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Combining PCA-AHP Combination Weighting to Prioritize Design Elements of Intelligent Wearable Masks

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Abstract: Intelligent wearable masks are gaining increasing interest due to COVID-19 and the problems and limitations of existing masks. This paper prioritizes the design elements of personal protective equipment-intelligent wearable masks from the perspective of the product design domain. Using principal component analysis (PCA), the principal components of the design elements were selected first in this paper. Using the combined weights (PCA-AHP) method, the intelligent wearable masks' prioritized design elements at each level were determined. The highest priority among the primary elements is comfort (0.3422), with the adjustable ear strap (0.1870) receiving the highest priority among the primary elements of comfort. The highest priority in functionality (0.2733) is anti-respiratory droplets/air purification (0.1097), the highest priority in usability (0.1686) is the easy removal and replacement of filters (0.0761), the highest priority in the aesthetic design (0.1192) is styling (0.0509), and the highest priority in material (0.0967) is flexible fabric material (0.0355). Finally, the six prioritized design elements were evaluated using fuzzy comprehensive evaluation (FCE), and overall, 76% of the experts considered them "appropriate" or "very appropriate" and 18% considered them "fair." Therefore, this study's six most prioritized design elements proposed for intelligent wearable masks can satisfy users' needs.

Keywords: intelligent wearable mask; design elements; personal protective equipment; combination weighted; fuzzy comprehensive evaluation; product design

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1. Introduction

The spread of coronavirus-2/coronavirus disease 2019 (SARS-CoV-2/COVID-19) has caused global panic [1]. COVID-19 was not only responsible for many deaths but also had a significant economic, social, and environmental impact. SARS-CoV-2 is a highly contagious respiratory virus transmitted through droplet, contact, and aerosol channels. When a carrier of SARS-CoV-2 coughs or sneezes, droplets containing the virus may adhere to nearby objects' surfaces, be inhaled by others, or mix with air to form aerosols, thereby spreading the virus [2]. Masks have been shown to effectively reduce the spread of influenza and coronaviruses in the population. Therefore, masks are one of the most effective means of preventing the spread of SARS-CoV-2 [3], hence the increased interest and demand.

As more people began to use disposable masks, the problems and limitations of disposable masks became apparent. First, disposable masks are unsustainable, and the plastic and micro-plastic waste they produce has become a global issue of grave concern [4,5]. Therefore, we must consider how we can make masks more environmentally friendly. Second, it is difficult for the wearer to determine their current health status, which places a great deal of psychological strain on individuals [6]. Third, disposable masks present numerous problems in terms of the wearing experience, such as discomfort from prolonged skin contact [7] and pain behind the ear from prolonged wear [8]. Therefore, when determining the design elements of new masks, it is necessary to consider the problems and limitations posed by the previously mentioned disposable masks.

Current research on mask improvement focuses primarily on usability [9,10], comfort [8,11,12], new materials [13–15], and breathability [16–18] to address these issues and limitations. Even though these studies provide reasonable solutions for a better mask design, innovative solutions are still required to help people transition into a post-pandemic world. During the pandemic, intelligent masks have proved their superiority with a range of functions and have become a research priority [19–22]. In a study by Lee, P et al., the range of applications was investigated by reviewing 25 intelligent masks (12 from marketed products and 13 from academic prototypes) that have emerged since COVID-19, considering design aspects such as reliability, repeatability, ergonomic design, and data handling for privacy, and deducing that intelligent masks have the potential to become the next generation of wearable devices [23]. This study offers a valuable guide for enhancing the functionality of intelligent wearable masks. Intelligent wearable masks with additional functions can not only expand the application scope and scenario of masks but also reduce the use of disposable masks to a certain extent, thereby reducing environmental pollution. In addition, since the COVID-19 pandemic, researchers in the field have reported intelligent wearable masks as a component of personal protective equipment (PPE) primarily at the technical and functional level, including health monitoring [24–26], sensing viruses [27,28], infection notification [29], and self-powering [30,31]. It is rarely investigated at the level of product design. However, the final product is user-centric, so the attitudes and preferences of users toward intelligent wearable masks are crucial. Hu, B. and Koo, S. [32] developed an intelligent wearable mask to prevent respiratory infections and defined design guidelines for intelligent wearable masks by analyzing user preferences for the functionality and design of intelligent wearable masks. This study complements the research on intelligent wearable masks at the level of users. However, Hu, B. and Koo, S. [32] did not thoroughly explore the prioritization of design elements. When prioritizing the design aspects of intelligent wearable masks, it is vital to discuss and investigate various existing intelligent features. This is due to the fact that intelligent functionality is a crucial factor in determining the importance of the design aspects of this mask, and one of the advantages of this mask is represented in its intelligent characteristics. In addition, the problems and limitations shown by disposable masks are essential references for this investigation. Given the future of intelligent wearing masks, this work is essential. Therefore, additional replenishment of this void is required.

