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Computer-Aided Design AND APPLICATIONS

High-fidelity Rendering of Physical Colour References for Projected-based Spatial Augmented Reality Design Applications

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Abstract. Spatial Augmented Reality allows users to visualise information onto physical objects by projecting digital contents on them. Product design applications could profitably exploit this feature to create prototypes partially real and partially virtual (mixed prototypes) to be used for the evaluation of products during the development processes. A mixed prototype needs a high visual quality, because design decisions are taken on the base of its aspect, and projected colours should match the colour standards (e.g. Pantone, RAL, etc.) to be able to rely on the visualised colours. The current paper analyzes the effect of a colour calibration method, based on the iteration of comparison and compensation phases, onto the projected images using objective measurements and subjective users' evaluations. The procedure, whose effectiveness is verified thanks to the presented results, allows to replicate any colour available inside the projector gamut by simply using a physical sample.

Keywords: Colour fidelity; Spatial Augmented Reality; Product Design; Colour Calibration;
DOI: https://doi.org/10.14733/cadaps.2021.343-356

1 INTRODUCTION

Spatial Augmented Reality (SAR) augments users perception of real-world objects or scenes by projecting digital contents on their surfaces. This technology is able to overcome some of the technological and ergonomic limitations of conventional Augmented Reality (AR) systems because it does not involve the use of additional displays such as monitors, head-mounted displays or handheld devices [4]. Their hands and eyes free capabilities foster the team working allowing collaboration between users. In addition, SAR enables the perception of haptic information along with visual information; the awareness of the augmented object is increased by the passive tactile feedback provided by the use of a physical object for the projection [19].

Thanks to the advantages provided by SAR technique, interesting applications have been developed. They range over fields of different nature but they all exploit SAR natural interaction between the users and the digital content. *Illuminating Clay* [7], for example, uses a infrared camera coupled with SAR technologies to project digital contents onto a clay which can be deformed by the users to modify in real time the augmented images of a landscape scenario. A similar approach, but with a depth camera, is also used to scan a room in *RoomAlive* application [9]. After the computation of the room point clouds, the software is able to project digital graphics coherently with the real space, transforming the ambient into an interactive experience with touch interactions for the users. More related to the gaming field there is the application developed by the Disney research centre [25]: with *HideOut* they exploit mobile projectors to augment everyday objects like tables, walls, or books. It couples SAR technology with specially formulated infrared-absorbing markers, visible from a camera embedded in the projection device, but hidden from the human eyes. The use of markers as tracking system has been also investigated in *PapArt* Project [10] where SAR technologies enable physical drawings by projecting on a marked paper the information necessary to support artistic creations. The markers on the paper are tracked by the camera to guarantee that the image projected keeps the same location even if the paper is moved.

SAR technology is also profitably used in the product design field. It allows to augment physical objects by projecting digital contents on their surfaces with the possibility to change in real-time the design. Numerous applications of this type have been developed in the research domain or as a new product ready for the market. An example is the *WARP* (Workbench for Augmented Rapid Prototyping) system [23] which involves real-time projection on real prototypes with monochromatic white surface finishing or real products realized by 3D printing technologies. Since it also integrates a rendering software, textures and colours can be projected on the mapped physical object. *Vizera*, a commercial software created for costumers and dealers, allows real-time projection of colours, textures, graphics etc. on physical products, directly in the store, to make real-time changes of the design through a mobile device (tablet, smartphone). Moreover, the product is mapped with 3D scanning technique allowing the users to move it from its original position while the system is updating and adapting its projection to the new object location. *BuildMyKitchen* [11], instead, is an example of SAR systems that allow the user to interact directly with the augmented objects and to make the modification directly on them. In particular, it works with a room-sized model of the kitchen that can be modified in its materials, finishing of the surfaces and design chosen among some presets.

SAR applications applied in the product design sector can significantly speed up the creation process by reducing the number of iterations and the amount of real prototypes that need to be made before the definitive solution is determined [22]. On the other hand, such technologies need to be improved in their limitations by providing a high image quality for the digital content projected on the object surface: all the decisions regarding the task are made on the basis of what the designers visualize. For this reasons, the Mixed Prototype (MP), partially physical and partially virtual, must be realistic and show all the details that users need in order to take the proper decisions. Among the elements to consider for the realism of the MP, colours are the most critical in a projection-based system where the additive features of the device limits the available gamut [1]. The same colour, in fact, may vary if chosen from a standard code (e.g. Pantone, RAL or NCS), printed or displayed by different devices (e.g. monitors, projectors, etc.) due to the involved technology and its own calibration. As indicated by the colour standards producers, it is mandatory to refer to the physical colour set of standards to be sure of the actual hue, whether working on plastic, textile, paper, etc. An additional issue is connected to the high brightness of the image displayed by the projector that makes, from the user point of view, the MP not fully comparable with a real object.

