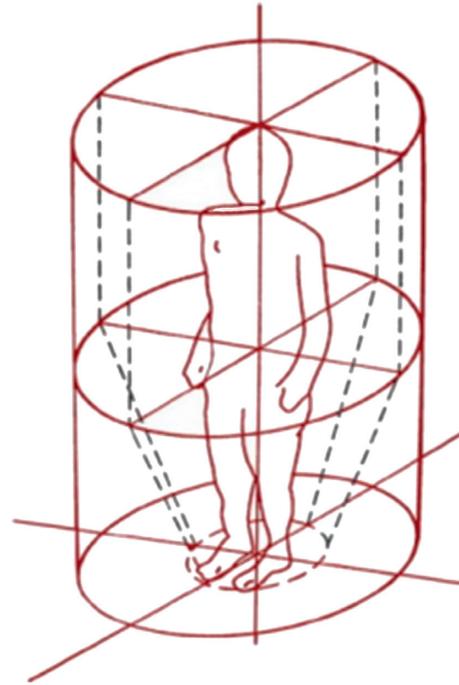


FIGURE 1: The bubble model for personal space described by Cochran et al. [27].

subjective feelings when their personal space was invaded during air travel. Lewis et al. [16] conducted a survey on the perception of PSI and what aircraft passengers may do to make themselves feel more comfortable when their personal space is invaded, and suggested that PSI is often a contributory factor to discomfort for aircraft passengers. Although Lewis' research results can inform the design of aircraft cabin environments to enhance the passenger experience, they did not discuss the specific aircraft interior design indexes (such as seat layout, seat width, passage width, physical partitioning, and storage space) related to passengers' PSI. This is the research gap that we aim to fill in the present study.

The subjective feeling of comfort is usually measured by scales and questionnaires designed to evaluate the psychological state of the subjects. Surveys by questionnaire have become such an important tool to qualitative researchers that many qualitative methods rely heavily or solely on them as the primary mechanism for data collection. Some classic comfort measurement questionnaires (for example, the general comfort rating (GCR) [38], body part discomfort rating (BPD) [39], and overall comfort index (OCI) [40]) are simple and intuitive tools to evaluate comfort. However, due to different research goals, researchers must design more suitable questionnaires to meet their specific needs [6]. Some scholars collect data through the descriptions of the interviewees, summarize the description of the research problems, and obtain the key factors [16, 24, 35]. For example, Kremser et al. [41] defined passengers' well-being with regard to their sitting posture based on 10 subjective descriptions, which were divided into postural sensation, spatial perception, privacy, and mood. These were then linked to the optimum seat pitch range and the eye-height

level to provide a comfortable visual impression. The method of obtaining the key factors through the descriptions from the interviewees is suitable for the present study on passenger PSI.

In previous studies, some evaluation methods and models are used to establish the relationship between comfort and measurement. The artificial neural network (ANN) method is used to establish the relationship between input and output. An ANN model has been applied to predict automobile seat comfort [42]. Zhao et al. [12] established the prediction model of aircraft seat comfort by employing an ANN model. Studies like these have not been used to evaluate passenger comfort from an overall perspective. The prediction target of previous studies often focused on a specific product. Many factors must be discussed in the study of aircraft passenger comfort. Some methods like the analytic hierarchy process (AHP) and the analytic network process (ANP) could be used to calculate the weight of each factor. Although the ANP can be used to analyze the relationship between factors through the weight of each factor, it cannot provide the visualized cause-effect relationships between factors. A more effective method is needed to study the factors that affect aircraft passenger comfort [6]. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) is an effective method of extracting and visualizing the cause-and-effect relationship between contributing factors in complex systems with a causal diagram [43, 44]. We believe that the DEMATEL method is suitable for dealing with the interrelationship between the aircraft interior design indexes related to passenger PSI.

In summary, there is a lack of research on the personal space of passengers in the previous studies of aircraft passenger comfort. The available research [7, 16, 36, 37] on the personal space of aircraft passengers has not yet discussed the interrelationship between passenger PSI and cabin comfort design. Therefore, the purpose of this article was to develop an understanding of how PSI impacts passenger comfort, and to determine strategies that can improve comfort design in aircraft cabins. To achieve our research purpose, the study was performed in two parts as follows. A qualitative study was carried out in study 1 to investigate the subjective feelings of passengers when their personal space was invaded in the cabin as well as the impact of PSI on aircraft passenger comfort. The descriptors related to passenger PSI from study 1 were collected and classified into 14 PSI factors. Study 2 presents a DEMATEL model to analyze the interrelationship between the 14 PSI factors. A priority ranking of 14 aircraft interior design indexes was constructed based on the corresponding relationships between the indexes and PSI factors. This paper is organized as follows: Section 2 presents the methodologies for the investigation of the PSI of passengers in economy class (study 1) and the interrelation analysis based on DEMATEL methods (study 2), which includes the information of specific aims, tools, subjects, and procedures. Section 3 reports the results of study 1 and study 2, and the results are discussed in Section 4. Section 5 concludes the paper.

2. Methods

2.1. Study 1: Investigation of the PSI of Passengers in Economy Class. The purpose of this investigation was to understand the ways the invasion of aircraft passenger personal space are caused and how the passenger feels. There are many ways to cause passenger PSI [16], so it is difficult to use the traditional quantitative analysis method. Our analysis method referred to the studies of Lewis et al. [16] and Ahmadpour et al. [35, 37]. These works collected participants' descriptions from different themes and classified and qualitatively analyzed them by simplifying and summarizing them into short concepts or factors.

A questionnaire comprising seven questions was designed. At the beginning of the questionnaire, the definitions [35] of comfort (a pleasant state of well-being; ease; and physical, physiological, and psychological harmony between a person and the environment) and discomfort (a state in which one experiences hardship of some sort that could be physical, physiological, or psychological) were provided to ensure a common understanding of these two concepts. The questionnaire included four demographic questions about age, gender, education level (senior high or below/junior college/bachelor degree/master's degree or above), cabin class, and number of previous flights in total (0/1–5 flights/more than 5 flights), followed by an open-ended question prompting respondents to describe some experiences (in detail) of personal space invasion while flying. Next, a multiple-choice question asked respondents to choose their attitude when their personal space is invaded by people of different genders and different interpersonal relationships. Finally, using a five-point scale, respondents were asked to identify the degree to which the impact on their comfort was affected by the aforementioned experiences (with 1 being a slight effect on comfort and 5 being a significant effect on comfort).

A total of 240 questionnaires were distributed online over four weeks. A convenience sample of 193 respondents (male: 117, female: 76), all aged between 16 and 75 years old (below 20, $n = 19$; 20–39, $n = 84$; 40–59, $n = 53$; 60 and above, $n = 37$), was established by recruiting from a tourist agency, the Student Union of Northwestern Polytechnical University, and personal contact in Xi'an, China. Each participant received an e-mail with a link to the online questionnaire and an informed consent form. The selection criteria [35, 37] for respondents were to have had more than five flight experiences (at least one in economy class) in the past.