Given the numerous problems and limits of existing masks and the superiority of intelligent wearing masks, the purpose of this study was to establish which aspects of intelligent wearable masks should be prioritized using the PCA-AHP method. It is anticipated that the results of this study will be helpful to designers and developers of intelligent wearable masks.

2. Methodology

This study analyzed the priority of the intelligent wearable mask design elements using principal component analysis (PCA) and the analytic hierarchy process (AHP). Fuzzy comprehensive evaluation (FCE) was then used to evaluate the prioritized design elements to increase the reliability of the results. The steps of this study are shown in Figure 1.

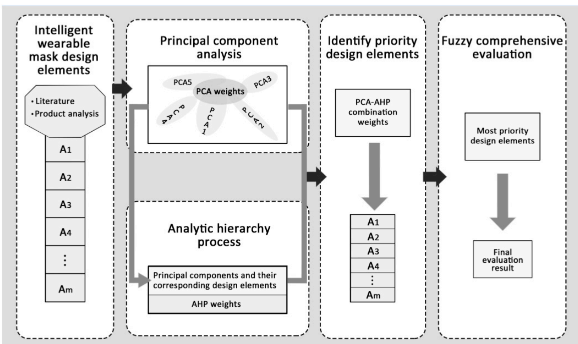

Figure 1. Flow chart of the study.

2.1. Principal Component Analysis

Principal component analysis (PCA) can be used to reveal the relationship between variables and is a method of dimensionality reduction with reduced correlation variables [33]. PCA can transform variables that may be correlated in the original data into a set of linearly uncorrelated variables, thereby preserving the original information with minimal information loss [34]. In addition, PCA can compute the weights of relevant variables based on data such as loading coefficients.

This study relied heavily on PCA for intelligent wearable mask design element principal component extraction and objective weight calculation. In addition, we collected the necessary data via an online questionnaire on the Credamo platform between 21 August 2022 and 23 August 2022 and utilized it for the PCA analysis. All participants were made aware of the study and agreed to the use of the completed questionnaire for academic research. Furthermore, 360 questionnaires were distributed, with 300 valid and 60 invalid questionnaires. The subjects of the survey are Chinese users over the age of 18. These questionnaires investigated Chinese users' opinions about the appropriateness of various design elements of intelligent wearable masks and measured them on a 5-point Likert scale.

2.2. Analytic Hierarchy Process

Saaty proposed the analytic hierarchy process (AHP) in 1988 as a method for making decisions with multiple objectives [35]. Due to its versatility and usability, the method has been successfully applied to a variety of fields and problems. After a lengthy development and application period, most studies today combine AHP with other methodologies and techniques [36–38].

In this study, the design elements were therefore subjected to PCA dimensionality reduction prior to AHP analysis, and the reduced design elements and principal components will be utilized in the AHP hierarchical analysis framework. AHP is primarily used to determine the subjective weights of design elements in this context. For the AHP weighting, we invited 20 design professionals with more than two years of experience to complete the questionnaire and rate it on a 5-point Likert scale. Ten of them are academics employed by universities and 10 are designers employed by companies.

2.3. Fuzzy Comprehensive Evaluation

A fuzzy comprehensive evaluation is a method of evaluation based on fuzzy theory. The objective is to consider the contributions of multiple relevant factors based on the weighting factors and to reduce ambiguity by applying the principle of maximum affiliation to determine the final evaluation results [39]. FCE has been widely utilized in engineering, design, and environmental evaluations.

