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# Improving Naturalness in Transparent Augmented Reality with Image Gamma and Black Level

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## Abstract

*In this study, we used a custom-built Optical See-Through Augmented Reality (OST AR) system to conduct a psychophysical experiment to determine the preferred gamma and black level for high naturalness perception in OST-AR. We utilized 6 different fruit stimuli and 11 different backgrounds to do this experiment. We used two-way ANOVA to analyze the data and concluded that only the effect of different fruits on virtual objects' gamma preference for high naturalness is considered statistically significant. Surprisingly, all ANOVA analyses indicate background's color does not contribute to observers' gamma or black level preference for naturalness. We found that gamma preference has a strong correlation with the average lightness of the virtual stimuli. There is no clear correlation between chroma, hue, and gamma preference in terms of naturalness perception. This finding suggests that the background can be ignored in future imaging pipelines emphasizing high naturalness appearance in Augmented Reality.*

## Introduction

Augmented reality (AR) is one of the emerging technologies that will bring a significant impact on daily life. Augmented reality has potential in education, entertainment, medical science, and industry. The rapid development of optical see-through head-mounted displays (OST-HMDs) will play a key role in promoting AR. The advantage of OST-HMDs is to give the user both information in the real-world and additional overlay information from Augmented reality, while one disadvantage is that their transparent nature allows the background to distort displayed AR stimuli.

There are a lot of studies on AR related to color appearance and object perception. But, there are few studying the naturalness of AR content and its relationship with other color attributes. Kim et al. have studied the preferred image gamma for public information display (PID) using transparent OLED displays and found out the preferred gamma value decreases as surround luminance increases [1]. Due to the similarities between transparent OLED and our current AR research equipment, their study provides a starting image gamma range in our psychophysical experiment. Another study by Zhang et al. aims to enhance the contrast between virtual objects and real background and keep the consistency with the original color [2]. Their work makes the virtual object more distinguishable from the background. In Lili Zhang's dissertation, she studies the brightness scale for rendered stimuli in OST AR and perceived transparency related to different background conditions [3].

The objective of this study is to explore the relationship between naturalness and simple image manipulations: gamma and black level adjustments. One goal is to determine the preferred image gamma of transparent AR to improve or maximize naturalness. Additionally, due to the optical transparency in the OST AR system, black color cannot be generated in AR virtual stimuli, and a lifted black level might make shadow regions more visible by replacing the original black shadow region with grey color. The black level in this context means that the RGB of the virtual stimuli's black shadow is raised from (0, 0, 0).

## Method

### *Experiment setup*

We utilized a custom-built OST AR system in a dark room to conduct the experiment, shown in Figure 1. This system contains two 27-inch LCDs and a beam splitter. Both displays have a resolution of $1920 \times 1080$ and are calibrated to sRGB color gamut with D65 white point. The background display can be seen through the beam splitter in the optical path labeled orange. The AR virtual object is rendered at the bottom AR display. The image of the rendered object will be reflected by the beam splitter and seen by the observer through the blue optical path. The background and AR rendering display were set to have the same optical path length of 110 cm for a co-planar appearance. The observers view the image content combined from both background and AR displays through a viewing port with a field of view of $25° \times 13°$. A white panel behind the background LCD is illuminated with a D65 light source, which provides the observer with a natural viewing environment rather than complete dark [4].

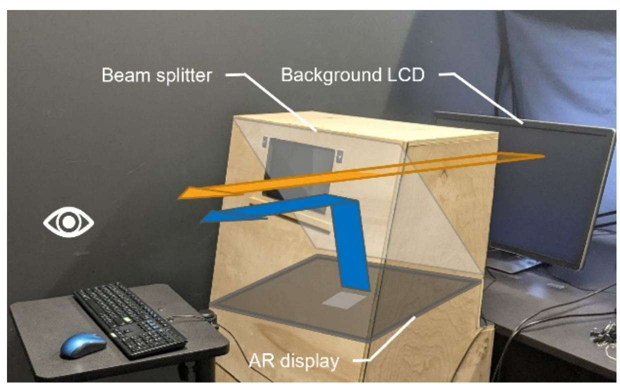


***Figure 1.*** *This figure shows the custom-built OST-AR setup used for this experiment [3]. The beam splitter combines the background LCD (in transmission) and the AR display (in reflection) so that they appear co-planar to the observer.*

