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Evaluation of Wearing Comfort in Virtual Reality Devices Using Analytic Hierarchy Process

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ABSTRACT

This paper aims to evaluate the comfort of wearing virtual reality (VR) devices using a popular multi-criteria decision-making technique, the Analytic Hierarchy Process (AHP),which systematically organizes and simplifies complex decision-making issues by breaking them down into more manageable components. A hierarchy model was developed through factor analysis and the Delphi method, comprising a primary goal (comfort of VR devices), six main criteria (stability, fit, tenderness, weightiness, breathability and skin friendliness), and twenty sub-criteria. The paper details the methodology employed, including the construction of a pairwise comparison matrix and the assessment of consistency. The robustness of this approach was verified via a case study. This research introduces a novel methodology for assessing VR device comfort and prioritizing the elements related to this aspect. The findings offer significant insights for manufacturers by identifying specific aspects for product design enhancement.

Keywords: Wearing comfort, VR devices, Evaluation, Analytic hierarchy process

INTRODUCTION

Today people increasingly expect more from the immersive interaction of Virtual Reality (VR), the wearing comfort of head mounted devices (HMDs) has emerged as an important topic. Especially, the wide application of VR devices in various fields have proposed huge challenges to the wear experience in prolonged use, which becomes a decisive factor in the development of XR industry. The psychological concept of comfort can be consisted of material, aesthetic, socialization and conformity comfort (Dumur, Barnard et al., 2004). From physical point of view, comfort involves the physiological state, the bio-mechanical state and health problems (Dumur, Barnard et al., 2004). Vink and Hallbeck (2012) claimed that the definition of comfort is not only a mental state of a human being but also a feeling of the human body in reaction to its physical environment. This complex construct defies simplistic measurement and is intricately tied to product usage (Kokosis, Gould et al., 2022). Consequently, the subjective nature of comfort evaluation presents significant obstacles in conducting swift and systematic assessments within the design and testing phases.

In the field of wearables, scholars have promoted various perspective to evaluate products' wearing comfort. Knight and Baber (2005) and Knight, Deen-Williams et al. (2006) decomposed the comfort of wearables with virtual reality (VR) or augmented reality (AR) technology into visual impact and overall comfort, which included emotion, attachment, harm, perceived change, movement and anxiety. Song, Shin et al. (2020) divided the wearing comfort of wireless earphones into comfort, pain, pressure and fixation. Kouchi and Mochimaru (2004) pointed that the preference of glasses' frame size can be deduced by overall fit, and slip sensation and pressure sensation. Pearson (2009) found that most studies evaluated comfort or discomfort as a single indicator, small of them divided comfort by body regions, but the impact of symptoms, environmental variables and emotion factors were generally not considered. Lin, Ze-yuan et al. (2021) proposed that the ergonomic assessment should integrate quantitative methods such as geometric adaptation, physical measurement, and interactive characteristics, as well as qualitative methods such as user experience and expert evaluation.

It is obvious that decomposing the wearing comfort into sub-criteria is an effective method to make the final decision. During the last two decades, the analytic hierarchy process (AHP) (Saaty 1990) has become one of the most widely used methods for the practical solution of multi-criteria decision-making (MCDM) problems and also in ergonomic evaluation. Liu et al. (Liu, Lee et al., 2011) investigated the relationship between the pillow shape design and subjective comfort level by AHP method. Marciano et al. (Marciano, Rossi et al., 2018) developed an efficient and generally multi-criteria methodology based on AHP for choosing the optimal ultrasound device. Nukman et al. (Nukman, Ariff et al., 2009) evaluated various conceptual design alternatives using AHP and selected the best wheelchair design concept. The AHP, which is a flexible strategy for organizing complex concerns by decomposing them into simple components, is suitable to this specific application making judgment in VR devices' wearing comfort.

This study studies the assessment of wearing comfort in VR devices and highlights the essential components of user experience as decontaminated from a comprehensive literature review, factor analysis (FA), and the Delphi method. It further defines the efficacy of the AHP methodology in the judgement and hierarchical prioritization of criteria, thereby offering a robust framework for evaluating user comfort in VR applications.

