Evaluating the Use of the Perceptual Reference Medium Gamut in ICC Printing Workflows

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Abstract

The International Color Consortium (ICC) specifies a standard profile format and associated color management architecture. In the version 4 of its specifications, it adopted a Perceptual Reference Medium and an associated gamut (PRMG) for perceptual workflows. The goals of this change were improved interoperability and more pleasing results. In this paper we start evaluating the effect of using of the PRMG on the quality of printed images. A series of psychophysical experiments were conducted with a large set of sRGB images. A small number of expert observers found that they tended to prefer the quality of prints obtained via a v4 workflow when printing with a printing system having a medium sized gamut. However, when printing with a system having a gamut similar to the PRMG, they did not find any significant preference. They also found that the use of v4 led to a better consistency of the rendering of the prints when using two printing systems with different gamuts. None of the algorithms were strongly preferred by the observers of a larger panel.

Introduction

The International Color Consortium (ICC) framework is widely used in color management workflows [1, 2]. The underlying architecture is based around a reference color space (the Profile Connection Space or PCS) and profiles which embody color transforms that convert between device encodings and this reference colorimetry. A Color Management Module (CMM) provides the mathematical engine to perform the profile-to-profile transformations, allowing input and output transforms to be paired arbitrarily at run time even though they are created independently. ICC profiles incorporate color rendering and re-rendering algorithms, expressed as rendering intents. Four color rendering intents are specified by the ICC: absolute colorimetric, media-relative colorimetric, perceptual and saturation [1]. Each one represents a different color reproduction goal. The profile creator has the responsibility to select appropriate color rendering algorithms for each of the intents.

In this paper, we focus on the perceptual rendering intent. The goal of this intent is to produce a pleasing reproduction of an original on a destination output medium, compensating for differences in viewing conditions and gamuts between source and reproduction. It is also called preferred reproduction: “It aims to maximize the correspondence of the reproduction with preconceived ideas of how a given image should look according to an individual whereby this criterion encompassed contrast, the lack of artifacts, sharpness, etc. ” [3] The perceptual intent is useful for general reproduction of pictorial images, when the input and output media are substantially different and it is not required to exactly maintain image colorimetry. In a perceptual workflow, the image is re-rendered from the source encoding to the PCS by the source profile perceptual intent transform and re-rendered from the PCS to the destination encoding by the destination profile perceptual intent, changing the appearance of the image content, as necessary to produce a pleasing reproduction for the output medium [4]. The ICC profile format has undergone continued evolution since its first publication, and a number of recent developments have made significant improvements to the range of workflows supported and removed considerable ambiguity from the specification [5].

One such development was the specification of a reference color gamut, the *Perceptual Reference Medium Gamut* (PRMG) adopted in 2005 in the first amendment to the version 4 of the ICC specifications (v4). It was defined as an unambiguous reference gamut to render, or re-render, to and from [1,6]. The shape of the PRMG is similar to that of a gamut of a printing system, thus quite different in shape from a reference display gamut. Hence the rendering embedded in an RGB source profile can be quite complex. Koh et al. have created an sRGB v4 profile embedding a perceptual rendering transform from the sRGB to the PRMG [7]. Since in a v4 perceptual workflow the image is rendered or re-rendered to the reference gamut, the re-rendering in a v4 output profile perceptual intent should in principle be less complex than in a v2 profile [7]. The ICC expects more pleasing results for most images when combined with any correctly constructed v4 output profile using the perceptual rendering intent [8]. Furthermore, final images printed on different devices should be very similar since “they all tap the same input-side re-rendering”. The goal of this paper is to evaluate the consequences of the use of the PRMG, in an ICC perceptual workflow, on the quality of the printed images. The aim of the perceptual intent is to produce pleasing reproductions, and therefore the quality of this transform is evaluated by asking observers to judge the reproduction of pictorial images in a psychophysical experiment [3].

In this paper we briefly discuss the use of the PRMG in perceptual intent workflows together with the different aspects of the present evaluation. We then present the results of several psychophysical experiments and discuss the future work required to complete the evaluation.

Perceptual Intent and PRMG

The Perceptual Reference Medium Gamut [6] includes the great majority of surface colors that might be encountered in color reproduction. The reference medium has white and black points having a neutral reflectance of 89 %, and 0.3% respectively. The maximum C*ab chroma values of the reference gamut at a range of different L* lightnesses are specified in ISO 12640-3 [6].