### *AR Stimuli and Backgrounds*

Experimental stimuli were generated by combining photographs of a light booth environment as a background with photographs of individual fruits as transparent AR foreground stimuli. There were six AR fruit stimuli and eleven image backgrounds in this experiment. The backgrounds displayed on the background LCD are a variation of simple scenes that only contain a color checker. All background images and AR stimuli images were photographed in a light booth with a D65 illumination. There are three main categories of the backgrounds, shown in Figure 2. All the backgrounds' color information is recorded in Table 2. The first category is the original neutral-color light booth and neutral-color floor with a wooden-colored wall. The light booth in the second category has black felt cloth on the floor and different colors of paper on the wall of the light booth. There are seven colors for the wall: neutral, black, green, yellow, blue, and two kinds of red. The light booth in the third category also has neutral color on the floor and wall. But other than only containing a color checker, the light booth in this category includes an additional fruit on the side of the color checker (a lime and an apple). The fruit in the background aimed to serve as a natural anchor point for the AR stimuli.

The six AR stimuli are two kinds of apples (matte and glossy surface), lemon, lime, orange, and pear. Each fruit's representative color is shown in Table 1, their CIELAB values are plotted in Figure 11. All the stimuli were made by cropping the fruit object from a black floor and neutral wall scene in the light booth. Image pixels surrounding the cropped fruit were all set to black (RGB=0), which means fully transparent on the AR display. Photographs were used rather than computer renderings of fruits, because synthetic fruit may look less natural. Figure 3 shows a selection of the appearance of all AR fruit stimuli as viewed in the OST AR system.

The AR stimuli were made to be adjustable in both image Gamma and Black level, both of which can be used to make darker regions of the transparent AR images brighter and more visible. Gamma ($\gamma$) was implemented as a power-law function applied to the encoded RGB pixel values (for example, R), where the observer was given control of the gamma value:

$$R' = 255 * (R/255)^{\gamma}$$

Note that $\gamma = 1$ is the identity function. $\gamma < 1$ provides a concave-down transfer function that results in brighter image pixel values and higher contrast in darker portions of the image. $\gamma > 1$ provides a concave-up transfer function that results in darker image pixels. However, because typical display systems, including the sRGB displays used in this experiment, use an EOTF approximately equivalent to $\gamma = 2.2$, from this point forward, all of the gamma values quoted in this report have been multiplied by 2.2. The gamma values available to observers were 51 steps in the range [0.44, 6.6]. After adjusting the Gamma value of the image, black level was adjusted by replacing all pixel values below a threshold with the threshold value, effectively clipping the low values of the image. The observer was given control of the black level threshold, constrained to the range [0, 50] with 51 steps in 8-bit code values. The appearance of different black level and Gamma value of the fruit stimuli are shown in both Figure 4 and 5.


***Figure 2**. Eleven background images in three categories were used in this experiment.*

**Table 1. The representative color of each fruit stimulus in XYZ and CIELAB space**

| | X | Y | Z | L* | a* | b* |
|---|---|---|---|---|---|---|
| Apple | 14.98 | 10.62 | 5.26 | 38.93 | 33.35 | 21.85 |
| Apple2 | 15.22 | 10.66 | 4.87 | 39.00 | 34.43 | 23.83 |
| Lemon | 43.73 | 47.23 | 13.47 | 74.34 | -3.39 | 56.11 |
| Lime | 6.48 | 8.13 | 2.52 | 34.26 | -12.41 | 29.62 |
| Pear | 52.64 | 60.64 | 24.56 | 82.19 | -12.60 | 47.56 |
| Orange | 27.86 | 25.54 | 7.33 | 57.60 | 14.88 | 45.53 |