Several researches have already studied how to dynamically adapt the projected images according with the finishing of the target objects or with the external factors that influence the light beam. The compensation methods are applied in different fields with the aim of creating digital contents whose colours appear uniform inside the whole projection area and with the rest of the surface. This is the case of [2, 26] where single or multiple light beams augment ancient and deteriorated objects or arts in order to rapidly visualize how they should originally appear and thus facilitating the restoration process. In [21] the colour correction was applied to compensate all the shadows and brights caused by the global illumination on a neutral target surface to simulate different lighting conditions. The current paper, instead, uses a colour calibration procedure inside a fully controlled environment (e.g. ambient light, surface material, virtual environment) with the aim of investigating how the user's perception of the augmented outputs changes when the projected colours are directly compared with physical references.

2 COLOUR CALIBRATION

As monitors, printers and all the other display devices, also projectors may experience distortions in the way they process the input image, resulting in a perceivable error of the output colours. Plug and play measurement instruments are already available on the market to evaluate and consequently improve the performance of the projector by considering their way of generating an image. These devices, belonging to the standard colours manufacturers, perform the calibration by displaying a path of colours and by simultaneously acquiring their luminance values. According to the data, then, a new colour profile is computed in order to change the modalities for processing the values of each colour channel of the input image. These evaluations can be performed by considering the properties of the physical environment in which the projection takes place with an influence on the results generated on the target surface (e.g. ambient lighting, surface incidence, etc.). On the other hand, these devices are affected by several drawbacks with high relevance in the design domain:

- the evaluation is restricted to a single colour standard;
- the comparison cannot be performed with respect to physical reproduction of the colours (e.g. when dealing with not fully calibrated printer);
- the results are not promising for those shades of colours that are not projected and evaluated during the calibration procedure;
- the brightness of the colours is not measured during the calibration.

For these reasons a colour calibration method based on iterative computations (Figure 1) has been developed to (i) acquire the colour projected on the target surface and its physical representation, (ii) compare the two inputs with the calculation of their differences in terms of lightness, chroma, hue and (iii) compensate the input image of the display device so that the accuracy of the projection is optimized according with the reference standard that has to be reproduced.

The colour calibration method here presented starts with the acquisition of two input images, i.e. the projected and the reference colours, by means of a standard reflex camera. The first iteration of the process sets the projector to display the same RGB values of the reference colour as they are established by the producers of the physical colour standards (e.g. Pantone, RAL (Reichsausschuss für Lieferbedingungen), NCS

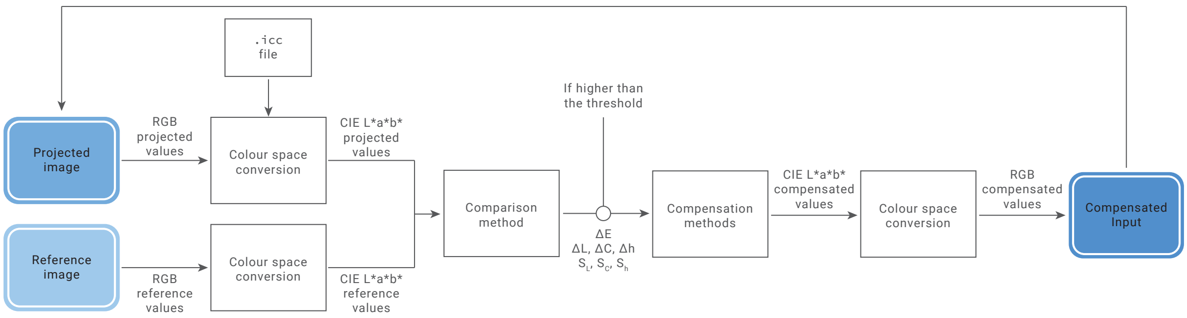

Figure 1: Schema representing the full calibration methods developed to compensate an input image of a projector according with the measured colour difference between the projected and the reference images.

(Natural Colour System), etc.). Calibrated and uncalibrated projector's profile can be equally used to direct the projection beam towards the target surface that should be placed to achieve the maximum light incidence and prepared with a white matte finishing. The mitigation of any undesired variation on the acquired images is achieved by manually controlling the camera's settings parameters that influence how the light is detected (i.e. manual white balance calibrated with a target chart, maximum focal length, spot metering mode, ISO 100, minimum size of the available lens aperture or focal ratio and fixed shutter speed to make neutral the exposure value) and by keeping them fixed during the whole process. The latter, in fact, allows to have identical approaches and configurations on both the acquisitions and thus to erase any systematic error thanks to the application of the colour difference formula. The biggest difference between the two acquisition conditions is related to the divergent brightness of the subjects. Because of the technology of projectors, in fact, the exposure value registered by the camera when acquiring a projected image is significantly greater than the one indicated for an object that is illuminated by the ambient light only. The problem is mitigated by illuminating the colour reference with a controlled white light of the projector in order to generate a lighting condition for the target real colour that is equal to the projected one. Furthermore, the use of physical colour samples rather than a monitor display during the comparative method, as done by Park et al. [17], allows to exclude the dependency of this calibration approach from the colour rendering capabilities of additional devices that, having a limited profile, are affected by a low reproducibility. This choice has relevant advantages especially when dealing with printed objects, such as cardboard or plastic packagings, where a colour sample made by the same printer used for the production can be directly involved for the comparison phase. In this way, it is possible to include any variation of the colour that are caused by a non perfect calibration of the printer [6] and to render a SAR prototype more similar to the one that will be obtained after the manufacturing process.

