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Background-Aware Colorization Technique for Augmented Reality Applications

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ABSTRACT A major challenge in the field of Augmented Reality (AR) is the way in which augmented information is presented in a wide range of uncontrollable environmental conditions. In fact, the variability of colours and illumination conditions of the real environment makes it difficult to choose the most suitable appearance properties for augmented contents. In many AR applications, the colours of virtual objects play a crucial role in blending digital information into the real environment, therefore these colours should be selected according to the appearance of the real background. In some use cases, the colours of virtual objects need to be harmonised with the ones of the real environment; in other cases, the colours should be chosen to ensure the visibility (e.g. maximizing the contrast) of the augmented data with respect to the background. To this end, the paper presents a background-aware colourisation technique that allows for selecting virtual objects' colours in accordance with the real environment in real-time. Given an arbitrary real background, virtual objects' colours are automatically chosen according to three different strategies, i.e. harmonic, disharmonic, and balanced. The proposed AR colourisation technique was assessed with a user study that focused on three different case studies. The results were promising and suggest the potential of the proposed technique for many different application areas. In particular, disharmonic and balanced strategies ensured the distinctiveness of virtual objects according to the real background. Instead, the harmonic strategy was less effective in the case of colourful complex AR scenarios.

INDEX TERMS Augmented reality, image processing, colourisation, colour harmonisation, user studies.

I. INTRODUCTION

Augmented Reality (AR) is evolving rapidly to become a more cost-friendly and accessible technology, especially when mobile devices such as smartphones and tablets are considered. In fact, an ever-increasing number of AR-based applications are used in everyday life and several sectors, such as gaming, learning, marketing, tourism, cultural heritage, interior design, medical, military, industry, and many others [1]–[5]. In the AR scenario, computer-generated information, such as images, videos, texts, GPS location data, or other elements, is superimposed on a real-world view and presented to a user in real-time.

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Recently, Kim *et al.* [6] explored the versatility of AR, including applications, limitations, and future direction. They pointed out that there is a sharp increase in AR rendering research. In most cases, AR content is generated by 3D artists and application developers who define its visual proprieties without any prior knowledge of the real-world environment in which virtual objects are integrated. In all these cases, it is difficult to predict how digital content will appear in the real environment with adverse consequences on the AR experience. Researchers are still attempting to solve many fundamental problems in the design of effective AR.

As reported in [7], many perceptual problems may occur while observing and interpreting virtual information that is blended with the real-world view. Among them, colour schemes, as well as the variety of an environment, can hinder a correct perception. In many cases, uncontrollable environmental conditions may alter users' perception of augmented information. Colours and textures of the background environment, in fact, have a direct influence on the visibility and readability of a virtual text in AR scenarios [8]–[15], with the consequence that augmented data cannot be easily distinguished from the real object. This problem is not only related to the augmentation of virtual texts, but also to the augmented visualization of 3D virtual elements. In AR applications for the tourism sector, for instance, 3D virtual pointers can be displayed on a paper map to highlight points of interest and provide additional information to users [16], [17].

Another typical example of AR applications in which 3D virtual information is augmented onto real objects is related to the industrial scenario [18], [19]. In these cases, as well, virtual objects' colours can affect the visibility of information if not chosen appropriately. This problem is also quite common in AR applications for gaming and entertainment [20], [21] because virtual objects' colours are usually predefined regardless of the scenario in which they appear. In these circumstances, it is very difficult to ensure that virtual content fits into its real-world environment to yield a better visual match between virtual and real elements. This may lead to unnatural augmented environments and, therefore, users may perceive AR scenarios as unpleasant and unrealistic.

This paper describes a background-aware colourisation technique for mobile AR applications, suitable for handheld devices (smartphone, tablet). The technique allows for selecting virtual objects' colours in accordance with the real environment in real-time performance. Given an arbitrary real background, the colours of virtual objects are automatically chosen according to three different strategies, i.e. harmonic, disharmonic, and balanced. The first approach generates colours that are in harmony with the real environment according to the colour theory [22]–[25], so that the virtual objects could be pleasantly integrated into the real world. The second approach produces colours that are disharmonic with respect to the colours of the real background to ensure that virtual objects stand out from the background. Whereas the third approach called ''balanced'', aims at matching both the previous goals. The abovementioned strategies are based on the colour harmonisation technique that exploits harmonic colour schemes described in the literature [33]. A user study with 36 participants was conducted to assess if the proposed technique was able to colourise augmented content according to the specific goal set for each strategy, i.e. harmonic, disharmonic, and balanced.

The paper is structured as follows: Section 2 summarizes the related works, whereas Section 3 describes the proposed AR colourisation technique. Experiments are detailed in Section 4. Results and discussion are presented in Sections 5 and 6, followed by conclusions.

II. RELATED WORK

In the past decades, researchers have focused on a variety of graphical aspects to improve AR visualization. Many efforts have been made by researchers in the context of augmented text in order to identify variables that affect text readability.

Azuma and Furmanski [15] analysed different algorithms for the placement of 2D virtual labels to evaluate text readability. The main finding reveals that human observers were able to read labels faster when texts are not overlapped. Leykin and Tuceryan [14] proposed a supervised classifier methodology, based on a pattern recognition technique, to determine the readability of virtual labels in AR systems. During their experiments, they considered grey texts superimposed on grey-scale images, which is the main limitation of this work. In [8]–[11], several user studies were presented to evaluate the influence of outdoor background textures on ease of text identification by providing design guidelines for AR scenarios. In particular, it was confirmed that several factors, including background texture, text drawing styles, lighting conditions, and their interaction, strongly affect text readability. In [12], [13], authors addressed the text readability limits in industrial environments by considering different augmented reality head-worn displays and background lighting conditions.