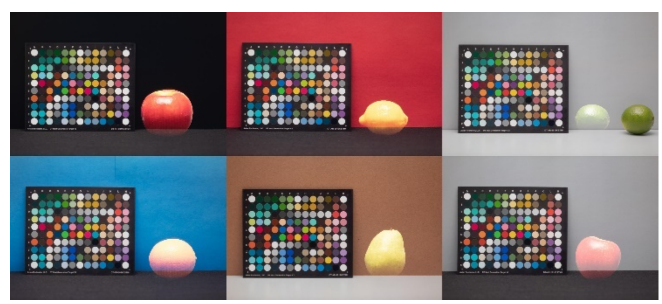

***Figure 3.** All six AR fruit stimuli with example backgrounds photographed from the observers' perspective in the OST AR system. In presentation order, left-to-right, top-to-bottom: Apple (glossy surface), Lemon, Lime, Orange, Pear, and Apple2(matte surface). All virtual stimuli in this figure have a Gamma value of 2.2.*

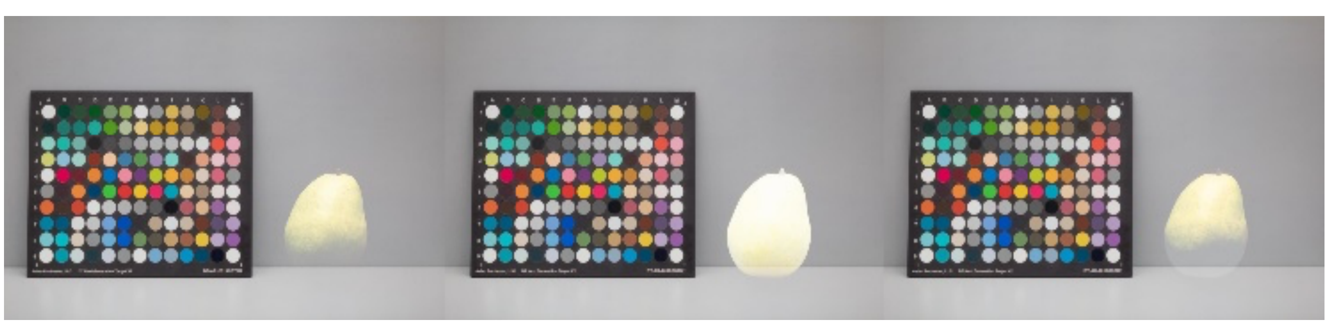

***Figure 4.** The appearance of pear stimulus in the OST AR system seen by observers. From left to right: high Gamma with low Black level, low Gamma with low Black level, and high Gamma with high Black level.*