METHODOLOGY

Related Work

In order to ascertain the principal factors influencing the comfort of VR devices, a comprehensive examination of relevant literature was conducted. Chen et al. (Chen, Wang et al., 2021) discussed that the comfort analysis of VR devices focused on human performance, pressure, fatigue and visual induced motion sickness. Ito et al. (Ito, Tada et al., 2019, Ito, Tada et al., 2021) conducted a subjective evaluation for HMDs with respect to five aspects, well fitted, well focused, fatigue by vision, fatigue by weight and fatigue by balance. Jin et al. (Jin 2018) decomposed the suitability of VR devices into three indicators: shading, stability, and heat dissipation. Generally, researches on VR wearing comfort have centered around fit, mechanical factors and thermodynamics.

Fit. Due to the complexity and variety of human facial morphology, the fit of a VR device is key to its ability to provide a satisfying virtual immersion experience. Zhuozhe (Chi 2020) explored the effect of head type on VR interface wearing preference using fit as the indictor. Wang et al. (Wang and Chi 2021) proposed a method testing the fit of VR headsets combining real and virtual procedure and obtained the correspondence between the deviation analysis and subjective evaluation.

Mechanical factors. Mechanical studies of VR devices have focused on the effects of weight factors and human posture. Theis et al. (Theis, Alexander et al., 2013) evaluated the physical and perceptual load of an HMD through visual clarity, visual area, muscle electricity, and postural analysis. Yan et al. (Yan, Chen et al., 2018) and Song et al. (Song, Liu et al., 2018) explored the effect of weight and weight distribution of HMDs on wearing discomfort. Lee et al. (Lee, Park et al., 2023) investigated the effect of different head positions on the perceived wearing comfort. In addition, surface electromyography (sEMG) is often used to record muscle activity and contraction reflecting the degree of muscle fatigue. For example, neck joint loading was an important indicator for assessing the load exerted by the HMD (Chihara and Seo, 2018); head position while using the HMD had a significant effect on trapezius muscle activity (Knight and Baber, 2007).

Thermodynamics. To compare the thermodynamic performance of different brands of VR devices, Wang et al. (Wang, He et al., 2020) used a Thermal Imaging Camera to obtain the temperature change of VR devices after a short-term wearing. Rupp et al. (Rupp, Michaelis et al., 2018) pointed out that discomfort occurred if the forehead temperature exceeds 38 degrees when wearing VR devices.

Subsequent to the literature review, the Delphi method was employed to identify discomfort points experienced during the use of VR devices. Thirteen subjects who are physically healthy and have rich experience in using VR devices were invited to participate in the interviews. Participants were provided with five VR devices from well-regarded market brands such as Pico, Oculus, and HTC for random usage. They were instructed to detail and assess their psychological and physical sensations throughout the duration of wear. The frequently mentioned concerns of the users were compiled, drawing from both the literature and interview findings, and are tabulated as high-priority dimensions in Table 1.

Table 1. Indicators obtained based on literature review and Delphi method.

Number	Indicator	Number	Indicator
1	Loose	11	Balance
2	Squeeze	12	Hot and humid
3	Pressure	13	Fatigue

(Continued)

Table 1. Continued

Number	Indicator	Number	Indicator
4	Light leakage	14	Weight
5	Permeability	15	Softness
6	Stuffiness	16	Itchiness
7	Dizziness	17	Wrapping sensation
8	Falling head sensation	18	Shoulder & Neck Soreness
9	Fitness	19	construction
10	Slippery	20	Stickiness

Factor Analysis

FA was conducted to evaluate the indicators and cluster the related indicators into one group to extracted main elements of comfort. A total of ninety questionnaires with the importance of each indicator rated according to a five-point Likert were collected. Bartlett's Sphere Test (df =754.734, p <0.001) was used to assess the appropriateness of the correlation matrix for FA and the Kaiser–Meyer–Olkin (KMO) (0.810) was used to measure of overall sampling adequacy. The results were well above the accepted level indicating the suitability of the FA performed (Sharma, 1995). Finally, six factors were extracted based on Kaiser criterion (Kaiser, 1960), and a clear factor structure was derived that explaining 70.09 % of the variance of various indicators using Varimax rotation (Table 2). Based on the results of FA, the initial set of 20 indicators were reduced to six underlying factors. The variables in each factor provide a heuristic of labeled suggestions signifying different dimensions of VR devices' wearing comfort. The titles of the factors, presented in the first column of Table 2, were derived from a descriptive methodology that captures the essence of the items grouped under each factor. Definitions for each designated factor are illustrated as below.

Table 2. Wearing comfort elements of VR devices, their explained variance and the primary variables of each element.