The PRMG was incorporated in the v4 of the ICC specification in 2005, with a means to identify whether the PRMG was used through the rig0 tag. The adoption of the PRMG is still not widespread. On the input side, an sRGB v4 preference profile [7–9] and a ROMM RGB v4 profile [10] are available on the ICC website [11]. Unfortunately for professional photographers, no v4 profile for the widely-used Adobe RGB (1998) encoding is available yet [12]. On the output side, while several vendors have internally implemented profile-making tools that use the PRMG in perceptual transforms, currently there seems to be no available commercial application explicitly using the PRMG.

Perceptual Intent: V2 versus V4

There are several significant differences between the v2 and the v4 perceptual intent workflows. In a v2 workflow, the input transform rendering intent is ambiguous since in a v2 input profile only a single rendering intent is required. This intent is nominally perceptual, with the goal of producing "the CIE colorimetry which will produce the desired color appearance if rendered on a reference imaging media and viewed in a reference viewing environment. This reference corresponds to an ideal reflection print viewed in an ANSI standard viewing booth." [13]. In practice v2 input profiles often incorporate minimal rendering to the ICC PCS and are closer to a colorimetric rendering. Most of the re-rendering thus has to be performed by the output profile. Therefore the quality of a v2 workflow depends to a considerable extent on the color transform of the output profile. Two key issues are, first that the output profile does not have a defined gamut to re-render from (and therefore the profile maker has to select an arbitrary one within the PCS), and second that multiple output profiles needed for all the printing systems settings and media combinations might be complex to build and therefore require significant resources. Because the source gamut is unknown when the destination profile is created, the quality of the output profile perceptual intent also depends on the nominal gamut which the transform renders from, and the difference between this and the actual gamut of the source medium.

In a v4 perceptual workflow, the Perceptual Reference Medium Gamut is used as an intermediate gamut to render to and from: first the input transform re-renders the image color data from the input color space (e.g. sRGB) to the PRMG. Then the output transform re-renders the image color data from the PRMG to the output color space (e.g. CMYK). While building elaborated input profiles require resources, the multiple output profiles are expected to be easier to build by the ICC: "Simple media white and black scaling can accommodate differences in dynamic range between an original and a reproduction and (to some extent) differences in color gamut size. In cases where color gamut shapes are roughly similar, and gamut size differences correlate with white and black point differences, media-relative colorimetric plus black point compensation may produce excellent perceptual rendering" [14], see also [15, 16]. Therefore the quality of a v4 perceptual workflow has a strong dependence on the perceptual intent of the input profile.

Perceptual Rendering Intent Transforms

The exact content of ICC rendering transforms is not defined, it is vendor specific as Koh et al. explain: "State-of-the-art color re-rendering algorithms are closely guarded trade secrets [...] Also, in some cases, the color re-rendering transforms produced by the proprietary algorithms are manually optimized (tweaked). Such optimizations can be included in profiles" [7]. A perceptual re-rendering transform of a typical v4 input profile involves:

- Adjustment of the colorimetry to compensate for differences in viewing conditions between the source medium and the ICC Perceptual PCS.
- Warping of the primaries of the input gamut to those of the PRMG to achieve 'unpolluted' reproduction of the primaries, especially in halftoning-based printing technologies, and to maximize the available gamut for the reproduction.
- Local expansion or contraction of the modified input gamut to compensate for differences in gamut shape.
- Overall gamut mapping of the modified input gamut to fit within the boundary of the PRMG.

This re-rendering transform will be incorporated into the AToB (device encoding-to-PCS) intent. An input profile may optionally include a BToA (PCS-to-device encoding) intent which represents the inverse of the above transform.

On the output side, the degree of complexity of the output transform needed depends on the degree of the difference between the PRMG and the output profile [14]. A perceptual re-rendering transform of a v4 output profile will involve the same operations as an input profile, and both BToA and its inverse AToB transforms are required. When the viewing conditions and destination gamuts are similar to those of the ICC perceptual PCS, some of these re-rendering steps may be omitted.

Evaluation

Several aspects of the use of the PRMG in ICC workflows need to be evaluated. Since transforms are vendor specific, a comprehensive assessment should include input and output perceptual transforms provided by a number of different vendors. Given that v4 profiles are not yet ubiquitous, actual workflows include those which have either v2 or v4 profiles on both input and output sides of the transform, and also those where there is a mix of v2 and v4 profiles. As far as possible these different combinations should be evaluated where they reflect actual workflows. In this paper, we evaluate several v4 and v2 workflows using typical perceptual transforms.

