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A RESEARCH ON METHODS OF COLOR ADAPTATION IN GRAPHICAL USER INTERFACES

Approaches to the color adaptation of graphical user interfaces for people with color vision deficiencies have been analyzed, and it has been found that, for practical application, the most appropriate are algorithmic methods capable of providing not only color correction but also acceptable performance when processing high-resolution images. Unlike complete vision loss, color blindness does not require the creation of fundamentally new hardware or software solutions, but rather necessitates the adaptation of existing graphical user interfaces to specific types of color vision deficiency, which determines the relevance of the conducted study. The paper investigates the implementation features of three color transformation algorithms, namely a naive per-pixel algorithm, a matrix-based algorithm, and a hybrid method based on the physiologically grounded Machado model and CLAHE. An accelerated GPU pipeline for the color transformation of graphical interface elements has been developed using CUDA and CuPy. A comparative performance analysis of CPU- and GPU-based implementations has been carried out for HD, FHD, and 4K images under protanopia, deuteranopia, and tritanopia conditions. It has been established that the results for different types of color vision deficiency differ only slightly; therefore, representative data are presented for protanopia. It has been shown that transferring the per-pixel algorithm to the GPU reduces the processing time of a 4K image from 81.51 s to 0.234 s, i.e., by approximately 349 times. It has been determined that the matrix-based method provides the shortest GPU processing time for 4K images; however, the hybrid approach combining the Machado model and CLAHE ensures better preservation of local contrast and visual expressiveness of interface elements. It has been shown that, for HD images, the advantage of the GPU is less noticeable due to data transfer overhead, whereas for FHD and especially 4K images, the use of a graphics processor is advisable. The proposed approach can be used in the development of inclusive software systems for graphical user interface adaptation. Thus, the proposed hybrid approach combines effective color correction with contrast preservation through the use of CLAHE adaptive histogram equalization, which determines its potential for inclusive graphical user interface design systems. Further development of this work involves integrating the obtained results into widely used software systems in order to provide more accessible and effective adaptation of graphical user interfaces.

Keywords: color blindness; accelerated GPU pipeline; CUDA; CuPy; Machado matrices; CLAHE; GUI; inclusivity.

Introduction / Вступ

Color blindness is a common problem that affects approximately 8 % of men and 0.4 % of women worldwide [1]. In total, this amounts to more than 300 million people [15], all of whom interact with computers, phones, and various applications on a daily basis. The problem is that most interfaces are designed without considering that some users simply cannot distinguish certain colors. For example, a red error button or a green success indicator may look identical to someone with deuteranopia.

Most modern applications do not have built-in color adaptation modes for people with CVD at all – developers simply do not include such functionality. The user either is unaware of their condition or is forced to install separate third-party software to convert colors at the operating system level. This is inconvenient, not always available, and doesn't always work correctly with a specific application.

Performance is a critical issue in practical color adaptation systems, since most existing software solutions perform color correction on the CPU only. While such an approach may be sufficient for low-resolution images, it becomes inefficient for FHD and 4K content, especially in the case of dynamic user interfaces or video streams. In studies [2, 3], the effectiveness of parallel computing approaches for computationally intensive processing tasks was demonstrated, which supports the expediency of applying parallel architectures to raster image transformation problems. Because a raster image can be treated as a matrix structure, color conversion procedures are well suited for parallel implementation due to regular data organization, independence of pixel-level operations, and fine-grained decompo-

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sition. This makes GPU acceleration a justified and promising solution for improving the performance of color adaptation methods in inclusive graphical user interface systems.

Object of research – color adaptation of graphical user interfaces for users with color vision deficiencies.

Object of research – the methods and means of color transformation of graphical user interface images and the specific features of their implementation on CPU and GPU architectures.

The purpose *of the* research – to investigate the efficiency of color correction algorithms for the adaptation of graphical user interfaces to various forms of color blindness depending on the selected computing architecture, which will make it possible to formulate practical recommendations for selecting color correction algorithms and computing architecture for the development of inclusive graphical user interfaces.