The analysis of survey data was conducted in three steps. In the first step, each PSI experience report was divided into several specific descriptions, and each description was unique in content. The descriptions that emerged more than once in a report were only accounted for once [35]. Next, those descriptions were sorted by cause type of PSI and generalized into the set of 14 different PSI factors (such as interpersonal distance, room for passengers' limbs, and noise). These 14 PSI factors were classified into four dimensions (such as physical space). This is similar to the concept of "higher order themes" mentioned in a study by Lewis et al. [16]. For classified example, the description

“passenger’s arms or legs being in another person’s personal space zone” in a PSI experience report was associated with concern for the limb space of passengers, assigned to the “room for passengers’ limbs” factor, and then classified into physical space dimension.

In the second step, basic statistics were conducted on the questionnaire reports. The description numbers of the four PSI dimensions were counted by gender. We wanted to know the difference in PSI perceptions between men and women in different dimensions. We also counted the number of descriptions according to different interpersonal relationships (close friends/strangers) and gender combinations.

In the third step, we looked for differences in the ratings by which respondents of different genders, ages, and educational backgrounds think that PSI affects their comfort. First, a *t*-test was conducted to examine whether or not there were gender differences in the rating results. Then, a univariate analysis of variance (ANOVA) was employed to analyze the main and interaction effects of respondents’ gender, age, and educational background on their rating results. The dependent variable is the rating results, and the fixed factors are two (gender: male/female) \times four (age group (years): below 20/20–39/40–59/60 and above) \times four (educational level: senior, high, or below (SH)/junior college (JC)/bachelor’s degree (BA)/master’s degree or above (MD)). The effects were considered “significant” when *P* value < 0.05 . Statistics were calculated in SPSS 24.0 software (SPSS Inc., Chicago, IL, USA).

2.2. Study 2: Interrelation Analysis Based on DEMATEL Methods. We looked for some new strategies of aircraft cabin interior design by analyzing the interrelationship between PSI factors. Six experts were invited to help define the aircraft interior design indexes [5, 6, 10] corresponding to each PSI factor and score the pairwise comparison in the DEMATEL process. As Vink et al. stated, aircraft passenger comfort is discussed by aircraft engineers, designers, and passengers [7]. To ensure that the experts had equal weights in the survey, the six experts included two aircraft interior designers, two industrial designers, and two volunteer passengers [6]. The two aircraft interior designers work in the Department of Interior Design, China Aviation Industry First Aircraft Design and Research Institute, Xi’an, China, and the two industrial designers work at the Long Xiang Design Co., Ltd, Xi’an, China.

DEMATEL is a system element analysis method based on matrix theory and graph theory proposed by the Battelle Memorial Institute of Geneva in 1976 [43]. DEMATEL is an effective method to extract and visualize the cause-and-effect relationship between contributing factors in complex systems through causal diagrams [44]. Compared with the traditional methods for multiple factor analysis, such as AHP and ANP, DEMATEL does not need to assume that factors are independent. DEMATEL can also calculate the weight of each factor according to its importance level. Factors can be separated into two groups, a cause group (factors imposing an effect on others) and an effect group (factors receiving effects from others), according to the value

of their relation degree obtained by DEMATEL. It is generally accepted that factors in the cause group should be considered more carefully, because their performance can have a great influence on the entire system goal [45]. The central degree is the degree of relation of each factor with others; the greater the central degree of the factor, the closer the relationship between the factor and others [46]. This can make the structural relationship between factors more easily understood by researchers. In 2017, Liu et al. [6] successfully discussed the interrelation between the key factors affecting passenger comfort using DEMATEL, and some rational strategies to assign the priority of factors in the aircraft interior design process have been provided for cabin designers. The DEMATEL method was adopted in this article to identify the PSI factors that affect aircraft passenger comfort and to discuss the interaction mechanism between the PSI and aircraft cabin comfort design.

Before the DEMATEL process, six experts selected the corresponding 14 design indexes for the 14 PSI factors. First, one of the two aircraft interior designers proposed two aircraft interior design indexes for each PSI factor. Then, two industrial designers and volunteer passengers voted on each index. If two indexes had the same number of votes in the first round of voting, another aircraft interior designer voted. Finally, the factor with more votes from the two indexes was chosen as the corresponding index of the PSI factor. The DEMATEL analysis was conducted using the following steps:

- Step 1: define the effect scale. In this paper, there were 14 factors in the system, which were contained in a set $U = (u_1, u_2, u_3, \dots, u_n)$, $n = 14$. The DEMATEL is based on a pairwise comparison. We divided the effect scale into values of 0–4, with 0 representing no effect, 1 low effect, 2 moderate effect, 3 strong effect, and 4 great effect.
- Step 2: establish a direct-relation matrix. Pairwise comparison between PSI factors was conducted based on the scoring results of the six experts mentioned above. The results were recorded as initial direct-relation matrix $S = (S_{ij})_{n \times n}$ where s was an $n \times n$ nonnegative matrix in this paper and S_{ij} represents the direct effect that factor i imposes on factor j according to the scale. When $i = j$ (factor self-comparison), the values of the diagonal elements are equal to 0.
- Step 3: normalize the direct-relation matrix. The normalized direct-relation matrix $G = (G_{ij})_{n \times n}$ was obtained by (1), where $0 < g_{ij} < 1$, and the values of principle diagonal elements are equal to 0:

$$G = \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n S_{ij}} S. \quad (1)$$

- Step 4: calculate the total relation matrix. The total relation matrix $T = (t_{ij})_{n \times n}$ was obtained using

(2), for which I was an $n \times n$ identity matrix, and t_{ij} indicates the indirect effect that factor i imposes on factor j . Therefore, the matrix T reflects the total relation between every pair factor:

$$T = \sum_{i=1}^n G^i = G(I - G)^{-1}. \quad (2)$$

Step 5: calculate affecting degree D_i and affected degree C_i . The sum of rows was denoted as affecting degree D_i in total relation to matrix T , which represents the total effect factor imposed on others. The sum of columns is denoted as influenced degree C_i , which represents the total effect factor perceived from others. D_i and C_i were calculated using the following equations, respectively:

$$D = \left[\sum_{j=1}^n t_{ij} \right]_{n \times 1}, \quad (i = 1, 2, \dots, n), \quad (3)$$

$$C_i = \left[\sum_{i=1}^n t_{ij} \right]_{1 \times n}, \quad (j = 1, 2, \dots, n). \quad (4)$$

Step 6: calculate central degree M_i and relation degree R_i . The value of M_i represents all effects given and received by factor i , which reveals the importance of factor i . When the value of R_i is positive, the factor is grouped into the cause group, which represents a factor that has great influence on others. When the value of R_i is negative, the factor belongs to the effect group, which implies that this factor is highly influenced by others. The central degree M_i and relation degree R_i were calculated by the following equations, respectively:

$$M_i = D_i + C_i, \quad (5)$$

$$R_i = D_i - C_i. \quad (6)$$

Step 7: calculate the weight of factors. The weight of factors W_i can be obtained by the following equation:

$$W_i = \frac{M_i}{\sum_{i=1}^n M_i}, \quad (i = 1, 2, 3, \dots, n), \quad (7)$$

$$0 \leq W_i \leq 1, \quad \sum_{i=1}^n W_i = 1.$$

Factors could be classified into two groups according to the value of their relation degree: cause group (relation degree >0) and effect group (relation degree <0).

