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Research article

Effect of prolonged wear and frame tightness of AR glasses on comfort

Yujia Du, Kexiang Liu, Yuxin Ju, Haining Wang *

School of Design, Hunan University, 410012, Changsha, China

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ABSTRACT

The present study aimed to investigate the effect of frame tightness on the wearing comfort of augmented reality (AR) glasses during a prolonged video viewing task. A frame prototype of AR glasses with an adjustable frame width was adopted to accommodate variations in head size within the Chinese population, and two hundred participants were recruited to wear the glasses for an hour under five different tightness conditions. Local and overall discomfort ratings were obtained as outcome measures, and the ratings exhibited a significant increase with higher tightness levels. Furthermore, females and older people reported greater discomfort than other participants did, whereas previous spectacle use and body type had nonsignificant effects on wearing comfort. Consideration of approaches to alleviate frame tightness is crucial in the design of AR glasses targeting females and older people. These findings provide valuable ergonomic insights for AR glasses design and offer considerations applicable to the glasses-type wearable device industry.

1. Introduction

Smart glasses have applications in various fields, including entertainment, tourism, and medical settings [1–5]. Augmented reality (AR) glasses, in particular, represent one of the latest advancements in communication technology [6] and are gaining increasing acceptance among individual consumers. However, the diversity of their usage scenarios and prolonged wear have revealed substantial ergonomic design challenges.

Considering user public opinion and market feedback, several design issues have been recognized. First, consumer AR glasses are typically at least twice as heavy as normal spectacles [7], and the load caused by their weight is usually concentrated on the front of the glasses [8], causing imbalance, rotation, and sliding. This can result in high nasal pressure and make it difficult to ensure that the AR glasses are worn correctly. Furthermore, to provide an optimal immersive experience, a tight frame is often used in the design of AR glasses. However, tight frames of spectacle-type wearables lead to pressure near the ears and on the head, which can result in swelling, inconvenience, dizziness, skin abrasions, and even pain after long-term wear [9–13]. There is a strong need to maintain a stable frame to enhance correct wearing; furthermore, maintaining a contact pressure that does not exceed the user discomfort threshold is necessary to ensure prolonged usage of AR glasses.

Proper frame size and tightness play a crucial role in enhancing the usability of AR glasses. While research on the frame design of AR glasses is relatively limited, longstanding concerns about frame fit issues in traditional spectacles have provided a reference for our

* Corresponding author.
E-mail addresses: yoka@hnu.edu.cn (Y. Du), lllkx001@hnu.edu.cn (K. Liu), cherleenjyx@163.com (Y. Ju), wanghn@hnu.edu.cn (H. Wang).

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study. Maseedupalli et al. [14] underscored the significance of fit between head-and-face dimensions and spectacle frames and advocated for a customized spectacle frame design that enhances optics, cosmesis, and wearer comfort. Many other studies have described the methodology of anthropometry knowledge in size design. For example, Kaye and Obstfeld [12] conducted facial measurements on 154 Caucasian children, which offered statistical insights for manufacturers of children's spectacle frames. Another study by Rosyidi et al. [15] provided recommendations for crucial dimensions of glasses frames, including the rim, bridge width, and temple length, based on head and facial anthropometry. However, the same size relations between head and glasses frame measurements cannot provide a perfect fit for all users for many reasons, such as mechanical and assembly issues as well as material deformation. Some researchers [16] have emphasized that a better fit for users can be achieved by making fit adjustments, such as bending the frame arms or modifying the frame angle. Kouchi and Mouchimaru [17] found that people with wider or larger faces preferred tighter spectacle frames because they were concerned that the frames might slip.

A relevant question that arises is how the tightness level of glasses-type frames influences users' wearing experience and preference. Zhang et al. [18] used the difference between anthropometric measurements and product parameters for children's eyeglasses, which was found to significantly influence the children's comfort perceptions. Mashima et al. (2011) [11]. noted that the clamping force was correlated with the difference between the ear-to-ear distance of the subject and the frame size and explored the positive effect of the clamping force on wearing discomfort with an emphasis on pain around the ears. These investigations have been limited to the examination of basic dimensional variances, neglecting the influence of soft tissue deformation in the lateral regions of the human head and its sensitivity to pressure. Furthermore, the specific product characteristics of AR glasses have not been considered. To date, the quantification of AR glasses frame tightness still needs to be explored and has proved challenging due to the variability in participants' cranial morphologies, pressure sensitivities, and soft tissue distributions.

With the increasing awareness of these problems, a methodology has been explored to offer solutions in this study investigating the effect of frame tightness conditions on subjective discomfort during long-term video viewing. The levels of tightness were established based on pressure thresholds identified in the work of [19]. An innovative prototype of an AR glasses frame was designed to ensure a consistent clamping force across different head widths for each specified level of frame tightness. Furthermore, this research delved into individual differences, aiming to provide more personalized product design recommendations, accounting for factors such as gender [20], age [21], and prior experience with wearing spectacles [7]. To determine the influence of variations in the soft tissue thickness of the head, body type [19,22] was also considered to provide industrial design references.

2. Materials and methods

2.1. Participants

Two hundred participants (female: 98, male: 102) between 18 and 45 years of age with different body types voluntarily participated in this study. Body type was categorized into 3 groups based on body mass index (BMI) [23]. The distribution and demographic characteristics of the participants are depicted in Table 1. In addition, the participants were divided into spectacle users and non-spectacle users according to their daily duration of wearing glasses [24]. All participants in this experiment were healthy, and no participants reported discomfort or medical problems occurring over the previous four weeks. This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of Hunan University. Informed consent was obtained from each participant before the start of the trials.

Table 1
Distribution and demographic characteristics of the participants (means and standard deviations (SDs)).

