Scoping review on automatic color equalization algorithm

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Abstract. Digital image processing is at the base of everyday applications aiding humans in several fields, such as underwater monitoring, analysis of cultural heritage drawings, and medical imaging for computer-aided diagnosis. The starting point of all such application regards the image enhancement step. A desirable image enhancement step should simultaneously standardize the illumination in the image set, possibly removing bad or not-uniform illumination effects, and reveal all hidden details. In 2002, a successful perceptual image enhancement model, the automatic color equalization (ACE) algorithm, was proposed, which mimics the color and contrast adjustment of the human visual system (HVS). Given its widespread usage, its correlation with the HVS, and since it is easily implementable, we propose a scoping review to identify and classify the available evidence on ACE, starting from the papers citing the two funding papers on the algorithm. The aim of this work is the identification of what extent and in which ways ACE may have influenced the research in the color imaging field. Thanks to an accurate process of papers tagging, classification, and validation, we provide an overview of the main application domains in which ACE was successfully used and of the different ways in which this algorithm was implemented, modified, used, or compared. © *2021 SPIE and IS&T* [DOI: 10.1117/1.JEI.30.2.020901]

Keywords: automatic color equalization; digital image processing; human visual system; scoping review.

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1 Introduction

The starting point of this scoping review is the automatic color equalization (ACE) algorithm.[1–3] This algorithm is part of the spatial color algorithms (SCA) family,[4] a group of algorithms that mimic the human visual system (HVS), enhancing contrast and colors according to the spatial distribution of pixels values in the scene.[1] The SCAs are mainly based on the visual mechanism for which color sensation depends on the spatial arrangement of the stimuli in the scene. This mechanism has been well studied and employed in many fields (e.g., art, design, psychology, and optometry), where it is well known that identical color stimuli can originate different color sensations according to their distribution in the image. An example of this phenomenon is the visual illusions (e.g., simultaneous contrast). In general, SCA enhancement is based on a qualitative estimate of the appearance of each point according to the influence of the surrounding spatial arrangement of the scene. This principle is derived from Retinex,[5,6] the first computational model of color sensation, founding member of the SCA family from which ACE derives.[2]

ACE is easily understandable, implementable, and applicable and allows the user to enhance the image depending on its content and on pixels spatial arrangements, thus simulating some of the main behaviors of the HVS. Nevertheless, ACE computational costs are $O(n^2)$, where n is the number of pixels in the image, thus the high computational costs are the main disadvantage of ACE. As presented in the next sections, speed-up methods have been devised to overcome this limit.

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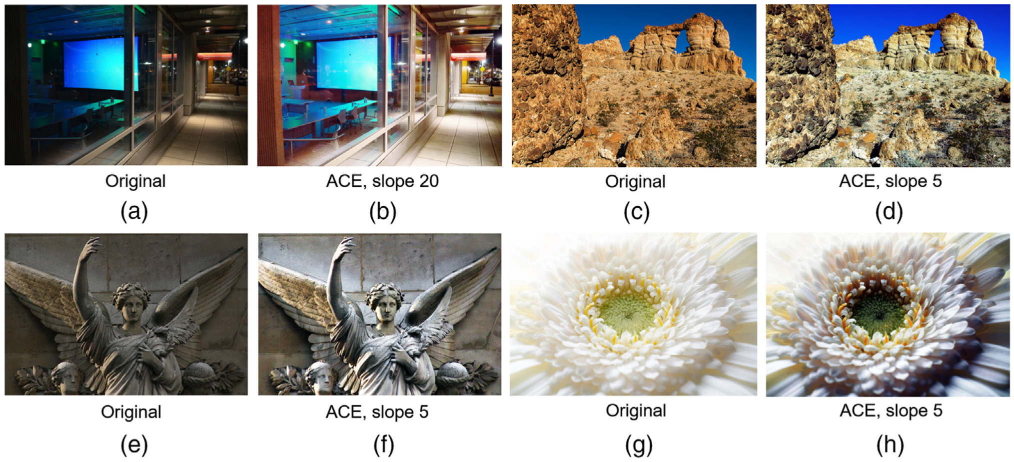

Fig. 1 Example of ACE application on images from the dataset Ex-Dark[7] and NPRgeneral.[8]

In this research, we show that since its presentation ACE has been widely used, mathematically formalized, and even reimplemented for optimizing its computational performance so that it is currently used as one of the preprocessing steps of different applications in disparate fields and image enhancement workflows. The technical reasons determining the success of this image enhancement algorithm may be quite different, e.g., the visual quality of the output images, the normalizing effect on images illumination, or its easy implementation (see Fig. 1). Due to ACE correlation with the HVS, the output images are enhanced in contrast and colors as observers would expect/like to see them and are therefore usually preferred compared to the original.[9–11] Due to ACE properties, this algorithm and this scoping review can be of interest to researchers addressing the problem of color constancy both for machine vision and human vision applications. Moreover, when a dataset where images characterized by different illumination conditions are treated, ACE, like other SCAs,[12] has the useful property of normalizing the effects of the illumination, therefore producing a more uniform dataset. An overview of the different implementations of ACE is presented in Sec. 4.2.2, anyway different implementations are also available online (among the different ACE implementations, the following one is available in Python language).

Another advantage of ACE, which makes this algorithm widely usable and applicable, is that it does not require user supervision, statistic characterization, *a-priori* information on the scene, nor data preparation. Moreover, ACE presents just a single parameter to tune [r in Eq. (1)], which is easily understandable and manageable, so that also nonexpert users can apply and use this algorithm to achieve the desired image enhancements.

In this scoping review, we selected ACE among the whole family of Retinex-based algorithms, because it has a medium-high citation score, it is easily implementable, and correlated with the HVS. For these reasons, from the study of ACE applications and roles, we can understand and define the main needs and research directions in the SCAs field, to define new trends and directions to improve the research on spatial models and algorithms able to deal with complex scenes in a global and local approaches. More specifically, in this work, we are interested in the identification and analysis of the application domain and roles of ACE and in the mapping of these characteristics. To this aim, we have collected and analyzed a wide set of papers using it.

Following the indications reported by Munn et al.,[13] a scope review has been considered more appropriate at this purpose, instead of a systematic review, since we do not aim at produce a critical answer to specific queries but to provide an overview of evidence. Thus, as suggested by Peters et al.,[14] an assessment of methodological limitations or biases of the papers included in the study is not performed, and we focus on identifying and examining the applications and roles of ACE in the many researches using and citing it. The goal of this scoping review is to better understand the motivations behind the many different ACE applications and roles, to define the main needs, and provide the scientific community with new research directions.

The research methodology of this study is presented in Sec. 3, and in Sec. 4 the results are discussed.

2 Automatic Color Equalization

ACE was presented for the first time in 2002 at the *Conference on Colour in Graphics, Imaging, and Vision*[3] and published in 2003 by Rizzi et al.[1] SCA family of algorithms tries to simulate some characteristics of the HVS enhancing images with a global and local approach, from the idea that color sensation derives from the spatial ratios of the reflected light intensity in specific wavelengths bands computed between adjacent areas of the image. One of the main characteristics of ACE[1] is the integration of local and global gray world (GW) and white patch (WP) approaches. The local WP accounts for color adjustment while the GW accounts for an automatic local adjustment of average lightness and contrast.

Like all SCA algortihms, ACE is performed in two stages. In the first stage, the chromatic and spatial adjustment produces an output image, in which every pixel is recomputed due to the image content. In the second stage, the use of image dynamic range is maximized, by normalizing the white at a global level.