After the acquisition phase, image processing algorithms are used in order to (i) detect the two colour patches in interest to the comparison method, (ii) cut out the surroundings details and (iii) calculate the two means of the RGB values contained by each pixel of both the cropped images. The outputs given by the previous step, the measured RGB values, are firstly converted in the $CIE\ L^*a^*b^*$ colour space (where L^* is lightness, a^* and b^* are the colour expressed in the green-red and blue-yellow fields respectively [18]) and then evaluated by means of the $CIE\ \Delta E2000$ formula [20]. This formulation, selected since it takes into account also the human perception, gives as output the ΔE_{00}, a single value that displays all the differences between the colours and it is computed as:

$$\Delta E_{00} = \sqrt{\Delta L + \Delta C + \Delta h + M} \tag{1}$$

where ΔL, ΔC and Δh measure the differences between the 2 colours of their lightness, chroma and hue respectively calculated in the $CIE\ L^*C^*h^*$ colour space and weighted considering the perceptual uniformity issues, while M is a factor that deals with the problematic blue region (hue angles in the neighbourhood of $275°$). The transformation between the 2 different colour spaces takes into account also the novel colour profile of the projector that, if present, is contained inside the `.icc` file obtained after the calibration with professional instruments. This file, in fact, defines how the projector process a given colour by means of three descriptive curves and thus it is relevant to determine in advance which is the input signal necessary to obtain a certain output image. With the $\Delta E2000$ formula, a colour is acceptably closed to a given reference when its difference to the reference is lower than a Just Noticeable Difference (JND) constant threshold (or a function of the reference colour, varying according to its lightness). Similarly to previous relevant works in this field [12, 13, 14], this paper considers the JND threshold equal to 2.3. This choice is further supported by the chromaticity study presented by Baldevbhai and Anand [3], which states that values higher or equal to 4 of the difference ΔE_{00} are normally detectable by an average person, while those below 4 are visible by an experienced person only.

Upon completion of the comparison phase between the projected and the reference colours captured with the camera, the difference ΔE is obtained and, if higher than the JND threshold, is used for the colour compensation. This second step of the calibration method aims at reducing the difference between the 2 colours by moving the input of the projector in a different position of its chromaticity diagram that is able to increase the colour fidelity of the projection with respect to the target. The evaluation of this difference inside the $CIE\ L^*C^*h^*$ colour space, however, does not provide sufficient information to perform the input correction since each of the three components, i.e. lightness, chroma and hue, have to be considered separately inside the three-dimensional volume of the projector colour space. Moreover, despite the $CIE\ L^*C^*h^*$ has uniform hue and absolute ranges for lightness and chroma, which are useful for the comparison of two different colours, it presents dips in the chroma space that correspond to impossible colours. For this reason, the $CIE\ L^*a^*b^*$ colour space is used in this formulation for the generation of the compensated input due to its uniformity and absence of dips in its representation. Furthermore, thanks to the fact that in the $CIE\ L^*a^*b^*$ space the relative perceptual differences between any two colours can be approximated by treating each of the two as a point in a three-dimensional space and taking the Euclidean difference between them [24], the calculation can be processed linearly as:

$$L_C = L_S + \Delta L; \quad a_C = a_S + \Delta a; \quad b_C = b_S + \Delta b \tag{2}$$

where ΔL, Δa and Δb express the differences between the input and the projected colours for the lightness, colours in the green-red and blue-yellow fields respectively, as calculated by the comparison algorithm but weighted according to factors that consider the human perception; L_S, a_S and b_S indicate the three components inside the $CIE\ L^*a^*b^*$ colour space of the colour in input to the projector (derived from the reference standard, if during the first iteration, or from the compensated input calculated in the previous iteration, if during the subsequent ones); L_C, a_c and b_c are the three components inside the $CIE\ L^*a^*b^*$ colour space of the compensated colour to give as new input to the projector.

Once the compensated colour has been computed by the developed algorithm, it is finally converted into the RGB space before being used for the projection on the target surface. At this point it is possible to measure the quality of the achieved result by capturing an image of the novel projected colour and performing a second comparison with respect to the physical reference using the same modalities previously described. If the new

