Decoding Emotions: How Eye Features Influence Perception of Emotional Intensity in Virtual Characters

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Abstract. The way we perceive emotions in virtual characters significantly impacts our engagement with digital applications. A deeper understanding of how eye features such as astigmatism, eye size, and pupil color influence the perception of emotional intensity can provide more targeted guidance for virtual character design, enhancing emotional intensity and evoking richer emotional experiences. In this study, we investigated how variations in these eye features affect the perception of emotional intensity. We compared virtual characters displaying different states of these features and analyzed how each state influences six primary emotions. Our findings reveal that astigmatism is a key factor in conveying happiness, eye size is crucial to expressing fear, surprise, and anger. Conversely, pupil color does not significantly affect the perception of emotional intensity. Our findings offer valuable insight into the creation of targeted emotional expressions in interactive virtual agents, especially in face-to-face communication.

Keywords: Virtual characters · eye features · emotion intensity perception · perceptual study

1 Introduction

In recent years, digital humans have been increasingly integrated in various domains. Accurately and vividly expressing facial emotions is crucial for developing interconnected 3D virtual metaverses [6]. Eye features, along with facial expressions, body language, and voice quality, are key to effective emotional conveyance [14]. Thus, systematically exploring the relationship between eye features and emotional intensity expression is essential.

Eyes are a vital medium for emotional communication [12], offering rich emotional cues through their subtle changes and expressiveness, closely associated with the six primary emotions [16]: happiness, anger, disgust, surprise, sadness, and fear. Existing animation systems often prioritize basic facial expressions, neglecting the critical role of eye features in emotional communication [1], such as astigmatism and pupil fluctuations. This simplification limits the authenticity

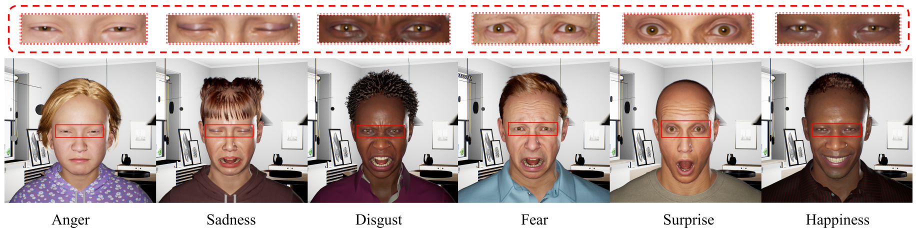

Fig. 1. Our stimulus examples contain six emotions expressed by each of six different characters: Anger, Sadness, Disgust, Fear, Surprise, and Happiness. We chose six different avatars (three females and three males) representing light, medium, and dark skin tones.

of virtual characters' emotional expressions, reducing user immersion and emotional connection. Current methods also struggle to accurately represent how pupil changes and light exposure impact perceived emotional intensity [5], leading to a disconnection between emotional expression and viewer perception. To enhance emotional authenticity in virtual characters, it is crucial to explore the influence of eye attributes on emotional perception, paving the way for more sophisticated animation techniques.

In this study, we examine how eye features impact nonverbal emotional portrayal and whether interactions between factors preserve or alter these expressions. Focusing on anger, sadness, disgust, fear, happiness, and surprise, we used Unreal Engine 5.2 to create 3D virtual characters varying in gender, skin tone, astigmatism, eye size, and pupil color. Findings reveal differential effects: eye size amplifies fear, surprise, and anger but suppresses sadness and disgust; astigmatism enhances happiness but not sadness; male characters show more intense anger, females exhibit nuanced happiness/sadness; dark-skinned characters display pronounced anger/sadness under specific lighting, while light/medium tones show sensitivity in happiness. This pioneering research provides critical insights for designing emotionally expressive virtual agents.