Sex	Age (years)			BMI (kg/m^2)		
	Age group	n	Mean ± SD	Body type	n	Mean ± SD
Male	18–25	33	21.91 ± 2.13	Underweight	11	17.82 ± 0.81
				Normal	11	21.60 ± 1.62
				Overweight	11	28.88 ± 4.29
	26–35	36	30.11 ± 3.50	Underweight	13	17.90 ± 0.97
				Normal	12	21.95 ± 1.57
				Overweight	11	26.55 ± 1.99
	36–45	33	38.86 ± 3.22	Underweight	11	18.20 ± 0.52
				Normal	11	22.57 ± 1.23
				Overweight	11	28.89 ± 3.99
Female	18–25	30	22.57 ± 1.72	Underweight	9	17.37 ± 1.04
				Normal	11	20.72 ± 1.07
				Overweight	10	26.17 ± 1.74
	26–35	33	30.09 ± 3.21	Underweight	12	18.30 ± 0.49
				Normal	11	21.56 ± 1.36
				Overweight	10	27.10 ± 2.27
	36–45	35	39.54 ± 3.20	Underweight	11	18.38 ± 0.26
				Normal	12	20.82 ± 1.15
				Overweight	12	27.14 ± 1.74

2.2. Prototype design

Researchers have claimed that comfort can be enhanced by appropriately adjusting the frame dimensions of glasses according to the facial morphology [11,17]. To maintain a consistent perceived tightness level for each participant, a customized frame width should be implemented. Thus, an adjustable frame that was adaptable to various head widths in the target population and was compliant with the characteristics of AR glasses, such as a front-located center of mass and folded temples, was used to improve the usability of the prototype in this study. The frame prototype shown in Fig. 1 was designed in our previous studies [24]. The total weight of the prototype was 62.1 g, which is similar to the average weight of AR glasses for the five major brands on the market [24].

2.3. Tightness level derivation

The maximum clamping force between the temple and head region was used to quantify the tightness of the glasses frame, which is correlated with the perceived pressure on the side of the head. Considering the correspondence between pressure and subjective feelings, the results of our previous study on the side of the head pressure threshold [19] were adopted in this study. The average pressure thresholds of various compression levels for different regions of the side of the head shown in Fig. 2 were obtained.

Reflecting the interplay between head morphology and prototype characteristics, the maximal contact pressure within the prototype was observed at locations H10, H5, and H12. Thus, the mean values of the pressure thresholds for these three landmarks were used as references to determine the clamping force range (Table 2). The level at which intolerable contact pressure occurred was excessively high for spectacle wearing. Therefore, a range of 0.25–1.47 N was assumed to be sufficient for the clamping force setting, which represented a frame tightness level that ranged from “just noticeable” to “strong”. Five tightness levels, referring to a maximum clamping force of 0.30 N, 0.60 N, 0.90 N, 1.20 N and 1.50 N, were implemented in this study.

2.4. Experimental design

2.4.1. Independent variable

Considering the identified clamping force range, a 0.3-N gap of clamping force was adopted for various tightness levels. Five levels of frame tightness (level A: 0.30 N, level B: 0.60 N, level C: 0.90 N, level D: 1.20 N, and level E: 1.50 N) were implemented in this study as dependent variables to investigate the influence of frame tightness on spectacle wearing. The maximum clamping force between the side of the head and the temples of the glasses was used to determine the tightness level and was measured by an FSR film sensor (FlexiForce® A201 1 lb, Tekscan Inc., USA; accuracy 1⁄4 ± 3 %) and one encoder (Flexcomp Infinity, Thought Technology Ltd., Canada).

2.4.2. Dependent variable

Changes in subjective discomfort caused by frame tightness were recorded every 10 min during the 60-min TV viewing task while the participants wore the given prototype. The Borg CR-100 [25] (<20: weak, 25: moderate, 35: somewhat strong, 50: strong/heavy) was employed as the rating scale to evaluate discomfort (1) on the side of the head, (2) on the ear and (3) overall. Since the content of TV programs may affect perceived discomfort, the participants were only asked to rate the discomfort caused by wearing the prototype.

2.5. Procedure

The experiment consisted of five sessions. Each session, which included a 10-min preparation period and a 1-h video viewing task, was conducted independently using a prototype designed with different tightness conditions. Two sessions were completed within the same day, with a minimum half-hour break. Three days were required to complete all five sessions (a total of 410 min per participant). The experiment was implemented in an indoor laboratory setup with a controlled temperature of 25 °C to prevent sweating on the head

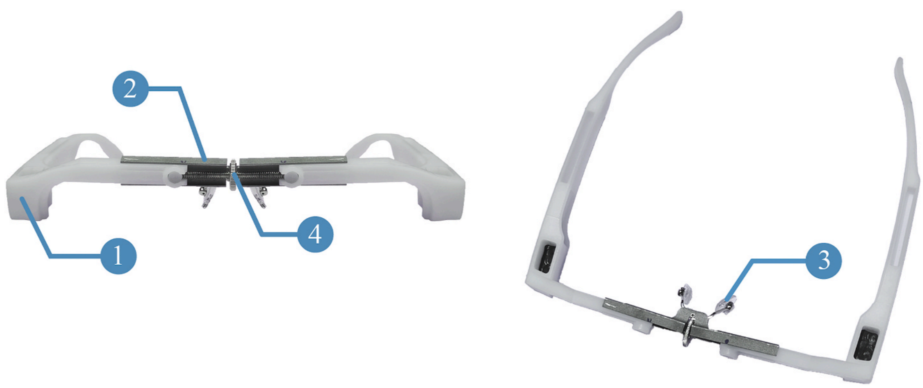

Fig. 1. Prototype: (1) frame, (2) U-groove guide rail, (3) nose pad and (4) screw.

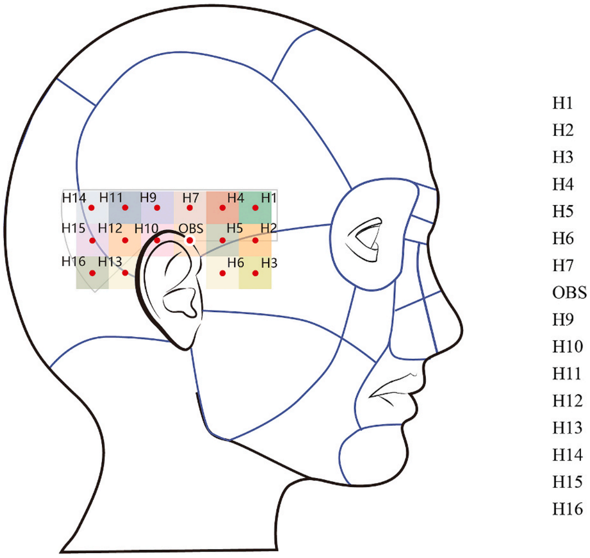

Fig. 2. Landmarks on the side of the head.