Other works proposed techniques that combine the colours of the virtual and real objects in order to higher visualization quality of AR scenarios. In this context, Gruber *et al.* [26] proposed a method to harmonise the combination of colours in video-based AR systems aiming at achieving more visually pleasant AR scenarios. In this regard, a constrained colour harmonisation process was adopted by identifying different types of colour-to-object assignments. However, no user studies were carried out to assess the effectiveness of the proposed methodology. In the same context, the work presented by Thomas *et al.* [20] addressed the problem of selecting the appropriate colours of the 3D models displayed in the ARQuake game. In their work, the authors pointed out how the choice of colours is important for outdoor AR applications, and how real environment conditions, such as bright sunlight and natural surroundings, may affect the usability of the AR application. To this end, they experimented the influence of colours on the distinctiveness of AR objects. But their experimentations dealt with the assignment of a limited number of colours, with four different intensities, tested in different scenarios. In [27], authors presented an AR application to augment pieces of furniture with different colours and styles within the real environment through a head-mounted headset device. Their method was based on semantic segmentation with deep learning algorithm and fast-speed colour transformation to recognise and segment furniture in the user's field of view, and then overlap a virtual colour on top of them. Nevertheless, the automation of the process of colour selection was not taken into account. In [28], [29], an investigation about what adaptation should be chosen to improve the visibility of graphical symbols superimposed on real-world images was carried out. More specifically, they considered different types of adaptation and light/black background images to conduct their studies. What emerged is that the perception of virtual symbols depends on colours of the surrounding background. Furthermore, they stated that only not distinguishable objects needed to have an adjustment in luminosity to improve their distinctiveness from the real background. However, no different lighting environmental conditions have been considered to provide robust guidelines on how presents symbols in an AR scenario.

Unlike previous works, the present paper proposes a background-aware colourisation technique that allows for selecting virtual objects' colours in accordance with the real environment. Given a real scenario and its light conditions, the colours of the augmented virtual objects are automatically set in real-time according to three different strategies: harmonic, disharmonic, and balanced.

III. COLOURISATION TECHNIQUE

As mentioned before, the proposed technique allows for an automatic colourisation of virtual objects according to the real background by means of three different strategies, i.e. harmonic, disharmonic, and balanced. To this end, the proposed technique exploits colour's schemes from colour theory and an optimization problem is formulated. In particular, an objective function is defined, which measures the harmony of colours of the real background with respect to the selected scheme. By optimizing this function different colouring solutions are generated, and then applied to the virtual content. Figure 1 shows the workflow of the proposed technique that consists of four main stages: colour space conversion; colour scheme optimization; colour generation; and scene analysis. Unlike the technique proposed in [30], this work presents improvements related to the light estimation and the shadow generation processes depicted in the fourth stage of figure 1.

In the first stage, the background image of the real environment is given as an input to the colour space conversion. In particular, the first stage starts with the image analysis in which the red (R), green (G), and blue (B) components are specified for each pixel of the image background in RGB colour space [0, 255]. Then, RGB values are converted into HSV colour space that uses three different channels: hue (H), saturation (S), and value (V), defined in the ranges [0, 360], [0, 100], and [0, 100], respectively. Next, the colour histogram is computed by grouping colour values into L bins (typically L = 360) of equal width. Each bin corresponds to each degree of the colour hue defined in the range [0, 359]. Finally, each value is normalized according to the highest frequency value of the whole colour distribution.

In the second stage, a colour scheme optimization allows for identifying the region of colours to be used to set the colours of the virtual objects. In particular, this process is based on a colour harmonisation technique, which exploits

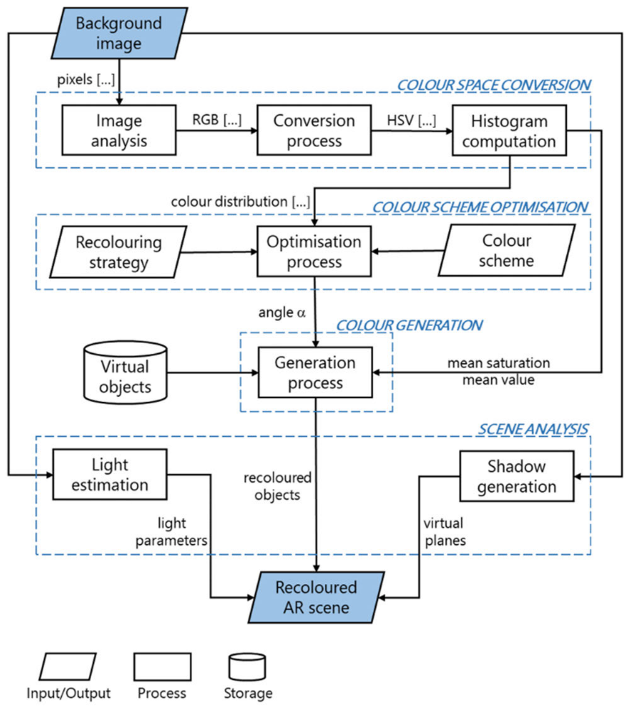


FIGURE 1. Workflow of the proposed colourisation technique.

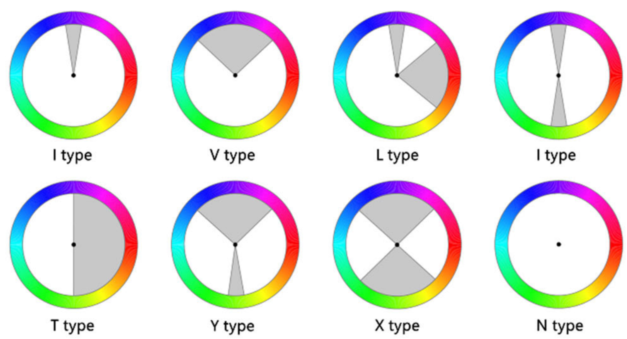


FIGURE 2. Harmonic templates defined in HSV colour space [32].

eight different colour templates proposed in [32], [33], and shown in Figure 2. Each harmonic template is defined over the hue wheel in HSV colour space, and consists of one or two sectors, which are in relation to each other in terms of radial position. In general, each template can identify shades of the same colours (i, V, T), shades of complementary colours (I, Y, X), or a more complex combination (L). In this work, all harmonic templates have been considered, except for N-type as it corresponds to grey-scale images. In particular, a harmonic scheme is defined by a specific template (Tm), where m is the type of the template, rotated by an angle α on the hue wheel. The templates can be rotated in arbitrary angles in the range $[0, 2\pi]$ in steps of one degree. The rotation of the template can be executed by solving an optimization problem [34]. In this regard, an objective function F can be defined as follows:

$$F(X, (m, \alpha)) = \sum_{p \in X} \|H(p) - E_{Tm(\alpha)}(p)\| \, S(p)\, V(p) \quad (1)$$

where:

- || ▪ || is the arc-length distance measured in radians between the hue of the pixel P of the image background (X) and the sector border of the template T indicated by $E_{Tm(\alpha)}$;
- S(p) and V(p) are the saturation and value channels of pixel P, respectively.