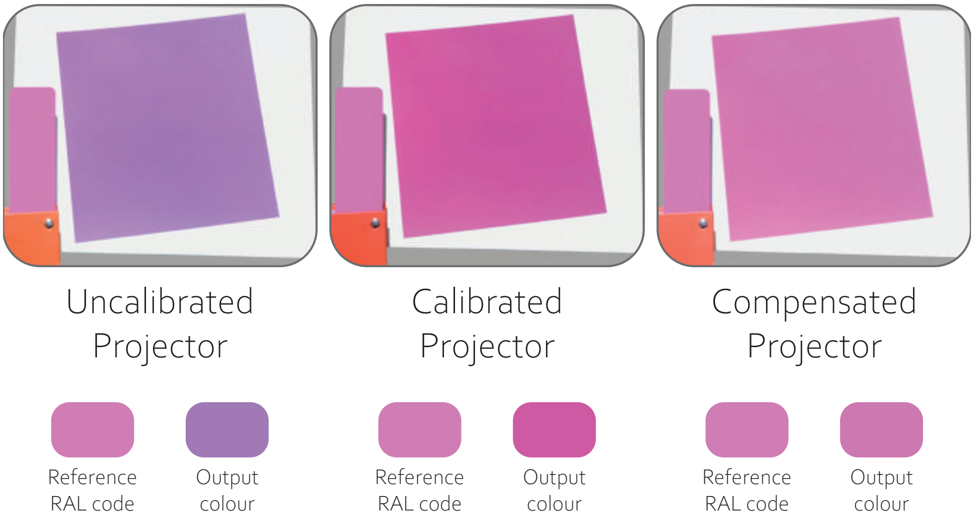

Figure 2: Projected images and comparison with the correspondent RAL reference during the three states of the colour calibration procedure: uncalibrated (left), calibrated (middle) and compensated (right) devices.

difference ΔE is higher than the threshold 2.3, a repetition of the full calibration is required where the only difference is related to the projected colour (now is the same obtained after the compensation). If the ΔE value is lower than the threshold, instead, the algorithm stops its iterations. Figure 2 perfectly summarizes the effect of the proposed colour calibration methods onto the projected image of a specific RAL colour (RAL 4003 with standard RGB input: 197,97,140 and compensated RGB input: 185,90,130): starting from the left side it is easy to notice the big difference of the two colours while using an uncalibrated projector (i.e. with all the factory default settings), the improvement introduced by a professional calibration devices despite a still noticeable difference and finally the high-quality result achieved by iterating the compensation algorithm here presented.

3 EVALUATIONS

The evaluation of the efficiency and effectiveness of the implemented colour calibration method is done with objective tests performed using the RAL standard and subjective evaluations involving the human sensitivity. The scope of the first activity is to quantitatively measure how much the compensated output matches the reference colours thanks to the improvements introduced with the calibration method. With the second, instead, it is established how much the user's perception of a projected image is distant from the compensated colours. Both the testing activities took place in a controlled environment where the illumination was done by artificial lights on the ceiling and by the natural sunlight entering the windows. The projector, mounted on a structure fixed on the ceiling, was a HITACHI CP-WU8600W with 3LCD technology (brightness = $6000\ ANSI\ lumens$ in normal mode and $4800\ ANSI\ lumens$ in eco mode, resolution = $1920 \times 1080\ pixels$, contrast = $10000 : 1$). The lens configuration (trow ratio = $2.8 - 4.9 : 1$) generated a projection area of $0.63\ m^2$ when the trow difference was around $3\ m$. The ambient light was equal to $330\ lx$ and it had been calculated in order to ensure the full repeatability of the experiment. The value, measured by a lightmeter placed at the centre of the working volume, had been considered due to its high influence in the colour accuracy of the projection (i.e. light distortions when is added on a surface).

3.1 OBJECTIVE EVALUATION: RAL TEST

For the RAL test, 3 patches for each of the 9 shades of colours identified by the classic RAL palette have been used as references to measure their differences ΔE with the projected images. The 27 RAL samples have been chosen among the ones that are inside the colour gamut of the projector used that, according to the ambient lighting, can achieve a minimum difference of $L_{min} = 27$.

The colours are projected on a smooth cardboard whose finishing is made uniform thanks to a matte spray paint with "pure white" RAL 9010 colour standard. The matte texture of the paint and the smoothness of the cardboard avoid problems of light reflection during the images acquisitions. The projection surface is placed perpendicularly to the light beam of the device to prevent the distortion of the pixels and thus obtaining a constant projected colour in the whole image area. The camera used for the acquisitions, a Nikon D3100, is placed fixed on a tripod in front of the projection surface and it is oriented perpendicularly to the cardboard. The shutter speed, the only parameter that vary according to the lightness of the colour shade to achieve a neutrally exposed image, is not changed between the acquisition of the reference and the correspondent projected colour to be able to make an accurate comparison.

The comparison and compensation methods have been subsequently applied on a projector whose colour profile was already calibrated by means of a commercial available device based on the Pantone standard. The results of this procedure, expressed as ΔE difference, are listed in Table 1 and illustrated in Figure 3 where they are also compared with the measurements of uncalibrated and calibrated images. These data, one for each of the three standards selected from the 9 RAL groups, are organized according to the type of input and calibration profile. By comparing the the green and blue dots, which are referred to acquisitions