Here, we will use FCE to evaluate the appropriateness of the highest-priority design elements. We invited 60 professionals with at least two years of experience in design fields to complete the questionnaire. The questionnaire for evaluation was administered online. The prioritized design elements derived from the preceding analysis were used as evaluation items and evaluated once the experts had fully comprehended them. The evaluation levels were "very inappropriate", "inappropriate", "average", "appropriate", and "very appropriate". The professionals assigned a score to each design element based on their professional opinion. Finally, we computed the evaluation results to thoroughly assess the priority of intelligent wearable mask design elements to be considered.

3. Research Execution and Analysis

3.1. Design Element Extraction and Analysis

The extraction and evaluation of intelligent wearable mask design elements are presented here. The first step in the design process consisted of identifying the characteristics (in this study, the wearer) required in the designed product (i.e., the intelligent wearable mask). As a result, we investigated all types of academic prototype masks and mask products, including general masks and intelligent masks, via a literature review and analysis of commercially available masks, and extracted and integrated the design elements, with the results shown in Table 1.

Table 1. Extraction of design elements for masks.

Design Elements for Masks
Anti-Respiratory Droplets/Air Purification [40]
Information display [32]
Matching face shape [9]
Adjustable ear strap [8]
Lightweight [29]
Environmentally friendly materials [41]
Antibacterial materials [14]
Color [32]
Patterns [32]
health monitoring/infection notification [26,29]
Easy removal and replacement of filters [12]
Ease of Donning and Doffing [12]
Easy to clean [12]
Bluetooth communication [42]
Connect intelligent phone app [29]
Flexible fabric material [43]
Styling [32]

As shown in Table 1, intelligent wearable masks used as personal protective equipment are equipped with anti-respiratory droplets or air purification capabilities to combat the risk of respiratory diseases or air pollution. In addition, as a wearable device, intelligent wearable masks must be equipped with a health monitoring/infection notification function and the user must be provided with the necessary information via a connected intelligent phone app. Considering the diversified needs of users, intelligent wearable masks should also include Bluetooth communication capabilities. As a cutting-edge device that considers individual needs, it is also necessary to display information on the surface of the mask, such as air quality and user-defined information.

Intelligent wearable masks must conform to the user's face; if they do not, external threats may enter through the mask's gaps and endanger the user's health, and for those who wear glasses, exhaled air will adhere to the lenses in the form of water vapor, causing significant inconvenience. Intelligent masks must be lightweight; if they are too heavy, it will be difficult for users to appreciate them. Because prolonged mask use exerts pressure on the ear, the ear strap must be adjustable. In addition, the portion of the mask that comes into contact with the skin should be made from a soft fabric to prevent problems such as skin irritation.

Intelligent wearable masks, such as reusable masks, should have easily cleanable surfaces and interiors and filters that are simple to remove and replace. Given that intelligent wearable masks are intended for public use, they should be easy to use and simple to don and doff. Given the problem of environmental pollution caused by disposable masks, intelligent wearable masks must be constructed from eco-friendly materials. Antibacterial materials are also considered a potential solution to the problem of bacteria and odor within the mask. Because of the prolonged use of the mask, during the pandemic, masks have become an indispensable accessory through which individuals can express themselves; moreover, wearing a mask adds a social dimension. Therefore, styling, color, and patterns must be considered when determining the design elements of an intelligent wearable mask.

Based on the preceding analysis, we initially classified elements using professional discretion. Health monitoring/infection notification, anti-respiratory droplets/air purification, connection to an intelligent phone app, information display, and Bluetooth communication make up the first group (functionality). Matching face shape, adjustable ear strap, and lightweight and flexible fabric material comprise the second group (comfort). The third group (usability) includes easy removal and replacement of filters, ease of cleaning, and ease of donning and doffing. The fourth group (material) includes environmentally friendly materials and antibacterial materials. The fifth group (aesthetic design) includes styling, color, and patterns. Here, classification is primarily based on human judgment, and the outcomes are somewhat subjective. A new round of PCA analysis will be conducted to ensure the results' objectivity and scientific validity. Therefore, in addition to obtaining and discussing the analysis results alongside the initial classification, the rigor of the design process is also ensured.

3.2. PCA Design Elements Classification

The data were analyzed using version 25.0 of SPSS. Before PCA analysis, the questionnaire was analyzed for reliability to ensure item consistency and reliability, and correlations and bias correlations between variables were analyzed to determine if PCA analysis was appropriate. As shown in Table 2, Cronbach's alpha was 0.739 > 0.7, indicating good reliability, and KMO was 0.815 > 0.5, making it suitable for PCA analysis.