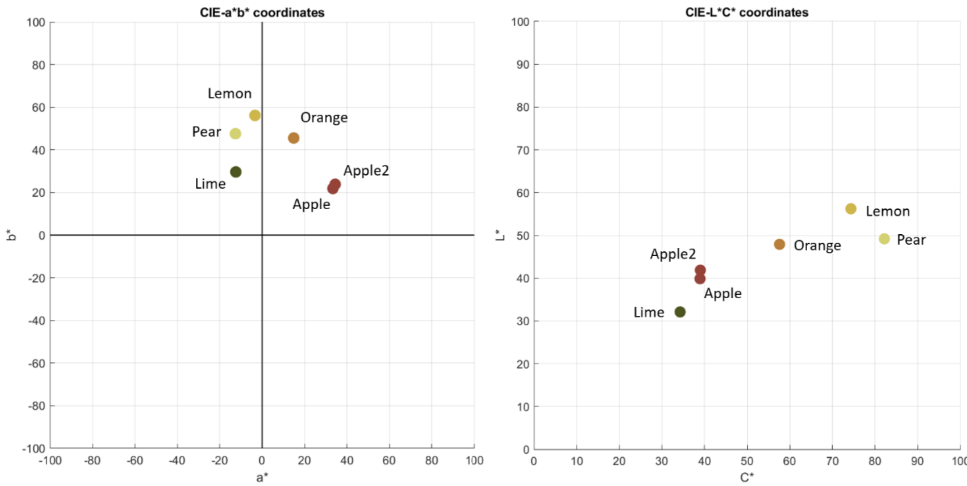


***Figure 11.*** *The CIELAB plot of the representative color for each fruit stimulus.*

**Table 2. The XYZ and CIELAB value of each background**

| | XYZ | L*a*b* |
|---|---|---|
| bg1 wall | (37.10, 38.79, 44.06) | (68.60, 0.77, -2.06) |
| bg1 floor | (61.39, 64.11, 72.09) | (84.02, 1.07, -1.85) |
| bg2 wall | (16.36, 16.23, 10.05) | (47.27, 5.44, 18.69) |
| bg2 floor | (56.14, 58.41, 62.35) | (80.97, 1.55, 1.11) |
| bg3 wall | (28.89, 30.18, 34.44) | (61.81, 0.78, -2.10) |
| bg3 floor | (4.63, 4.68, 5.36) | (25.80, 2.38, -1.23) |
| bg4 wall | (4.63, 4.68, 5.36) | (25.80, 2.38, -1.23) |
| bg4 floor | (5.05, 5.41, 4.92) | (27.86, -1.06, 4.41) |
| bg5 wall | (43.79, 48.19, 13.65) | (74.94, -5.80, 56.70) |
| bg5 floor | (5.35, 5.48, 4.52) | (28.07, 1.69, 6.74) |
| bg6 wall | (17.01, 11.99, 6.89) | (41.20, 35.18, 18.94) |
| bg6 floor | (3.88, 3.75, 4.01) | (22.82, 4.86, 0.39) |
| bg7 wall | (13.37, 12.21, 36.30) | (41.54, 12.04, -39.46) |
| bg7 floor | (4.22, 4.24, 5.60) | (24.44, 2.74, -4.63) |
| bg8 wall | (15.66, 11.12, 6.32) | (39.79, 33.65, 18.74) |
| bg8 floor | (15.66, 11.12, 6.32) | (39.79, 33.65, 18.74) |
| bg9 wall | (0.48, 0.49, 0.56) | (4.42, 0.53, -0.38) |
| bg9 floor | (4.25, 4.34, 4.89) | (24.78, 1.74, -0.78) |
| bg10 wall | (38.61, 40.39, 44.79) | (69.74, 0.73, -0.90) |
| bg10 floor | (65.40, 68.31, 76.76) | (86.16, 1.07, -1.85) |
| bg11 wall | (36.61, 37.78, 41.92) | (67.86, 2.36, -0.91) |
| bg11 floor | (62.25, 64.55, 72.13) | (84.25, 2.09, -1.49) |

### *Procedure*

There were 11 observers who participated in this experiment. The experiment and procedure were approved by the Institutional Review Board (IRB). First, observers were asked to sit in a dark room with D65 light illuminating the white board and adapt for one minute. There are six fruits and eleven backgrounds in total. The fruit stimuli always appeared in the same order (as illustrated in Figure 3), but the associated backgrounds were presented in randomized order. Hence, each observer did 66 trials for the whole experiment. The observer was shown one stimulus on the AR display and one background image on the background LCD for each color-checker in the light booth on the background LCD. This lets the observer have an anchor point of what a natural scene looks like. The observers were then asked to do the main task, which is to adjust the AR fruit image gamma and black level until the fruit looks natural to them and appears to fit naturally in the scene with the background image. The adjustments of both gamma and black level were explained and demonstrated, and the observers were able to test a small selection of the stimuli before beginning the experiment. Examples of gamma-adjusted stimuli and black level adjusted stimuli displayed on the AR display (without the background image) is shown in Figure 5. Figure 4 shows examples of the Pear stimulus appearance as seen with a background image in the OST AR system with different gamma and black level settings.


***Figure 5.*** *Images of the Apple AR stimulus with six gamma and black level settings on AR display. Gamma changes from top left to top right, and black level changes from bottom left to bottom right.*

## Results

### *ANOVA analysis*

To find out what factors affect the observer's naturalness perception in this experiment, two two-way ANOVA analyses were done based on the data from observers' responses to test the null hypothesis. The ANOVA results are shown in Table 3.