On the input profile side, the quality of the perceptual transforms need to be assessed. In the case of sRGB, the evaluation can be done be comparing images rendered to sRGB on an sRGB monitor, against the result of the re-rendering to the PRMG. On the output profile side, the evaluation can be performed by comparing printed images obtained with different printing systems, using both v4 and v2 perceptual workflows.

Among the preference criteria for printed images, the following have been proposed in the literature: contrast, saturation, detail rendition in highlight and shadow areas [3], overall print quality, color rendition, colorfulness, naturalness, sharpness, contrast, color shift [17]. The ICC has not provided any standard method for the profile assessment, yet several previous studies of the quality of ICC profiles have been published: Büring et al. compare different profile making tools using one printing system in a paired comparison experiments by ten observers, followed by statistical evaluation, to rank the appearance and pleasantness of the reproductions [18]. Norberg et al. used a nine-point category scaling experiment with several quality attributes [17]. Koh et al. encouraged experiments focused on the perceptual transform of the sRGB v4 profile. They started by comparing the sRGB v2 and v4 profiles and found the visible advantages in the v4 output images, with a perceptually more accurate reproduction of the blue of the sky, smoother transitions from black to dark blue in the sky, and more pleasing and natural reproduction of skin tones, foliage and fruits.

In this paper, two experimental phases were carried out. In the first phase, two expert observers compared sRGB images on a reference sRGB monitor, an EIZO ColorEdge CG221 carefully calibrated to display the sRGB gamut, with the images re-rendered using v2 and v4 workows and printed with two significantly different printing systems. Although the small number of observers in the expert phase does not permit statistically valid conclusions to be drawn, our experience has been that the judgements of very experienced assessors of color images provide a valuable initial insight into rendering quality. In the second phase of these experiments, a series of category judgement experiments were performed in which observers scaled the quality of the resulting prints.

Experimental Setup

Images

The transformations produced by a preferred-reproduction model are generally dependent on the characteristics of the original scene and the output media [19]. Holm recommends the use of a broad range of “natural images” as well as test charts to reveal the quality of a perceptual transform [20]. The CIE suggests to include the following test image types to evaluate color rendering: high-key, low-key, low lightness contrast, flesh tones, leaves and sky, no neutrals, no white point, no black point, heavy cast, few hues, business graphic [3]. These suggestions are intended to provide a range of typical image content that includes some of the subject matter that has often required manual adjustment of color reproduction parameters. Büring et al. propose natural images, containing pastels as well as saturated colors [18]. Among the test charts proposed, an “sRGB gradient image containing the surfaces of an sRGB cube” is proposed by Koh et al. [7], while “L*a*b* slices” are proposed by Büring et al. [18]. Tastl propose to also include acceptable but not great images (containing noise, or adapted to the wrong white balance) to test the robustness of the transforms.

A total of 55 sRGB images were used in this study (see Figure 1): 7 images from the ISO 12640-2:2004 [21], 2 images from the CIE Guidelines [3], 2 test charts and 44 images captured by the authors. The test images were chosen to form an heterogenous set as complete as possible, based on the following criteria: low, medium and high levels of lightness; low, medium and high levels of saturation; low, medium and high contrast; large areas of the hue primaries; fine details; memory colors as skin tones, grass and sky blue; color transitions; neutral gray. Most of the images are pictorial with a wide range of scenes, such as landscapes, portraits and manufactured items (such as jewelry, books and clothes). Images were printed at a resolution of 150 pixels per inch and a size of approximately 8 by 10 inches.