Table 2. Results of KMO and Bartlett's Test and reliability analysis.

		Recommended Value	Test Value
Reliability test	Cronbach's Alpha	>0.7	0.739
KMO and Bartlett's Test	KMO	>0.5	0.815
	Sig.	<0.01	0.000

Table 3 displays the results of the principal component analysis. The most common varimax rotation method in PCA analysis was chosen to extract the main components. The method's structure is straightforward. Each factor derived by this method is linearly uncorrelated and can be interpreted independently [44]. Using a factor loading of 0.5 as an observation, five primary sets of design element components can be obtained.

Table 3. Factor loadings of design elements (varimax with Kaiser normalization); elements with reference factor loadings >0.5.

	Factor Loading (after Rotation)				
	Component				
	PC1	PC2	PC3	PC4	PC5
C1 Anti-respiratory droplets/Air purification	0.748	0.139	0.109	0.019	0.118
C2 Information display	0.730	−0.089	0.218	0.058	−0.037
C3 Health monitoring/Infection notification	0.555	0.418	0.165	−0.107	0.056
C4 Bluetooth communication	0.699	0.270	0.024	−0.073	−0.110
C5 Connect intelligent phone app	0.784	0.150	0.127	−0.010	−0.118
C6 Matching face shape	0.196	0.724	0.060	−0.021	0.060
C7 Adjustable ear strap	0.034	0.675	0.196	0.180	0.083
C8 Lightweight	0.173	0.763	−0.028	−0.076	0.010
C9 Ease of Donning and Doffing	0.139	0.044	0.781	−0.092	−0.050
C10 Easy to clean	0.182	0.064	0.716	−0.079	0.066
C11 Easy removal and replacement of filters	0.151	0.414	0.546	−0.045	−0.107
C12 Environmentally friendly materials	−0.138	0.105	−0.370	0.684	0.003
C13 Antibacterial materials	0.023	−0.042	−0.228	0.743	−0.032
C14 Flexible fabric material	0.044	−0.007	0.281	0.722	0.061
C15 Color	0.007	0.047	0.020	0.040	0.774
C16 Styling	0.009	0.146	0.022	0.003	0.785
C17 Patterns	0.295	0.273	0.356	0.059	−0.508

When the five principal components were extracted by PCA, the cumulative total variance explained was 59.056%.

The first principal component consists of five design elements: Anti-respiratory droplets/air purification, information display, health monitoring/infection notification, Bluetooth communication, and connection to an intelligent phone app. These five design elements are all functionally related. Given that intelligent wearable masks have not yet achieved widespread popularity and that COVID-19 affects all people, it is not difficult to understand why users are anticipating the function of masks. The first significant component can therefore be generalized as functionality.

The second principal component consists of three design elements: Matching face shape, adjustable ear strap, and lightweight. Existing masks have numerous problems considering the wearing experience, so it is essential to consider ways to improve the wearing experience. Otherwise, the user will take off the mask, which renders the intelligent wearable mask meaningless. Consequently, the second primary component can be summarized as comfort.

The third principal component consists of three design elements: Ease of donning and doffing, easy cleaning, and easy removal and replacement of filters. Users are concerned with the usability of intelligent wearable masks, so all three elements are related to usability. Usability is directly related to the likelihood that users will continue to select this mask over time. Usability is, therefore, a generalization of the third primary component.

The fourth principal component comprises three design elements: Environmentally friendly materials, antibacterial materials, and flexible fabric material. All three components pertain to materials. Different materials can impact the environment and the wearer's experience, making material selection crucial. Consequently, the fourth principal component is summarized primarily as material.

The fifth principal component consists of three design elements: Color, styling, and patterns. These three elements reflect the aesthetic concern of intelligent wearable mask users, where patterns are negatively correlated, which can be interpreted as user demand for no patterns. It indicates that mask simplicity is of greater importance to users. Therefore, aesthetic design can be summarized as the fifth principal component.

PCA categorizes flexible fabric as a material, whereas the initial classification placed it in the comfort category. Flexible fabric can enhance user comfort to some extent, but its primary characteristic is its composition. After careful consideration, we believe that PCA analysis results are more interpretable; therefore, PCA analysis results will be utilized in the subsequent study. Functionality, comfort, usability, materials, and aesthetic design are intelligent wearable masks' five primary design elements.