Pixels of the background image X with a hue that is already inside the grey sector are not considered in the summation by convention. The objective function F measures the harmony of the image background with respect to the selected scheme (m, α). The optimization process is performed through the adoption of Brent's algorithm, which is a hybrid root-finding algorithm [34]. The solution to the optimization problem consists of an angle α that optimizes the radial position of the specific template with respect to the real colour distribution on the hue wheel. In this way, different combinations of harmonic colours can be extracted from the harmonised sectors to recolour virtual objects. Furthermore, the optimization process can follow three different strategies: harmonic, disharmonic, and balanced. The first one minimises the distance between sectors of the template and the real colour distribution by generating colours similar to the real ones. In this way, virtual objects should be pleasantly and harmonically integrated into the real-world. Conversely, the second strategy maximises the function F in order to generate different colours from those contained in the real background. Thanks to the disharmonic approach, virtual objects stand out from the image background. The last one balances the previous goals by considering templates with two sectors. In fact, one of them tries to minimise the distance with the real colour distribution, whereas the other maximises this quantity. To this end, it considers a modified version of the objective function F that includes borders of each sector.

In the third stage, the generation process allows for generating the colours that are assigned to the virtual objects by using the angle α given as an output by the optimisation process, and the saturation and light values obtained from the real colour distribution. More specifically, the generation process can handle the setting of colours' hue of both non-textured and textured virtual objects in real-time. In the first case, the optimised sectors are split into equally spaced subsectors. Therefore, the centre of each subsector identifies a new colour hue. The number of subsectors is defined by the number of colours to be generated. Figure 3 shows an example in which three different colours' hues have been generated by considering the V-type template.

In the second case, instead, a colour shifting technique is adopted. This is based on the use of a shader programmed in ShaderLab, which is a Unity declarative language for shaders. In particular, the hue radial distance is firstly calculated, which represents the distance between the centre of the optimised sector and the texture colour's hue with the maximum occurrence. Then, all colours' hues of the texture are shifted of this quantity. This allows for setting virtual

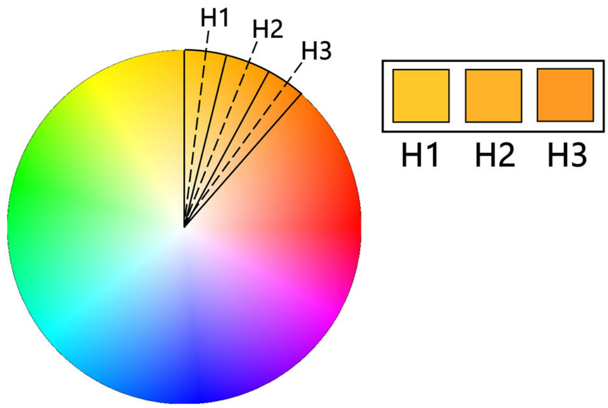


FIGURE 3. Three colours generated in the case of V-type template.

objects' colours' hues coherently, resulting in a continuity of colours. In both cases, the last two colour channels, i.e. saturation and value, are set equal to their correspondent average values obtained from the colour distribution of the real background. This is justified by the fact that, in real environmental lighting conditions, users' colours perception can be altered by inducing a subject to perceive different colours as the same ones, and vice versa [35]. The estimation of the average values for both saturation and light of the real background is of crucial importance also in the case of the augmentation of virtual objects that contain text. For example, virtual labels are often superimposed onto the user's field of view of the real world to provide information about the elements present in the scene, e.g. the name of the places on a map or the name of the characters in a painting. In these cases, the colours of the virtual labels can still be selected by means of the proposed technique in order to present them pleasantly and harmonically. To ensure the readability of the text contained in the labels an adequate contrast between the text and its background needs to be set. Therefore, the saturation of the label is set to be equal to the mean saturation of the real background. The text colour is selected based on the saturation of the label. If the saturation of the label is greater than 50%, then the colour text is set to black colour, otherwise it is set to white. Instead, the value channel of the colour is set to the mean value of the real background. In this way, the readability of the text, contained in the labels, is ensured as well.

In the fourth stage, two main processes are performed: light estimation and shadow generation. Light estimation process estimates several light parameters from the real image background, and in particular, intensity, colour, temperature, and position of the real light. To obtain the first three parameters, the proposed technique adopts the light estimation functionality provided by the AR framework. Instead, the position of the real sunlight is estimated by means of date and time, and device sensors data (GPS, IMU). In this way, the virtual light source is calibrated based on the real light parameters when rendering virtual objects. This allows

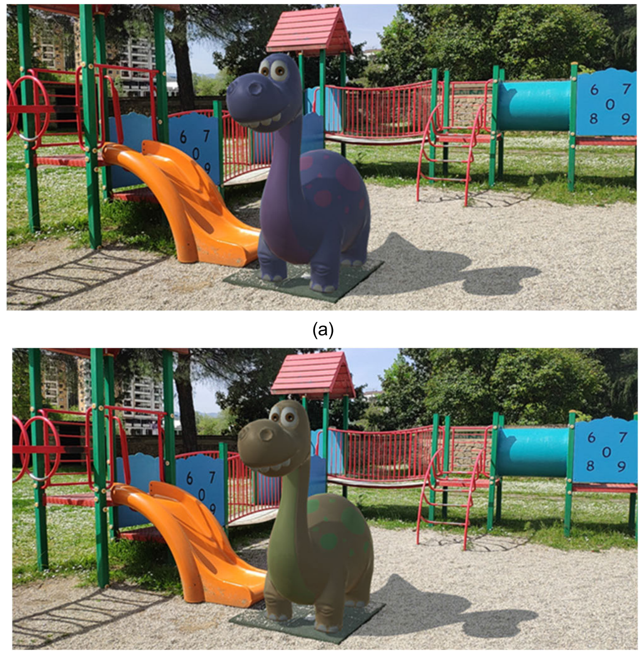
TABLE 1. Colourisation solutions used in this study.