2 Related Work

Emotion perception significantly influences interactions and emotional experiences with virtual characters [2].This perception is shaped by both verbal and non-verbal cues, including facial expressions [8], rendering styles [15], culture background [18], etc. Facial expressions are a primary method for conveying emotions, with the eyes being a central element in expressing and recognizing these emotions [8]. Six primary emotions [11] — anger, disgust, fear, happiness, sadness, and surprise — that can be distinguished through subtle variations in eye expressions. Cultural differences influence how individuals interpret emotional signals from the eyes [9]. Furthermore, previous studies [4] reported that the facial features of different ethnic groups significantly influence the interpretation and perception of emotions. These findings underscore the significant role that eye features play in emotion perception and recognition, suggesting that incorporating more detailed eye features could enhance the accuracy of perceived or expressed emotional intensity in virtual characters.

Bradley et al. [3] demonstrated that pupil dilation varies in response to the intensity of emotions experienced when viewing emotionally evocative images. The precision of eye animations significantly affects how audiences interpret the emotional states of virtual characters, underscoring the importance of accurately simulating subtle eye movements to convey emotions in virtual characters [13]. Further research by Duchowski et al. [7] has shown that the shape and appearance of the eyes also play a critical role in emotion recognition. These findings highlight pupil dilation and eye shape as a physiological marker of emotional intensity, which can be leveraged to enhance the realism and impact of emotional expressions in virtual characters.

Astigmatism, a visual impairment that affects the eyes' ability to focus, may indirectly impact emotional expression. Webster and MacLeod [17] emphasize that visual processing impairments, such as astigmatism, might indirectly influence emotional reactions and the regulation of expressions by affecting the recognition of visual stimuli that trigger emotions. Astigmatism may alter the way emotional signals are conveyed to the observer, thereby affecting the appropriateness and accuracy of emotional expression.

The above research literature indicates that non-verbal features can significantly influence the emotional expression and perception of virtual characters. In this study, we investigate the effects of eye size (with the pupil size increasing proportionally with the eye size), astigmatism level, and pupil color under various conditions. We aim to determine whether the combination of these features enhances user perception of emotional intensity in virtual characters.

3 Stimuli Creation

As detailed in Section 2, astigmatism, eye size, and pupil color affect emotional intensity perception. Leveraging these insights, we designed six virtual characters with distinct visual features and appearances, featuring *Light*, *Medium*, and *Dark* skin tones. These characters, shown in Figure 1, had skin tones chosen from the first level of each of the three groups in the Monk Skin Tone Scale [3]. In this study, we centered on the eyes, controlling astigmatism, size, and pupil color as independent variables. Each variable had five selected states (Figure 2) to explore numerous combinations. During the experiment, we mixed variables across characters to generate diverse scenarios.

We developed a VR project in Unreal Engine 5.2 using a real - world - simulated virtual environment from the Epic Games Launcher store. We fixed the distance between virtual characters and the camera, and set point light sources for consistent lighting across all scenes. Then, we selected six virtual characters (Figure 1) of different genders (three females and three males) from