RAL code	Standard input		Compensated input			RAL code	Standard input		Compensated input		
	ΔE_{cal}	$Col.$	ΔE_{com}	RGB_{com}	$Col.$		ΔE_{cal}	$Col.$	ΔE_{com}	RGB_{com}	$Col.$
1011	7.2		1.6	(149,121,87)		5024	4.5		2.3	(107,146,174)	
1012	6.4		2.1	(205,175,41)		6018	4.4		2.0	(87,143,77)	
1014	7.3		1.1	(200,188,154)		6021	6.1		1.5	(125,149,124)	
2009	4.2		2.1	(208,85,0)		6032	9.5		2.2	(47,116,91)	
2010	3.9		1.7	(185,89,47)		7008	11.9		2.3	(102,97,79)	
2012	4.3		1.6	(196,100,81)		7033	4.0		2.0	(124,132,124)	
3017	5.2		2.3	(190,94,104)		7038	4.5		1.5	(165,172,171)	
3018	5.0		1.4	(181,2,78)		8000	7.1		1.3	(121,104,76)	
3022	3.8		0.6	(196,105,85)		8012	8.0		1.8	(89,29,73)	
4001	9.3		1.4	(118,89,119)		8023	3.3		1.3	(154,83,5)	
4003	3.8		0.8	(185,90,130)		9001	6.0		1.5	(205,203,197)	
4010	3.2		1.2	(177,61,112)		9002	7.5		1.7	(190,190,194)	
5007	5.3		0.9	(66,100,133)		9018	5.0		1.4	(174,180,184)	
5014	6.8		1.5	(90,106,133)							

Table 1: List of the 27 RAL colours used for the test with information on: the difference ΔE calculated with respect to the standard input of a calibrated projector, the difference ΔE calculated with respect to the compensated colour (obtained after the application of the presented calibration method) and the RGB value of the colour given as input to the projector in order to obtain the desired reference.

from the not calibrated and calibrated projector profile respectively, it is evident the improvement introduced by the calibration device that not only significantly reduces the mean value of the measured ΔE but also increases the constancy to the differences leading to a more coherent projected image. However, the accuracy of the projected colours is never below the threshold value previously defined as Just Noticeable difference, nor when using an not calibrated projector ($\overline{\Delta E} = 9.0$, $\sigma = \pm 4.1$) neither with the calibration ($\overline{\Delta E} = 5.8$, $\sigma = \pm 2.3$). This means that the calibrated profile is not sufficient to make the accurate the colour rendering of the projection with respect to a specific target value. The red dots, instead, shows the results of each ΔE value obtained with the application of the proposed compensation method ($\overline{\Delta E} = 1.6$, $\sigma = \pm 0.5$). The lower dispersion of the values with respect to the first two setups demonstrates the relevant improvement introduced on the colour rendering capability of the projector. The output colours, always below the threshold limit, have been obtained by iterating the comparison and compensation methods multiple times to obtain a calculated ΔE difference below 2.3. However, no more than 3 repetitions were necessary: half of the selected colour required only one iteration before leaving the loop while for 4 sample out of 27 it was necessary to repeat the compensation process three times. The analysis of the initial difference ΔE for each colour group shows that only partially it is related with the number of necessary computations ($\overline{\Delta E}_{1\,iteration} = 3.2$, $\sigma_{1\,iteration} = \pm 1.8$; $\overline{\Delta E}_{2\,iterations} = 5.8$, $\sigma_{2\,iterations} = \pm 1.5$; $\overline{\Delta E}_{3\,iterations} = 8.2$, $\sigma_{3\,iterations} = \pm 3.2$). While the dispersion of the ΔE of the third group (3 iterations) is two times higher than the others, the initial standard deviations of the first and second iteration groups (1 iteration and 2 iterations) are very close from each other.

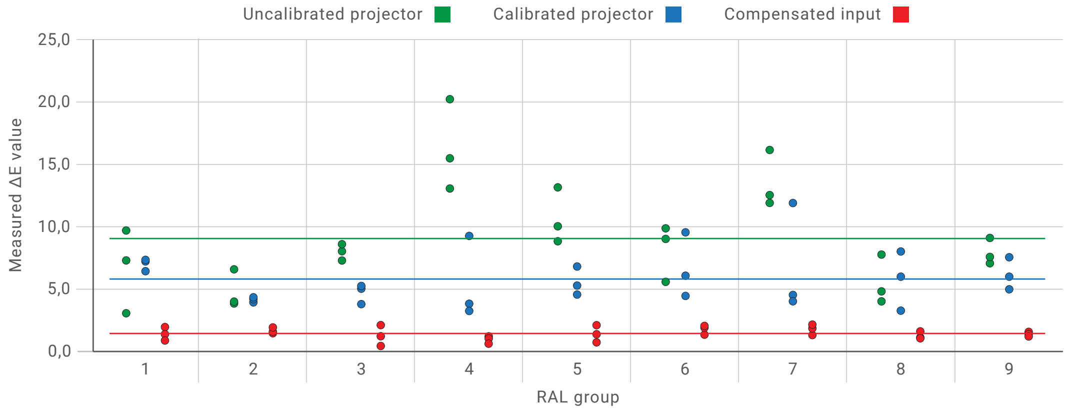

Figure 3: differences ΔE and their average calculated between the reference colours and the projected colours in the case of not calibrated projector (green data) and calibrated projector (blue data). The red data represent the differences ΔE and their average calculated between the colour projected with the compensated input and the colour reference.

3.2 SUBJECTIVE EVALUATION: USERS PERCEPTION TEST

The analysis of the human sensitivity when dealing with projected images is performed with a Spatial Augmented Reality (SAR) system named SPARK [15], which supports collaborative design activities for packaging or product. SPARK uses the projection to display directly onto a white 3D model the external finishing of a product, which can be modified in real-time thanks to a touch-screen interface. The generated MP combine the physical properties (e.g. dimension, shape, material), required for a complete design evaluation, with the digital contents to reduce the need of manufacturing each design solutions [16]. The effectiveness of the technology can be only ensured with an almost perfect coherence of the projected contents with the final output, nearly related with the colour rendering capability of the projectors.