Table 2
Descriptive statistics for the average pressure thresholds (in N) at H5, H10 and H12.

Landmark	Just noticeable		Slight		Moderate		Strong		Intolerable	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
H5	0.17	0.19	0.38	0.32	0.72	0.57	1.11	0.83	1.57	1.10
H10	0.36	0.27	0.70	0.58	1.19	0.75	1.91	1.38	2.22	1.17
H12	0.23	0.21	0.53	0.40	0.92	0.64	1.38	0.89	2.01	1.27
Mean	0.25		0.54		0.94		1.47		1.93	

and face. The objective and procedures of the experiment were briefly explained to each participant before the experiment.

The experimental process was as follows. First, basic information and measurements, such as age, height, weight and spectacle experience, were collected at the beginning of the experiment. Second, the frame width of the prototype was adjusted by an experimenter until the maximum clamping force met the magnitude of each tightness level. The trial order was completely randomized. Finally, each participant was directed to watch TV programs while wearing the prototype for an hour. The task setup and details were the same as that in Ref. [24] as shown in Fig. 3.

2.6. Statistical analysis

The data were statistically analyzed using SPSS software version 26.0 (SPSS Inc., Chicago, IL, USA). After checking the application conditions using the Levene and Kolmogorov–Smirnov tests, a two-factor repeated-measures analysis of variance (ANOVA) was employed to analyze the effect of the tightness condition (five levels) and wearing duration (six levels) on subjective discomfort (a. side of the head discomfort, b. ear discomfort and c. overall discomfort). Linear regression analyses were conducted on the subjective

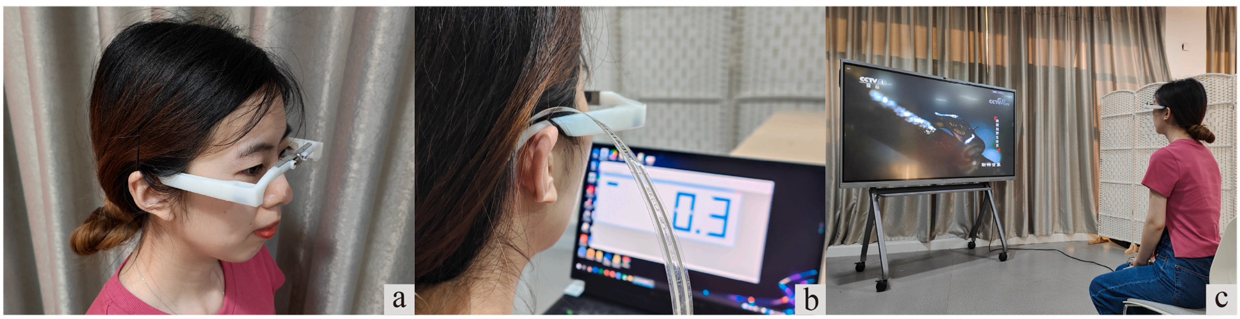

Fig. 3. Test procedure for (a) prototype wearing, (b) pressure measurement and (c) video viewing.

discomfort ratings over time and among the tightness levels. In addition, mixed factorial designs were utilized to conduct a three-way ANOVA with tightness levels and repeated measures over time. The effects of spectacle use (spectacle user or not), sex (female or male), age (18–25 years old, 26–35 years old or 36–45 years old) and body type (underweight, normal or overweight) were tested among the participants separately. The least significant difference (LSD) test was performed for post hoc multiple-range tests, and paired comparisons with Sidak correction were performed when interactions were significant. The estimated marginal means and standard errors were observed for each condition. To assess the magnitudes of changes between conditions, effect sizes were determined using partial eta squared (η_p^2). An alpha level equal to or less than 0.05 was accepted as significant for all the statistical tests.

3. Results

3.1. General results

Spearman rank correlation analysis revealed that all subjective discomfort ratings were positively and significantly correlated with the tightness level (Table 3). The linear regression analyses showed that the subjective discomfort of glasses with levels A, B, C, D and E linearly increased over a 60 min period. The slopes of the subjective discomfort and tightness level were also statistically significant at $\alpha = 0.05$.

After the repeated-measures ANOVA, a significant main effect of wearing duration on discomfort was obtained in all regions (side of the head: F [5, 923] = 151.727, $p < 0.001$, $\eta_p^2 = 0.451$; ear: F [5, 923] = 153.914, $p < 0.001$, $\eta_p^2 = 0.455$; overall: F [5, 924], $p < 0.001$, $\eta_p^2 = 0.479$); for each tightness level (side of the head: F [4, 927] = 105.531, $p < 0.001$, $\eta_p^2 = 0.313$; ear: F [4, 927] = 56.993, $p < 0.001$, $\eta_p^2 = 0.197$; and overall: F [4, 928] = 73.016, $p < 0.001$, $\eta_p^2 = 0.239$). The discomfort ratings significantly increased with time regardless of the tightness level (and similar to the increased discomfort with greater tightness levels), regardless of the wearing duration. The users' subjective ratings significantly increased with both time and tightness level, indicating that discomfort significantly rises as wearing time extends. Additionally, as the tightness level of the frame increases, the duration of comfortable wear significantly decreases. The estimated marginal means of the five tightness levels are illustrated in Fig. 4.

3.2. Personal factor results

The influence of sex on subjective discomfort caused by frame tightness for the ear was not significant. A significant interaction effect between sex and wearing duration was observed for the side of the head and overall discomfort. The results of the repeated-measures ANOVA are depicted in Table 4. The ratings of the female participants increased more than those of the male participants over 60 min, although the female participants initially reported lower discomfort of the side of the head. For overall discomfort, female and male participants exhibited similar discomfort ratings in the first 20 min, but female participants reported significantly higher discomfort ratings than male participants did at later times. The overall discomfort of female participants increased more than that of male participants over a 60 min period. According to the ANOVA results (Table 4), the rate and trend of increase in subjective discomfort ratings over time exhibited significant differences based on sex, particularly in side of the head and overall discomfort. Female's discomfort levels increased more rapidly, indicating greater sensitivity than male. The estimated marginal means for the two sexes are illustrated in Fig. 5.