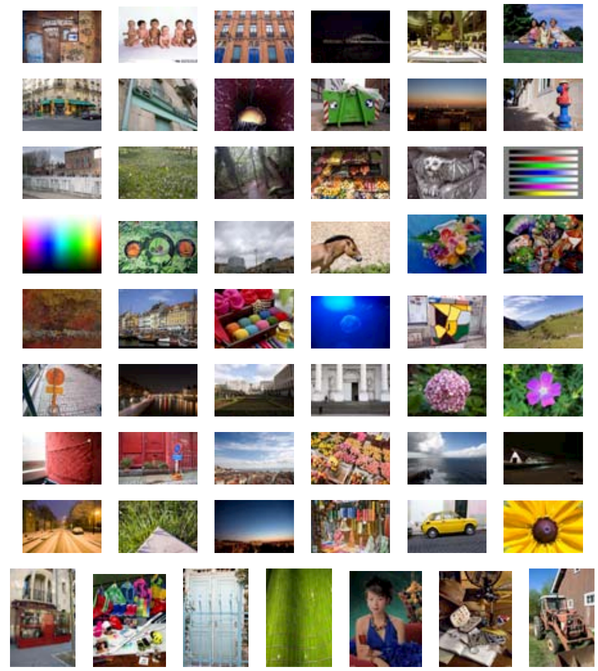

Figure 1. *Set of 55 sRGB images used in our experiments.*

Printing Systems

We first selected the Epson R800 printer and Epson Premium Glossy Photo Paper, that has a large gamut very similar to the PRMG. For this printer, the quality of the reproduction obtained in the v4 workflow depends mainly on the input transform. We also selected the Océ ColorWave 600 CMYK printer with standard uncoated paper, its gamut is significantly smaller than the PRMG. Therefore the quality of the reproduction obtained in the v4 workflow depends both on the input and the output transforms.

Color Workflows

Eight different ICC workflows were included in this study, four V2 and four V4. On the input side, the set of images was converted to the PCS using either the v2 or v4 sRGB profiles. On the output side of the ICC workflow, the image was re-rendered from the PCS to the gamuts and color encoding of the printing systems using either the perceptual intent of v2 or v4 profiles built using the following profiling solutions:

1. Océ Basic re-rendering: linear lightness scaling in CIE XYZ + the Hue Preserving Minimum ΔE clipping gamut mapping algorithm in CIELAB [3],
2. Gretag MacBeth Profile Maker 5.0.7 (Colorful),
3. Gretag MacBeth Profile Maker 5.0.7 (Chroma plus),
4. Onyx PosterShop 7 Media Creator.

Gretag MacBeth Profile Maker 5.0.7 and Onyx Media Creator generate v4 profiles, yet they do not explicitly use the PRMG in the perceptual intent. Nevertheless they are included here in order to broaden the experiment to existing v4 profiling solutions.

Phase 1: Expert Judgements

In this phase two expert observers evaluated the complete set of 55 images. One v2 and one v4 workflow were selected: the v2 workflow is composed of the v2 srgb profile and the v2 Gretag MacBeth Profile Maker 5.0.7 (colorful) output profiles. The v4 workflow is composed of the v4 srgb profile and the v4 Océ basic re-rendering output profiles. The printed images were presented in a controlled viewing room at a color temperature of 5200 Kelvins, a illuminance level of 450 lux ± 75 and color rendering index of 96. The two expert observers viewed simultaneously the reference image on the monitor and the printed images from a distance of approximately 60 cm.

Experiment 1.1: Comparing V2 and V4 with a Large Gamut Printing System

In this experiment, the output of two v2 and v4 workflows printed using the Epson R800 printer and Epson Premium Glossy Photo Paper were evaluated by the two expert observers. Their task was, for each image, to choose a preferred reproduction and then to describe the properties of the two reproductions.

	v2	v4	none
Expert 1	22	17	16
Expert 2	23	23	9
Intersection	15	11	4

Experiment 1.1: number of images for which the v2 print, the v4 print or none was preferred by each expert observer.

While differences were noticed between the printed images from the two workflows, overall the observers found the outputs of the two workflows to be on the same level of quality, they did not find any significant quality advantage to none of the workflows (see table above). When considering the intersection, the number of images for which the two experts agreed, we also notice that they had the same preference for only around half of the image set. This tends to indicate that the choice was not easy to make. The expert observers noted that v4 outputs presented the following changes of characteristics compared to v2 outputs:

- overall a better preserved contrast and saturation,
- better rendering of details in saturated green and red areas,
- blues shifted to dark and saturated blues, sometimes inducing a loss of details,
- yellow shifted to orange, sometimes leading to unpleasant results,
- significant artifacts in color gradients.

While these changes were constantly found across the image set, for some images it was considered as an improvement, for others as a degradation, and for the remaining as not changing the level of quality. Thus they only partially agreed with Koh et al.. Notice that these changes, dues to the differences in rendering transforms, might not be directly related to the use of the PRMG. In order to focus on the use of the PRMG, one should have attempted to implement equivalent transforms in v2 and v4, quite a difficult task. Thus these results mainly show that the available v2 and v4 profiles for our experimental setup achieve the same level of quality, according to the two expert observers.