**Table 3. The results of two two-way ANOVA analyses**

| First ANOVA (Dependent factor: Gamma) | | |
|---|---|---|
| | F (DFn, DFd) | *p*-value |
| Interaction | F (50, 660) = 0.5590 | *p* = 0.9941 |
| Background Factor | F (10, 660) = 0.5717 | *p* = 0.8377 |
| Fruit Factor | F (5, 660) = 17.75 | *p* < 0.0001 |
| **Second ANOVA (Dependent factor: Black level)** | | |
| | F (DFn, DFd) | *p* value |
| Interaction | F (50, 660) = 0.4522 | *p* = 0.9996 |
| Background Factor | F (10, 660) = 0.7397 | *p* = 0.6872 |
| Fruit Factor | F (5, 660) = 1.478 | *p* = 0.1950 |

In the first two-way ANOVA analysis, the dependent factor is the observer's gamma preference for high naturalness perception of the AR objects. The independent factors are different fruit stimuli and backgrounds. The *p*-value of the fruit factor is less than 0.0001. Hence, we can conclude that if the fruit stimuli factor has no effect overall, there is a less than 0.01% chance of randomly observing an effect of this big in an experiment of 11 observers. The effect of different fruits on virtual objects' gamma preference for high naturalness is considered statistically significant. On the other hand, the *p*-value for the background factor is 0.8377, which means the effect of the background factor is statistically nonsignificant.

In the second two-way ANOVA analysis, the independent factors are the same as in the first ANOVA, but the dependent factor becomes the observer's black level preference for high naturalness perception of the AR objects. The result shows neither background factor nor fruit factor has a statistically significance effect.

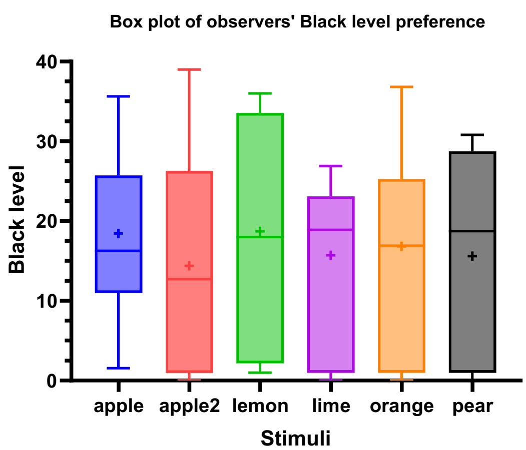


***Figure 6**. The box plot with all observers' mean preferred black level (+ mark) and group median (solid horizontal line) for each fruit stimulus.*

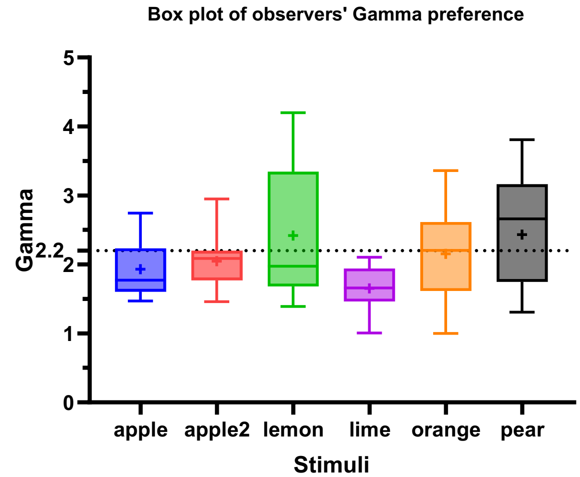


***Figure 7**. The box plot of all observers' mean preferred gamma (+ mark) and group median (solid horizontal line) for each fruit stimulus.*

Figure 6 and 7 present box plots illustrating the distributions and mean values of responses for black level and gamma preference of all observers. Because the AR fruit stimuli showed a significant effect for gamma preference, box plots are shown for each AR stimulus. The distribution of black level preference shows a wide range of variance covering almost the whole adjustable range of steps of black level. The mean and median value of gamma preference for all observers is mostly lower than the standard 2.2 gamma value, but shows more distinct variations between the fruits, corresponding to the significant effect noted via ANOVA.

### *CIELCh vs. Gamma*

In order to investigate the reason behind the significant effect of AR fruit stimuli, the mean gamma preference against lightness, chroma, and hue of stimuli are plotted in Figure 8, 9, and 10. Table 4 shows the average CIELCh values for each fruit. The LCh values were measured from the average RGB values of the fruit images, excluding specular reflection pixels and shadow covered pixels. Table 4 shows the average CIELCh values for each fruit.