3. Results

3.1. Study 1. Our investigation yielded a total of 450 descriptions. The statistical results are shown in Table 1. The count numbers of four dimensions are as follows: physical space (128), tactile sensation (140), other sensory factors (101), and interpersonal communication (81).

According to the respondent's description of question 1, it was ascertained how a passenger's personal space was invaded in aircraft economy class. The specific forms of PSI were summarized into factors and classified as shown in Table 1. The classification method referred to Lewis et al. [16], and the three higher order themes (human body, objects in environment, and other sensory factors) of the PSI factors were subdivided into four dimensions (physical space, tactile sensation, other sensory factors, and interpersonal communication).

Referring to the description of the bubble model of personal space in previous studies [27, 29, 30], the personal space of economy class passengers can also be visualized as an invisible bubble around the passenger's body. The shape of this personal space bubble changes in the environment of limited space in economy class in an aircraft cabin. The width of the bubble is now constrained to the distance between the two armrests of the seat. The length of the bubble is approximately equal to the seat pitch and changes as the seats recline. The front space of the passenger's body is limited to the leaning of the front seat back, and the back space is limited to the seat back. The height of the bubble is equal to the distance from the passenger service unit (PSU) panel to the cabin floor (see Figure 2).

We defined the reporting rate of a dimension as the number of respondents who perceived PSI belonging to this specific dimension divided by the total number of respondents. Then, we counted the reporting rate of male and female respondents separately. The reporting rate of different genders to the four PSI dimensions is shown in Figure 3. Among the four PSI dimensions, the reporting rate of female passengers is higher than that of male passengers. We counted the data of multiple-choice questions in the survey according to different interpersonal relationships (close friend/stranger) and gender combinations (see Figure 4).

The results of t -tests showed that rating scores (1–5-point scale, 1: slight effect on comfort, 10: great effect on comfort) from females (mean: 3.12, SD: ± 0.84) were significantly higher than those of males (mean: 2.80, SD: ± 0.99 , $P = 0.02$). There was a significant effect due to respondents' gender ($F(1, 172) = 3.78$, $P = 0.04$), age groups ($F(3, 172) = 30.57$, $P < 0.001$), and education levels ($F(3, 172) = 10.67$, $P < 0.001$) on their rating scores. Post-hoc tests showed significant differences between respondents' age groups (P values < 0.05), except for differences between groups of 40–59 years old (mean: 3.40, SD: ± 0.77) and 60 years old and older (mean: 3.12, SD: ± 0.82 , $P = 0.688$). Post-hoc tests also showed significant differences between respondents' education levels (P values < 0.05) (see Figures 5(a) and 5(b)).

TABLE 1: Summary of how personal space can be invaded in economy class (quantity: the number of respondents).

Respondents' description (quantity)	Factors (quantity)	Dimensions (quantity)
(i) The distance between seats in the same row is too close, and the width of seat surface, armrests, and armrest itself is not enough (27)	Interpersonal distance (46)	
(ii) Passengers stay in intimate distance (0–0.45 m, Hall [24]), which may not correspond to their interpersonal relationship (19)		
(i) Due to the seat pitch, the space for passengers to move their limbs is limited (16)	Room for passengers' limbs (43)	Physical space (128)
(ii) Adjacent passengers who sit with their legs/feet outstretched or elbows sticking out of their personal space (20)		
(iii) Monopolizing shared spaces including the armrest or controlling whether the armrest is raised or lowered (7)		
(i) Fully reclining their seat back (11)	Front-row passengers (26)	
(ii) Suddenly straightening/reclining the seat back (10)		
(iii) Shaking their body on the seat (causes the tray table behind to vibrate) (5)		
(i) Passengers placing their belongings in another person's space (13)	Belongings' placement (13)	
(i) Adjacent passengers can cause tactile sensation by opening a newspaper widely, dining, and adjusting their posture (27)	Adjacent passengers (53)	
(ii) Adjacent passengers lean when sleeping (26)		
(i) Passenger squeezing past or climbing over another passenger, asking others to let them out or reaching or leaning across other passengers (18)	Passenger movement (36)	Tactile sensation (140)
(ii) Cabin crew may also reach across passengers to pass something to the adjacent passenger (10)		
(iii) Passenger sitting in an aisle seat, others walking past may invade their personal space (8)		
(i) Back-row passenger kicking, pushing, and pulling the back of the seat (16)	Back-row passengers (28)	
(ii) Back-row passenger unfolding and folding up the tray table on front seat back (12)		
(i) Passengers' belongings have contact with other passengers (23)	Contact with objects (23)	
(i) Mechanical noise in cabin (8)	Noise (33)	
(ii) Passengers nearby being boisterous and loud (including bodily noises) (16)		
(iii) Passengers using their audiovisual equipment with external voice (5)		
(iv) Noise from cabin passenger service unit (PSU) and entertainment systems (4)		
(i) Bodily smells (including perfume) (23)	Smell (39)	Other sensory factors (101)
(ii) The smell of food and drinks (16)		
(i) Lighting factors including the cabin lighting system, atmosphere light, and light shield (12)	Illumination (29)	
(ii) Reading lights and the display lights of electronic equipment (17)		
(i) Listening to other passengers' conversations or talking to them when they do not want to engage in conversation (23)	Conversation (23)	
(i) Passenger looking at other people or at what they are doing (12)	Sight (23)	Interpersonal communication (81)
(ii) Unwanted eye contact (11)		
(i) A stranger tries to chat with me, even if I do not want to talk with him/her or they ask questions I do not want to answer (such as my salary, my family, or current politics) (35)	Content (35)	

A significant gender \times education levels interaction was also found ($F(3, 172) = 4.89, P = 0.003$) (see Figure 5(c)). Pairwise comparisons indicated that there was a significant main effect of gender on the SH level ($F(1, 185) = 8.70, P = 0.004$). We found that the rating scores of female respondents with SH level (mean: 2.89, SD: ± 0.17) were significantly higher than those of male respondents (mean: 2.28, SD: ± 0.12), while the gender main effect on the other three education levels (JC, BA, and MD) was not significant (F values (1, 185) $< 1.02, P$ values > 0.05).

3.2. *Study 2.* The four PSI dimensions, 14 PSI factors, and 14 aircraft interior design indexes corresponding to the PSI factors are summarized in Table 2.

The average of the direct-relation matrix was obtained based on the scoring results of the six experts. The normalized direct-relation matrix (Table 3) was acquired using (1). Finally, the total relation matrix (Table 4) was obtained by (2).

The affecting degree, affected degree, central degree, relation degree, and weight of factors were obtained by (3)–(7), respectively (Table 5).