[3] https://en.wikipedia.org/wiki/Monk_Skin_Tone_Scale

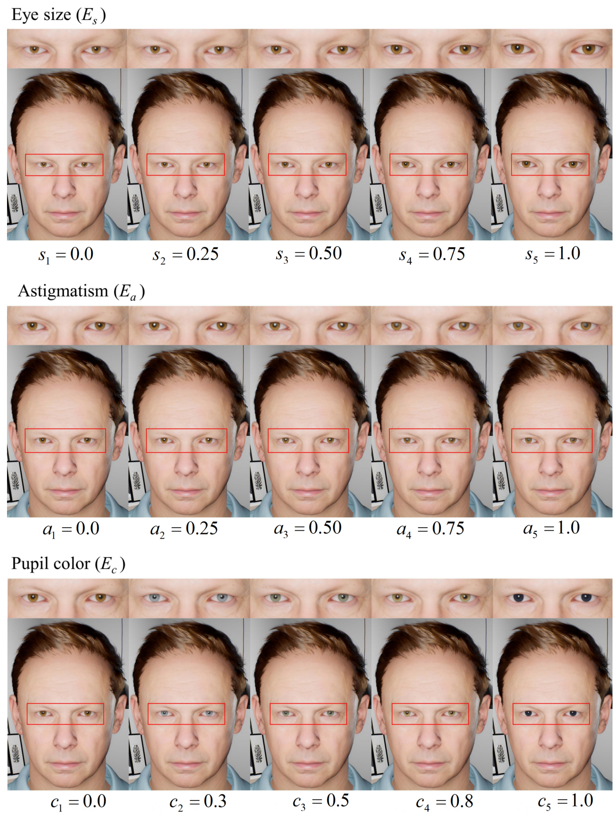

Fig. 2. The studied three eye features and their states. We randomly select one of the six virtual characters for illustration purposes. Each eye feature has five states.

the engine's built - in bridge. To ensure accurate results and consistent variable control, we kept the virtual environment constant throughout the experiment. After evaluating all possible scenarios, we chose six facial expression animations that met our requirements and applied them to each character. For the six virtual characters, to test the impact of their appearances on the emotion - eye feature interaction, we made them vary in clothing, appearance, and hairstyle.

Eye Size (E_s): We utilized the MetaHuman Creator within the Unreal Engine 5.2 platform to carefully sculpt eye shapes that optimally corresponded to the features of each virtual character. We classified eye shapes into five distinct sizes: tiny, small, normal, large, and huge. As shown in the first row in Figure 2, where s_1= 0.0, s_2= 0.25, s_3= 0.50, s_4= 0.75, and s_5= 1.0.

Astigmatism (E_a): Astigmatism is a refractive error caused by irregular corneal or lens curvature, leading to blurred vision due to light failing to focus on the retina. We classify it into five levels: Normal, Mild, Moderate, Severe, and Extreme Astigmatism. Using simulation software, we measured astigmatism degrees and adjusted eyeball material properties/texture maps to simulate different levels. The quantified values of astigmatism E_a range from 0 to 1, as shown in the middle row in Figure 2, a_1= 0.0, a_2= 0.25, a_3= 0.50, a_4= 0.75, a_5= 1.0.

Pupil Color (E_c): Iris colors include brown, blue, green, and gray, with brown being the most common in Africa, Asia, and South America. We used four preset iris colors ("003" brown, "006" sky blue, "008" light green, "011" gray) in MetaHuman Creator and added a custom "013" dark brown. Black irises are actually very dark brown due to pupil-iris optical illusions. We denote c_1= "003", c_2= "006", c_3= "008", c_4= "011", c_5= "013", quantified as c_1= 0.0, c_2= 0.3, c_3= 0.5, c_4= 0.8, c_5= 1.0 (bottom row of Figure 2).

The facial expressions depicting various emotions for our virtual characters were selected from MetaHuman's Facial Pose Library in the Unreal Engine. All of the facial expressions were generated by creating level sequences and using MetaHuman's access to the Facial Pose Library as Control Rig poses. To maintain consistency, we applied the same expressions to all virtual characters for evaluation.

4 Experiment

4.1 Experiment Process Design

We designed an experiment to study the effects and interactions of three key variables — eye astigmatism, eye size, and pupil color — on perception of emotional intensity. Two sessions were conducted to explore the nuanced relationship between eye features and emotion. The first session referred to *Factor I to Factor III*, focuses on the impact of each individual variable. For the details of the design of factor I to factor III please refer to the section 3. The second session focuses on *Factor IV*, examines the combined effects of pairs of variables among E_s and E_a.

A total of 50 students (25 females and 25 males) from a University campus were enrolled to participate in our user study. Their age range is 18 to 25, with an average of 22.84. All of the participants majored in computer science but without professional knowledge of computer graphics.

Before the experiment, participants were given sufficient time to freely observe the virtual characters. They wore VR headsets (i.e., HCT VIVE CE) and had the freedom to immerse themselves in the 3D environment, using a controller to zoom in or rotate the viewport as desired. To streamline the evaluation process, the virtual characters were positioned directly in front of the participants, with their initial positions fixed within the 3D world.