**Table 4. The mean LCh and preferred Gamma value for each fruit stimulus**

| | L | C | h | Gamma |
|---|---|---|---|---|
| Apple | 43.51 | 79.19 | 33.49 | 1.93 |
| Apple 2 | 47.21 | 78.24 | 29.42 | 2.05 |
| Lemon | 87.26 | 87.36 | 92.47 | 2.42 |
| Lime | 48.11 | 53.91 | 114.70 | 1.65 |
| Orange | 69.22 | 80.33 | 68.25 | 2.15 |
| Pear | 82.08 | 58.29 | 102.11 | 2.43 |

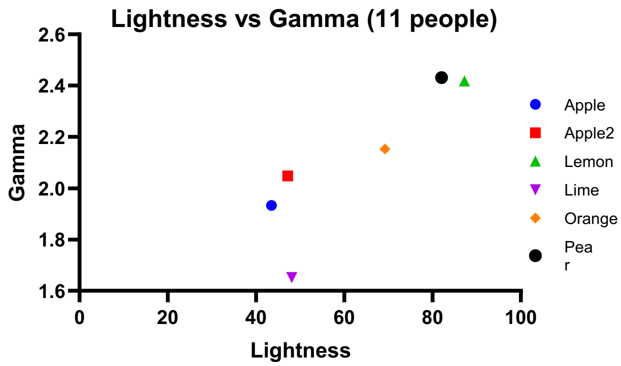


***Figure 8.*** *Mean Gamma preference against lightness for eleven observers.*

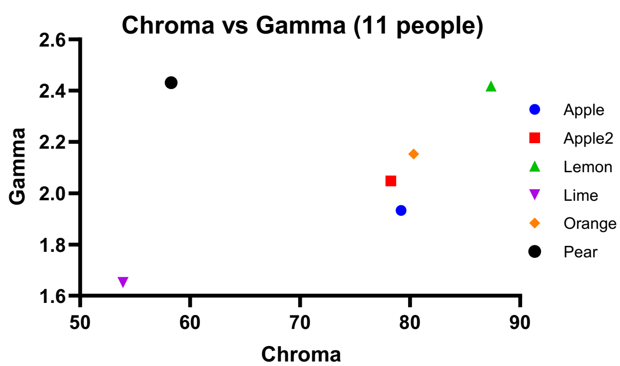


***Figure 9.*** *Mean Gamma preference against chroma for eleven observers.*

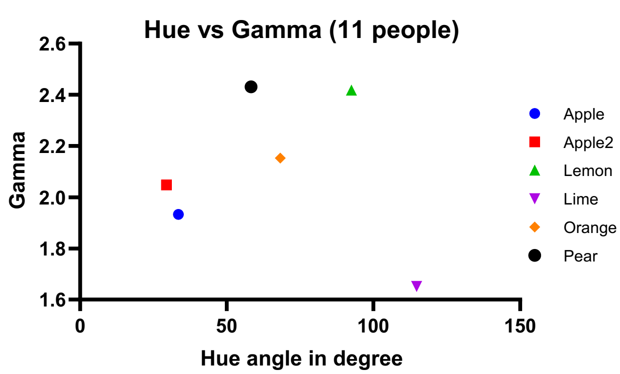


***Figure 10.*** *Mean Gamma preference against hue angle for eleven observers.*

## *Discussion*

The first ANOVA analysis shows observers' preferred Gamma for high naturalness perception in augmented reality varies with what fruit stimulus they saw. The second ANOVA analysis shows the variation in virtual stimuli and backgrounds has no impact on the observer's choice of Black level for a high naturalness perception in AR. The results of the two ANOVA tests reveal that the only factor that will affect the observer's preference for natural AR object rendering is fruit-based. For different fruit, there might be a corresponding Gamma value to make it look natural in Augmented Reality.

Surprisingly, both ANOVA analyses indicate that the background color does not contribute to observers' gamma or black level preference for naturalness. This finding suggests that when rendering virtual objects in augmented reality, the complicated background condition can be ignored for easier construction of future augmented reality imaging pipelines.