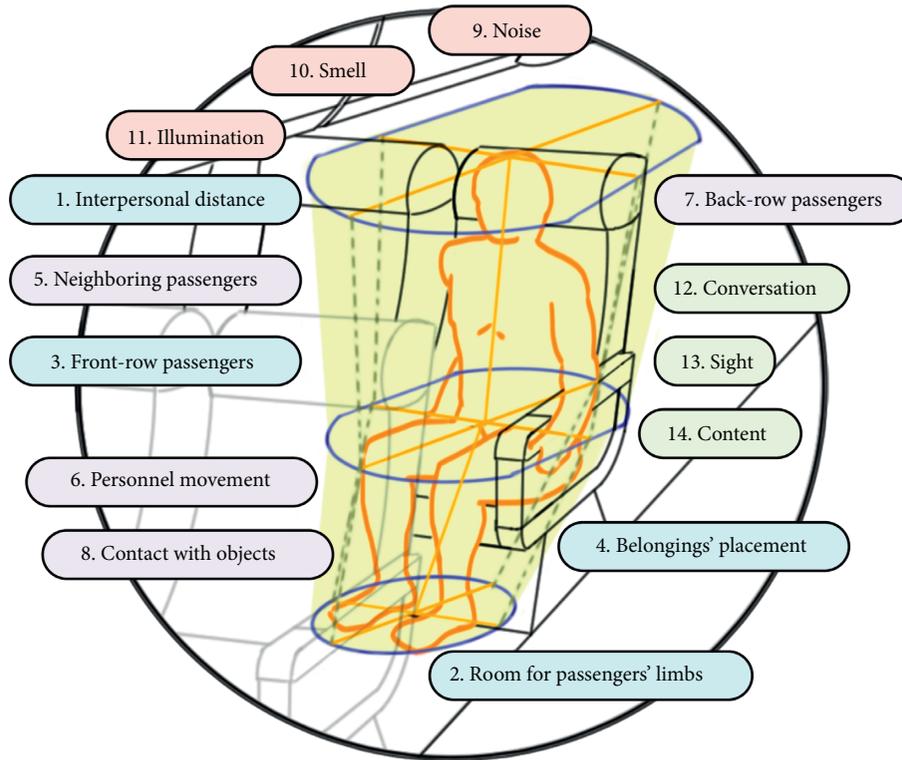


FIGURE 2: Bubble model of personal space in aircraft economy class.

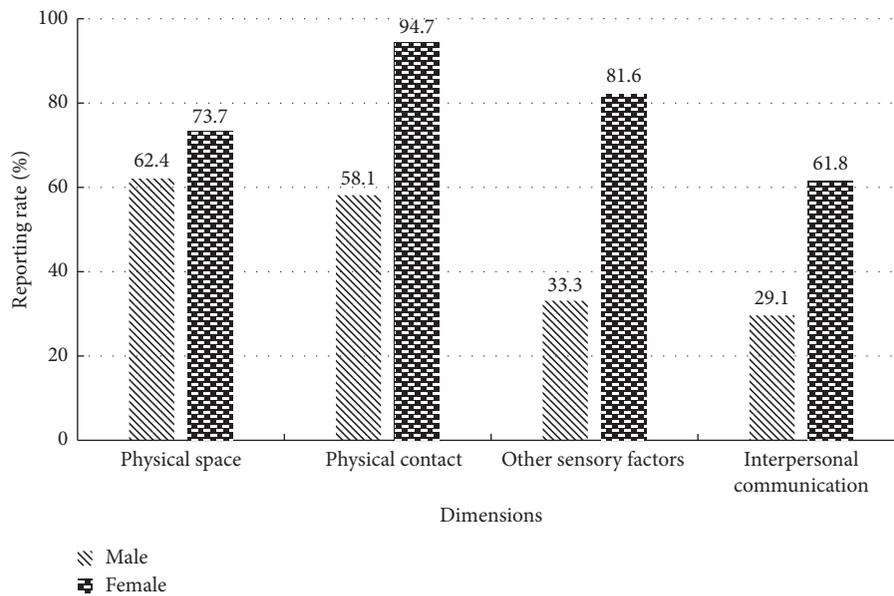


FIGURE 3: The reporting rate of different genders to the different PSI forms (%).

The causal diagram in Figure 6 visualizes the central degree as the horizontal axis and relation degree as the vertical axis, which converts complex causation to a simplified visual structure and thus provides valuable insight for understanding the relationship between factors. For instance, one can visually see from the causal diagram (see Figure 6) that *F1* is located mostly on the top, which means that *F1* is the most influential PSI factor. *F1* influenced the other factors the most and should be given priority.

4. Discussion

Based on the results of study 1, some indications were extracted. The statistical results of reporting rate showed a gender difference in perceiving PSI among passengers. According to the results shown in Figure 3, this could mean that females experience invasions of personal space more frequently than males, females have better memories for invasions of personal space than males, females have better

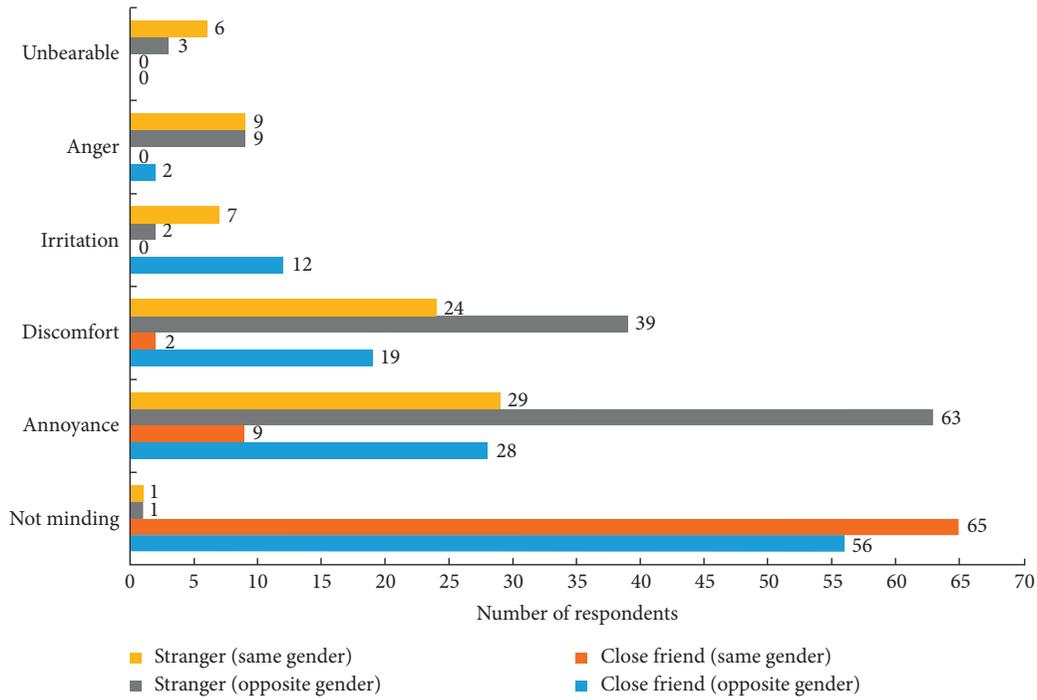


FIGURE 4: Passengers' common feelings of the PSI.