3.3. Calculation of Design Element Weights

3.3.1. PCA Weight Calculation

The calculation of the weight of each design element begins with an application of principal component analysis. It is necessary to obtain the linear combination coefficient of each principal component and the comprehensive score coefficient, as well as to normalize the comprehensive score coefficient to obtain the weight value of each design element's weight value. The calculation process is divided into the following three steps.

Step 1: Calculate the linear combination coefficients.

Among them, the factor loading coefficient and eigenvalue of the variance-explained rate satisfies the relationship given by Equation (1), and the coefficient of the design elements in the linear combination can be determined.

$$U_{ij} = \frac{f_{ij}}{\sqrt{\lambda_j}} \qquad (i = 1, 2, \cdots, h;\ j = 1, 2, \cdots, m) \tag{1}$$

U_{ij}: The coefficient of the jth variable of the ith indicator in the linear combination.

f_{ij}: Rotated factor loading factors.

λ_j: The eigenvalue of the rotated posterior interpretation rate.

h: Number of design elements.

m: Number of principal components.

Step 2: Calculate the comprehensive score coefficient.

We substitute U_{ij} in Equation (1) into Equation (2) to obtain the comprehensive score coefficient of each design element in each principal component.

$$Z_i = \frac{\sum_{j=1}^{m} U_{ij} P_{ij}}{\sum P_{ij}} \tag{2}$$

Z_i: The comprehensive score coefficient of a single design element in each principal component.
P_{ij}: The variance-explained rate of each principal component after rotation in Table 3.
Step 3: Weight calculation.

On this basis, the weight of each design element is calculated, and Equation (3) can be obtained. The results are shown in Table 4.

$$w_j = \frac{Z_i}{\sum_{i=1}^{h} Z_i} \tag{3}$$

w_j: The normalized weights of individual design elements.

Table 4. PCA design element weighting results.

Title	PC1	PC2	PC3	PC4	PC5	Comprehensive Score Coefficient	Weights
eigenvalue (after rotation)	2.756	2.148	1.962	1.622	1.551		
variance contribution rate (after rotation)	16.21%	12.64%	11.54%	9.54%	9.12%		
weights	0.2746	0.2139	0.1945	0.1616	0.1545		
Anti-respiratory droplets/Air purification	0.4501	0.0949	0.0783	0.0149	0.0944	0.1762	0.0813
Information display	0.4399	−0.0614	0.1560	0.0457	−0.0292	0.1410	0.0651
Flexible fabric material	0.0263	−0.0042	0.2010	0.5670	0.0483	0.1447	0.0668
Easy removal and replacement of filters	0.0908	0.2823	0.3897	−0.0356	−0.0860	0.1425	0.0658
Antibacterial materials	0.0138	−0.0293	−0.1624	0.5832	−0.0252	0.0562	0.0259
Easy to clean	0.1099	0.0436	0.5116	−0.0625	0.0532	0.1376	0.0635
Environmentally friendly materials	−0.0830	0.0714	−0.2640	0.5370	0.0024	0.0281	0.0130
Ease of donning and doffing	0.0835	0.0304	0.5573	−0.0727	−0.0406	0.1203	0.0556
Color	0.0043	0.0323	0.0147	0.0315	0.6211	0.1120	0.0517
Styling	0.0055	0.1000	0.0154	0.0022	0.6299	0.1236	0.0571
Patterns	0.1772	0.1868	0.2538	0.0462	−0.4087	0.0826	0.0381
Lightweight	0.1045	0.5204	−0.0199	−0.0598	0.0081	0.1277	0.0590
Adjustable ear strap	0.0203	0.4609	0.1400	0.1409	0.0657	0.1645	0.0759
Health monitoring/Infection notification	0.3341	0.2854	0.1172	−0.0843	0.0449	0.1690	0.0780
Matching face shape	0.1184	0.4936	0.0429	−0.0167	0.0489	0.1513	0.0699
Connect intelligent phone app	0.4722	0.1029	0.0902	−0.0079	−0.0953	0.1533	0.0708
Bluetooth communication	0.4211	0.1842	0.0168	−0.0569	−0.0889	0.1354	0.0625

3.3.2. AHP Weight Calculation

The PCA-obtained principal components and corresponding design elements are incorporated into the AHP decision-making framework, and the weights of each level are determined. In this study, twenty experts were asked to complete a questionnaire, and the AHP calculation process was broken down into the three steps below.