Before the experiment, we embedded attention checks and used a random sampling method to select one combination from each state of every variable, resulting in a total of four different groups, to ensure that participants understood the task. Each feature state for an emotion of a virtual character was displayed for 3 seconds within the viewport to capture immediate responses from the participants. After viewing all five feature states for an emotion of a character, participants were asked to respond to the following question: *Which state best expresses this emotion*? If participants do not choose promptly after viewing, the five characteristic states will repeat until a choice is made. They can then take a break or proceed to the next virtual character.

Consistency was maintained throughout the experiment in both the virtual environment and the characters. For Factor I to IV, attention checks were embedded in the pre-experiment instructions and post-experiment questions to ensure participants fully understood the task. Data from participants who failed the attention checks were excluded from the analysis. In each of the single-feature factors (I to III), we created 36 stimuli (6 virtual characters $\times$ 6 emotions). The duration of each stimulus is 15 seconds, sequentially showing a character with a specific emotion and with five different states of the feature studied. The Factor IV focused on the combined effects of variables, specifically the pairwise combinations of E_s and E_a. For studied feature pair, we generated a total of 72 stimuli (6 virtual characters $\times$ 6 emotions $\times$ 2 orders).

4.2 Studied Eye Features

As described in Section 2, factors including eye size, astigmatism level, and pupil color can significantly influence emotional expression. In this study, we focus on how these three eye features influence the emotional intensity in virtual characters. We treat each feature as a variable to depict six primary emotions. The studied eye features and feature values in this study are illustrated in Figure 2.

Factor I - Astigmatism. The scattering degree of virtual characters' eye surfaces significantly affects the emotional expressions conveyed through visual cues. This study simulates astigmatism by adjusting corneal scattering on the characters' eyeballs. We hypothesize that higher scattering levels will enhance the intensity of emotional expressions, making them more vivid and lifelike. The experiment systematically compares the impact of different scattering degrees on the perceived intensity of various emotional expressions.

Factor II - Eye Size. We hypothesize that smaller eyes will enhance expressions of disgust and sadness, while larger eyes will reduce their intensity. Conversely, we expect larger eyes to significantly amplify fear and surprise expressions. This experiment systematically examined how different eye sizes affect the perceived intensity of various emotions, manipulating only eye size to isolate its impact on emotional perception.

Factor III - Pupil color. Given the cultural, racial, and social diversity across different countries, the variation of iris colors can more accurately reflect the characteristics of different populations in the real world. We hypothesize that pupil color will significantly influence the perceived intensity of emotions in virtual characters. We also anticipate that participants may favor brown irises, as brown is the most prevalent iris color globally. In this experiment, only the pupil color of the virtual characters was altered to isolate its effect on emotional expression.

Factor IV - Features Combination. In the features combination experiment, we aim to assess the influence of one eye feature based on the state of another. For example, in the $E_{a,s}$ combination model, participants first view the five states of the E_a feature (astigmatism intensity). After selecting a astigmatism intensity, they then view the five states of the E_s feature (eye size) under the chosen astigmatism condition. This approach allows us to evaluate how the astigmatism condition, selected after viewing E_a, affects the perception of eye size in E_s.

We conducted these tests across all six virtual characters. To study the impact of testing sequences, we tested pair of combined variables in both orders, such as $E_{s,a}$ and $E_{a,s}$, to determine if different sequences yield distinct results.

5 Results

After the experiments, we conducted statistical analyzes of the results obtained. To analyze the relationship between different eye features (eye size, degree of astigmatism, and pupil color) and emotional intensity, we used the Chi-square test. Although the Chi-square test is typically used for categorical data, we categorized the continuous variables (eye size, degree of astigmatism, and pupil color) into discrete categories (e.g., eye size: tiny, small, normal, large, and huge) to meet the assumptions of the Chi-square test. This categorization method allowed us to evaluate how variations in these features influence the perception of emotional intensity. The Chi-square test demonstrated that all of the obtained results are reliable. Figure 3 shows the average selection rate and standard deviation of different emotions in single-feature and combined feature experiments.