A significant interaction effect between wearing duration and age group was observed for discomfort in all regions. From the results of the simple effect, the three age groups showed no significant difference in head discomfort in the first 30 min. The 36- to 45-year-old age group provided a greater discomfort rating than did the other two groups at later times, while people in the 18- to 25-year-old group and the 26- to 35-year-old group had similar discomfort ratings throughout the entire wearing process. The oldest group continuously had the highest ratings for ear discomfort. The youngest group showed similar discomfort ratings to those of the medium age group in the first 30 min but clearly lower ratings when wearing the glasses for longer periods. For overall discomfort, the 36- to 45-year-old age group reported the greatest discomfort when the wearing duration was no less than 30 min, while the other two age groups had similar discomfort ratings over a 60 min period. In general, for discomfort in all regions, the 36- to 45-year-old age group experienced the greatest increase during the 60-min wearing task, followed by the middle age group. The discomfort of the 18- to 25-year-old age group increased the least among the three groups. As wearing time increases, the differences in perceived comfort due to age also become more pronounced. Individuals with older ages tend to experience greater discomfort, while individuals with younger ages perceive relatively less discomfort over time. The estimated marginal means for the three age groups are illustrated in Fig. 6.

No significant main or interaction effect of spectacle use or body type was observed for any wearing discomfort caused by frame tightness, as depicted in Figs. 7 and 8. Notably, nonspectacle users showed slightly higher discomfort ratings overall and on the side of the head when the clamping force was less than 1.20 N, but this difference was not statistically significant. Additionally, when the clamping force was equal to or greater than 1.20 N, spectacle users reported slightly but insignificantly greater ear discomfort.

Table 3
Spearman's rank correlation coefficient between subjective discomfort ratings and tightness level.

Independent variable	10 min	20 min	30 min	40 min	50 min	60 min
Side of the head discomfort	0.554	0.569	0.559	0.540	0.517	0.493
Ear discomfort	0.459	0.447	0.439	0.419	0.402	0.392
Overall discomfort	0.500	0.503	0.488	0.468	0.453	0.434

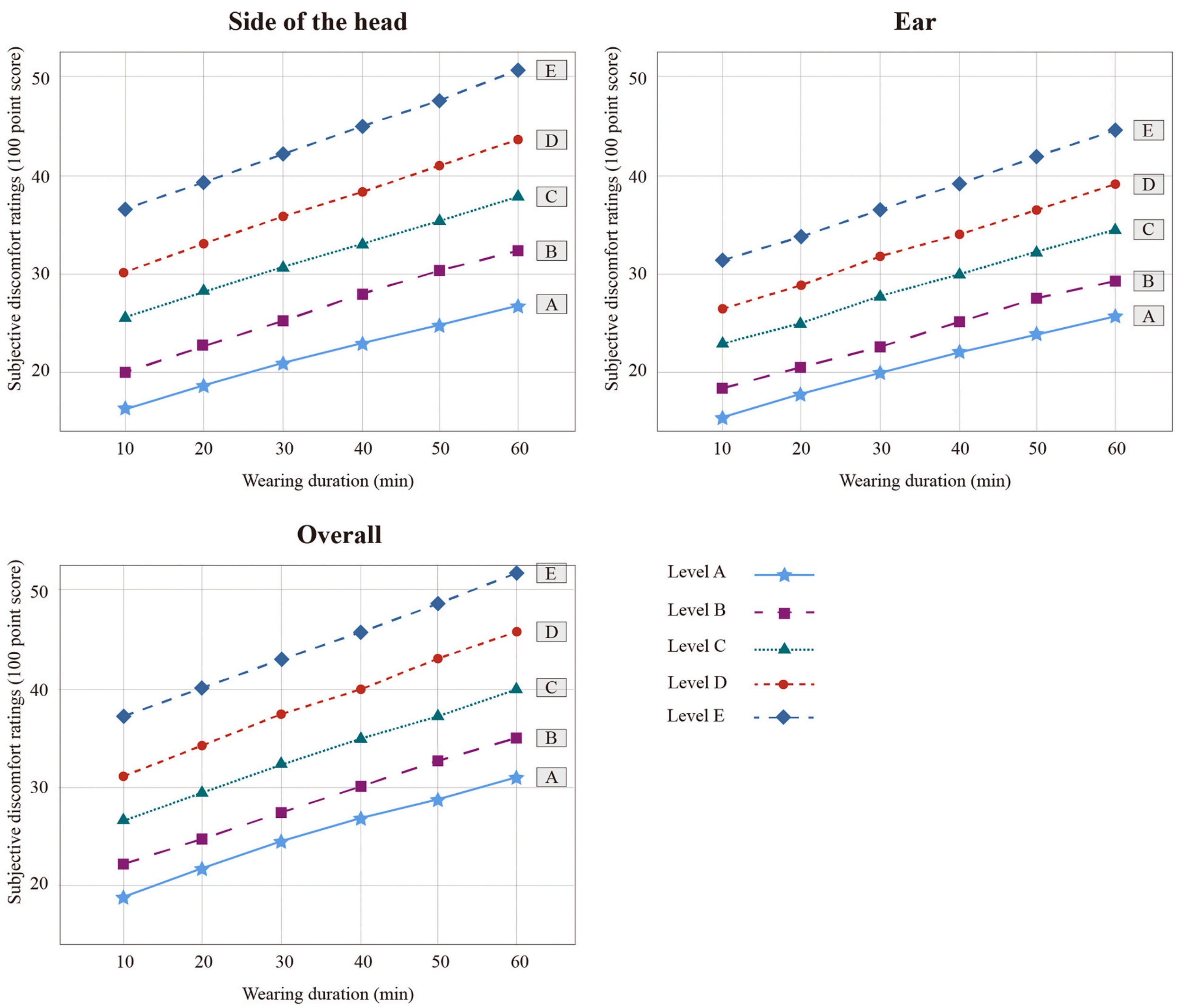

Fig. 4. Subjective discomfort ratings for the five tightness levels over 60 min (clamping force of level A: 0.30 N, level B: 0.60 N, level C: 0.90 N, level D: 1.20 N, and level E: 1.50 N).

Spectacle use tends to reduce perceived side head and overall discomfort at lower tightness levels, although this reduction is not statistically significant. Interestingly, spectacle use is associated with higher perceived ear discomfort with higher tightness levels.