Step 1: Build a consistent judgment matrix.

In this step, according to Table 5, the results of the questionnaire filled out by 20 experts are converted into a judgment matrix for the pairwise comparison of elements at all levels. Among them, the judgment matrix is:

$$A = (a_{ij})n \times n = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \ a_{ii} = 1, \ a_{ij} = \frac{1}{a_{ji}}(i, j = 1, 2, \cdots, n) \tag{4}$$

Table 5. Relative importance scale.

Scale	Meaning
1	Both metrics are equally important.
3	When comparing the two metrics, the former is slightly more important than the latter.
5	When two metrics are compared, the former is important than the latter.
7	When comparing the two metrics, the former is more important than the latter.
9	When comparing the two metrics, the former is extremely important than the latter.
2,4,6,8	The importance of the indicators is between the above scales.
Reciprocal	If the comparison between the factors i and j is judged as a_{ij}, then the judgment of the comparison between the indicators j and i is $1/a_{ij}$.

Step 2: Weight Calculation

When using AHP to calculate the element weights at each level, the data are first normalized by Equation (5), and each row of the new matrix is summed to yield the feature vector ω. The weights of the elements at each level can be obtained by Equation (6).

$$b_{ij} = \frac{a_{ij}}{\sum a_{ij}} \tag{5}$$

$$w_i = \frac{\omega}{\sum \omega} \tag{6}$$

Step 3: Consistency Check

This step is crucial for ensuring the accuracy of the weights. Equation (7) computes the maximum eigenvalue of each judgment matrix, and Equation (8) yields the consistency index CI (8). Equation (9) can be used to determine the consistency. The consistency test is passed if the consistency ratio CR < 0.1. Tables 6–11 display each index layer's judgment matrix, weight value, and consistency test results.

$$\lambda_{\max} = \frac{\sum (Aw)_i}{nw_i} \tag{7}$$

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{8}$$

$$CR = \frac{CI}{RI} \tag{9}$$

$\lambda_{\max}$: The maximum eigenvalue of the judgment matrix.
A: Judgment matrix.
w_i: Weight value of each indicator.
n: The order of the judgment matrix.
RI: Coefficient of consistency, as shown in Table 12.

Table 6. C1-C5 second-order judgment matrix and its weight vector.

	C1	C2	C3	C4	C5	w_i
C1	1	7	3	9	5	0.5075
C2	1/7	1	1/5	3	1/3	0.0698
C3	1/3	5	1	5	3	0.2472
C4	1/9	1/3	1/5	1	1/5	0.0379
C5	1/5	3	1/3	5	1	0.1376

$\lambda_{\max} = 5.277$, $CR = 0.062 < 0.1$ Consistency check passed.

Table 7. C6-C8 second-order judgment matrix and its weight vector.

	C6	**C7**	**C8**	w_i
C6	1	3	3	0.2605
C7	3	1	5	0.6334
C8	1/3	1/5	1	0.1061

$\lambda_{max} = 3.039$ $CR = 0.037 < 0.1$ Consistency check passed.

Table 8. C9-C11 second-order judgment matrix and its weight vector.

	C9	**C10**	**C11**	w_i
C9	1	1/3	1/4	0.1199
C10	3	1	1/3	0.2721
C11	4	3	1	0.6080

$\lambda_{max} = 3.074$ $CR = 0.071 < 0.1$ Consistency check passed.

Table 9. C12-C14 second-order judgment matrix and its weight vector.

	C12	**C13**	**C14**	w_i
C12	1	1/3	3	0.2605
C13	3	1	5	0.6334
C14	1/3	1/5	1	0.1061

$\lambda_{max} = 3.039$ $CR = 0.037 < 0.1$ Consistency check passed.

Table 10. C15-C17 second-order judgment matrix and its weight vector.

	C15	**C16**	**C17**	w_i
C15	1	1/2	3	0.3092
C16	2	1	5	0.5813
C17	1/3	1/5	1	0.1095

$\lambda_{max} = 3.004$ $CR = 0.004 < 0.1$ Consistency check passed.

Table 11. PCA1-PCA5 first-order judgment matrix and its weight vector.