5.1 Single Feature Experiment Result Analysis

Astigmatism: As shown in the left panel of Figure 3 (a), we observe that different degrees of astigmatism significantly impact the perception of the six primary emotions. The perception of anger is the highest when $E_a = a_1$ and decreases quickly as astigmatism increases. The perception of disgust generally decreases when astigmatism increases, reflecting a gradual reduction in the perceived intensity of disgust emotion as astigmatism increases. The perception of fear generally intensifies with increasing degrees of astigmatism, reaching its peak when $E_a = a_5$. The perception of happiness reaches its peak at $E_a = a_1$, and it is much lower at other states. We speculate that bright eyes may be associated with the experience of pleasure, likely because positive emotions stimulate the brain to release more adrenaline, resulting in sharper eyes and more focused light reflections. The perception of sadness is more pronounced at low levels of astigmatism (in particular, $E_a = a_2$) and gradually decreases as astigmatism increases. The perception of surprise peaks at a_5, and stays consistently low at other states. Because the main characteristic exhibited by astigmatism is blurriness on the surface of the eyeball, this experiment study suggests a guideline for the adaptation to visual blurriness.

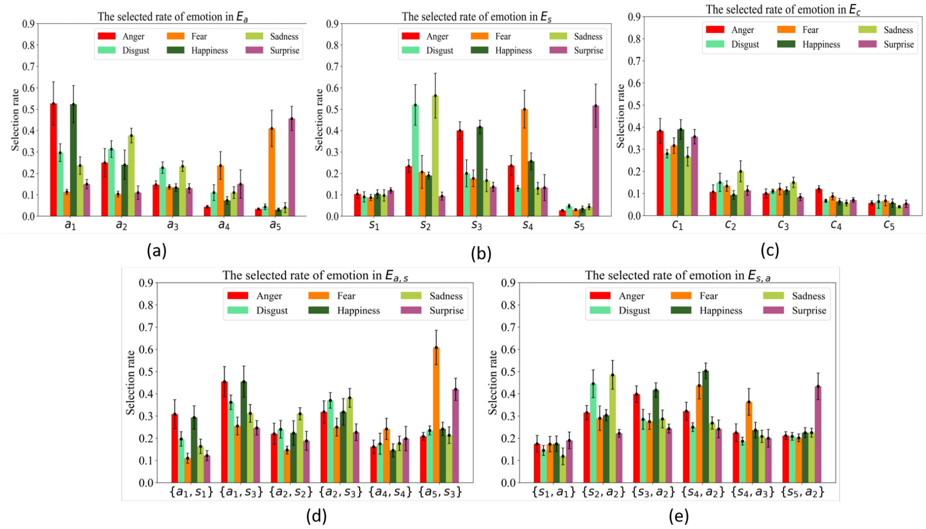

Fig. 3. The average selection rate and standard deviation of different emotions in our single-feature and combined feature experiments. The X-axis represents the five states of the features, and the Y-axis represents the average selection rate of different emotions under specific feature states (the average of six virtual characters). E_a represents astigmatism, E_s represents eye size, and E_c represents pupil color.

Eye size: As shown in the right panel of Figure 3 (b), the eye size has a significant effect on all the six primary emotions. The perception of anger emotion is extremely low when $E_s = s_5$, indicating that the s_5 state is not conducive to anger emotion; in contrast, $E_s = s_3$ is considered to be the most anger-inducing. The perception of disgust peaks at $E_s = s_2$, which is also substantially higher than at other states. The perception of fear at s_4 is substantially higher than at other states, in particular, it reaches the lowest point at s_5. The perception of happiness gradually increases from s_1 to s_3, reaching its highest at s_3, and then gradually declines with the further increase of the eye size E_s. The perception of sadness is most prominent when $E_s = s_2$, while it remains relatively low in other states. Finally, the perception of surprise surges when $E_s = s_5$, indicating that a big eye size is more easily perceived for the surprise emotion.