4. Discussion

Continuous wearing of the AR spectacle prototype for 1 h in this study led to the development of discomfort in the overall region (both the side of the head and the ear) for all tightness conditions, especially while wearing the prototype with a 1.5-N clamping force for 60 min. Linear and positive increases were discovered for all discomfort ratings with increased tightness levels, which indicates that the wearing discomfort was greater for AR glasses with tighter frames. Tight frames impose external force on cranial tissues, potentially instigating pressure-induced discomfort and pain that intensifies with increasing force and duration.

From the observation of skin conditions before and after the 1-hr assessment, indentations and reddening of the skin were found, and a swelling sensation was also reported by a small group of participants. This may have occurred because the skin and cartilage on the side of the head, especially the area in which the ear connects to the head, have many neural connections. The application of external force to cranial tissues via tight frames, which may precipitate vascular occlusion, leads to subsequent tissue hypoxia when such occlusion is maintained over extended periods, ultimately manifesting as pressure-induced discomfort and pain [26]. The longer the pressure is applied, the more intense the stimulus becomes, as well as the greater the discomfort the subject experiences.

Another important finding in this study was that effects of sex, age group, BMI and spectacle use were observed, and the differences among the groups can provide a reference for ergonomic design for targeted populations. Regarding sex, no significant difference between the sexes was detected in terms of discomfort on the side of the head or ears. This result indicates that male and female

Table 4
Summary of the repeated-measures ANOVA results.

Source of variance	Side of the head discomfort			Ear discomfort			Overall discomfort		
	F	p	η_p2	F	p	η_p2	F	p	η_p2
Sex									
Time	151.876	0.000[a]	0.453	154.664	0.000[a]	0.457	170.308	0.000[a]	0.481
Tightness level	105.270	0.000[a]	0.314	57.027	0.000[a]	0.198	73.123	0.000[a]	0.241
Sex	0.006	0.940	0.000	3.419	0.065	0.004	5.224	0.023*	0.006
Time × tightness level	0.855	0.647	0.005	1.479	0.078	0.008	0.955	0.516	0.005
Time × sex	3.510	0.004[a]	0.019	2.103	0.063	0.011	2.907	0.013*	0.016
Tightness level × sex	0.614	0.653	0.003	0.365	0.834	0.002	0.499	0.736	0.002
Time × tightness level × sex	0.500	0.968	0.003	0.910	0.574	0.005	0.644	0.882	0.003
Age group									
Time	142.081	0.000[a]	0.438	145.069	0.000[a]	0.443	160.446	0.000[a]	0.467
Tightness level	101.054	0.000[a]	0.306	59.679	0.000[a]	0.207	70.081	0.000[a]	0.234
Age group	3.876	0.021*	0.008	29.707	0.000[a]	0.061	7.126	0.001[a]	0.015
Time × tightness level	1.038	0.412	0.006	1.616	0.041*	0.009	1.145	0.294	0.006
Time × age group	3.002	0.001[a]	0.016	4.525	0.000[a]	0.024	3.134	0.001[a]	0.017
Tightness level × age group	1.379	0.202	0.012	1.201	0.295	0.010	1.010	0.427	0.009
Time × tightness level × age group	0.931	0.594	0.008	0.795	0.819	0.007	0.695	0.927	0.006
Spectacle use									
Time	139.089	0.000[a]	0.431	141.982	0.000[a]	0.436	155.144	0.000[a]	0.458
Tightness level	87.210	0.000[a]	0.274	45.788	0.000[a]	0.166	59.925	0.000[a]	0.206
Spectacle use	1.351	0.245	0.001	0.914	0.339	0.001	1.003	0.317	0.001
Time × tightness level	1.124	0.316	0.006	1.947	0.007[a]	0.010	1.554	0.055	0.008
Time × spectacle use	1.107	0.355	0.006	1.583	0.162	0.009	1.291	0.265	0.007
Tightness level × spectacle use	0.677	0.608	0.003	0.721	0.578	0.003	0.732	0.570	0.003
Time × tightness level × spectacle use	1.232	0.216	0.007	1.222	0.225	0.007	1.567	0.051	0.008
Body type									
Time	150.880	0.000[a]	0.452	152.566	0.000[a]	0.455	168.470	0.000[a]	0.480
Tightness level	104.541	0.000[a]	0.313	56.504	0.000[a]	0.198	72.522	0.000[a]	0.240
Body type	1.198	0.302	0.003	1.030	0.357	0.002	1.569	0.209	0.003
Time × tightness level	0.863	0.636	0.005	1.526	0.063	0.008	0.977	0.487	0.005
Time × body type	1.686	0.078	0.009	1.440	0.156	0.008	1.495	0.135	0.008
Tightness level × body type	0.341	0.950	0.003	0.655	0.731	0.006	0.508	0.851	0.004
Time × tightness level × body type	0.530	0.994	0.005	0.970	0.524	0.008	0.828	0.770	0.007

[a] The correlation is significant at the 0.01 level. *. The correlation is significant at the 0.05 level.

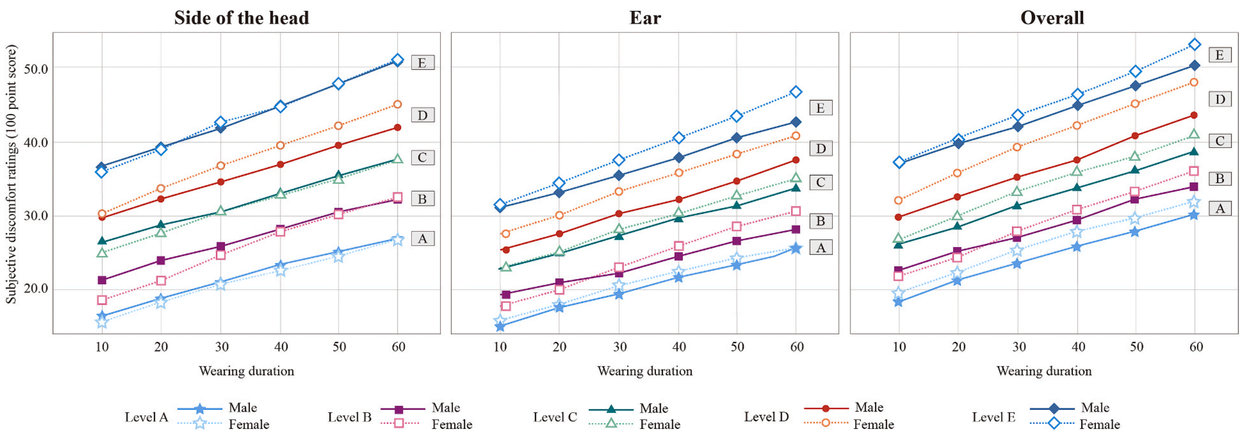

Fig. 5. Subjective discomfort ratings for the two genders over a 60 min period.