ACE works by comparing every pixel p_t in the image I to every other pixel independently in the RGB channels and summing all the difference to compute the final value:

$$p_{\text{new}} = \frac{1}{k_t} \sum_{p_j \in I, p_j \neq p_t} r(p_t - p_j) d(t, j), \tag{1}$$

$$k_t = \sum_{p_j \in I, p_j \neq p_t} d(t, j). \tag{2}$$

Before the sum, each difference is modified by a nonlinear function $r(\cdot)$ and weighted by $d(\cdot)$, the inverse of the Euclidean distance among the pixels p_t and p_j. The normalizing factor k_t is used to avoid border effect (i.e., overamplifications of local differences along the edges in the image content). The factor $r(\cdot)$ is the truncated gain function:

$$r(p_t - p_j) = \begin{cases} -1 & \text{if } (p_t - p_j) \leq -thr \\ \frac{(p_t - p_j)}{thr} & \text{if } -thr < (p_t - p_j) < thr \\ 1 & \text{if } (p_t - p_j) \geq thr \end{cases}. \tag{3}$$

This last function is a nonlinear amplification of the normalized difference between pixel values, responsible of the final pixel changes. The final contrast level depends on the slope value of $r(\cdot)$; the higher the slope, the higher the contrast.

A comparison and first evaluation of the performance of the two main SCA, Retinex and ACE, is presented by Rizzi et al.[2] In this second paper, the ACE algorithm is presented under a different light, and its computational model is compared with Retinex, to underline their peculiar characteristics and promote a more specific and aware use of those two algorithms. The two algorithms present similar properties of global and local enhancement for what concerns lightness, color constancy, and dynamic range stretching, and when applied to visual illusions (such as images of simultaneous contrast) both compute visual appearance presenting the same values of hue, but different brightness and saturation (see Ref. 2). Beside the steps of input and output data calibrations,[4] the main difference between ACE and Retinex is that Retinex is a WP algorithm, whereas ACE integrates a GQ compensation mechanism.[2]

In this paper, Refs. 1 and 2 will be considered as the first two papers that presented the ACE algorithm and promoted its performance among the algorithms of the Retinex family.

3 Methodology

For this scoping review study, we partially applied the guidelines described in Refs. 13 and 15. Scoping studies follow five main stages:[15] research question identification, relevant studies identification, study selection, data charting, and results discussion. Following the suggested steps of scoping review, this study was structured in seven different phases:

- Research question definition;

- Relevant studies identification;
- Papers selection;
- Tagging;
- Classification;
- Validation;
- Analysis and discussion.

Main characteristic of this work is that, after the research question definition, we identified the available evidence searching for works citing the two founding papers on ACE algorithm, described in Sec. 2.

3.1 *Research Question Definition*

As introduced in Sec. 1, aim of this scoping review is to better understand the motivations of the many different ACE applications and roles. At this scope, this study is aimed at finding answers to a specific research question: "After almost 20 years from its first publication, to what extent and in which ways the ACE algorithm may have influenced the scientific research in the color imaging field?" We considered two dimensions for organizing this study:

- (D1) Application domains: in case of practical use of ACE algorithm, the domains in which the method has been applied have been considered for classifying the citing works.
- (D2) Roles: we classified the citing works considering the role the ACE paper(s) had in the described studies.

3.2 *Relevant Studies Identification*

As starting point of our study, we selected two of the fundamental papers of ACE that have been described in Sec. 2:

- Paper A: Rizzi et al. (Ref. 1);
- Paper B: Rizzi et al. (Ref. 2).

To find answers to our research question, we searched for all papers citing paper A and/or paper B. To do so, we decided to interrogate both Google Scholar and Scopus.

For searching the citing papers on Google Scholar, we used Publish or Perish, an application that retrieves and analyzes academic citations (Harzing's Publish or Perish[16]). One of its features allows one to query Google Scholar for a specific paper and to also search for the works citing it. For paper search on Scopus, we first used Publish or Perish feature as described above, and we retrieved all citing works on Scopus website.

We repeated these two steps for both paper A and paper B, and we combined the results into one comprehensive spreadsheet. The search was performed on November 22, 2019, and we did not specify a time range, so the upper date range limit coincides with this date. The search activity provided 826 results. For each paper resulted in the search phase, we filled in a line in the spreadsheet, completing all columns detailed in Table 1.

3.3 *Paper Selection*

In this phase, we defined five exclusion criteria that we used to decide whether a paper was to be excluded or included in the study:

1. Language: we excluded all papers that are written in languages different from English and Italian (this choice is due to the authors' native language).
2. Type: we did not include in the study BSc and MSc theses, books and monographs, invited talk papers, papers from repositories and archives (those only available on ArXiv, ResearchGate, or institutional archives), technical reports, project deliverables, white papers, and other online content that are not scientific peer-reviewed papers (such as blog posts).

Table 1 Columns of the spreadsheet used for the study.

Column	Description
ID	Each paper was assigned with a unique identifier used to identify it in the discussion among the researchers
Title	Complete title of the paper
Author	List of paper's authors
Year	Year of publication of the paper
Source	Name of the source (e.g., journal title in case of a journal article, book title in case of a book chapter, name of the conference in case of a paper included in proceedings, nothing in case of PhD dissertation)
Reference	Complete reference of the paper
ACE paper	Indication of which of the reference papers is cited (i.e., A or B)
Scholar query	Checked if the paper appeared in results of the query on Google Scholar
Scopus query	Checked if the paper appeared in results of the query on Scopus
Citations	Number of citations of the paper
Type	Types of paper (i.e., journal, chapter, proceedings, and PhD dissertation)
Included	Checked if the paper was included in the study
Self-citation	Checked if one or more of the paper's authors are also authors of paper A and paper B
App domain	The domain of application described in the paper
Roles	Used to describe why paper A and/or paper B were cited (i.e., use of ACE, comparison of methods, implementation of ACE, modification of ACE, state of the art/survey, formalization of ACE)

3. Duplicates: if a paper resulted both in search results in Scopus and Google Scholar, we excluded the less-complete result.
4. Multiple citations: if a paper cited both reference papers we excluded one of the two.
5. Errors: we excluded those papers that appeared in the results but did not cite the reference papers or those that listed them in the references list but did not cite them in the text.

At the end of this phase, once the exclusion criteria were applied, the papers included in the study were 298 (the excluded were therefore 528). The included papers are listed in Table 2.

3.4 *Tagging*

We divided the 298 papers into three sets that were assigned to each of the three researchers (i.e., three of the paper's authors) that actively performed the study. During this phase, the researchers identified the papers written by at least one of the authors of the reference papers: Daniele Marini, Carlo Gatta, and Alessandro Rizzi. Those papers have been tagged as self-citations. Out of 298 papers, only 63 were self-citations (21.14%).

A graphical representation of the distribution of papers according to their type and considering both self-citation papers and papers written by other authors is shown in Fig. 2.

Moreover, Fig. 3 shows the distribution of the papers over the years.

We also performed an analysis to investigate where ACE is more diffused and in what sector it has been used the most (academy or industry). To do so, we considered the affiliation and the relative country of the first author (or the corresponding one). As shown in Fig. 4, China is the country with the highest number of papers (44), followed by Spain (17), France (21),

Table 2 Table of the papers included in the literature review.