Pupil color: The bottom-right panel of Figure 3 (c) shows that different pupil colors do not significantly enhance or inhibit the expression of emotional intensity. One interesting finding, however, is that most participants tended to choose pupil color c_1 in different emotional contexts, which may be related to the fact that there may exist a cultural or cognitive preference among participants. In addition, the participants could be influenced by other factors such as skin tone, clothing, hair, and eyebrow color, and they could tend to choose pupil colors that are harmonized with these characteristics, creating a more cohesive and visually consistent character appearance.

Skin tone differences: In addition, we found a noticeable interaction between skin tones and the perception of emotional intensity. The interaction between skin tones and emotion intensity perception may be attributed to changes in the intensity of external light. As shown in Figure 4, we can see that under specific lighting conditions, the highest selection rates for light and medium skin tone characters for emotions such as anger, disgust, sadness, and fear are 40.3% and 43.5%, respectively, while the highest selection rate for dark skin tone characters for the same emotions is 54.0%. Therefore, this suggests that virtual characters with light and medium skin tones, as well as those with dark skin tones, exhibit different expression intensities for emotions such as anger, disgust, sadness, and fear under specific lighting conditions.

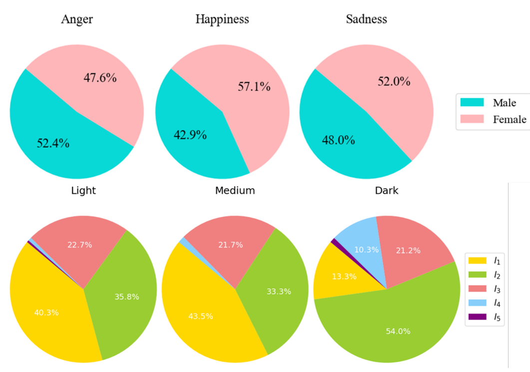

Fig. 4. The above is the average selection rate of virtual characters with different skin colors under different light intensities. The different colors in the chart represent different lighting intensities, and the proportion of the color areas indicates the average selection rate of the six emotions under each lighting intensity. "Light" represents the average selection rate of the virtual characters F1 and M1, "Medium" represents F2 and M2, and "Dark" represents F3 and M3. The following are the average choice rates of virtual characters of different genders under different emotions. We found that only three emotions, namely anger, happiness and sadness, have a high degree of gender bias in the emotional perception of virtual characters.

Gender differences: When analyzing the effect of the genders of virtual characters on emotion perception, we found that male characters generally received higher perception of anger than female characters (see the anger emotion chart in Figure 4, which is consistent with traditional gender role expectations that men are more inclined to express strong emotions. In contrast, female characters show more subtle and layered expressions of happiness and sadness (see the happiness and sadness emotion charts in Figure 4). In addition, our analysis showed that when it comes to choosing the size of an virtual character's eyes, women generally prefer larger eyes than men.

5.2 Features Combination Experiment Result Analysis

In Figure 3 (d) and (e), the optimal feature state combinations are identified for each emotion. For anger, the combinations $\{a_1, s_3\}$ and $\{s_3, a_2\}$ are considered to evoke the most anger. Regarding disgust, $\{a_2, s_3\}$ and $\{s_2, a_2\}$ are found to best express disgust. For fear, the most favorable outcomes are from the combinations $\{a_5, s_3\}$ and $\{s_5, a_2\}$. The optimal combinations for expressing happiness are $\{a_1, s_3\}$ and $\{s_5, a_2\}$. When targeting sadness, our experimental result shows that $\{a_2, s_3\}$ and $\{s_2, a_2\}$ evoke the most sadness. Finally, the greatest intensity of surprise occurs with the combinations $\{a_5, s_3\}$ and $\{s_5, a_2\}$.