Template	Strategy
i-type	Harmonic & Disharmonic
L-type	Balanced
Y-type	Balanced

for lighting the virtual content under the same conditions as the real scene they are placed in. This is motivated by the fact that when creating realistic AR scenes, it is crucial to acquire the knowledge of scene illumination to ensure an efficient integration of virtual contents into real-world environment.

In the same stage, the shadow generation process is executed as well. In particular, it allows for generating virtual shadows consistent with the real ones. To this end, the proposed technique implements the plane detection functionality provided by the AR framework, to recognize vertical and horizontal surfaces, and generate virtual planes on which cast synthetic shadows. Since the virtual light source is oriented as the real one, then virtual and real shadows results aligned correctly. The shadow casting is of crucial importance while creating realistic AR visualization. In fact, while real objects cast shadows on physical elements of the real environment such as planes and surfaces, virtual objects should cast shadows on virtual planes to improve the realism of the AR scenario.

Figure 4 shows an example outcome from our test application, with a virtual recoloured object according to the real background. In particular, a virtual dinosaur is augmented in a public garden, and recoloured by using the harmonic strategy. In figure 4a, the virtual content with original colours before the recolouring process is depicted, whereas the recoloured object is shown in figure 4b. Furthermore, it is possible to observe how the virtual dinosaur is well integrated into the real environment as it is correctly illuminated with consistent virtual shadows.



(a) (b)

FIGURE 4. A possible output of the proposed recolouring technique.

IV. EXPERIMENT

A preliminary study was carried out with in-person experiments in our laboratory to identify the most suitable colourisation solutions to be adopted during the main experimentation. More specifically, 10 experienced augmented reality developers were consulted. They evaluated a total of 18 different colourisation options (3 strategies × 7 templates) for three different case studies. For each of them, they selected four different recolouring (see Appendix), as shown in table 1, which was used during the main experimentation with end-users.

As reported in table 1, the i-type template was considered for both harmonic and disharmonic strategies since it allows for capturing the real colours with maximum frequency. Whereas L-type and Y-type templates were considered for the balanced strategy, since this strategy needs templates with at least two sectors.

Furthermore, prior to conducting the study, the following hypotheses were formulated:

H1: harmonic and balanced strategies can ensure pleasant colourisation of virtual objects according to the real background.

H2: disharmonic and balanced strategies make the virtual objects clearly distinguishable from the background.

H3: text readability on digital labels can be ensured, independently of the colour hue, if saturation and value are chosen appropriately.

The proposed colourisation technique has been implemented into an AR demo application programmed in Unity®, which is a real-time 3D development platform that consists of a rendering and physics engine coupled with a graphical user interface [36]. The AR application is based on ARCore™ SDK [37], an open-source framework used for creating AR-based applications compatible with Android™ devices. Regarding the hardware, the AR application has been implemented on a Xiaomi MI8 [38], equipped with a Qualcomm® Snapdragon™ 845 (4 × 2.8 GHz Kryo 385 Gold + 4 × 1.8 GHz Kryo 385 Silver) processor, a 12MP rear camera, 6.21-inch touchscreen with 1080 × 2248 resolution, and integrated sensors (GPS, IMU). Since all the computations are carried out on the device itself, there are no other external hardware components required for the data processing.

A. PARTICIPANTS

Thirty-six volunteers (32 males, 4 females), ages ranging from 20 to 24 years, participated in this study. Participants were divided into two groups to balance participant experience in experimentation. All of them were university students

FIGURE 5. 3D animated dinosaur placed in a public garden before the recolouring.

FIGURE 6. The map of Cosenza (Italy) with 3D virtual pointers before the recolouring.

and no one was affected by defective colour vision (e.g. colour blindness).

B. PROCEDURE

It was not possible to conduct a laboratory study because of the COVID-19 pandemic. As a consequence, all of the participants were asked to perform the test from their home. The procedure of the experiment was remotely explained to the participants before starting the test. Students were asked to sign an informed consent form and complete demographic questions (gender, age). In addition, they were also asked to indicate colour deficiencies (e.g. colour blindness).

Three different case studies were considered during the experimentation. The first one consisted of setting colours of an animated 3D virtual dinosaur [39] placed in a public garden (Figure 5). The colourisation of the textured 3D model was performed through the proposed hue shifting technique.

The second case study dealt with the colourisation of 3D virtual pointers, containing the name of a point of interest (POI), which were added to the map of Cosenza (Italy) (Figure 6). A total of six different POIs were placed in correspondence of buildings, monuments, a bridge, and a river. In this case, only one colour was used for the colourisation of POIs, which corresponds to the central value of the harmonised sector.

In the last case study, the famous painting *Birth of Venus* by Sandro Botticelli was considered for experimentation (Figure 7). Virtual labels with a semi-transparent billboard were added to the painting. The labels contained the names of the characters. The level of transparency was set to 30%.

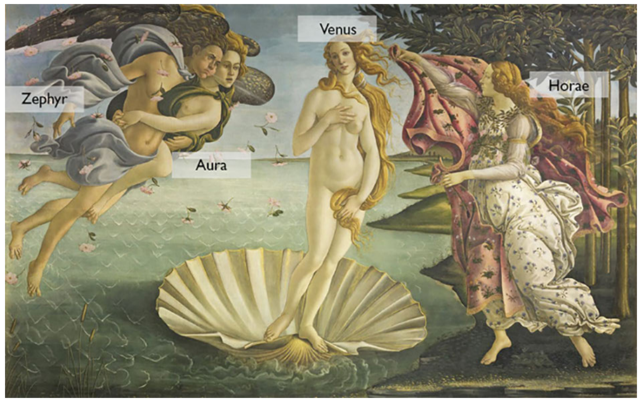


FIGURE 7. Birth of Venus by Sandro Botticelli before the recolouring.