Year	Journal	Proceedings	PhD thesis	Chapter
2003	17	18 to 21	—	—
2004	—	22 to 25	—	—
2005	26,27	28 to 34	—	—
2006	35 to 38	39 to 49	—	—
2007	50 to 58	4, 10, 59 to 66	67, 68	—
2008	69 to 72	73 to 78	—	—
2009	79 to 84	85 to 100	101	—
2010	102 to 107	108 to 116	—	—
2011	117 to 124	125 to 133	—	—
2012	134 to 141	142 to 146	147	148
2013	149 to 155	156 to 164	165, 166	—
2014	167 to 181	182 to 186	—	187
2015	188 to 207	192, 208 to 214	215, 216	217 to 220
2016	221 to 236	237 to 245	—	246
2017	9, 247 to 264	265 to 267	268, 269	270
2018	271 to 287	238, 288 to 294	295, 296	—
2019	297 to 305	306 to 310	—	311

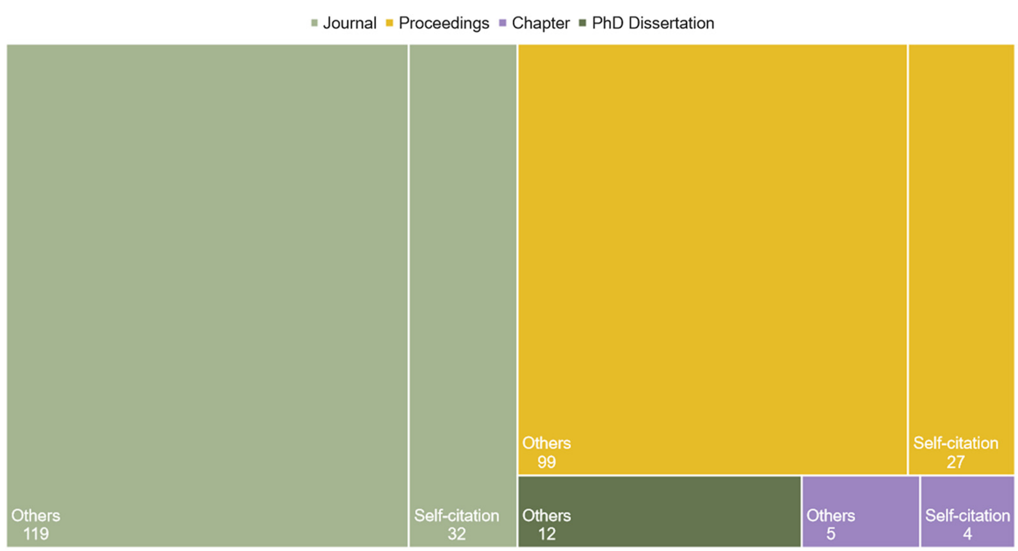

Fig. 2 Distribution of the papers according to their type.

United States (18), and Italy (17). As to the sector, out of the 235 papers that are not self-citation papers, only 8 are published by private companies; the other 227 are all written by academics. The eight industry papers have been published by researchers/practitioners in United states (2), Russia (2), Brazil (1), France (1), Germany (1), and Italy (1).

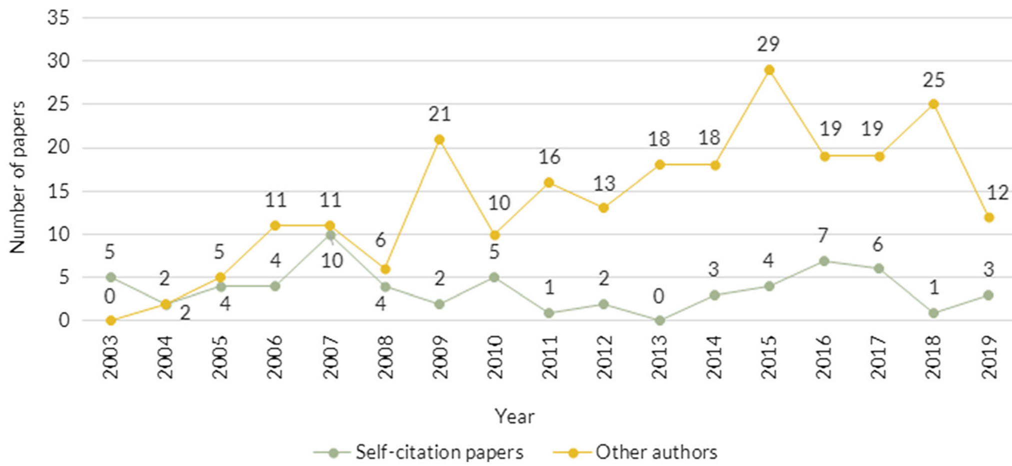

Fig. 3 Distribution of papers over the years.

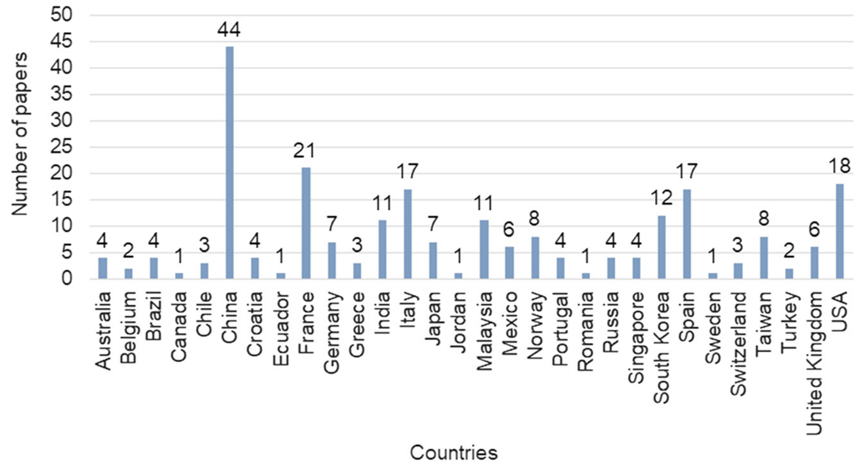

Fig. 4 Geographical distribution of the papers (the country of the institution of the first or the corresponding author has been considered).

3.5 *Classification*

Keeping the same assignment done for the tagging phase, the researchers independently analyzed and classified their set of papers by completing the other columns in the spreadsheet:

- Reference: the reference to the paper, in BibTeX format
- Application domain: this column is linked to the second dimension of this study (D1: application domains). Each paper was assigned to an application domain. The list of domains was finalized *a posteriori*, because the selection of its items was guided by the individual classifications of the researchers.
- Roles: this column is linked to the first of the two dimensions used for organizing this study (D2: roles). We classified each paper selecting one of the following values:
  - Comparison;
  - Formalization;
  - Implementation;
  - Modification;
  - State of the art/survey;
  - Use.

3.6 *Validation, Analysis, and Discussion*

For validating the classification done in the previous phase, the researchers exchanged their subset among them (researcher A validated researcher B, researcher C validated researcher A, and researcher B validated researcher C).

Finally, the researchers met to analyze and discuss the results of the study and to organize them for the preparation of this paper.

4 Results

4.1 *D1: Application Domains*

The analysis of the papers pointed out that only a limited number of papers are associated with a specific application domain: 84 out of 298 (28.19%).

The distribution of the 84 papers according to the application domain they describe is illustrated in Table 3. The first column lists all the application domains identified during the study while the second and the third columns show the number of papers published by the same authors of paper A and paper B (32 papers, 38.10%) and the ones published by other authors (52 papers, 61.90%), respectively.