Experiment 1.2: Comparing V2 and V4 with a Medium Gamut Printing System

In this experiment, the output of the two v2 and v4 workflows, printed using the CMYK Océ ColorWave 600 with standard uncoated paper, were evaluated by the two expert observers. Their task was, for each image, to choose a preferred reproduction and then to describe the properties of the two reproductions.

Differences were noticed between the printed images from the two workflows, and overall the two observers tended to prefer the output of the v4 workflow (see table below). The intersection shows that two observers had the same preference for more images, the choice might have been less ambiguous.

	v2	v4	none
Expert 1	19	31	5
Expert 2	19	34	2
Intersection	17	31	1

Experiment 1.2: number of images for which the v2 print, the v4 print or none was preferred by each expert observer.

When evaluating the printed images, the two experts observers found the outputs of the two workflows to differ more than in the previous experiment. They found that most of the v4 outputs presented characteristics similar to those described in Experiment 1, including more contrast and saturation, shifts of blues and yellows, significant artifacts in gradients. Overall, the v2 images lacked significantly of contrast and saturation compared to the v4. This might be the origin of the difference of preference between v2 and v4. We then consider the intersection between experiments 1.1 and 1.2, i.e. the number of images for which each expert observer had the same preference of workflow for the two experiments. Interestingly, the intersection is only partial: 9 images in v2 and 11 in v4 for the expert 1, 13 in v2 and 17 in v4 for the expert 2, showing that the preference for a given observer varies significantly with the printing system .

Experiment 1.3: Comparison of the V2 and V4 Consistencies

In this experiment we assessed the consistency of the perceptual transform of the v2 and v4 workflows for the two printing systems used in the two previous experiments. The experts compared the sRGB images on the reference sRGB monitor with the two couples of printed images. Their task was to select the couple with the best constancy (see table below).

	v2	v4	none
Expert 1	10	28	17
Expert 2	15	29	11
Intersection	9	21	0

Experiment 1.3: number of original images for which the v2 consistency, the v4 consistency or none was preferred by each expert observer.

The two experts found that overall the outputs of the v4 workflow presented similar characteristics, when the outputs of the v2 workflow presented more variation, mainly in contrast and saturation. The rendering of the v4 workflow was overall more consistent when using different printing systems than the v2.

Phase 2: Preference Experiments

Experimental Setup

A series of six psychophysical experiments was performed on a subset of the images printed with the Océ ColorWave 600. Both category judgement and paired comparison experiments were performed. The experiments A-E were carried out by MSc students at LCC, the experiment F was carried by Nicolas Cardin at Océ Paris, in a nominally ISO 3664 P2 viewing condition, using four different viewing booths fitted with D50 simulating lamps and with an average illuminance in the viewing area of 2000 lux +/- 125 lux for each booth. The smaller booths exhibited relatively poor uniformity over the viewing area. The numbers of test images and observers in the six experiments are summarized below:

	Experiment type	Obs	Images	Algos
A	Category judgement	15	6	8
B	Category judgement	15	5	8
C	Category judgement	15	3	7
D	Paired comparison	12	6	5
E	Paired comparison	12	5	5
F	Category judgement	30	15	8

Phase 2: Summary of psychophysical experiments.

The experiments were intended to determine rendering preferences only, and so no original or anchor image was on view. In the experiments A and B, observers were asked to scale each print in turn, using a five-point category scale from bad to excellent. In experiment C each print was judged on three separate occasions by each observer and the average of the three judgements recorded. Prints made by three different algorithms were on view at each judgement, and observers used a five-point category scale from bad to excellent. In experiments D and E, prints were presented pair-wise and observers were asked to state which they preferred. In the experiment F, observers were asked to scale the height prints simultaneously, using a three-point category scale: less pleasant, average, more pleasant.