One finding worth noticing is that 27% of observers in this experiment generally prefer higher gamma. These observers prefer a higher than 2.2 gamma value for more than half of the number of fruit stimuli. This might be due to purely personal preference. Or, the observer saw added light from the background LCD and AR display from the OST AR system, so they want to increase the gamma to decrease virtual stimuli's brightness appearance to compensate for the extra light they saw.

Based on observers' comments, the lower half of the virtual object that contains shadow is usually ignored. This means observers viewing the content in augmented reality can overcome the dark region and lack of shadow by decreasing the gamma to make stimuli brighter. Observers mainly want to use gamma to adjust the virtual stimuli, increasing the black level of virtual stimuli with lower gamma will make the appearance of stimuli less natural. This effect can be observed in the bottom right image in Figure 5, when adjusting the gamma to make the stimulus appears brighter, a very high black level reduces naturalness compared to a low black level.

Because the fruit images were always presented in the same order, it is worth considering if there are any order or learning effects in the experiment. It was observed that as observers were doing the experiment, they became faster in response speed, found it easier to find the gamma for their standard of high naturalness, and discovered that the black level provided limited help to increase the overall naturalness appearance. It is impossible to eliminate an order-based effect among the significant factor fruit, but the similarity in gamma settings between the two apples in Figure 7 suggests that these first and last fruits were treated similarly by observers. On the other hand, the non-significant difference between the black level settings for the two apples seen in Figure 6 may reflect observers' discovery that the black level made a smaller impact on appearance.

Figure 8 suggests the gamma preference depends on the lightness of the virtual object. As the lightness gets higher, the gamma preference of the virtual object became higher. Observers usually choose to raise the gamma value to decrease the high brightness appearance of virtual objects with high lightness and do the opposite for low lightness objects. In the case of low lightness and low chroma objects such as lime, observers show a more consistent choice to lower the gamma and increase the overall brightness of the object. There is no clear correlation between gamma preference and hue and chroma, shown in figure 9 and 10, suggesting the gamma preference of observers does not depend on the chroma and hue of the virtual object.

Finally, in this study, the background was provided as a still image on a display rather than a real-world scene, which may limit the generalization to typical AR usage. However, in our experience with AR setups and stimuli, additional cues such as depth differences and motion parallax only increase the perceived scission between the AR and background layers, allowing users to ignore the background. If this trend holds, the influence of the background would be expected to be lower in real AR usage than in the present study.

## Summary and Conclusion

We conducted a psychophysical experiment to let the observer adjust the gamma and black values of fruit AR stimuli to find the preferred value for high naturalness perception in AR. The psychophysical experiment was conducted in a dark room with a custom-built optical see-through augmented reality system (OST AR) and a D65 light source illuminating a white panel behind. Both AR and background display are calibrated to sRGB color gamut, similar brightness, and white point at D65. All the stimuli and backgrounds were photographed in a light booth with a D65 illumination. 11 observers participated in this experiment. The observers were first sat in the room for a while for adaptation and shown several anchor point images to establish anchors for a natural scene. Then, each observer did 66 trials to adjust six different virtual stimuli to fit them into the whole scene naturally.

The results of the study were first analyzed in two two-way ANOVA analyses. The first ANOVA, with Gamma as the dependent factor and background and fruit stimuli as the independent factors, revealed that observers' preferred Gamma for high naturalness perception in augmented reality varies with what fruit stimulus they saw. However, there was no significant effect of background. The second ANOVA, with Black level as the dependent factor, revealed that Black level is not significantly affected by background and fruit choices.

Finally, we plotted the CIELCh value of the average color of the fruit stimuli against the preferred mean Gamma value for all observers and eight observers. We discovered that gamma preference has a strong correlation with the lightness of the virtual stimuli, and no clear correlation with chroma and hue.

This study shows the observer's Gamma preference increases as the lightness of the stimulus increases. The background color has no effect on naturalness perception in this experiment, which is highly unexpected.

In the future, additional AR stimuli such as colorful objects or human faces, should be included to further study stimuli color attributes' influence to naturalness perception in augmented reality. The background image can contain more levels of brightness and illumination CCT, or the background can even be an actual light booth with various conditions. The parameter can expand to other color attributes that do not only limit to gamma and black levels.

## Acknowledgements

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