participants reported similar discomfort ratings for all airtightness levels for the AR glasses. However, the wearing duration affected side-of-the-head discomfort more for female participants than for male participants, which is similar to the overall discomfort. This result can be interpreted in two ways. First, women may be more affected by frame tightness, and therefore their discomfort may increase more quickly with longer wearing durations. Second, 60 min of wearing may be considered by women to be more stressful. In addition, female participants showed significantly greater discomfort during long-term wear (60 min), although there was no marked difference from male participants in the first 20 min of wear. Thus, women may be more sensitive to tight spectacle frames and may more easily experience wearing discomfort. Higher sensitivity of female participants was also reported in previous studies regarding foot sensitivity [27,28], back sensitivity [29] and the pressure pain threshold [30]. Similar results to those for ear discomfort were

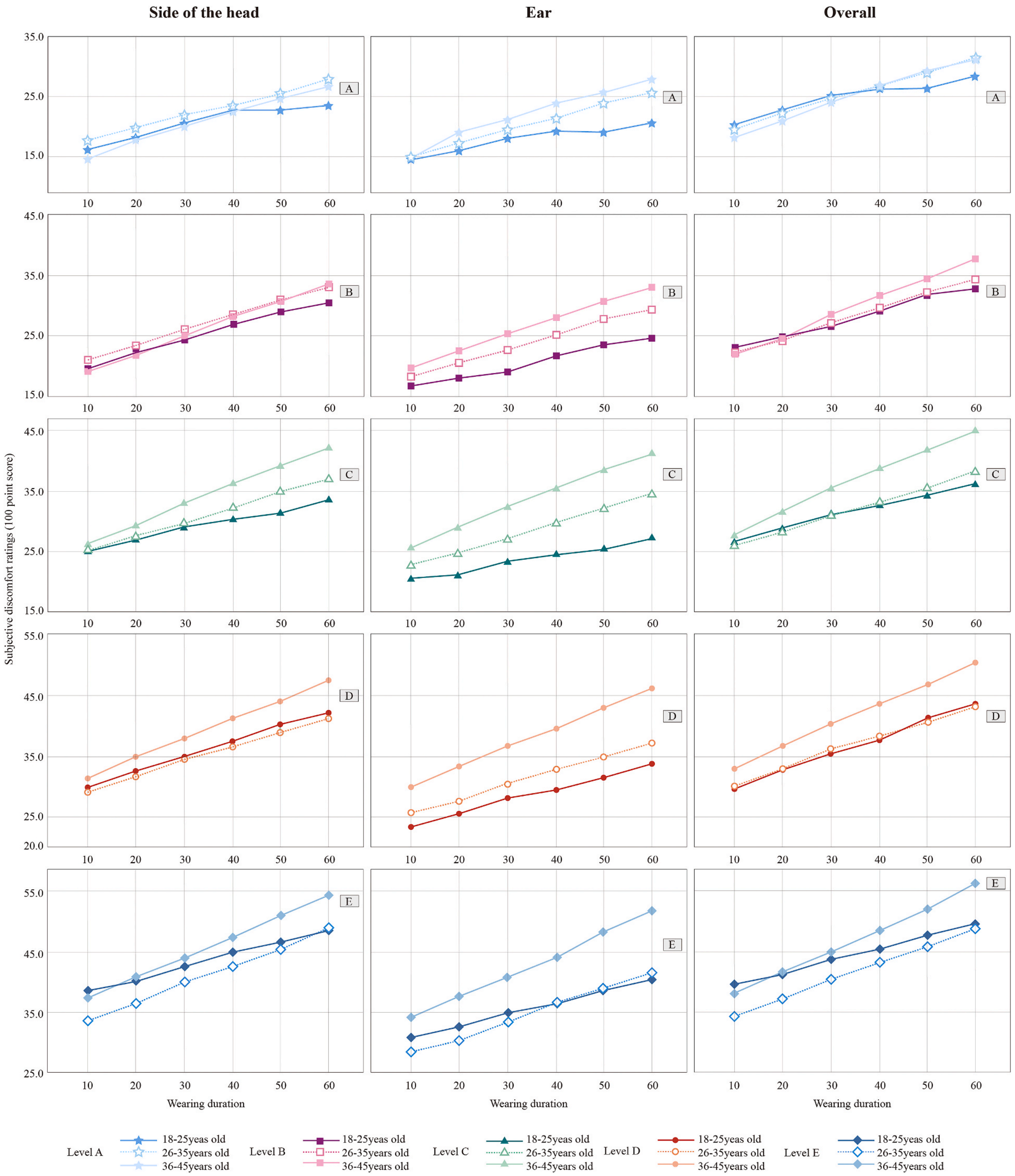

Fig. 6. Subjective discomfort ratings for the three age groups over a 60 min period.

found in our previous study on the head and face pressure threshold [19].

Participants in different age groups reported significantly different discomfort ratings in all regions. The significant interaction indicated that the effect of age was influenced by the duration of prolonged wearing of AR glasses. The older age group showed significantly greater discomfort scores for the side of the head after 30 min of wearing. Overall, the older age group showed the greatest discomfort from the beginning, while the difference between the other two groups increased with longer wearing. The older age group was more easily affected by the duration of wear, which may be due to many factors. First, older people are prone to fatigue and