As in the previous case study, only one colour was used for setting colours of labels.

All participants were asked to watch three different videos in the case of the first two case studies (i.e. animated dinosaur, city map) and look at the three different images in the case of the third case study (i.e. painting), without any limitations in time. Videos and images were related to the colourisation options shown in Table 1. The duration of the videos was approximately 20 sec. The experiment took about 15 minutes. A total of four questions were considered:

- **Q1-harmonic**: "*Are the colours associated with the virtual augmented dinosaur/labels/pointers harmonic with respect to the environment/painting/map?*".
- **Q2-pleasant**: "*Are the colours of virtual dinosaur/ labels/ pointers pleasant?*".
- **Q3-distinguishable**: "*Are the virtual dinosaur/labels/ pointers clearly distinguishable from the background?*".
- **Q4-readable**: "*Is the text clearly readable?" (only for the second and the third case studies)"*.

Each question was answered using a 5-item likert scale with 1 (strongly disagree) and 5 (strongly agree).

The experiment ended by inviting participants to fill out an online questionnaire including a series of questions related to the perceptual sensations they had about the colours associated with virtual objects of each case study.

V. RESULTS

Descriptive statistics and one-way ANOVA analysis were used for statistically significant differences among the four colourisation solutions. All analyses were conducted using the statistical package IBM SPSS. The statistical significance level was set at $p < 0.05$.

A. DINOSAUR

Figure 8 shows the results related to the three questions, i.e., Q1-HARMONIC, Q2-PLEASANT, and Q3-DISTINGUISHABLE, about the harmony, pleasantness, and distinctiveness of colours associated with the virtual dinosaur.

As shown in Figure 8, the highest value of harmony is reached when the balanced approach is adopted with an

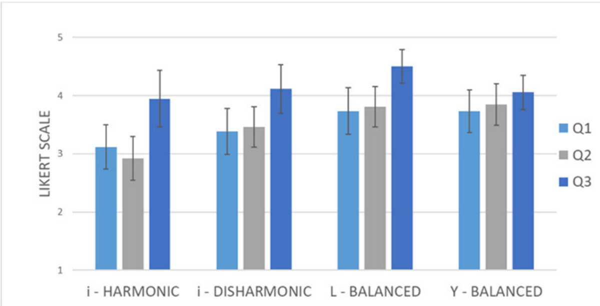


FIGURE 8. Results obtained for the three questions related to the virtual dinosaur.

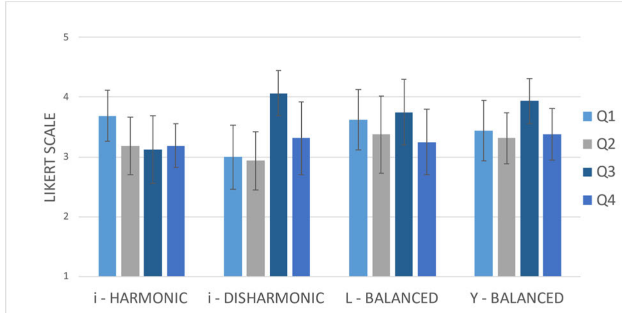


FIGURE 9. Results obtained for the four questions related to the city map.

average rate of M = 3.73 with SD of 1.04 for the L-type, and SD of 0.96 for the Y-type. The disharmonic approach, instead, presents an average rate of M = 3.38 with SD of 1.02. Similarly, the harmonic approach proposes an average value of M = 3.12 with SD of 0.99. Although the graph (Figure 8) shows such differences, these are not confirmed by a one-way ANOVA analysis, which indicates that there is no statistically significant difference in harmony among the four combinations ($F(3) = 2.29$, $p = 0.83$). The same trend can be observed in the case of question Q2-PLEASANT. In fact, as depicted in Figure 8, the results show that the balanced approach provides the higher pleasantness with an average rate of M = 3.81 with SD of 0.9 for the L-type, and of M = 3.85 with SD of 0.92 for the Y-type. The disharmonic and harmonic approaches reach an average value of M = 3.46 (SD = 0.90) and M = 2.92 (SD = 0.98), respectively. Unlike previous results, a one-way ANOVA shows that there is a statistically significant difference among the four combinations ($F(3) = 5.54$, $p = 0.001$).

Similarly, to the previous results, the highest value, in the case of Q3-DISTINGUISHABLE, can be observed when the balanced strategy (L-type) is adopted with an average rate of M = 4.50 with SD of 0.62. The second highest value is proposed by the disharmonic strategy with an average value of M = 4.11 with SD of 0.9. The balance strategy (Y-type) reaches an average value of M = 4.06 with SD of 0.64. The lowest value is related to the adoption of the harmonic strategy that proposes an average value of M = 3.94 with SD of 1.06. These results were also submitted to a one-way ANOVA analysis. What emerges is that although some differences are depicted in Figure 8, the results of one-way analysis show that there is no statistically significant difference in the distinctiveness of colours among the four combinations ($F(3) = 1.55$, $p = 0.210$).

B. CITY MAP

Figure 9 shows the results of the four questions, i.e. Q1-HARMONIC, Q2-PLEASANT, Q3-DISTINGUISHABLE, and Q4-READABLE, for the city map.