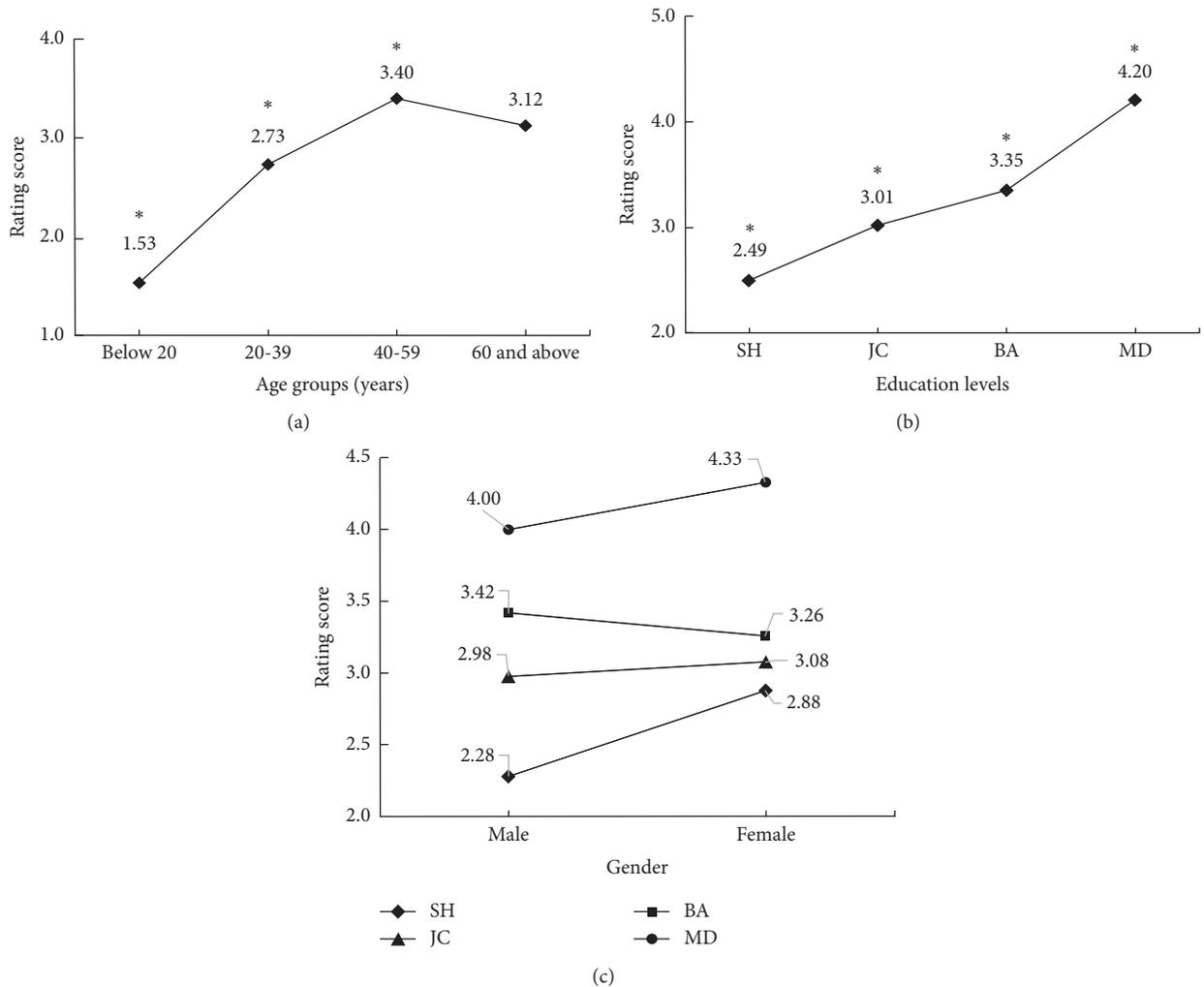


FIGURE 5: PSI rating scores (mean) of different age groups (a) and education levels (b), interaction of gender × education levels (c), and Education level: senior high or below (SH)/junior college (JC)/bachelor (BA)/master's degree or above (MD).

TABLE 2: Aircraft interior design indexes corresponding to PSI factors.

	PSI factors	Aircraft interior design indexes
F1	Interpersonal distance	Seat width and layout
F2	Room for passengers' limbs	Seat pitch
F3	Front-row passengers	Seat back
F4	Belongings' placement	Storage space
F5	Adjacent passengers	Armrest design
F6	Passenger movement	Passage width
F7	Back-row passengers	Seat pedal
F8	Contact with objects	Tray table
F9	Noise	Noise reduction
F10	Smell	Air circulation system,
F11	Illumination	Lighting system
F12	Conversation	Entertainment system
F13	Sight	Other privacy design
F14	Theme and content	Headrest partition

TABLE 3: Normalized direct-relation matrix.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
F1	—	0.108	0.103	0.086	0.103	0.103	0.081	0.076	0.054	0.076	0.038	0.076	0.086	0.011
F2	0.054	—	0.076	0.086	0.097	0.103	0.032	0.070	—	—	—	—	—	—
F3	0.043	0.097	—	0.049	0.043	0.059	0.005	0.005	0.027	0.005	—	—	—	—
F4	0.038	0.081	0.022	—	0.065	0.059	0.027	0.108	—	—	—	—	—	—
F5	0.097	0.092	0.011	0.054	—	0.097	0.005	0.027	0.097	0.103	0.049	0.103	0.108	0.070
F6	0.022	0.081	0.092	0.065	0.103	—	0.011	0.059	0.016	0.038	—	—	0.005	—
F7	0.027	0.011	—	0.016	0.011	0.043	—	0.038	0.076	0.092	0.005	0.005	—	—
F8	—	—	—	0.065	0.081	—	0.000	—	—	—	—	—	—	—
F9	—	—	0.065	—	0.103	—	0.032	—	—	—	—	0.038	—	0.005
F10	—	—	0.070	—	0.108	—	0.043	—	—	—	—	0.016	—	0.005
F11	0.043	—	—	—	—	—	0.011	—	—	—	—	0.011	0.043	0.005
F12	—	—	0.016	—	0.097	—	0.005	—	—	—	—	—	0.016	0.043
F13	—	—	—	—	0.016	—	—	—	—	—	—	0.011	—	0.005
F14	—	—	0.005	—	0.070	—	—	—	0.027	—	—	0.097	—	—

TABLE 4: Total relation matrix.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
F1	0.051	0.175	0.159	0.146	0.208	0.169	0.108	0.128	0.095	0.118	0.050	0.112	0.118	0.033
F2	0.088	0.059	0.112	0.131	0.161	0.150	0.051	0.111	0.031	0.034	0.011	0.027	0.027	0.014
F3	0.067	0.131	0.033	0.081	0.093	0.097	0.022	0.038	0.044	0.026	0.007	0.018	0.017	0.009
F4	0.063	0.115	0.051	0.040	0.116	0.096	0.041	0.136	0.021	0.024	0.008	0.019	0.019	0.010
F5	0.129	0.143	0.072	0.102	0.108	0.148	0.037	0.071	0.127	0.133	0.059	0.141	0.137	0.088
F6	0.056	0.127	0.123	0.105	0.161	0.049	0.029	0.093	0.042	0.064	0.010	0.025	0.029	0.014
F7	0.038	0.030	0.026	0.034	0.054	0.060	0.014	0.052	0.086	0.104	0.010	0.020	0.010	0.006
F8	0.015	0.019	0.009	0.076	0.097	0.018	0.006	0.015	0.012	0.012	0.005	0.013	0.012	0.008
F9	0.019	0.025	0.076	0.017	0.126	0.024	0.039	0.012	0.020	0.019	0.007	0.056	0.017	0.017
F10	0.021	0.026	0.082	0.018	0.131	0.026	0.050	0.013	0.021	0.021	0.007	0.035	0.017	0.017
F11	0.046	0.008	0.008	0.007	0.012	0.008	0.016	0.006	0.006	0.007	0.002	0.017	0.049	0.008
F12	0.015	0.017	0.026	0.012	0.116	0.017	0.010	0.008	0.032	0.015	0.006	0.020	0.031	0.053
F13	0.002	0.003	0.002	0.002	0.020	0.003	0.001	0.001	0.003	0.002	0.001	0.014	0.003	0.007
F14	0.011	0.013	0.015	0.009	0.093	0.013	0.005	0.006	0.040	0.011	0.005	0.111	0.013	0.012