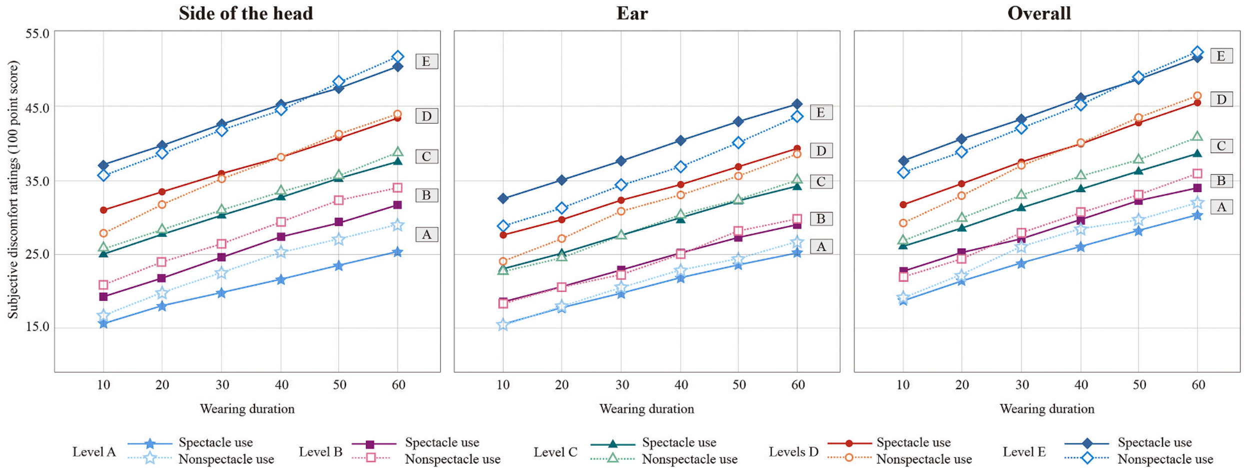

Fig. 7. Subjective discomfort ratings for the two spectacle use conditions over a 60 min period.

discomfort during long-term wear. Second, the participants in the 18- to 25-year-old group and the 26- to 35-year-old group might have adapted more easily to the pressure caused by the spectacle temple pieces and may have been more tolerant of tight frames. However, the findings were inconsistent with those of a prior investigation [19] that found that younger people had a lower pressure threshold. Previous findings reported an insignificant influence of age on the pressure sensitivity of soft tissues [31] and the perception or thermal sensation of draft discomfort [32]. Previous research [20] also showed no significant difference between age groups in the residual effects felt by the eyes, head or neck after a shooting game with VR devices.

No significant difference between spectacle and nonspectacle users was found for subjective discomfort ratings, which indicates that spectacle use experience does not have significant positive effects, consistent with the results of previous studies [7,33]. Two probable explanations can explain this result. First, the spectacle users were accustomed to their customized glasses, which were much looser than the AR glasses used in this study. Second, wearing AR glasses for an hour could have been stressful for all participants regardless of whether they had previous spectacle use experience. On the other hand, nonspectacle users showed slightly higher discomfort ratings overall and on the side of the head when the clamping force was less than 1.20 N. When the clamping force exceeded 1.20 N, spectacle users reported slightly greater ear discomfort. The reason may be that spectacle users are more accepting of side-of-the-head pressure but are more sensitive to ear discomfort. In contrast, we assumed that nonspectacle users were more sensitive to tightness on the side of the head and overall tightness, while they could better withstand ear discomfort when the frame was tighter.

The effect of body type categorized by BMI on subjective discomfort was not significant. This result indicates that overweight and underweight participants showed no remarkable difference from normal weight participants in terms of the perceived discomfort from wearing glasses under different airtightness conditions. The soft tissue layer of overweight people can mitigate the head and ear pain caused by pressure from glasses, and the bone structure, which is less sensitive than cartilage and skin, is relatively more exposed in underweight individuals. However, the reason for the nonsignificant difference between normal-weight participants and the other two groups was unclear. Similar results were presented in a previous study [22], where participants with various BMIs showed nonsignificant sensitivities to most foot landmarks. Another study [19] reported no significant difference between individuals with various body types in terms of the sensitivity to pressure in most regions on the side of the head.

The market size of AR glasses has steadily grown worldwide, and there are strong demands for design suggestions that can improve convenience and ensure functional excellence for successful product development. The outcomes of this research on wearing comfort regarding various degrees of tightness of AR glasses can be used in frame size design to improve user experiences with commercially available smart glasses. The following design recommendations are suggested to improve the wearing comfort of AR glasses. First, the glasses frame should fit properly based on the head size, which requires a less tight frame. However, it may not be possible to set the frame as loosely as possible because the AR glasses could then slip down the nose and cause a poor immersive experience. Thus, wearing discomfort can be decreased by reducing the frame tightness when the glasses are lighter, while for heavier glasses, the frame should be tighter for a better immersive experience. Second, various AR glasses have different sizes and weights due to their unique functions and specific environments of use. Thus, the situation may be aggravated for different sizes and weights of glasses under different conditions of use. Products for long-term wearing, such as for film viewing and online meetings, should have a reduced frame tightness. For AR glasses for specific work scenarios that require many movements, even if the duration is long, a tighter frame should be designed to guarantee the correct wearing method and enhance stability. Third, since females and older individuals are more sensitive to discomfort when wearing AR glasses, specific design characteristics should be optimized to achieve a comfortable wearing state. In addition, nonspectacle users are slightly more sensitive to discomfort on the side of the head but are more accepting of ear discomfort. Specific design features for the temples can be adopted for targeted AR glasses design.

Perceived comfort was studied through a prototype design that can adjust the frame tightness according to the head size of various participants. This study makes four major contributions. First, tightness was adopted as the variable to investigate particular issues related to subjective discomfort. In contrast to other studies on the relationship between frame size and anthropometry [12,15,17], this