	PCA1	**PCA3**	**PCA5**	**PCA4**	**PCA2**	w_i
PCA1	1	3	5	7	1/3	0.2719
PCA3	1/3	1	3	5	1/5	0.1419
PCA5	1/5	1/3	1	3	1/5	0.0769
PCA4	1/7	1/5	1/3	1	1/7	0.0389
PCA2	3	5	5	7	1	0.4704

$\lambda_{max} = 5.334$ $CR = 0.075 < 0.1$ Consistency check passed.

Table 12. Average random consistency index (RI).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
R.I.	0.00	0.00	0.52	0.89	1.12	1.24	1.36	1.41	1.46	1.49

3.3.3. Determination of Combined Weights

Most researchers use multiplicative synthesis and weighted linear combination methods to obtain more reasonable and scientifically weighted results [45–47]. The disadvantage of the multiplicative synthesis method is more pronounced, and it will make the initial large results larger and the small results smaller, so it is appropriate for situations where the number of items is large and the weights are more evenly distributed [48]. In this study, despite many items, the weights are not distributed uniformly; therefore, weighted linear combination methods will be used to determine the combination weights. Weighted linear combination methods employ Equation (10). Table 13 contains the final weight results.

$$W = aw_j + (1 - a)w_i\ ,\ (a = 0.5) \tag{10}$$

Table 13. Combined weights of design elements.

Primary Elements	Weights	Secondary Elements	Weights
Functional	0.2733	C1 Anti-respiratory droplets/Air purification	0.1097
		C2 Information display	0.0421
		C3 Health monitoring/Infection notification	0.0726
		C4 Bluetooth communication	0.0364
		C5 Connect intelligent phone app	0.0541
Comfort	0.3422	C6 Matching face shape	0.0962
		C7 Adjustable ear strap	0.1870
		C8 Lightweight	0.0545
Usability	0.1686	C9 Ease of donning and doffing	0.0363
		C10 Easy to clean	0.0511
		C11 Easy removal and replacement of filters	0.0761
Material	0.0967	C12 Environmentally friendly materials	0.0116
		C13 Antibacterial materials	0.0253
		C14 Flexible fabric material	0.0355
Aesthetic Design	0.1192	C15 Color	0.0378
		C16 Styling	0.0509
		C17 Pattern	0.0233

3.4. Fuzzy Comprehensive Evaluation

In this study, 60 experts were invited to complete an evaluation questionnaire of evaluation set V to determine whether the design elements prioritized for intelligent wearable masks were appropriate. Each expert makes judgments based on his or her own personal knowledge and expertise. There were 36 men and 24 women. Since the evaluated project is a priority design element, only the design element with the most significant weight among the first-level elements and the corresponding second-level design element with the most significant weight among the first-level elements are chosen, namely, comfort (first-level element) and anti-respiratory droplets/air purification, adjustable ear strap, easy removal and replacement of filters, flexible fabric material, and styling (five secondary elements). We set the evaluation set V = {V1, V2, V3, V4, V5} = {very inappropriate, inappropriate, general, appropriate, very appropriate}. The experts evaluated the six most essential design elements using the evaluation set. It is possible to obtain the evaluation matrix R (11), in which r_{mn} denotes the membership of the n th evaluation factor in the m th design requirement, and the matrix data are shown in Table 14.

$$R = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix}, \ (m = 1, 2, \cdots, 6;\ n = 1, 2, \cdots, 5) \quad (11)$$

Table 14. Evaluation metrics R (rounded to the second decimal place).

	V1	V2	V3	V4	V5
C1	0.05	0.11	0.15	0.37	0.32
C7	0	0.05	0.17	0.53	0.25
C11	0	0.08	0.22	0.43	0.27
C16	0.02	0.13	0.3	0.37	0.18
C14	0.03	0.17	0.27	0.32	0.21
PCA2	0	0	0.16	0.52	0.32

After obtaining the matrix, a thorough evaluation is conducted using Equation (12), where A is the normalized weight of the six design elements. The results of the comprehensive evaluation are shown in Table 15. A total of 1%, 5%, 18%, 47%, and 29% of experts rated the six design elements of priority consideration as “very inappropriate”, “inappropriate”, “average”, “appropriate”, and “very appropriate”. Furthermore, 76% of the experts rated the priority design elements as “appropriate” or “very appropriate” based on the final evaluation results. According to the maximum degree of membership principle, the expert's final evaluation was "appropriate". Most experts agreed that the six priority design elements we proposed for this study were suitable.

$$B = A \circ R = (a_1,\ a_2, \cdots,\ a_m) \circ \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{pmatrix} \tag{12}$$

Table 15. FCE Evaluation Results (rounded to the second decimal place).