Results

In the A-C category judgement experiments it was not possible to ensure that the categories used were equal-appearing across all three experiments, and so equal-interval scaling was not considered appropriate. For each image, the average category value was calculated for each algorithm, where numbers 1-5 were assigned to the bad-to-excellent scale. To provide relative scale values, and a basis for comparison with the results from the paired comparison experiments, the category values given to each algorithm for a given image were offset by the average category value for the image. This has the effect of centering the category values on zero. The results obtained by this analysis were similar, but not identical, to those obtained by an equal-appearing interval analysis using Torgersons Law of Category Judgement. An average category value for each algorithm was calculated by taking the mean of the category value for each of the 14 images, shown in table below. Confidence intervals for the results for each image were calculated as $CI_{95} = \pm 1.96 \frac{\sigma}{\sqrt{n}}$, where n is the number of observers and σ is the standard deviation of the observations for that image. The confidence intervals for each image ranged from 0.10 to 0.47, with an average of 0.22. From this it can be seen that the

Algorithm	V2	V4	Var v2	Var v4
Océ Basic	0.09	-0.07	0.11	0.07
PM Colorful	0.10	0.04	0.08	0.15
PM Chroma Plus	0.14	0.02	0.08	0.09
Onyx	-0.24	-0.18	-0.30	0.19

Phase 2: Combined results and variances for category judgement experiments A-C.

differences between v2 and v4 algorithms is not significant at the 95% confidence level. The paired comparison data was analyzed according to Thurstones Law of Comparative Judgement. The z-scores for each algorithm were averaged as above to give a mean score for each algorithm across the 11 images assessed. These are shown in table below. There was some variation between scores for the same algorithm between different images, implying a degree of image-dependence in the results. A summary of the score variance is also given in table above.

Algorithm	V2	V4
Océ Basic	0	-0.06
PM Colorful	0.27	0.34
PM Chroma Plus	0.14	0.06
Onyx	-0.03	-0.39

Phase 2: Combined results for category judgement experiments D-E.

Confidence intervals for the paired comparison experiments D-E were calculated, giving intervals of 0.4 for each image and an interval for the combined data shown in table above of 0.16. Differences between v2 and v4 workflows cannot be considered significant at the 95% confidence interval for algorithms A-D. The magnitude of variances between v2 and v4 workflows are similar, with the v4 workflows having on average smaller variances implying slightly less image-dependence in the results. Z-scores were computed from the results of experiment F [22–24], they are shown in table below and Figure 2. Overall the results are similar for v4 and v2 workflows, overall there were no algorithms which were strongly preferred by the observers. Partial v4 workflows, in which the output profile may make a PRMG-like assumption of the source gamut but does not actually use the PRMG, perform as well as v2 workflows, and it could be expected that where the PRMG is used on both source and destination side, more consistently preferred images would be obtained.

Algorithm	V2	V4
Océ Basic	-0.0666	-0.0962
PM Colorful	-0.0260	-0.1323
PM Chroma Plus	0.0097	-0.0136
Onyx	0.1193	0.2057

Phase 2: Z-scores for category judgement experiment F.

Conclusions

The phase 1 *Expert Judgments* shows interesting results: while the v2 and v4 workflows produced different images, the quality achieved was overall at the same level. In the experiment 1.2, the experts found that the v4 workflow presented qualitative advantage when using a medium gamut printer. The output side

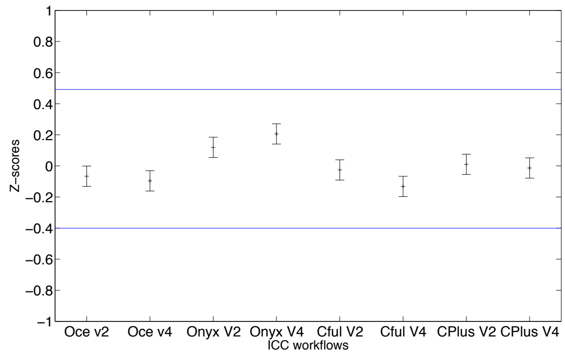

Figure 2. *Z-scores resulting of experiment F, average over 15 images and 30 observers.*

re-rendering applied in this experiment is a simple baseline re-rendering transform. As such re-rendering is sufficient to achieve consistency and good quality, the v4 output profiles might indeed be easier to build. The experiment 1.3 showed that a higher consistency was achieved by the v4 workflow than the v2 workflow. Since the re-rendering in v4 is embedded in the input profile, by using v4 instead of v2 the user is trading the control that it might have over the construction of the color transform for the better reliability induced by using the same re-rendering in multiple printer scenarios. The results of the phase 2 *Preference Experiments* indicate that none of the algorithms were strongly preferred by the observers. The difference between v2 and v4 workflows was not statistically significant at the 95% confidence interval and in general was smaller than the differences between the workflows. Future work includes experimenting the use of the ROMM v4 input profile, testing more elaborated v4 output profiles and v4 workflows involving a "smart" CMM [25].

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