memories overall than males, females are more willing to report invasions of personal space than males, or any combinations of these. Based on some studies on gender differences in sensory sensitivity [47–50], one possible reason for these results is that women are more sensitive than men in many senses, such as touch, smell, hearing, and

environmental perception. In economy class, the interpersonal distance between adjacent passengers has been reduced to an intimate distance [24], which means that their touch, smell, and hearing are the main sensory channels for their communication [32]. We found that passengers' feelings differ when invaders have different genders and

TABLE 5: Causal effect levels and the weights of factors.

Factors	D_i	C_i	M_i	R_i	W_i
F_1	1.669	0.621	2.290	1.049	0.122
F_2	1.007	0.891	1.898	0.116	0.101
F_3	0.682	0.795	1.477	-0.113	0.079
F_4	0.761	0.781	1.541	-0.020	0.082
F_5	1.495	1.497	2.992	-0.002	0.160
F_6	0.926	0.878	1.804	0.048	0.096
F_7	0.544	0.426	0.970	0.118	0.052
F_8	0.317	0.691	1.007	-0.374	0.054
F_9	0.475	0.579	1.054	-0.104	0.056
F_{10}	0.484	0.591	1.075	-0.106	0.057
F_{11}	0.200	0.191	0.391	0.010	0.021
F_{12}	0.378	0.627	1.006	-0.249	0.055
F_{13}	0.063	0.498	0.561	-0.435	0.030
F_{14}	0.358	0.295	0.653	0.063	0.035

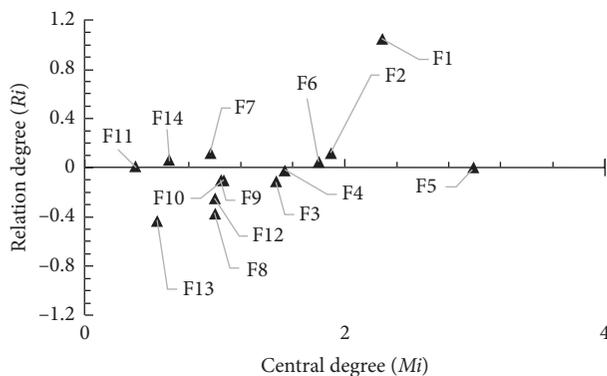


FIGURE 6: The causal diagram of 14 PSI factors.

interpersonal relations. When passengers' personal spaces were invaded, the passengers of the same gender show higher tolerance than opposite gender passengers; likewise, opposite gender passengers were more sensitive than same gender passengers. Passengers feel more negatively about PSI from strangers than from close friends. These results are consistent with a previous study by Lewis et al. [16].

A significant gender difference was found in the rating results of the respondents; namely, rating scores from females were higher than those of males. This shows that females are more mindful of the effect of PSI on their comfort than males. This is consistent with previous research proposing that women are more sensitive to intrusion from the side of the body, while men are more sensitive to intrusion from the front [51]. Due to the particularity of aircraft seats, most PSI experienced by passengers originated from the side of the body, thus explaining the greater PSI effect on female passengers compared to males. The rating scores of PSI on passenger comfort tended to increase with the age of passengers, with a peak at 40–59 years old, and then decrease with older age. This is consistent with a previous study by Aiello and De Carlo [52], which suggested that the scope of personal space first increases with age but gradually decreases at older ages. Our results show that the effect of PSI on passenger comfort increases with education level. People's cultural background is closely related to their

education level. This concept is consistent with previous studies [21, 25, 26], which proposed that people of different cultural backgrounds have different requirements regarding the scope of their personal space. For instance, Hall et al. [26] found that people with cultural backgrounds in which close contact is acceptable have closer interaction distance and smaller personal space than people with noncontact culture backgrounds. Thus, people with a high level of education are more aware of their personal space and think that PSI has more effect on their comfort. This will be a direction of future research. We also found that women are more mindful of the effect of PSI on their comfort than men with SH education level. This difference does not exist among the passengers with higher education levels. This finding may be related to gender differences for individuals of high school age. Women aged 15–19 years are typically more conscious of personal space than men. Similar conclusions have not been reported in the literature and may need further research.

According to the results of study 2, some information and indications were also extracted. By combining Tables 2 and 5 and Figure 6, the PSI factors and corresponding interior design indexes were analyzed and discussed in terms of how to improve passenger discomfort relating to PSI. First, 14 PSI factors were classified into two groups according to their relation degree, as shown in Table 5. The cause group (relation degree >0) included F_1 , F_2 , F_6 , F_7 , F_{11} , and F_{14} ; the effect group (relation degree <0) included F_3 , F_4 , F_5 , F_8 , F_9 , F_{10} , F_{12} , and F_{13} . It was necessary to focus on the cause group factors in advance due to their influence on the effect group factors. Next, a comprehensive discussion was conducted according to the values of the relation degree, central degree, and weight. The central degree and weight represent the status and importance of factors in the system, respectively [43]. Factors that belong to the cause group have an impact on the entire system, and thus they should be considered more carefully [45].

Interpersonal distance (F_1) had the highest value of the relation degrees, which means that F_1 was the most influential PSI factor. F_1 influenced the other PSI factors the most and was influenced by the other factors the least. In addition, the central degree and weight of F_1 ranked second among all the causal factors. This indicated that F_1 had a remarkable effect on the other PSI factors. The interior design indexes corresponding to interpersonal distance (F_1) were seat width and layout. Improvements in the seat width and layout can reduce the effect of PSI on passenger comfort. Therefore, the seat design and layout should be designed first during the process of cabin interior design, which includes the seat width, the armrest spacing, and the number of seats in each row. This is consistent with the conclusions of some previous studies [35–37] that considered that the seat design and passenger space allocations can help to increase comfort. In summary, seat width and layout are some of the key design indexes that should be focused on in aircraft interior design to reduce the passenger PSI. This finding is in accordance with research from Liu et al. [6] and Vink et al. [11], where the cabin seat had a higher correlation with passenger comfort.