28 students from the engineering and design departments, aged between 21 and 27 years old, were asked to replicate as accurate as possible, the the external layout of the packaging of a soup container using SPARK (Figure 4). Three versions of the same packaging have been designed and printed to obtain real-scaled mock-ups to be compared with the MP generated by the platform whose physical part is made by a white cardboard with the same finishing of the target surfaces previously described. The only parameter consider in this analysis is the users' selection of background colour, performed on a palette visible on the tablet interface, that has to match the one of the randomly assigned reference packs. The latter are chosen from the Pantone standard and are characterized by their orange, green and blue shades (Table 2). The graphical elements placed on the prototype surfaces are used to give a more realistic design context to the test activity and to not focus the user on a single application. Each participant, confident of the results achieved on the MP, were finally asked to confirm the task completion with a specific interface button in order to save the current configuration of the packaging included the RGB values of the background colours.

The digital part of the MP is rendered inside a virtual environment created by a game engine. Its settings are extremely important to ensure a "neutral" projection and to avoid external factors that may influence the colour selection. The position and type of light source, for instance, have been chosen to prevent the virtual ambient from influencing the colour shade, while its intensity has been defined according to the camera exposition, whose neutrality has to be ensured for both the illuminated physical target and the MP. The

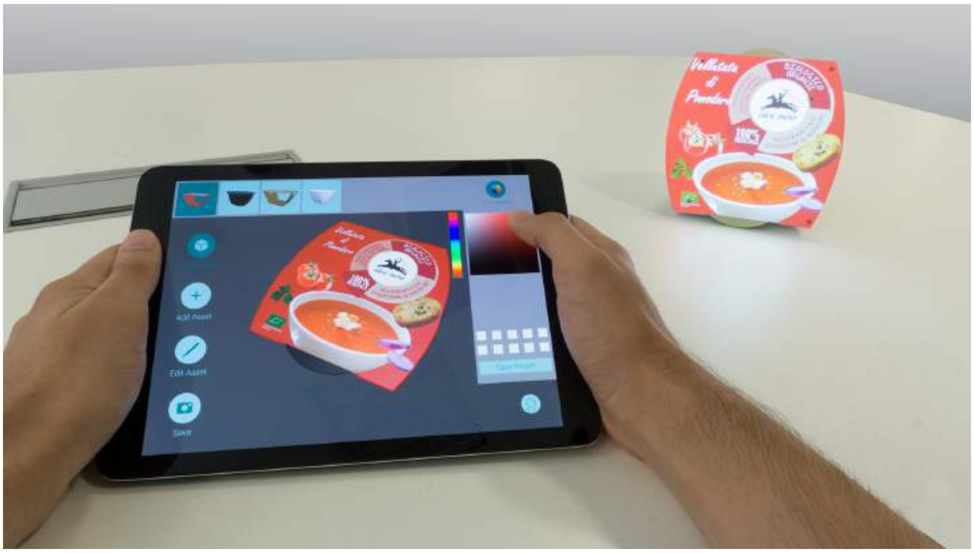

Figure 4: Interface of the SPARK application with the palette used by the users for the selection of the background colour of the mixed prototype

rendering material, instead, was determined in order to reproduce the visual effect of the ambient light on the surface of the paper model without causing reflections. The different brightness of the two prototypes, caused by the light beam used by the projector to display the digital contents, is the only effect that cannot be controlled without illuminating the references with artificial lights. Moreover, thanks to the use of a tracking system for detecting the placement and orientation of the physical prototype and to its known 3D shape, it has been possible to integrate computer graphic algorithms for adjusting the projected images according with the incidence of the light onto the target external surface. This approach based on shaders allows to obtain a mixed prototype whose colours are less influenced by external factors and thus with a more reliable rendering.

The measurements of the users' perceptions is made thanks to the difference ΔE between the selected colour and the compensated one, also decomposed in its lightness (ΔL), chroma (ΔC) and hue (Δh) components. The averages and standard deviations of the delta's modulus are illustrated in Figure 5 distinguished according to the colour base of the reference object (green, orange and blue) in order to consider the impact of different configurations on the user's perception. The most emerging information is the considerable lower

First input					**Compensated input**					**N of**
R	G	B	ΔE_{cal}	$Col.$	R	G	B	ΔE_{comp}	$Col.$	**iterations**
158	185	62	8.21		136	177	106	0.97		4
218	122	43	11.93		226	141	82	1.79		2
92	188	168	8.42		74	184	175	1.93		4

Table 2: RGB values of the standard and compensated input of the three colours used as reference during the user perception test. For each of them is also indicated the number of iterations required for the calculations of the compensated values and the relative differences ΔE.