Table 3 Application domains identified during the study and distribution of the papers according to this classification.

Application domain	Self-citation papers	Other authors
Advertising posters	1	0
Art	0	2
Astrophotography	3	0
Biology	0	1
Color	2	1
Cultural heritage	3	1
Fish behavior monitoring	0	1
High dynamic range	1	0
Image enhancement	2	19
Image fusion	0	1
Image quality	2	3
Interfaces	3	0
Medicine	0	3
Movies	10	2
Printing	1	0
Psychophysical studies	2	0
Steel bridges	0	1
Stereo images	1	0
Underwater imaging	0	12
Virtual reality	1	0

Focusing on the paper written by other authors, it is quite clear that "image enhancement" and "underwater imaging" are the most diffused application domains in which ACE algorithm has been used with 19 and 12 papers, respectively. In what follows, all the 52 papers will be briefly presented and discussed from the application of ACE in the specific application domains.

4.1.1 *Movies and film restoration*

In Ref. 271, the process of digitization, color enhancement, and digital restoration of a specific type of movies, the reversal films, is illustrated. Reversal films produce a positive image on a transparent celluloid base, with a low cost approach that has been very popular in the 20th century. In the paper, the authors faced specifically one of the main degradation phenomena that affects the reversal film, due to aging process: color dye fading. In Ref. 125, the authors discussed the vulnerability of motion pictures archives, especially the problems related to distortions, such as color fading.

4.1.2 *Cultural heritage*

As an example of cultural heritage preservation and restoration, Ref. 142 focuses on a collection of old colored postcards from the 19th century. This particular kind of document is made of a type of paper that tends to become brown and yellow with the passing of time. Moreover, the pigments of the postcards become faded and also other problems may occur, such as humidity or fungi.

4.1.3 *Art*

ACE algorithm, in Ref. 39, is used for a nonphotorealistic image rendering. In this work, Lam et al. aim at creating an image processing system where the output image that looks like the input but with an artistic twist. In this application, ACE is used to enhance dull colors into vivid ones for cartoon- or comics-like renderings. In the art application domain, the authors of Ref. 40 presented a study made on nonphotorealistic rendering, a discipline that aims at translating photographs into paintings simulating different techniques and media.

4.1.4 *Underwater monitoring*

Another domain in which ACE has been considered is the one related to the assessment of security and quality of drinking water by the observation of fish behavior. This approach, described in Ref. 221, is based on the monitoring of group of fish put in fish tanks in which water flows in a continuous manner. The behavior of the fish (erratic or even death) is used as indicator of presence of toxins in the water. Instead of monitoring this process, all day long, in a manual way, video surveillance and computer vision techniques are adopted.

4.1.5 *Biology*

Another application domain that is related to fish is the one in which biologists work for automatic recognition of coastal fish; specifically, in Ref. 126, the authors describe their work in Gaoquiao district of Zhanjiang, China, where the automatic identification of fish is made difficult by the water condition (the underwater serious noise, strong, and nonuniform color cast, etc.).

4.1.6 *Color*

Tateyama et al. in Ref. 288 describe a new color enhancement technology, which aims at avoiding color saturation for images displayed on big LED screens or on digitally controllable decorative LED illuminations. In this work, ACE algorithm is used to estimate the wider LED color gamut, in fact this algorithm allows to enlarge the color difference while moving all the input colors inside the destination gamut.

4.1.7 *Medicine*

In Refs. 85, 86, and 117, an interesting research work on the analysis of dermoscopic skin lesion images is presented. The precise automatic analysis of lesion borders a very critical task in medicine. The main problems related with poor contrast and lack of color calibration are successfully solved using ACE.

4.1.8 *Image enhancement*

Morel et al.[167] presented a high pass filter method, which eliminates the effect of nonuniform illumination, preserves image details, and enhances the contrast. In this work, authors compare the proposed method with more complex methods, ACE among them. In Ref. 108, Islam and Farup proposed and analyzed several methods to enhance the output of SCA to preserve the non-neutral properties of the original image along with the enhancement. The results of this paper are promising, also if authors underline the low running time and the possibility to introduce some distortion in the output. In Ref. 41, Chambah presented two methods for correcting nonuniform color casts in images: ACE and progressive hybrid method. In this paper, ACE gives the best results due to its adaptation to different color casts and because it is unsupervised. Lisani in Ref. 289 presented a local image enhancement technique based on a logarithmic mapping adapted on the luminance of each pixel neighborhood. This new technique is inspired by ACE, which is used to make comparisons. In this paper, authors add value mainly to the ability of ACE to adapt to widely varying light conditions. This characteristic inspired also a fuzzy logic-based algorithm, presented in Ref. 87. Here, authors developed a technique to deweather fog-degraded images and use an algorithm similar to ACE in the color correction step. In Ref. 79, Palma-Amestoy et al. devised a set of basic requirements to be fulfilled by models, to be considered "perceptually based." Due to the translation of human color vision in mathematical assumptions, it was possible for the author to analyze algorithms such as Retinex and ACE. In this paper, authors found that those algorithms effectively enhance details and remove color cast without introducing noise. Furthermore, authors provided processing to avoid noise amplification in extremely dark images.

A color image enhancement method, which applies a weighted multiscale compensation based on the GW assumption, is presented in Ref. 247. ACE algorithm is used to make comparison with the proposed algorithm, due to its ability in preserving color constancy. Results show that images enhanced through ACE and the proposed method have low color differences, but the results obtained using ACE are brighter than those using the second method. A similar work was described by Choudhury and Medioni.[102] Also in this paper, authors developed an algorithm of color enhancement focused on color constancy. This algorithm has the main characteristic to estimate the illumination separating it from the reflectance component in the image. In this work, the new algorithm is compared statistically and subjectively with ACE and other algorithms of the Retinex family.

Wang et al.[168] describe a variational Bayesian method for Retinex (named VBR), which aims at simulating and interpreting how the visual system perceives colors. In the paper, the VBR algorithm was compared with some Retinex and some non-Retinex method, ACE among them. In Ref. 182, authors try to give an answer to the question "What is the right center/surround for Retinex?" To answer this question, authors analyze the formal properties of the center/surround versions of Retinex. From this study, ACE was found to be the best Retinex method considering the conditions imposed in this study.

An algorithm to enhance and denoise low-light images is presented in Ref. 127. The main characteristic of this method is that it uses different color spaces to achieve different enhancements. Results show that the color preservation framework used by the algorithm is satisfactory and can generate higher contrast and sharpness in comparison to ACE and other image enhancement methods. Also in Refs. 80 and 88, Han and Sohn deal with the problem of restoring images taken under arbitrary light conditions. In Ref. 80, an automatic framework: illumination and color compensation algorithm using mean shift and the sigma filter (ICCMS) is presented. In this paper, the results show that all the compared algorithms, ACE among them, increase local contrast and visual perception, but ICCMS performed a better illumination and color enhancement in underexposed regions of the image. Due to the satisfactory results, in Ref. 88 authors develop a framework inspired by ICCMS color restoration and by the free region-of-interest illumination compensation for digital cameras with touch screen. This method named HRICR allows to restore distorted images taken under arbitrary light conditions. Han and Sohn,[89] present another framework to restore illumination and color fidelity in digital camera, but unlike the previous method, this latter one is based on a human visual perception model. The proposed method was compared to other algorithms of shadow correction such as ACE. Results show that the proposed method enhances illumination and color in underexposed image regions. Nevertheless in some images it produces an unwanted halo effect with distortions of colors and noise amplification.