As shown in Figure 6, the relation degree values of F_2 , F_6 , F_7 , F_{11} , and F_{14} are very close. Therefore, it is necessary to refer to their central degrees and weights when discussing the importance of these factors. The centrality is shown in Figure 6. Although the room for passengers' limbs (F_2) had the third-highest value of relation degree, it was only 0.002 less than the back-row passengers (F_7). The central degrees and weights of F_2 all ranked third among the causal factors, which were all higher than that of F_7 . This means that the design index corresponding to F_2 should be paid more attention to than that corresponding to F_7 . Hence, it is of great significance to maintain a reasonable seat pitch in the cabin to reduce the PSI of passengers. This is in accordance with the study by Zhao et al. [12] where seat pitch was one of the most important factors affecting passengers. According to Figure 6, F_2 is markedly lower than F_1 , indicating that the effect of F_2 on the entire system is not as strong as that of F_1 . That is to say, in order to reduce the effect of PSI on passenger comfort, adjusting the seat pitch should be considered after adjusting the seat width and layout. In addition, an excessive increase in seat pitch will reduce the number of seats in the cabin, which may reduce the economy of the aircraft. Therefore, the influence of seat pitch on the aircraft economy and passenger PSI should be further studied.

Passenger movement (F_6) had the third-highest value of the central degree and weight. The relation degree of F_7 was only 0.048. This indicated that F_6 had little effect on the entire PSI factor system, but it was closely related to other PSI factors. Therefore, it also requires research attention. The interior design index corresponding to passenger movement (F_6) was the passage width. The width of the passage in the cabin was closely related to many indexes such as space arrangement, seat layout, and seat pitch. Passengers sitting near the aisle are often disturbed by physical contact from passing passengers or cabin attendants in service. Therefore, a reasonable passage width design can reduce the PSI caused by passenger movement.

Back-row passengers (F_7) had the second-highest value of the relation degree. However, the central degree and weight of F_7 were very low. The interior design index corresponding to back-row passengers (F_7) was the seat pedal. Nevertheless, the seat pedal design still plays a role in reducing the PSI from the rear passengers. For example, setting up pedals that are not connected to the front seats can reduce the interference of the back-row passengers with the front passengers.

The central degree and weight of the illumination (F_{11}) and theme and content (F_{14}) were both low; however, they were in the cause group. Therefore, their corresponding design indexes (lighting system and headrest partition) also require attention in the design process. For instance, a well-designed reading light can be used by one passenger without affecting other passengers who are resting on his/her side. The relation degree, central degree, and weight of F_{14} were all higher than those of F_{11} . Therefore, the lighting system and headrest partition need to be improved at the same time, to better reduce the PSI of passengers; the headrest partition design should be given priority. Adding a pair of small partitions on the headrest can effectively improve the

protection the seat provides to the privacy of the passenger's line of sight. Similar designs can be found in previous books written by Vink [5].

In general, factors in the effect group were highly influenced by other factors, which make effect factors unsuitable as direct improvement measures [6]. Nevertheless, it is still necessary to discuss effect factors to reveal the features of each PSI factor and their corresponding design indexes.

One can see from the causal diagram that F_5 is located mostly on the right. Although the relation degree value of the adjacent passengers (F_5) is slightly below zero, the central degree and weight of F_5 is the highest among all the PSI factors. This means that F_5 was slightly impacted by the other factors while exerting a large effect on the entire PSI factor system. This indicates that adjacent passengers are the primary source of PSI for passengers. This is consistent with a previous study by Lewis et al. [16], which suggested that most of the PSI originates from the passengers nearby. This is also consistent with the survey results in study 1; the PSI description number of the adjacent passengers was the largest. The interior design index corresponding to F_5 is the armrest design. The reason why this index is the "armrest design" is that the armrest is an important physical boundary between two adjacent passengers. Currently, the common design of economy class seats is to share an armrest with the adjacent seats [5]. The two passengers often have to face the embarrassing situation of competing for the armrest [16]. Hence, it is necessary to improve the armrest design between adjacent seats.

The relation degree, central degree, and weight of the belongings placement (F_4) all ranked second in the effect group. The relation degree value of F_4 was also slightly below zero. However, the causal diagram shows that F_4 is far away from F_5 and close to the other effect factors. This indicates that F_4 was slightly impacted by the other factors, while F_4 itself had a certain effect on the entire PSI factor system. The interior design index corresponding to F_4 was the storage space. In the cabin, except for the luggage carrier, the spaces where passengers are allowed to place objects are the space under their seat, the seat back storage bag, and the tray table (during cruising). There is no clear boundary for these storage spaces, however, and some PSI was caused by improper placement of belongings by passengers.

The relation degree values of the front-row passengers (F_3), noise (F_9), and smell (F_{10}) were very close. Therefore, the importance order of these three factors should refer to their central degree and weight. Among the three effect factors, F_3 had the largest central degree and weight, followed by F_{10} and then F_9 . This indicated that F_3 , F_{10} , and F_9 had limited effects on the entire PSI factor system. The interior design indexes corresponding to F_3 , F_{10} , and F_9 were the seat back, noise reduction, and air circulation system, respectively. A sudden adjustment of the seat back by the front-row passenger will affect the rear passenger. In addition, the seat back with too much tilt will occupy the rear passenger space. Controlling the tilt range of the seat back and adding a damping device to the adjusting mechanism can reduce the disturbance of the seat back to the rear passenger. Noise reduction measures can be used to reduce

the disturbance of cabin noise to passengers. The circulation path of the air circulation system can be optimized to help eliminate bad smells in the cabin.

Contact with objects ($F8$) and conversation ($F12$) were similar in their central degree and weight values. Therefore, the decision of their priority order was based on their relation degree values. The relation degree of $F12$ was larger than that of $F8$. The interior design indexes corresponding to $F8$ and $F12$ were the tray table and the entertainment system, respectively. Therefore, improving the entertainment system to reduce the passenger PSI was more important than improving the tray table. A good entertainment system can distract passengers from their attention to the cabin context and weaken their sensitivity to PSI. The relation degree, central degree, and weight values of sight ($F13$) were the lowest of all the effect factors. This indicates that $F13$ had the least effect on the entire PSI factor system. The interior design index corresponding to $F13$ is another privacy design. This showed that the addition of a passenger privacy protection device is the last measure that should be considered.

According to the discussion above, the following ranking of the 14 PSI factors (from strongest to weakest) was obtained: $F1, F2, F6, F7, F2, F14, F11, F5, F4, F3, F10, F9, F12, F8,$ and $F13$. Subsequently, the optimization design sequence of the 14 aircraft interior design indexes was obtained. In summary, to reduce the invasion of passengers' personal space, a specialized priority ranking should be constructed for many aircraft interior design indexes. Following this ranking during the process of aircraft interior design can effectively reduce the occurrence of passengers' PSI and improve aircraft passenger comfort.