Factors	Variance (%)	Primary variables	Factor loading
1. Stability	5.998	Loose	0.756
		Fitness	0.681
2. Fit	4.666	Slippery	0.644
		Balance	0.588
		Light leakage	-0.516
3. Tenderness	11.104	Pressure	0.823
		Squeeze	0.798
		construction	0.557
4. Weightiness	33.643	Fatigue	0.825
		Fall	0.777
		Dizziness	0.750

(Continued)

Table 2. Continued

Factors	Variance (%)	Primary variables	Factor loading
		Shoulder & Neck Soreness	0.737
		Weight	0.704
		Itchiness	0.601
5. Breathability	8.980	Hot and humid	0.739
		Permeability	0.725
		Stuffiness	0.648
		Stickiness	0.612
6. Skin Friendliness	5.700	Softness	0.749
		Wrapping sensation	0.688
Cumulative variance (%)	70.091		

N = 20 primary variables

Stability relates to the steadiness maintained by the device; it should move in unison with head movements without causing slippage or looseness. Fit involves the degree to which the device conforms to the user's facial contours, avoiding issues such as light leakage or uncomfortable gaps. Tenderness relates to the absence of excessive pressure or squeezing sensations. Weightiness is characterized by the minimization of fatigue in the head and neck regions, as well as the reduction of sensations such as vertigo. Breathability is concerned with preventing a hot and humid microclimate against the facial skin, thereby avoiding a stifling experience. Skin friendliness is defined by the gentle interaction between the device's contact surfaces and the skin, ensuring no irritation or tingling sensations occur.

Analytic Hierarchy Process

This paper discusses the use of AHP in the area of VR devices' wearing comfort evaluation. Generally, there are three main steps consisted in AHP, hierarchy framework, priority analysis and consistency verification.

Develop a hierarchy model. According to the AHP, the general objective to be met is defined first, followed by the criteria to achieve this objective, the possible sub-criteria into which the criteria can possibly be broken down, etc. Specifically, the overall goal of this application was to evaluate the wearing comfort level of VR devices. Six criteria were obtained through previous work, and sub-criteria was presented as twenty indicators described by body regions. The hierarchy model for evaluating wearing comfort of VR devices is introduced as Figure 1.

Construct a pair-wise comparison matrix. In order to determine the matrices' coefficients, a 9-point semantic Saaty scale (Saaty, 1990) was employed to quantify qualitative judgments. The pair-wise comparisons generated a matrix of relative rankings for each level of the hierarchy. 30 subjects who have rich experience in using VR devices were recruited to complete the comparisons based on their experience and knowledge.

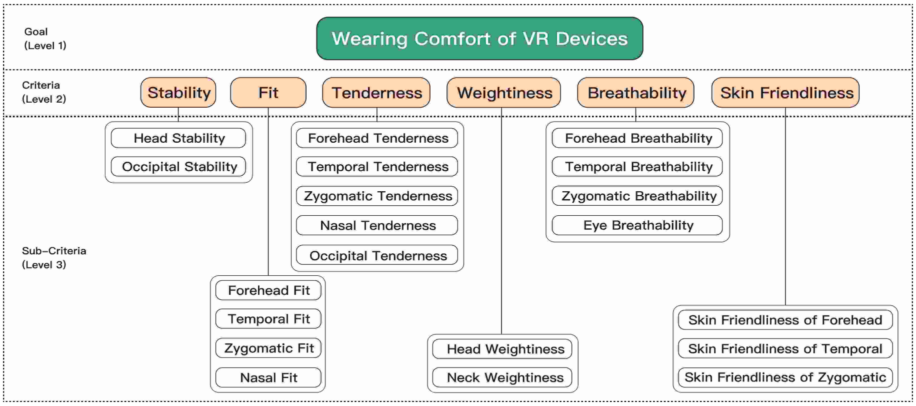

Figure 1: The hierarchy model for evaluating wearing comfort of VR devices.