6 Discussion and Conclusion

Based on our experimental results, we propose the following guidelines for designing virtual characters with targeted emotions:

Anger, Fear, and Surprise: The size of the eyes plays a significant role in the expression of emotions. Larger eyes can enhance the display of these emotions. Particularly in the case of anger, larger eyes may convey a stronger emotional impact, potentially related to humans' intuitive response to large eyes, especially when emotions are accompanied by stress, as changes in the eyes may become more noticeable. In contrast, the impact of corneal astigmatism is more complex. Higher corneal astigmatism (e.g., severe astigmatism) significantly enhances the expression of fear and surprise. The degree of astigmatism causes visual blurriness in the eyes, thereby intensifying the expression of these emotions. Therefore, both the size of the eyes and corneal astigmatism play a key role not only in the expression of anger, fear, and surprise but also in the emotional communication of virtual characters.

Disgust and Sadness: The size of the eyes has a significant impact on these negative emotions. Smaller eyes can enhance the expression of sadness and disgust. Small eyes often give an impression of being restrained and closed off, which aligns well with the display of negative emotions like sadness and disgust. Corneal astigmatism has a more subtle effect on the expression of sadness. Low levels of astigmatism (e.g., mild astigmatism) can enhance the expression of sadness, as lower astigmatism results in clearer eyes and more focused vision, which strengthens the emotional expression. However, higher astigmatism weakens the expression of sadness by increasing the dispersal of the eyes. Compared to previous research, our study further reveals how the size of the eyes and corneal astigmatism interact to produce different effects on the emotional expression of disgust and sadness in virtual characters.

Happiness: Corneal astigmatism plays a significant role in the expression of happiness. Lower levels of corneal astigmatism (e.g., mild astigmatism) can significantly enhance the expression of happiness. Low astigmatism makes the eyes clearer and the vision more focused, creating a bright and pleasant visual effect that enhances the communication of happiness. In contrast, higher astigmatism increases the dispersal of the eyes, weakening the expression of happiness. The size of the eyes has a relatively small impact on happiness, but smaller and medium-sized eyes show an enhancing effect on happiness. Larger eyes do not significantly enhance the expression of happiness, possibly because the expression of happiness relies more on other facial features, such as the mouth and eyebrows. Compared to previous studies that mainly focused on dynamic changes in the eyes and facial expressions on the expression of happiness [10], our research fills the gap in understanding the enhancing effect of corneal astigmatism on happiness, offering a new perspective.

Skin color: Research shows that skin tone significantly impacts the emotional expression of virtual characters under different lighting conditions. In low-light environments, characters with darker skin tones express negative emotions (anger, disgust, sadness, and fear) more intensely than those with lighter skin tones. This may be due to the light absorption properties of darker skin, which enhances emotional perception, particularly for negative emotions. Our study fills a gap in research by highlighting the importance of this interaction in the emotional communication of virtual characters.

Gender differences: Male virtual characters typically express anger more intensely than female characters, which aligns with traditional gender role expectations. Societal norms often associate anger with male emotional expression, leading to higher intensity of anger in male virtual characters. In contrast, female virtual characters exhibit more nuanced and multi-layered emotional expressions in happiness and sadness, which corresponds with the perception that women are generally more capable of expressing complex and profound emotions. We also observed that female characters tend to choose larger eyes, believing that big eyes better convey emotions.

Our study reveals the complexity and diversity of virtual characters' emotional intensity expressions, emphasizing the key role of eye features in emotion conveyance and showing how emotions rely on them. These findings offer crucial design guidance, stressing the importance of combining eye features for realistic emotional expressions. Future research could involve various age groups and diverse 3D virtual interactions to strengthen data validity. But VR headset - induced visual fatigue may impact data reliability. So, optimizing gaze data collection and creating more comprehensive emotional expression models are needed. These improvements will enhance human - computer interaction and expand virtual characters' applications.

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