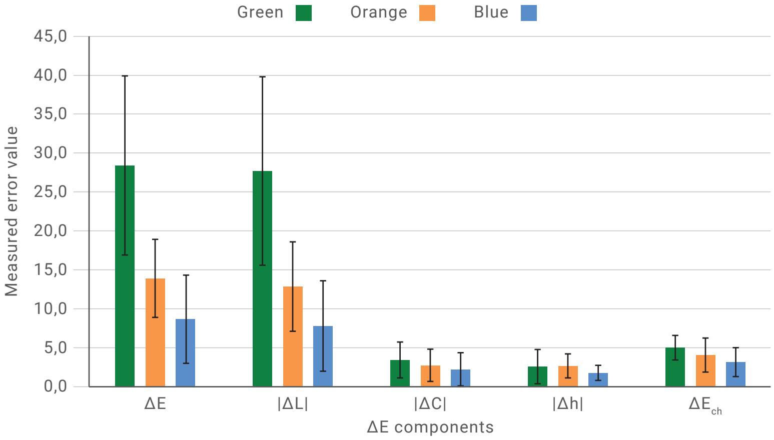

Figure 5: Averages and standard deviations of the deltas calculated (ΔE, ΔL, ΔC, Δh and ΔE_{ch}), and distinguished according to the colour base of the reference object (green, orange and blue).

value of the chroma and hue differences with respect to the lightness: the high brightness of the MP perceived by the users, expressed with the ΔL trend, is the main reason behind the high values obtained for the ΔE. This effect, being a consequence of the projector technology, can be mitigated by using a physical prototype material capable to absorb the light (as will be investigated in Section 3.3). By analysing the results within the same ΔE components, it emerges clearly that the mean values of ΔL (as well as the dispersion) are different according to the background colours. This trend allows to conclude that (i) the user's perception of the MP brightness varies according to the colour displayed and (ii) the sensitivity to the colour lightness cannot be considered equal among all the users working on the same reference prototype.

The latter values displayed in Figure 5 are the colour differences ΔE_{ch} that, by neglecting the lightness, consider only the hue and chroma components of the projected image with respect to the compensated one. This value, commonly used to calculate the closest available colour when dealing with projections outside the gamut [13, 14], is necessary to evaluate the users' sensitivity to the colour shade only. The low results obtained for all three references revealed, with some bias due to the different brightness between the two prototypes, the elevated colour perception of the participants. To evaluate whether the results of the ΔE_{ch} differences depend on the specific colour shade, the one-way ANOVA analysis [5] has been applied on the collected values, grouped on the basis of the reference colours. According to the significance level ($\alpha = 0.05$) and the degrees of freedom of the data set ($DoF_{num} = 2$ and $DoF_{den} = 25$), it is obtained a *p-value* higher than cut-off value for significance ($0.2039 > 0.05$) or a F value lower than the F_{crit} ($1.64 < 3.39$). By not rejecting the null hypothesis and thus by demonstrating the absence of a statistically significant difference between the three groups, the analysis reveals that user's sensitivity is not affected by the specific colour shade. The result becomes even more relevant if extended to the design activity where the improvements introduced by the colour calibration method are considerable for all the background colours of the packagings that are contained in the projector chromaticity diagram.

3.3 LIGHTNESS EVALUATION: GRAY-SCALE FINISHING TEST

As demonstrated in the previous section, the involved technologies create a MP with bright surfaces that reduce the human capability of comparing the results with respect to a reference colour illuminated by the ambient light only. In order to evaluate these aspects of the user perception, an additional testing activity has been performed in which the projection target surfaces are changed by applying different paints with matte finishing on equal smooth white card-boards. The test involves a white paint, the same used for the objective (Section 3.1) and subjective (Section 3.2) evaluations, and three paints in the shades of grey with different lightness (Table 3). The purpose of this evaluation is to control if the colour accuracy achieved applying the calibration method on a white surface is lost when using a different shades of achromatic grey.

The colour calibration method, however, needs to be applied on a white target surface to be able to correlate the lightness of the colours together with its chroma and hue. During the acquisition of the comparison phase, in fact, the projected the reference images can be correctly compared by illuminating the standard colour with the white light beam of the projector, in order to achieve a brightness condition equal to the one of the projection. When the image is displayed on a darker surface to have a low brightness, the compensated input results increased in its lightness component in order to bring the colour projected to the same brightness of the projection on a white surface.

	RAL code	**Name**	**Colour**	**LRV**	LM_{max} $[cd/m^2]$	LM_{min} $[cd/m^2]$	C
Paint 1	9010	Pure white		84	85.6	1719	1:20.1
Paint 2	9002	Grey white		66	63.0	1314	1:20.9
Paint 3	9006	White aluminum		45	47.9	992	1:20.7
Paint 4	7037	Dust grey		20	25.8	526	1:20.4

Table 3: Definition of the four paints used for the tests of the projection surfaces. For each of them is indicated the RAL code, the name, the Light Reflectance Value (LRV is a percentage of visible and usable light that is reflected from a surface when illuminated by a light source [8]), the maximum (LM_{max}) and minimum (LM_{min}) luminance values measured using the the calibration device with the related contrast (C).