In particular, the highest value of harmony is observed when the harmonic approach is used with an average rate of M = 3.69 with SD of 1.0. The balanced strategy proposes lower values than the previous one, with an average rate of M = 3.63 with SD of 1.02 for the L-type, and of M = 3.44 with SD of 1.03 for the Y-type. The lower value, instead, is reached in the case of the disharmonic approach with an average rate of M = 3.0 (SD = 1.10). These data were also compared by means of a one-way ANOVA analysis which indicates that there is no statistically significant difference among the four combinations ($F(3) = 1.66$, $p = 0.185$). Figure 9 also shows results of the colours pleasantness associated with 3D virtual pointers added to the city map. As depicted in Figure 9, the balanced approach proposes the highest values with an average rate of M = 3.38 with SD of 1.31 for the L-type, and M = 3.31 with SD of 0.87 for the Y-type. The harmonic approach reaches an average value M = 3.0 (SD = 1.0). The lowest value is observed in the case of the disharmonic approach with an average rate of M = 2.94 with SD of 1.0. These results were also submitted to a one-way ANOVA analysis. What emerges is that although some differences are depicted in figure 9, the results of one-way analysis show that there is no statistically significant difference in the pleasantness of colours among the four combinations ($F(3) = 0.54$, $p = 0.657$). The results of the third question are also shown in Figure 9. In this case, the highest value is reached with the adoption of the disharmonic strategy with an average rate of M = 4.06 with SD of 0.77. The balanced strategies, instead, propose similar results, and in particular, an average rate of M = 3.94 (SD = 0.77) in the case of Y-type, and of M = 3.75 (SD = 1.13) in the case of L-type, respectively. The lowest value is reached in the case of the harmonic approach with an average rate of M = 3.13 with SD of 1.15. Unlike previous results, a one-way ANOVA shows that there is a statistically significant difference among the four combinations ($F(3) = 2.93$, $p = 0.04$). The outcomes of the fourth question are also shown in Figure 9. Overall, all combinations present an average value greater than 3 points. In particular, the highest value is reached by the balanced approach related to the Y-type template with an average value of M = 3.38 with SD of 0.89. The second highest value is observed when the disharmonic approach is adopted with M = 3.31 (SD = 1.25). The two last values are proposed by the balanced (L-type) and harmonic approaches with an average value of M = 3.25 with SD of 1.13, and of M = 3.19 with SD of 0.75. These results are confirmed

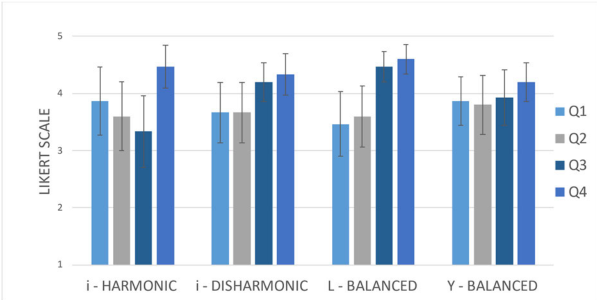


FIGURE 10. Results obtained for the four questions related to the painting.

by a one-way ANOVA analysis which shows that there is no statistically significant difference among the four combinations (F(3) = 0.132, p = 941).

C. PAINTING

Figure 10 shows results related to the four proposed questions for this case study.

When considering the outcomes of the first question (Q1-HARMONIC), it can be noted that the highest value is reached with the adoption of both harmonic and balanced (Y-type) approaches with an average rate of M = 3.87 with SD of 1.19 and SD of 0.83, respectively. The second highest value is observed for the disharmonic approach with an average rate of M = 3.67 (SD = 1.05). The balanced strategy (L-type), instead, proposes the lowest value with an average rate of M = 3.47 with SD of 1.13. However, the differences are not statistically significant as indicated by one-way ANOVA analysis with F(3) = 0.493 and p = 0.689. Moreover, the outcomes of the second question (Q2-PLEASANT) show similar results. In particular, the highest value is presented by the balanced approach (Y-type) with an average value of M = 3.80 with SD of 1.01. Then, the disharmonic approach proposes the second highest value with M = 3.67 (SD = 1.05). The same average value M = 3.60 is observed in correspondence of both harmonic and balanced (L-type) approaches with SD of 1.18 and with SD of 1.06, respectively. Furthermore, there is no statistically significant difference among average values (F(3) = 0.115, p = 0.951).

The outcomes related to the third question (Q3-DISTINGUISHABLE) are shown in Figure 10. In particular, the highest value can be observed in the case of the balanced strategy (L-type) with an average rate of M = 4.47 with SD of 0.52. Then the disharmonic strategy proposes the second highest value with an average rate of M = 4.20 with SD of 0.68. The balanced strategy (Y-type) proposes an average rate of M = 3.93 with SD of 0.96. The lowest value is reached in the case of the harmonic approach with an average rate of M = 3.33 (SD = 1.23). This data has been also compared by means of a one-way ANOVA analysis which indicates that there is a statistically significant difference among the four combinations (F(3) = 4.45, p = 0.007).

As far as the outcomes of the fourth question (Q4-READABLE) are concerned, Figure 10 shows that the balanced approach (L-type) leads to the highest value with an average rate of M = 4.60 with SD of 0.51. Similarly, the harmonic strategy reaches an average value of M = 4.47 with SD of 0.74. On the contrary, the lowest values are observed in the case of both disharmonic and balanced (Y-type) approaches with an average rate of respectively M = 4.33 with SD of 0.72, and of M = 4.20 with SD of 0.68. A one-way ANOVA analysis shows that there is no statistically significant difference in text readability for the four combinations (F(3) = 0.993, p = 0.403).

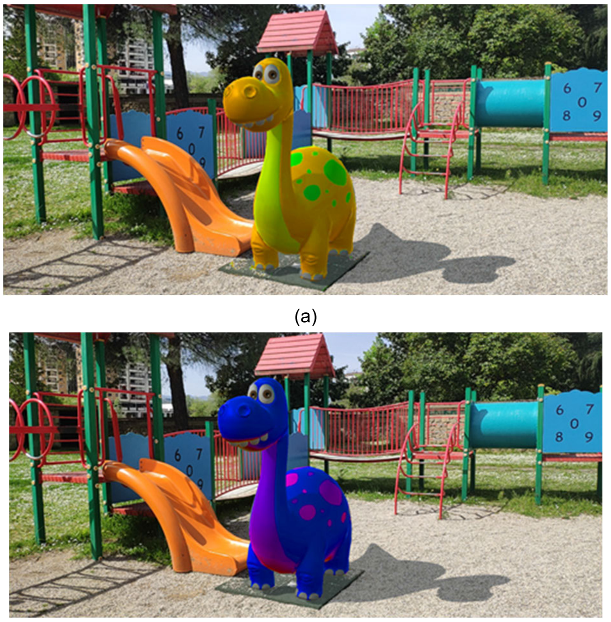
VI. DISCUSSIONS

Considering the results presented in Section 5, the three research hypotheses can be discussed.