We note that space in the aircraft cabin cannot be expanded indefinitely. To increase passengers' interpersonal distance would reduce the number of seats in the cabin, which could affect the business of air travel. Here, we discuss potential solutions within this context. First, more space in the cabin would translate into higher flight fares as there would be fewer seats. Physical space will become an important measure standard to highlight passenger comfort as a selling point for an airline. Airlines can balance these costs by offering more seats with different comfort levels in the same cabin class. Second, optimizing seat design can make it easier to adjust seat layout in the cabin. Airlines can adjust the seat layout strategy more flexibly according to the flight time. For example, when the flight duration is long, the physical space of a seat can be increased by adjusting the seat layout, and vice versa. Third, if the original seat layout remains unchanged, one can also consider improving other interior design indexes (such as seat pitch, passage width, headrest partition, and armrest design) to reduce the impact of PSI on passenger comfort. The findings of previous studies show that people are more willing to maintain closer distances to objects than people [53]. Moreover, we are in the times of COVID-19, and maintaining the personal space of passengers can not only improve their comfort, but also help reduce the mutual transmission of the virus in the cabin.

Passenger comfort issues are present not only in the cabin of the aircraft, but also in other forms of public transport, of which high-speed rail is one of the most representative. Chen et al.'s research [54, 55] provided two different ways to collect high-speed rail passenger demands on comfort from social media. One way was to use a quality function deployment method to extract the factors that affect passenger comfort, and then prioritize these factors using a fuzzy linguistic group decision-making approach based on the adoption of generalized comparative linguistic expressions. The other way was to use a combination of online review analysis and a large-scale group decision-making method to extract passenger demands, and then determine the rankings of those demands. High-speed rail and aircraft cabins have many common characteristics (such as seat width, seat pitch, and lighting). Therefore, it is possible to extend the method of this paper to the study of the comfort of high-speed rail passengers.

Figure 7 illustrates an imperfect concept seat sketch and seat layout plans that originated from this study. This concept sketch was based on the design indexes (including seat width and layout, seat pitch, and headrest partition) corresponding to the PSI factors in the cause group. The headrest partition may reduce the disturbances of sight and light from the passenger's surroundings as well as increasing privacy. Improving armrests and adding leg (knee) partitions may reduce unnecessary physical contact between passengers. Adjusting the seat layout may help maintain interpersonal distance between passengers. In the future, there will be great changes in the configuration of the airliner. For example, the layout of the cabin seats in the blended wing body (BWB) airliner will be more flexible and diverse [56]. Although the concept sketch is not perfect in many aspects, such as production cost or cleaning workload, the sketch represents a suggestion for future aircraft seat design.

There are some limitations to this study. First, the survey results are based on a convenience sample. The convenience sample may be unrepresentative in some ways, such as the religiosity, race, and geographic region of all aircraft passengers. Second, the survey data reflected the retrospective experience of passengers. Future studies should examine the real-time experiences of passengers during flights. Third, the weights of design indexes in this study are only applicable for the influence of PSI on passenger comfort. However, PSI is one of many aspects that affect passenger comfort, and thus a more comprehensive weighting method is needed in the future. Fourth, according to studies of Weber et al. [57] and Ozcan et al. [58], aircraft interior noise is an important environmental factor that affects passengers' comfort and health. Therefore, the PSI and discomfort of passengers due to noise will be a valuable direction for future research. Finally, the findings of this study are within the context of aircraft economy class, and thus future research can be extended to other aircraft cabin classes or other public transport modes.

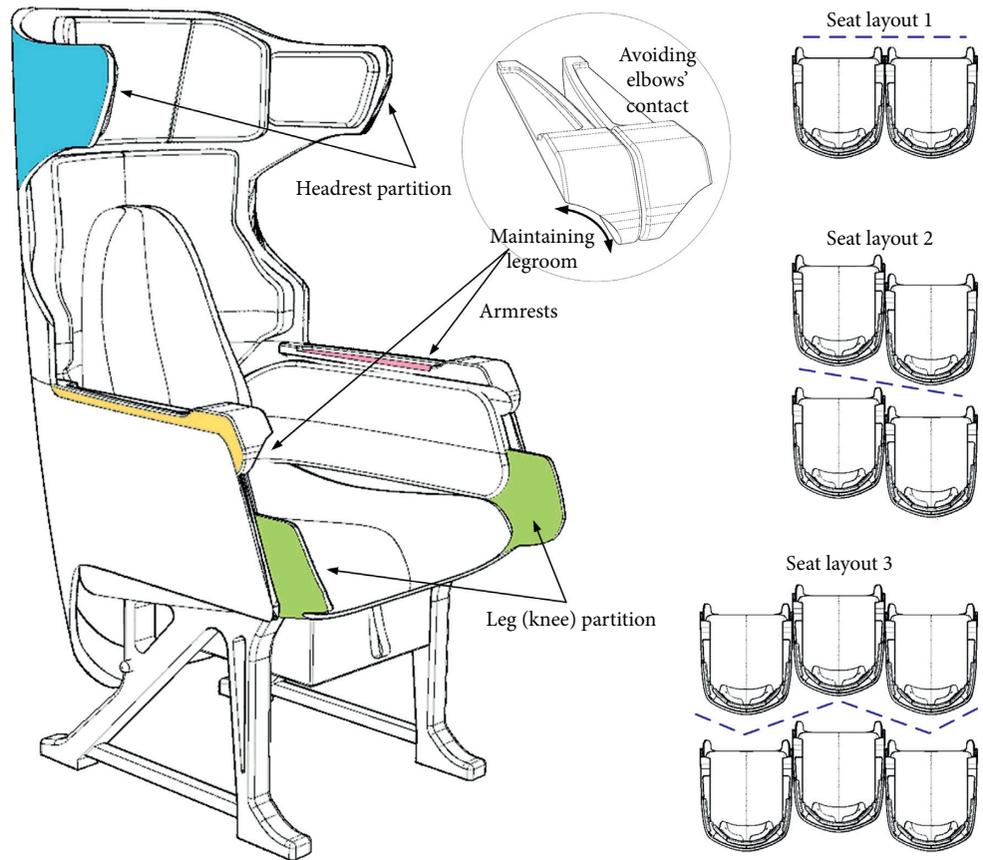


FIGURE 7: Concept seat sketch and seat layout suggestions.

5. Conclusions

This study identifies the key factors of passenger PSI and analyzes the relationships between them, which is of great significance to improve passenger comfort and aircraft interior design. This aligns with findings from other studies regarding the invasion of personal space as a common cause of discomfort and distress for aircraft passengers. This study provides an effective way to analyze the PSI factors and the cause-and-effect relationships between them using questionnaire data and DEMATEL method. Furthermore, this work forms a structural model, which intuitively shows the causal relationships between factors through a causal diagram. A specialized priority ranking of aircraft interior design indexes, which is beneficial to the reduction of passenger PSI, was extracted from the results. The findings of this study provide aircraft designers with some rationalization for prioritizing certain indexes in aircraft interior design to improve passenger discomfort relating to the invasion of personal space.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The funders had no role in the design of the study, in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The authors would like to acknowledge the support of the students and staff of the Key Laboratory of Industrial Design and Ergonomics (Ministry of Industry and Information Technology of China) for their assistance in data collection and analysis. The authors also thank LetPub (<http://www.letpub.com>) for its linguistic assistance and scientific consultation during the preparation of this manuscript. This research was funded in part by the Programme of Introducing Talents of Discipline to Universities of Ministry of Education of China, under Grant no. B13044, and in part by the Special Research Foundation for Civil Aircraft of Ministry of Industry and Information Technology of China, under Grant no. MJ-2015-F-018.

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