With a similar ambient lighting configuration of the previous tests, the calibration device has been used to create a calibrated profile for each of the four finishes of the target surface. These profiles are then used in turn to acquire, using the camera setup of Section 3.1, 3 different input colours displayed on one of the projection surfaces. The four captured images are then used to compute the differences ΔE between the data obtained when profile and finishing are referred to the same paint and each of the other three measurements. The averages and standard deviations of these results are reported in Figure 6 (left) according to each color paint. Since the differences ΔE are always below the threshold, it can be stated that the application of different colour profiles does no affect the projection on surfaces with different finishing colours. Moreover, the luminance values measured by the device with a constant contrast of the image (Table 3) demonstrates that this approach maintains unchanged the colour gamut achievable by the projector.

The non-distortion of the colours projected on different materials and the lowering of their brightness is further tested by using the compensated input of the RAL colours computed in the test of Section 3.1. One colour for each of the 9 RAL groups is projected on the four target surfaces while the projector calibration profile is maintained to the one obtained with the paint 1. The camera, required during the acquisition, was used as a lightmeter where the shutter speed changed according to the exposure value in order to obtain a neutrally exposed image. The trend of the light value of each colour tested when changing the projection surface, indicated in the metadata of the related pictures, is illustrated in Figure 6 (right). It can be noticed that for every colour, the camera light exposition lowers with the lightness of the colour surface, proving the decreasing perceived brightness.

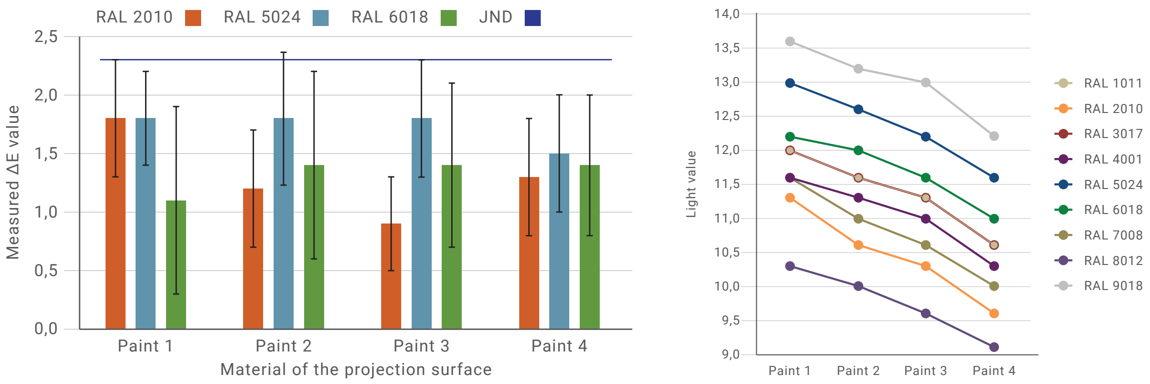

Figure 6: Results of the differences ΔE (left) and light value (right) belonging to the specific colour paint used for the projection surface during the acquisition of the materials test.

4 CONCLUSIONS

Specifications and technologies of the projection device utilized in SAR applications are important factors that influence the quality of the projection. However, the realism of colour renderings is not only influenced by the choice of a specific device, but also by the ambient in which the projection takes place, by the features of the objects involved, by the virtual scene describing the application and by the human's perception.

By using a colour calibration method that optimizes the accuracy of the projection according to a physical reference is improved the rendering capability of the SAR application. The method, in fact, acquires the projected and the reference colours, which is illuminated by the white projector light, to enable a direct comparison of the three colour components (lightness, chroma and hue). Then, the calculated mismatch is used to compute a compensated input that allows the projector to display a more accurate colour.

The experimental results successfully demonstrate that the proposed calibration method increases the accuracy of the projection since a colour difference, between real and projected, is lower than the minimum noticeable value used as threshold. Thanks to this, it is possible to use projected images with the compensated input in professional environment with a significant level of confidence regarding the realism of the colour rendering. The effectiveness of the proposed method has been further assessed through a testing activity carried out with users. Colours selected by the users, who were invited to replicate a reference colour in a SAR environment, confirmed the improvement of the colour accuracy thanks to the calibration method but underline the issue related to the higher brightness of projected colours. Their selections, in fact,were considerably closer to the values obtained after the compensation rather than to the ones coming from the standards. The aspect related to the perceived brightness of the projection has been also addressed by analyzing the behaviour of colours when displayed on surfaces painted with different shades of grey. As the projection surface gets darker, in fact, the brightness of the image displayed by the projector lowers making the image more realistic and closer to the real reference object. Moreover, from the tests conducted, it can be stated that only the perceived brightness changes when the different surfaces are neutral while the values of the colour perceived are unaltered.

In conclusion, the use of colour calibration methods is important to effectively improve the realism and the reliability of projected colours of product design applications based on SAR technologies. Using these methods it is possible to create a colour palette based on real standard colours that can be used, during design sessions, to make simpler the users' decisions related to the final colour finishing of a product.

ACKNOWLEDGEMENTS

The work reported in this paper is part of the SPARK project, funded by the European Unions Horizon 2020 research and innovation programme under grant agreement No. 688417. This paper reflects only the authors' views and the European Commission is not responsible for any use that may be made of the information it contains. The authors would like to thank Alice Colombo, Iacopo Carli and all the partners of the SPARK Consortium for the extensive support and valuable contribution provided in the development of this activity.

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