Regarding **H1**, it is not supported by the answers given to Q1-HARMONIC and Q2-PLEASANT in all the 3 case studies. As for the first case study, i.e. the 3D virtual dinosaur placed in the public garden, the results are between 3 and 4 and, surprisingly, the lowest score is reached by the harmonic strategy. The balanced strategy performs better than the others on both templates, but it does not reach the value of 4. For this case study, the three recolouring strategies seem to lead to similar results without showing significant differences.

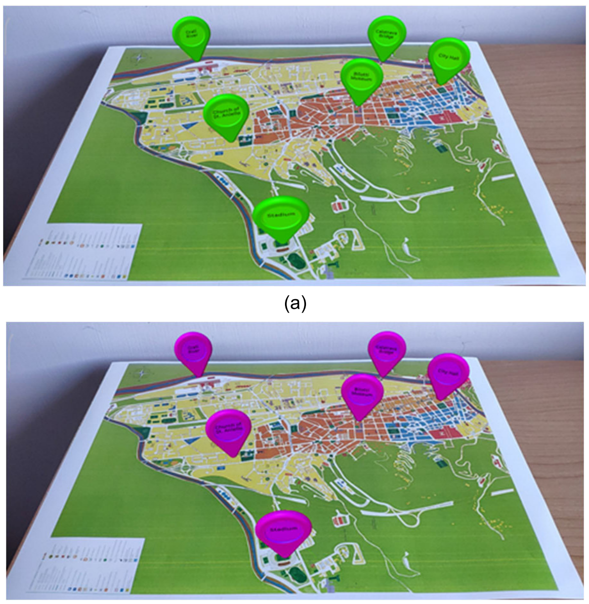
Similarly, the outcomes related to the case study of the painting did not confirm **H1** as the value reached by Q1-HARMONIC and Q2-PLEASANT did not reach a mean value of 4. Moreover, we can observe that, for the city map, there is no significant difference among the three proposed colourisation strategies. Even if better results were observed in the case of the city map, it also does not allow us to confirm **H1** and it does not provide any evidence of significant difference among the strategy as far it concerns harmony and pleasantness. These unexpected results may be due to the choice of real backgrounds that have a wide range of colours. In this case, it is difficult to evaluate what – with respect to the real background – is harmonic and pleasant, and what is not. Furthermore, as aforementioned, various and uncontrollable lightning conditions of the real background can strongly affect the users' colours perception by inducing a subject to perceive different colours as the same colours, and vice versa [35]. Under this circumstance, the appearance of virtual objects – in terms of harmony and pleasantness – could not strictly depend just on the colour hue, but likely on saturation as well.

To this end, further experiments were conducted to evaluate the effect obtained by changing not only the hue, but also the saturation of virtual objects' colours. Thus, also in this case, the colourisation solutions of the previous case studies were submitted to users. Unlike previous experimentation, only colourisation solutions provided by the harmonic and disharmonic approaches were considered with the saturation value equal to 100% for each case study. This choice is justified by the fact that the maximum saturation value may have the greatest impact on colourisation. Figures 11, 12, and 13 show the different recolouring solutions considered for the



(a) (b)

FIGURE 11. Recolouring solutions for the dinosaur with 100% of saturation: i-type harmonic (a), i-type disharmonic (b).

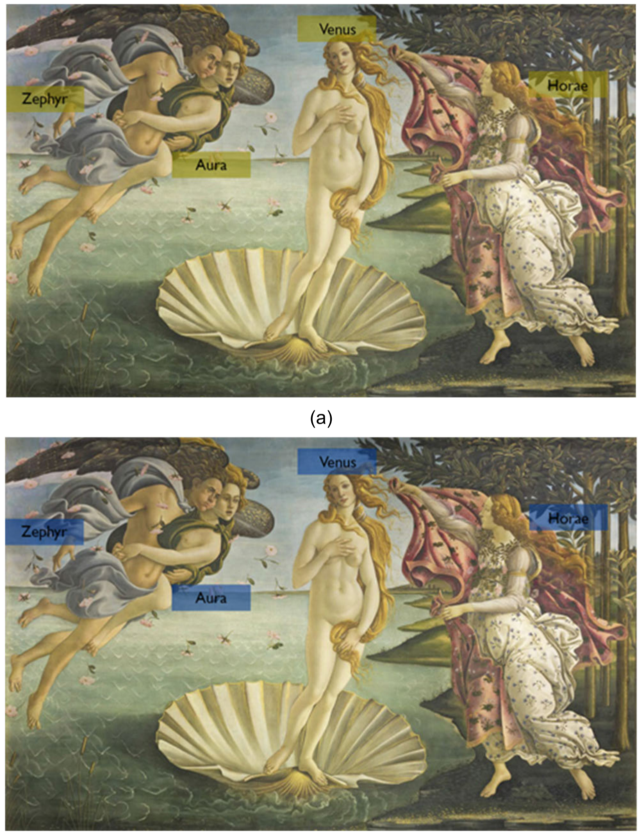


(a) (b)

FIGURE 12. Recolouring solutions for the city map with 100% of saturation: i-type harmonic (a), i-type disharmonic (b).

three case studies, whereas numerical results are reported in table 2.

Results confirm that the harmony and pleasantness of colourisation solutions related to the harmonic strategy remain the same. This is also confirmed by t-test analysis which shows that there is no statistically significant difference between the previous colourisation solutions and the new ones for each case study. This means that harmonic colourisation was perceived by users as harmonious and pleasant regardless of the value assigned to the saturation.



(a) (b)

FIGURE 13. Recolouring solutions for the painting with 100% of saturation: i-type harmonic (a), i-type disharmonic (b).

TABLE 2. Descriptive statistics related to Q1 and Q2 for each case study.