Another algorithm to automatically adjust luminance in under- and overexposed images is presented in Ref. 109. This approach is based on a recursive local intensity adaptation defined for each pixel through a nonlinear recursive framework. In this work, the proposed method is mutually compared with different algorithms, and if on some images ACE gives results comparable to the new method, in some cases it introduces color alterations. A method based on histogram equalization is presented in Ref. 222. This method reflects the characteristics of the global histogram equalization method locally to avoid artifacts and produce a global and local contrasts enhancement. The new method is compared with color constancy algorithms such as ACE, and an objective and subjective assessments is provided in the results. In Ref. 149, an improvement of random spray Retinex (RSR) is proposed: the light random sprays retinex (LRSR). The main purpose of the authors is to reduce the noise introduced by RSR and computation costs. In this paper, LRSR is compared with ACE and other algorithms that apply local illuminant correction. Nevertheless all the tested methods differed significantly among them in perceptual difference and computational costs, LRSR gives very similar results to RSR reducing significantly the computation time. The same authors, in Ref. 188, propose a new algorithm, named smart light random memory sprays Retinex (SLRMSR), which is an improvement of LRSR. From the comparison with other image enhancement methods, it was seen that SLRMSR is slightly outperformed by ACE in brightness adjustment and outperforms all other methods. In conclusion, the results demonstrated that SLRMSR is a good candidate for real-time applications due to the high quality of the output and low computational costs. A similar work to optimize the computational time of one Milano Retinex algorithm, STAR, is presented by Lecca[272] The performance of the new algorithm, named SuPeR, was compared to other approaches through objective assessment. Results show that SuPeR enhances color images similarly to other Milano Retinex algorithms but with much shorted computation time, also if not in real time.

4.1.9 *Image fusion*

Image fusion is a technique used for producing a single image from the merge of two or more images. An example of the application of ACE to this domain is given in Ref. 128. The goal of image fusion is to produce a new picture that contains more information than the one included in the single pictures used for the merge.

4.1.10 *Image quality*

Ouni et al.[90] present a full reference color metric called spatial color image difference (SCID), which is perceptually correlated with the HVS. In this work, ACE algorithm is used when a reference image is missing; thus, the color difference is computed between the target image and the same image enhanced/restored through ACE. In Ref. 91, ACE has been used for a comparison of methods aimed at addressing the problem of illuminant variation in image recognition. Finally, in Ref. 208, the problem of brightness adjustment in real-time image enhancement process is considered.

4.1.11 *Machine and computer vision*

One of the most popular applications of machine vision today is pedestrian detection. In our study, three papers reported the use of ACE in this application domain (i.e,. Refs. 156, 183, and 273). Another application of ACE to this domain is focused on face detection: in

Ref. 184 improvements in terms of detection performance and evaluation protocols are presented and discussed. Reference 67 presents a study on the use of computer vision applied to painterly rendering. The authors used ACE to link the process to human vision because of the important influence that perception and painting play on one another.

4.1.12 *Steel bridges*

In Ref. 248, the authors applied different restorative methods to steel bridges photographs to prepare them for bridges health assessments procedures. A discoloration of the coatings is often an important sign of the progressive damage process of steel bridges, but visual inspections may easily lead to errors in human interpretation. To reduce the influence of any environmental noises (e.g., light sources), the distorted colors need to be restored to their authentic ones.

4.1.13 *Underwater imaging*

In this peculiar application domain, several papers present methods for overcoming problems of nonuniform contrast and poor visibility caused by bad illumination and color cast that are typical in underwater imaging. References 185, 274, 297, 298 present studies that compare some of them. In Ref. 290, a method for addressing nonuniform illumination of underwater images through segmentation and local enhancement (instead of global) is presented. References 143, 144, 187 present the ROV three-dimensional (3D) project that aimed at creating tools for applying underwater photogrammetry and acoustic measurements to underwater archaeology practice. The tools are meant to offer a nonintrusive alternative that would reduce the *in-situ* investigation time. Another study performed in underwater archaeology is presented in Ref. 306 and applies a color enhancement method for reconstructing the 3D model of a shipwreck. Another method is presented in Ref. 157 that is focused on solving problems due to scattering and color distortion. Reference 299 presents an enhancement method, based on Retinex, that applies both on underwater images and videos taking care of low contrast, color degradation, and nonuniform illumination. Finally, in Ref. 295, a PhD thesis, an underwater imaging system based on several algorithms for color and illumination normalization has been presented.

4.2 *D2: Roles*

In column ROLES of the spreadsheet, we assigned to each paper a description of the way they used the reference papers, choosing by a finite set of values:

- Comparison: ACE is compared with other algorithms;
- Formalization: the paper presents a formal description of ACE algorithm;
- Implementation: the paper illustrates an implementation of ACE algorithm in some programming language;
- Modification: the authors modified ACE algorithm and present their own new version;
- State of the art/survey: ACE is cited in systematic review, state of the art, or related work sections but not used, formalized, implemented, or modified.
- Use: ACE is actually used and its results are presented and discussed.

Figure 5 shows the distribution of the papers according to the roles values and the self-citation/other authors attribute.

4.2.1 *Comparison*

All the 39 papers that belong to the comparison class cite ACE in a comparison with one or more other methods. We analyzed these papers and identified the methods used by each paper and its frequency of use. We then classified the methods into eight families of methods:

- Bilateral filtering and processing miscellanea;
- Dehazing and underwater various methods;
- Histogram equalization or derived;

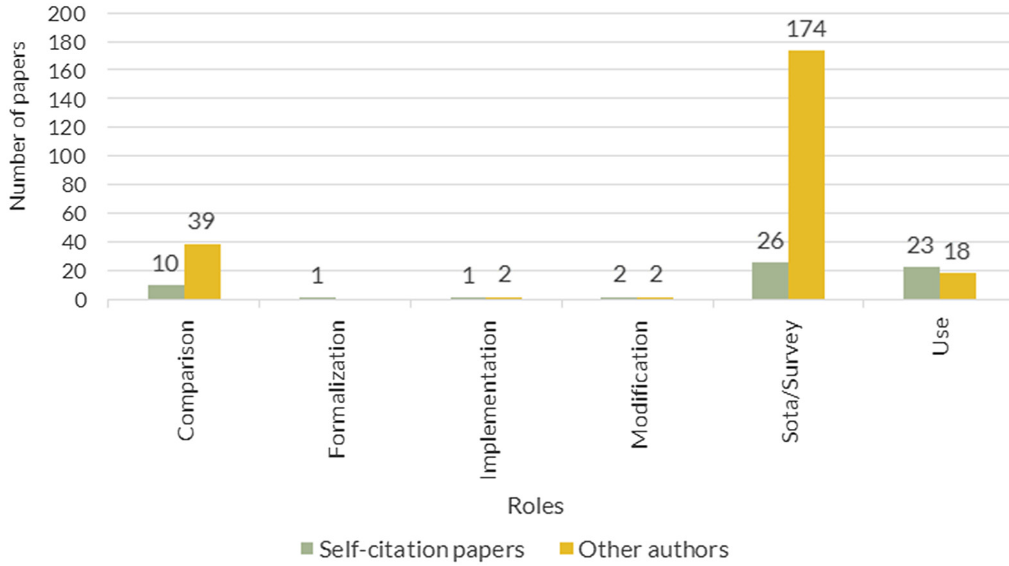

Fig. 5 Roles identified during the study and distribution of the papers according to this classification.