Perform the consistency. To ensure the reliability of the subjects' evaluations, a final step known as consistency verification was implemented. First, a process of averaging over the normalized columns was conducted to synthesize the pairwise comparison. The eigenvalue ($\lambda_{\max}$) was computed, and the right matrix of judgements was multiplied by the priority vector or eigenvector (1) to obtain matrix size. Then the consistency index (CI) was calculated according to (2). The consistency is determined by the consistency ratio (CR) which is the ratio of consistency index (CI) to random index (RI) for the same order matrices (3). A CR value below 0.1 signifies that the judgments are within acceptable consistency thresholds.

$$\lambda_{max} = \sum_{i=0}^{n} \frac{(AW)_i}{nW_i} \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

Upon the completion of consistency checks across all levels, further calculation of the overall priority vector to obtain the final wearing comfort level was performed. The elements in Table 3 correspond to the priority vectors assigned to the criteria and sub-criteria.

Table 3. Priority vectors assigned to the criteria and sub-criteria.

Factors	Priority Vector (PV)	Primary Variables	Priority Vector (PV)
Stability	0.2320	Head stability	0.7143
		Occipital stability	0.2857
Fit	0.1155	Forehead fit	0.2460
		Temporal fit	0.2010
		Zygomatic fit	0.2768
		Nasal fit	0.2762

(Continued)

Table 3. Continued

Factors	Priority Vector (PV)	Primary Variables	Priority Vector (PV)
Tenderness	0.2395	Forehead tenderness	0.1921
		Temporal tenderness	0.1953
		Zygomatic tenderness	0.2612
		Nasal tenderness	0.2388
		Occipital tenderness	0.1126
Weightiness	0.2074	Head weightiness	0.6436
		Neck weightiness	0.3564
Breathability	0.1113	Forehead breathability	0.2633
		Temporal breathability	0.1670
		Zygomatic breathability	0.2209
		Eye breathability	0.3489
Skin Friendliness	0.0944	Skin Friendliness of forehead	0.3393
		Skin Friendliness of temporal	0.2804
		Skin Friendliness of zygomatic	0.3803

REALITY TEST: A CASE STUDY

To verify the applicability of the methodology for comfort evaluation of VR devices through AHP, fifteen participants were invited to participant a wearing test. They were instructed to use the Oculus Quest 2 and Pico 4 for thirty minutes each, on separate occasions. Each participant was required to undergo the wear test three times, on different days. Following each session, they were asked to rate their overall comfort as well as the individual criteria and sub-criteria, based on the Borg CR-10 scale, across the three trials.

Statistical analysis was conducted in SPSS 26. Overall comfort reported from the test was named as C, comfort which was calculated by criteria PV and criteria scores named C_1, comfort which was calculated by the PV of sub-criteria and sub-criteria scores was named C_2. The three sets of data all satisfy the conditions of normal distribution, and Pearson coefficients were used to test the correlation among them. The results are shown in Table 4. The correlation coefficients, exceeding 0.8, indicated a strong consistency in the wearing comfort scores obtained through the three different evaluation instances. This high degree of correlation highlighted the validity of the AHP-based methodology, confirming that the scores computed at both the criteria and sub-criteria levels were robust predictors of overall wearing comfort. Consequently, the decision-making process regarding the comfort of VR devices can be effectively guided by the practical methods presented in this study.

Table 4. Corelation analysis results of C, C_1 and C_2.

Various	Mean	SD	C	C_1	C_2
C	3.417	1.930	1		
C_1	2.945	1.414	0.903**	1	
C_2	2.439	1.167	0.842**	0.905**	1

SD = standard deviation. * $p < 0.05$, ** $p < 0.01$.

CONCLUSION

Wearing comfort is intrinsically linked to the user experience of VR devices and is a decisive factor in product satisfaction. This study introduces an AHP-based methodology designed to facilitate the assessment of VR device comfort levels. A hierarchical model was constructed, comprising six criteria—skin friendliness, breathability, weightiness, stability, tenderness, and fit—and twenty sub-criteria. The practicality of this methodology was tested in a case study, revealing that the AHP-derived results were in harmony with the subjective comfort ratings provided by the participants. The case study underlined the efficacy and user-friendliness of the proposed hierarchical approach. Findings indicate that "tenderness" is the predominant factor affecting comfort during VR use, with zygomatic tenderness identified as the most critical element. Stability emerged as the second most important, with head stability being a key concern. Subsequent priorities in descending order were weightiness, fit, breathability, and skin friendliness.

The insights from this study provide a more streamlined and thorough method for users to evaluate the comfort performance of wearable devices. Additionally, it offers manufacturers a useful benchmark for pinpointing specific design elements that require enhancement. The implications of this research are substantial for the fields of ergonomics and industrial design, with potential applications that extend well beyond VR devices to a wide array of head-wearables.

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