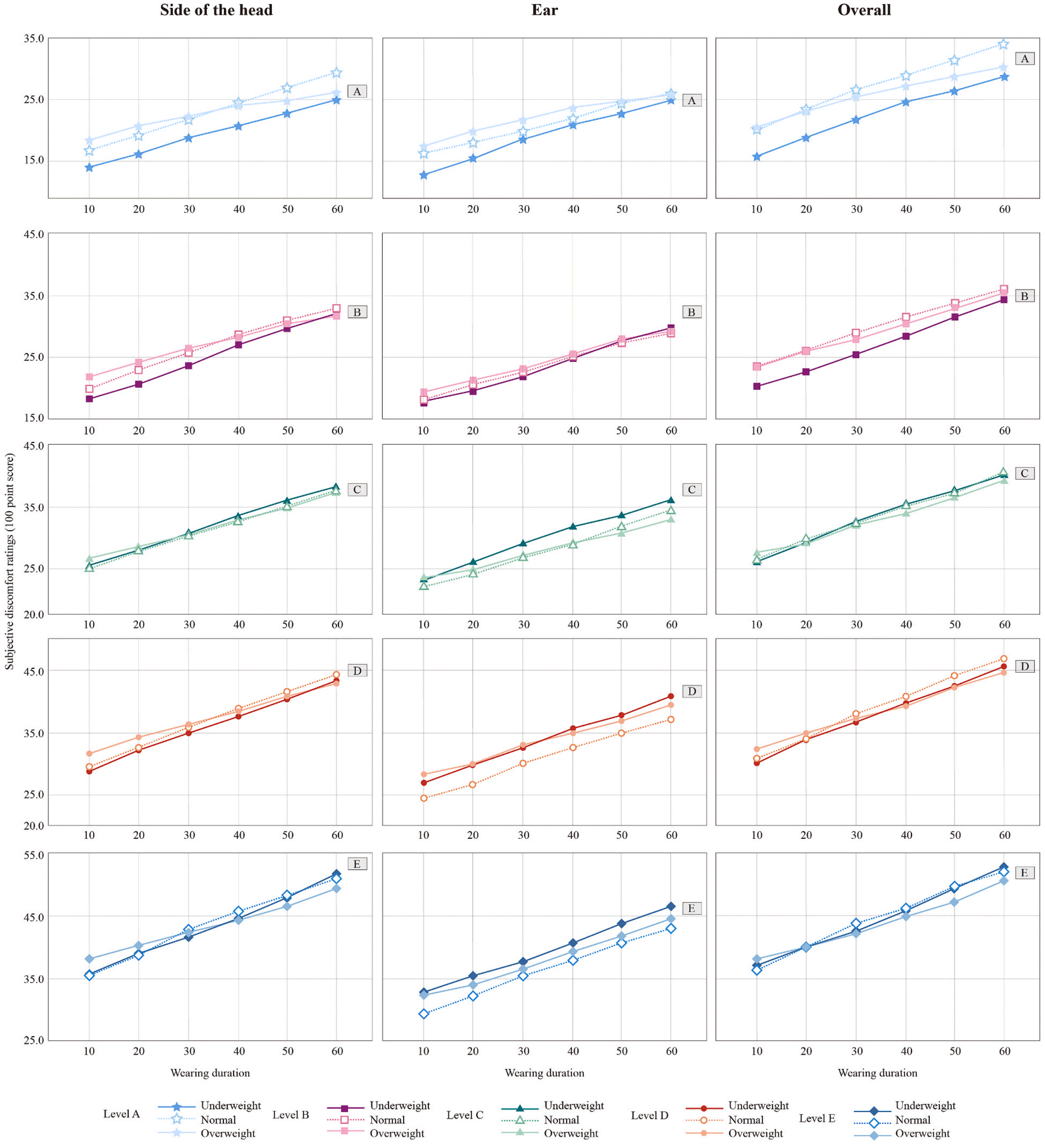

Fig. 8. Subjective discomfort ratings for the three BMI categories over a 60 min period.

study considered pressure sensitivity, which ensured that all participants experienced identical experimental conditions and allowed for better observation of the performance between groups. Second, the effect of head size was considered in this research, and the frame width was smoothly adjusted by the prototype based on anthropometric data [34]. A customized size can be set for various participants, and the same tightness level can be achieved. According to a previous study [8,11], taking specific glasses types as the independent variable may cause the subjective feeling of wearing glasses to be affected by head shape. The customized prototype used in this study guaranteed that the only independent variable was the tightness condition. Third, the tightness level was evaluated by the maximum clamping force. Thus, frame tightness was measured by a quantitative method and better adjusted during the experiment. In addition, the effects of personal factors on perceived comfort have seldom been mentioned in previous studies. Considering the differences in wearing experience among groups with different personal factors is essential to the design of AR glasses and glasses-type devices.

This study has several limitations in relation to the different tasks, the parameters involved, and the subject category. First, because our research objective was AR glasses for individuals, specific task analyses such as virtual manufacturing and clinical surgery, were not performed in this experiment. Thus, it would be meaningful to consider the effects of wearing AR glasses in different real-world scenarios. Second, the weight of the glasses was controlled as a fixed value in this study. Further research combining weight and frame tightness to better study the interaction effect of these two factors on the wearing experience is still needed. Third, in addition to BMI, accurate soft tissue thickness values of the head and face should be considered. People with identical BMIs may have different amounts of local fat, which may have an insignificant effect on wearing discomfort. Thus, data indicating the effects of soft tissue on user comfort should also be studied. Further investigation should be conducted from a product design perspective to explore how design strategies can enhance the performance of eyewear products. In the future, the findings of this study can also be integrated with finite element simulations and virtual fitting in the ergonomic evaluation process of eyewear products, to achieve virtual assessments of ergonomic design. This will provide significance for the design process of eyewear and other head-mounted products.

5. Conclusions

This study highlighted the influence of the frame tightness of AR glasses on subjective discomfort during long-term video viewing. To our knowledge, this study is the first to quantify the tightness of the frames of AR glasses through the clamping force on the temples, which was controlled by adjusting the frame width for each subject. This is also the first comfort-related study to analyze prolonged subjective discomfort according to frame tightness and in relation to sex, age, spectacle use and body type.

Generally, discomfort in all regions strongly and positively correlated with the frame tightness condition. For the five tightness levels, both wearing duration and tightness had significant effects. Subjective discomfort was greatest when the clamping force was 1.50 N after 60 min of wear. Moreover, changes in subjective discomfort with sex, age, spectacle use and body type were explored. Females and older users were more sensitive to discomfort in all head regions, while nonspectacle users were more accepting of tightness on their ears but more sensitive to tightness on their temples. Comprehensive consideration should be given to the tightness of frames induced by poorly fitting frame widths when designing AR glasses for women and older people. Overall, this study contributes to the design of AR glasses based on anthropometric data and makes recommendations for the frame size profiles of AR glasses. The design process and findings from this study are expected to address potential human factor issues related to spectacle-type wearables and improve their usability and user experience.

Ethical approval

This study was reviewed and approved by Institutional Review Board of Hunan University with the approval number: IRB #18-304, dated September 16, 2021.

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Data availability

The data associated with this study has not been deposited into a publicly available repository, and all relevant data was included in article/supplementary material/referenced in article.

CRediT authorship contribution statement

Yujia Du: Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Kexiang Liu:** Validation, Investigation. **Yuxin Ju:** Visualization, Validation. **Haining Wang:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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