- No-reset Retinex;
- Reset Retinex;
- Variant of ACE;
- Variational Retinex;
- WP/GW normalization.

Figure 6 shows the number of methods grouped in the families, whereas Fig. 7 shows how many times methods belonging to the families have been used in the 39 analyzed papers.

4.2.2 *Implementation*

ACE's implementation by Getreuer has been documented in Ref. 134. Also in Ref. 291, an implementation of ACE is presented.

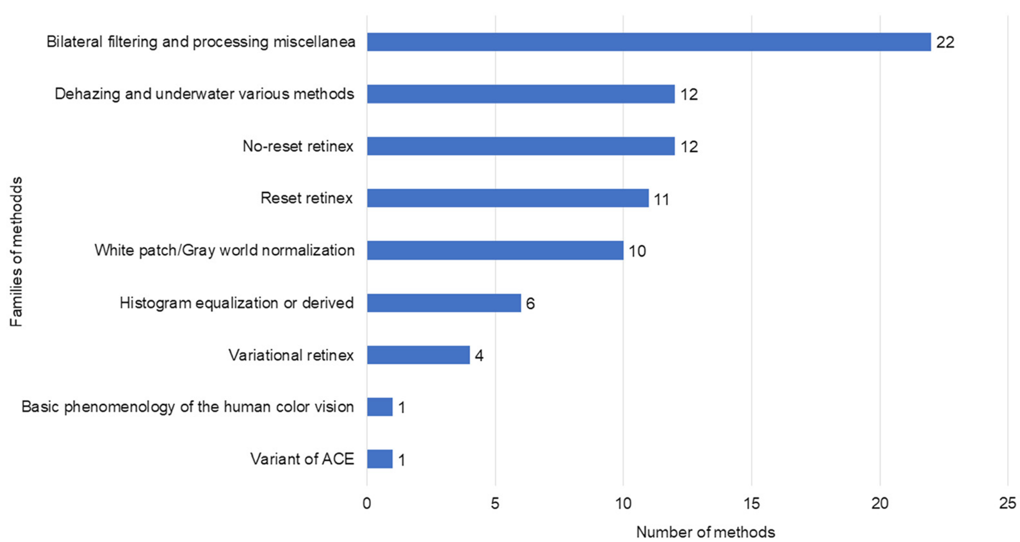

Fig. 6 The methods used in the 39 papers are organized into families of methods. Here, the number of methods belonging to each family is depicted.

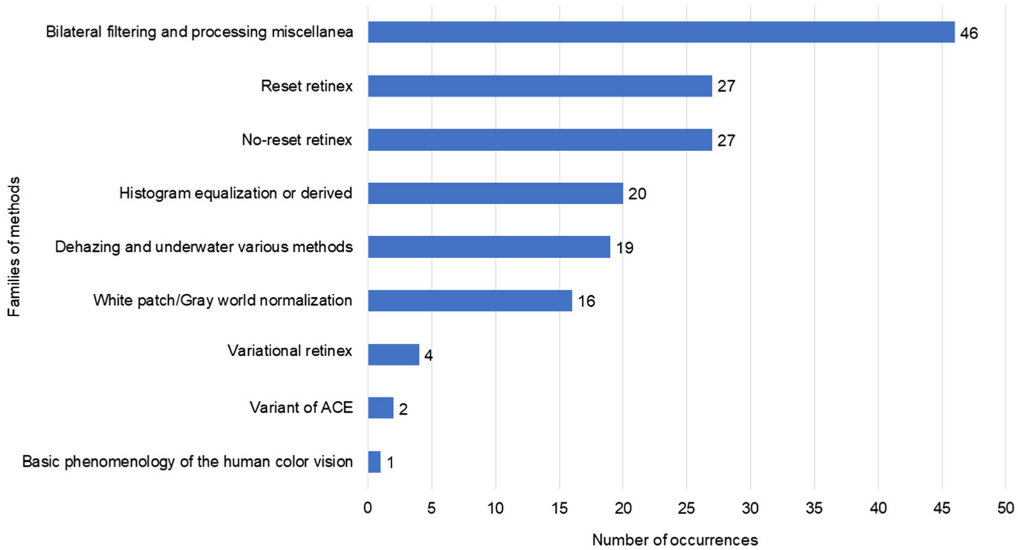

Fig. 7 The chart shows how many times the methods included in the families have been compared with ACE in the 39 comparison papers.

4.2.3 *Modification*

The authors of Ref. 157 propose a faster version of ACE, called αACE and tested it on underwater images. Also the work published in Ref. 292 proposes a modified version of ACE, called L-ACE, that uses the acyclic side suppression model for brightness correction and Gaussian distribution to reduce the number of samples.

4.2.4 *State of the art/survey*

In this section, we discuss the most cited papers that cite ACE algorithm in the systematic review, in the state of the art, or in related work sections. The papers that result in this classification are 200, with the exclusion of the ones that present self-citations, the considered papers are 174. Among them, the 1.15% has more than 200 citations, the 2.30% has between 200 and 50 citations, the 28.74% between 49 and 10 citations, the 37.93% between 9 and 1 citations, and the 29.89% has no citations. Here, we describe highly cited papers.

The most cited paper, by Meylan and Susstrunk,[35] presents a new method for the rendering of HDR images based on the Retinex model. This paper cites the paper B[2] while exploring the state of the art of Retinex path-based methods. This paper underlines the practical problems of ACE subgroup of algorithms, which have high computational costs and free parameters. Thus, the authors focus on surround-based Retinex models to implement a new HDR image rendering method. The theme of HDR images concerns also a paper made by McCann,[50] where the author focuses on the theme of veiling glare. Here, ACE algorithm is presented as a computational approach that uses spatial comparison to synthesize the optimal display and to reduce the effect of glare miming the physiological mechanisms such as simultaneous contrast.

A paper with more than 200 citations, which cites ACE as state of the art, was presented by Schettini and Corchs.[103] This paper is a review of methods and techniques to process underwater images, and authors cite paper A[1] in the section concerning the algorithms of image enhancement and color correction. This paper describes the ACE algorithm and reports some images of its application for the enhancement of an underwater video, but focuses, in particular, on the tests and results presented by Chambah et al.[312] Similarly, in Ref. 110 by Iqbal et al., ACE algorithm is reported in the state of the art while introducing different image enhancement techniques for underwater imaging. Also in this case, the citation of paper A[1] is presented together with the applications made by Chambah et al.[312] In this paper, the ACE algorithm is discarded by the authors due to its computational costs. Considering the topic of underwater imaging, the works by Yang et al.[129] and by Ghani and Isa[189] present two different underwater image processing methods. In the first paper, the image enhancement algorithm is based on dark channel prior and in the second work, authors propose a technique which applies the histogram modification of the integrated RGB and HVS color models. In both the works, ACE papers A and B are presented as systematic review and no further comments about the algorithm are made.