	HARMONIC				DISHARMONIC			
	Q1		Q2		Q1		Q2	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dinosaur	3.18	1.05	3.34	1.06	2.26	1.14	2.34	1.07
City map	3.48	1.05	3.33	.96	1.94	0.81	2.16	1.09
Painting	3.68	0.97	3.47	1.10	2.12	0.95	2.26	1.06

This result is in line with ones reported in [30]. In fact, also in that case, harmonious recolouring solutions have been obtained even if the saturation was changed in the range 40-100%. As for the disharmonic strategy, colourisation solutions were perceived by users as more disharmonious and unpleasant than the previous experimentation.

Unlike previous results, a t-test analysis confirms statistically significant differences for both Q1-HARMONIC and Q2-PLEASANT questions. This means that saturation affects the colourisation solutions provided by the disharmonic strategy. In particular, if the saturation value increased, users felt virtual objects as more disharmonic and unpleasant.

The verification of **H2**, which is about the distinctiveness of virtual information, can be analysed by considering the answers given to Q3-DISTINGUISHABLE. For this question, the Dino case reached almost an average score around of 4 for all the strategies having the best one on the L-Balanced with an average score of 4.5. No significant differences can be observed among the various strategies in this case. Instead, for the cases related to the map and the painting, the results clearly show that the disharmonic and the balanced strategies contribute to making the virtual objects more distinguishable from the background, reaching average values around 4 and highlighting a significant difference with respect to the harmonic strategy. Unlike approach adopted in [28], [29] to make virtual information more salient from the background by means of changing its value channel, here we also adjusted both hue and saturation since we believe that these are critical for distinctiveness of virtual information when blended into a real-world environment. In any case, it is of crucial importance to have distinguishable virtual objects from the real background, especially in contexts where virtual information is used to support task execution as in the case of industrial activities [18].

H3, which is about the readability of the text in the labels placed on the map and the painting, can be analysed by considering the answers given to Q4-READABLE. The two case studies provided different results. For the city map, the average scores are slightly over 3, whereas for the painting they always surpass 4 (min 4.2, max 4.6). This probably was due to a wrong choice of the font size in the labels of the map that invalidated the result, as confirmed also by the personal opinions gathered at the end of the test. What emerges from the analysis of the answers given to Q4-READABLE in the case of the painting is that all the colourisation solutions ensured high text readability. This result supports **H3** according to which text readability does not depend from the colour hue if saturation and value are chosen appropriately. This result is in line with industry practices, where the importance to have a uniform synthetic billboard for the augmented text with high contrast helps improve text readability [12], [13]. In the same way, it is necessary to create good contrast between virtual information and outdoor background texture as suggested by Gabbard *et al.* [9]–[11].

As above mentioned, due to the outbreak of COVID-19, it was not possible to run a laboratory study. In fact, users participated in this study remotely by filling out an online questionnaire. For this reason, the influence of users' devices (screen brightness, screen colour accuracy, screen size) was not taken into account.

Additionally, the user study involved only 36 participants, and more users should be involved to achieve more consistent results. The recolouring of virtual objects is performed in real-time. Nevertheless, no specific benchmarking tests were carried out to this end. Furthermore, the whole real image background was considered for the recolouring without taking into account the possibility to recolour virtual objects according to a local recolouring approach.

VII. CONCLUSION

The aim of the present paper was to propose a background-aware colourisation technique that sets the colours of the virtual objects in accordance with the real background. The choice of colours, in fact, is an important component for augmented reality applications, depending on the circumstances. In many cases, uncontrollable environmental conditions may alter users' perception of augmented information. As a consequence, the colours of the augmented models should always be set in relation to the real scenario in which these models are contextualized in order to improve their realism and visibility. Nevertheless, there are some exceptions in which it is not convenient to change the colour of the virtual models as it would also alter their meaning [28], [29], as in the case of digital replica of a real artifact in a museum, or when colours must satisfy and communicate some design requirements. On the contrary, in those situations in which the recolouring of virtual objects is not limited, it is necessary to investigate and provide different recolouring strategies to satisfy different needs in different settings. To this end, three different recolouring strategies, i.e. harmonic, disharmonic, and balanced, have been developed to achieve different goals. Furthermore, preliminary experiments have been conducted with experts to select the best colourisation solutions to use during the tests performed by users recruited among university students. Due to the outbreak of COVID-19, it was not possible to run a controlled user study. Therefore, online experimentation was carried out by considering three different case studies: an animated 3D dinosaur; a city map; and the famous painting *Birth of Venus* by Sandro Botticelli. From the analysis of the results, several conclusions can be drawn since the different contexts have made the difference.

Considering **H1**, it is not supported by the outcomes of the first two questions (Q1 and Q2) since no statistically significant differences can be observed. The results are particularly confusing when the colourisation has been applied to real environments with a wide range of colours (e.g. animated dinosaur in a public garden) where the presence of many colours does not allow for identifying what is harmonic and what is not with respect to the real background. Moreover, attractiveness and realism of virtual information should be given priority above harmony, depending on the user's tastes and on the goal of the AR application. However, further experimentation has been conducted in which saturation value has been also modified to evaluate its effects on user's perception. Although it has been observed that – as far as the users' perception of colours is not affected by the harmonic strategy saturation – this is not true for the disharmonic approach. In fact, colourisation solutions provided by the disharmonic approach were perceived by users as more disharmonious and unpleasant with very high saturation.

As for **H2**, the adoption of the disharmonic or the balanced approaches leads to recolouring solutions in which virtual objects are more distinguishable from the real background with respect to the harmonic strategy.

Furthermore, more interesting results have been obtained in the case of **H3** which is about the readability of augmented text. In fact, the results confirm that the text readability does not strictly depend on the hue channel if saturation and value are chosen appropriately.

In the future, a further investigation will be carried out with a larger number of participants, aiming at investigating the effects of colours on users' perception. Therefore, different application fields will be considered, and the experimentation will focus on the adoption of this colourisation technique also in industrial scenarios.

APPENDIX

FIGURE 14. Recolouring solutions used for the main experimentation with end-users: animated dinosaur (a, b, c, d), city map (e, f, g, h), painting (i, l,m, n).

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