V1	V2	V3	V4	V5
0.01	0.05	0.18	0.47	0.29

4. Results and Discussion

In recent years, due to the development of wearable technology, intelligent wearable devices such as masks have entered the public's view, and more and more people have started to recognize their benefits. This study ranks the importance of intelligent wearable mask design elements using a systematic methodology, thus complementing the design-level investigation of this mask. The results indicate that the order of importance for the first-level design elements is comfort, functionality, usability, aesthetic design, and material. Priority in terms of comfort is (from highest to lowest) an adjustable ear strap, matching face shape, and lightweight. Adjustable ear strap was given the utmost consideration regarding comfort. This is not difficult to comprehend, as those who have experienced COVID-19 are well aware that the pain behind the ear induced by wearing the mask for extended periods of time is a source of discomfort that the majority of people find intolerable. On the subject of reducing discomfort behind the ear, one might refer to the study by Xinyi Niu et al. [49] in which the ear loop strap system (ELSS) was shown to prevent pain behind the ear. Using the Ergonomics Function Deployment (EFD) method, Prahesti, A., et al. suggested four conceptual designs, with the adjustable ear loop and head loop rating the highest [50]. These studies serve as a valuable resource for specific designs. We believe that the reason matching face shape has a lower priority than adjustable ear straps is that this element has a weaker impact on daily life, and the users affected by it are primarily concerned with the psychological aspect of the user or wear glasses. The innovative facial seal (NFS) technology [49], which has been proven to improve the fit of masks to the face, is proposed for adoption [51]. Lightweight has the lowest priority in terms of comfort, most likely because the mask is not widely available and because this element is unique to smart wearable masks versus ordinary masks, which may have led to incorrect judgments by some testers. This is considered a limitation of this study. In terms of lightweight (weight), the smart mask designed by J. Hyysalo et al. [29] with a total weight of 93 g can be cited. The design and selection of materials can serve as a reference for future studies, despite the fact that this mask is obviously overly hefty compared to conventional masks. In summary, the following are some recommendations for the comfort design of intelligent wearable masks.

The ear straps are available with either an adjustable ear loop or an adjustable head loop.

The utilization of novel face seal (NFS) technology.

Adjustment to the size of the battery and optimization of the mask's interior construction to decrease its weight.

Compared to the research of Hu, B. and Koo, S. [32], we came to the same conclusion that anti-respiratory droplets/air purification should be prioritized in the function of the design element, confirming that this element is essential in the function of the intelligent wearable mask. Due to COVID-19, users and experts are more concerned with the properties of intelligent wearable mask PPE than with health monitoring/infection notification. It is not difficult to comprehend why anti-respiratory droplet/air purification should precede health monitoring/infection notification among intelligent wearable masks' functional elements.

The following aspects are limitations of this study: Since intelligent wearable masks are cutting-edge products, some testers may lack adequate knowledge about them, which may have a minor impact on the final results. In the future, we will, therefore, determine more specific design elements based on various demographic backgrounds (e.g., age, gender, geography, etc.). Given the specificity of smart wearable masks, our recommendation for future research is to create actual products, as opposed to models, and to conduct user and performance tests using actual products.

The critical point of this study is that the shortcomings of the previous subjective judgment classification are improved by introducing the PCA method when classifying design elements. The rigor of the design process is increased. The study's conclusions can assist designers and developers of intelligent wearable masks in comprehending the most important user requirements.

5. Conclusions

The research examined smart wearable masks from the standpoint of product design and ultimately identified six priority design elements, namely, comfort (first-level element) and anti-respiratory droplets/air purification, an adjustable ear strap, easy removal and replacement of filters, flexible fabric material, and styling (five secondary elements). According to the findings of the FCE evaluation, 76% of the experts agreed with the six proposed design priorities. Complementing the research on design features of intelligent wearing masks, we have developed suggestions and metrics pertaining to the greatest priority: Comfort. Therefore, when designing and developing intelligent wearable masks, we recommend that the prioritized design aspects be the primary design direction, while additional design elements should also be considered to satisfy the user's needs.

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