The Retinex theory and its implementation laid the foundations for many other image enhancement algorithms and ACE is often cited in the state of the art. An example is the paper by Tao and Asari,[26] which presents a new image enhancement algorithm called adaptive and integrated neighborhood-dependent approach for nonlinear enhancement and cites ACE paper B in the "related work" section. Furthermore, in Ref. 81, Bertalmío et al. present the kernel-based Retinex algorithm. This algorithm has the same characteristics of the original Retinex and shares some correspondences with ACE model. Similarly, in a work Li et al. in Ref. 135, authors propose a perceptually inspired image enhancement method for correcting uneven intensity in remote sensing images, which is inspired by the Retinex theory. In this work, ACE papers A and B are presented in the state of the art when presenting the Retinex theory and the developed method differs mainly by ACE algorithm because the reflectance is solved within a limited dynamic range and is supposed compliant to gray word assumption. ACE approach to white balancing is discussed also in a work by Kwok et al.[150] In this paper, ACE paper A is cited as state of the art, when reviewing the systematic of the different white balancing methods applied by algorithms of color correction. ACE paper B is cited as state of the art also in a work presented by Tao et al.[42] in the field of face detection. In this paper, authors describe the multiscale Retinex (MSR) as an effective image enhancement technique and cite ACE as one of the many other implementations of Retinex theory. In this context, the authors discard the Retinex family of algorithms for their application due to some issues in rendering images in complex lighting environment.

Another interesting review was presented in 2006 by Agarwal et al.[36] This work introduces a review of the color enhancement algorithms that preserves the color constancy and cites ACE while explaining the Retinex approach. Authors cite paper B[2] with others implementations of Retinex and then focus on MSR.

The strong correlation between the ACE algorithm and the Retinex theory has been described in several papers. An interesting work, made by Bertalmío and Cowan,[82] demonstrated the close relationship between Retinex algorithms and the Wilson–Cowan equations (e.g., a set of equations that describe the temporal evolution of the mean activity of a population of neurons in some region of the neocortex), which could result in numerous applications to many neural network problems. In this work, ACE is mentioned to demonstrate this correlation.

Another work where ACE and its family of algorithms is examined for its correlation with visual perception is presented by Hardeberg et al.[69] Here, the authors evaluate the quality of several color image difference metrics to find out if it is possible to evaluate color gamut mapping using color image difference metrics. In this work, ACE is cited in the future research directions as possible perceptual predictor for the development of new color image metrics that correlate better with HVS.

Since algorithms based on random spray sampling techniques tend to introduce noise in the output, in Ref. 151 a method is presented to reduce noise based dual tree complex wavelet transform coefficients shrinkage. In this work, the RSR and RACE algorithms are analyzed and enhanced, and it was seen that the proposed method produces good quality images, removing noise without altering the underlying image directional structures. An overview of color equalization algorithms is presented in Ref. 217. In this paper, ACE is reported among all the other Retinex family algorithms. Another overview is presented in Ref. 275. Here, different interpretations and mathematical formalization of Retinex model are presented and several color enhancement algorithms with a focus on different variational formulations are described. Since Retinex was widely implemented, in Ref. 190, Zosso et al. made a first overview of the Retinex implementations existing in the systematic and unified them in a single computation framework. Fitschen et al.[209] present a variational model for adapting colors of an image based on a defined target intensity image. In this paper, ACE is presented as example of hue preserving color adjustment algorithms.

In Ref. 210, Wang et al. present the technology assisted dietary assessment, a system that automatically identifies and quantifies foods and beverages consumed by the user from mobile images. In this application, ACE is cited in the step of color calibration as a method that combines Retinex with the GW and the WP assumptions.

Huang et al., in Ref. 276, review development of different types of smartphone-based analytical biosensory systems for point-of-care. In this work, ACE paper A[1] is cited in the smartphone-based colorimetric sensors, when underlining the importance of a correct white balance and color correction.

In Ref. 300, different center/surround Retinex algorithms are discussed and the authors provide a quantitative and qualitative analysis to provide suggestion of the best pair of local/global transformations for a center/surround method.

In Ref. 237, the authors propose an image enhancement approach that goes against the common assumption that that underwater images have bluish color cast.

In Ref. 169, the authors present an image enhancement algorithm aimed at conserving the hue and preserve the gamut of R, G, B channels. The intensity input image is transformed into a target intensity image according to a reference histogram. They define a color assignment methodology that makes the enhanced image fit a target intensity image.

Finally, Ref. 108 illustrates and discusses a number of techniques that can be used when a specific application domain demands the preservation of appearance of the original image and not just its enhancement.

4.2.5 *Use*

ACE algorithm was successfully used in Refs. 39 and 67 for nonphotorealistic rendering. In these studies, authors analyze and describe the functioning of the visual cortex through the analysis and use of computational models. Similarly, in Ref. 40, authors develop a perception-based painterly rendering, including ACE dynamic range-normalization as one function of the developed system. In Refs. 183 and 273, authors present two new pedestrian detection models that provide efficient training and detecting. In both models, ACE is applied on the experimental data-sets before the extraction channel features. This use of ACE is proposed by Benenson et al., in Ref. 156. Here, authors use ACE algorithm as global image normalization before computing the three image channels in a system of object detection. ACE algorithm was found useful also to to de-weather fog-affected images, as presented in Ref. 87. In this work, ACE is used in the color enhancement step of the algorithm to restore the natural contrast of the image. Schaefer et al., in Refs. 85 and 117, use ACE algorithm to normalize the colors of dermoscopy images before the segmentation step. In another work,[86] the same authors archive an accurate segmentation using a co-operative neural network edge detection system, always using ACE in the preprocessing step. ACE algorithm was used in the preprocessing step also in Ref. 184. In this work, a high performing face detector model is presented, and ACE was found successful to enhance the image colors before the detection step. Feng et al. in Ref. 128 propose a new image fusion method. In this work, ACE is used to enhance the colors in the images resulting from the fusion, producing images more useful for human perception or machine vision. In Ref. 126, authors combine a region-based segmentation with ACE algorithm, to segment fish in images with a complex background in water. A new full-reference image quality metric, named SCID is presented by Ouni et al. in Ref. 90. The metric is based on characteristics of the HVS and when an image reference is not available the SCID is combined with ACE. In Ref. 288, ACE is used to enhance the colors for LED illuminants by increasing the color difference between pixels while changing the image color gamut. Prado et al. in Ref. 306 use ACE for 3D reconstruction and virtual reality applications. In this work, ACE is used to perform a color enhancement on the input images before the 3D reconstruction of the Rio Miera wreck ship. Finally, in Ref. 298, ACE is used for color enhancement of underwater images, together with HIST and PCA methods.

4.3 *Brief Overview on Self-Citation Papers*

4.3.1 *D1: application domains*

As can be seen in Table 3, some of the application domains that have been identified in this study are only addressed in papers published by the authors of paper A and paper B. These application domains and their occurrences are shown in Fig. 8.

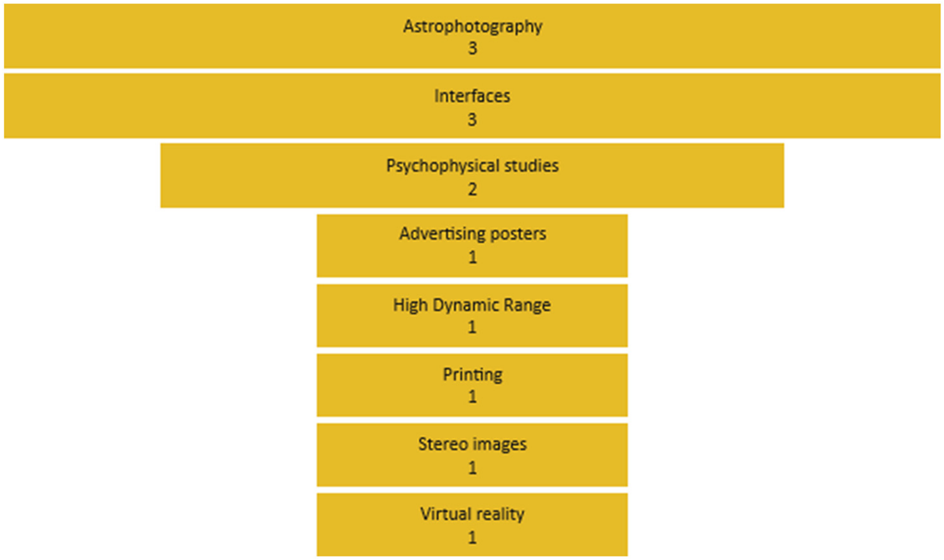

Fig. 8 The application domains used only by papers published by paper A and paper B authors.

- Advertising posters[92]
- Astrophotography[238,249,277]
- High dynamic range[51]
- Interfaces[9,17,18]
- Printing[10]
- Psychophysical studies[93,104]
- Stereo images[111]
- Virtual reality[28]

4.3.2 *D2: roles*

As visually reported in Fig. 5, only one paper included in this study has been classified as having formalized ACE in a variational form and has been published by paper A and paper B authors.[52]

4.4 *D1 and D2 Interrelation*

To conclude the analysis of the data gathered in this study, we want to present some results on the interrelation between D1 and D2, i.e., application domains and roles. Among the six different roles used for classifying the papers, those that present an implementation of ACE, its formalization, or cite it in state of the art/survey sections are not linked to a specific application domain. On the other hand, the papers that cite ACE as comparison with their own method and/or with other methods, and those that modify or use it, most of the times describe a specific application domain.

For the papers published by paper A and paper B authors, of the two papers with role modification, one is linked to image quality, whereas the other has no specific application domain. Out of the 10 comparison papers, 2 have no application domain, whereas the other 8 describe works in astrophotography, color, image enhancement, movies and film restoration, printing, and stereo images. The 23 use papers are all linked to a specific application domain: movies and film restoration, cultural heritage, interfaces, psychophysical studies, advertising posters, astrophotography, high dynamic range, image enhancement, image quality, and virtual reality. Figure 9 shows the details for comparison and use papers.

For the papers published by other authors, of the two papers with role modification, one is linked to underwater imaging, whereas the other has no specific application domain. Out of the 39 comparison papers, 6 have no application domain, whereas the other 33 describe works in image enhancement, underwater imaging, image quality, movies and film restoration, cultural

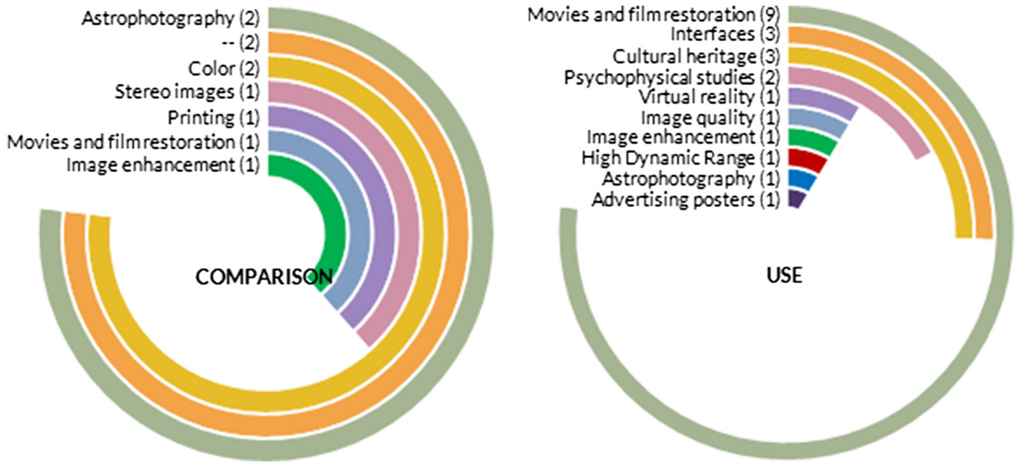

Fig. 9 The interrelation between D2 and D1 for the self-citation papers classified with role comparison and use.

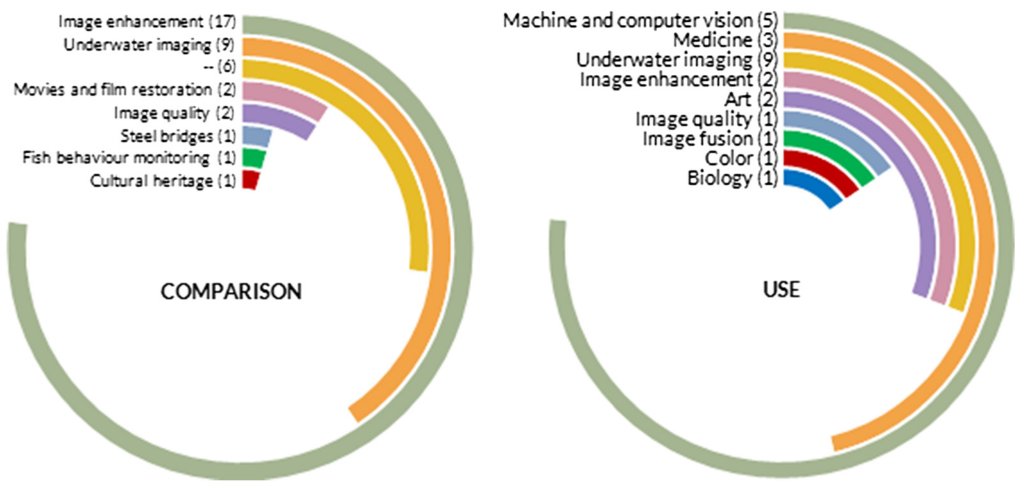

Fig. 10 The interrelation between D2 and D1 for the papers written by other authors classified with role comparison and use.

heritage, fish behavior monitoring, and steel bridges. The 18 use papers are all linked to a specific application domain: machine and computer vision, medicine, art, image enhancement, underwater imaging, biology, color, image fusion, and image quality. Figure 10 shows the details for comparison and use papers.

5 Conclusions

The scoping review presented in this paper shows the widespread use and implementation of the automatic color enhancement algorithm. The most diffused fields of application of ACE algorithm are image enhancement (25% of the considered papers) and underwater imaging (14.29% of the considered papers). The main roles of ACE, as identified by our study are: state of the art/survey (67.11% of the considered papers) and comparison (16.44% of the considered papers).

In this scoping review, we have found that ACE algorithm is appreciated for its capability of simultaneously standardizing the image illumination, revealing hidden details, and enhancing the image contrast so that the images it produces are not only particularly pleasant for observers but also improve the following steps of object localization and segmentation. Moreover, ACE can be easily implemented though parallel, optimized computation is advisable due to its high computational costs. Nevertheless, during years of applications, ACE demonstrated promising results among all the SCAs so that some optimized implementations have been developed, which also perform automatic parameters tuning. From this analysis, we have found a growing interest of the scientific community in ACE algorithm and, in general, toward the usage of SCAs. Thanks to this work, it has been possible to better understand the directions in which the application of ACE is in course of development. Furthermore, the main advantages in the use of this algorithm have been underlined, together with its limits and needs. Starting from this study, we hope that the research in the field of SCAs will continue in the future and that the fields of colorimetry and image enhancement will develop new spatial models and algorithms able to deal with complex scenes in a global and local approach.

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