To achieve this *purpose*, the following main *research objectives are identified*:

- to analyze approaches to the inclusive adaptation of graphical user interfaces, which will make it possible to determine the role of algorithmic color adaptation among modern accessibility tools and to substantiate its applicability for users with color vision deficiencies;
- to develop an accelerated GPU pipeline for the color transformation of graphical user interface elements, which will make it possible to reduce the processing time of high-resolution images and to assess the practical feasibility of such an approach for dynamic interfaces;
- to conduct an empirical analysis of the performance of the naive per-pixel conversion, matrix conversion, and the proposed hybrid conversion algorithm (Machado + CLAHE) on different types of computing architectures, which will ensure the determination of the optimal balance between processing speed and the quality of visual interface adaptation.

Analysis of recent research and publications. In paper [4], reseaerchers presented a physiologically based model for the simulation of color vision deficiency. The significance of this work lies in the fact that the proposed transformation matrices are grounded in the spectral sensitivity changes of the L, M, and S cones, which makes this model more justified than simplified recoloring approaches. For this reason, the Machado model was selected in the present study as the basis for the hybrid color adaptation algorithm.

In study [6], a methodology for the heuristic evaluation of the accessibility of statistical charts for people with low vision and color vision deficiency was proposed. The authors emphasized that accessibility for such users depends not only on the choice of colors themselves, but also on the preservation of readability and distinguishability of visual elements. This conclusion is important for the present research because it supports the need to consider local contrast preservation in addition to color conversion.

In paper [7], authors investigated whether color enhancement algorithms improve the experience of color-deficient users in smartphone-based scenarios. The study is important because it focuses on the actual perceptual effect of color enhancement rather than on formal color transformation alone. At the same time, it does not address the computational efficiency of such algorithms for high-resolution graphical interfaces, which leaves open the issue of performance-oriented implementation.

In paper [8], a fast image recoloring approach for red-green anomalous trichromacy with contrast enhancement and naturalness preservation was studied. This work is highly relevant because it combines recoloring with additional attention to contrast and visual naturalness, which are also critical for interface adaptation. However, the paper does not focus on comparing CPU and GPU implementations of several alternative algorithms for high-resolution GUI processing, which is one of the tasks addressed in the present study.

In review [9], scientists summarized available devices for patients with color vision deficiency. The review demonstrates that many existing solutions are implemented as external aids or specialized tools rather than as integrated mechanisms of software interface adaptation. This highlights the practical relevance of developing methods that can be embedded directly into digital graphical systems without requiring additional hardware.

Thus, the analysis of recent publications shows that existing studies address the prevalence and user impact of color vision deficiency [1, 15], physiologically grounded models of color transformation [4], accessibility evaluation issues [6], perceptual effectiveness of enhancement methods [7], recoloring with contrast preservation [8], and available assistive devices [9]. At the same time, the literature reviewed does not provide a comparative study of naive per-pixel, matrix-based, and hybrid Machado + CLAHE color adaptation algorithms implemented on both CPU and GPU for HD, FHD, and 4K graphical interfaces. This determines the need for the present research.

Materials and methods of research. In this study, methods of comparative experimental analysis were applied to assess the efficiency of color adaptation algorithms for graphical user interfaces under different computing architectures. The naive per-pixel, matrix-based, and hybrid Machado + CLAHE algorithms were implemented for CPU and GPU execution using Python tools, including OpenCV, CUDA, and CuPy. Experimental testing was performed on HD, FHD, and 4K images for protanopia, deuteranopia, and tritanopia using a computing platform equipped with an AMD Ryzen 5 4600H processor and an NVIDIA GeForce GTX 1650 Ti Mobile graphics adapter. The execution time of each algorithm was measured by means of time.perf_counter, and the obtained results were compared according to processing speed and the visual preservation of local contrast after color transformation.

Research results and their discussion / Результати дослідження та їх обговорення

Methods for the inclusive adaptation of graphical user interfaces should be viewed as a multi-level system encompassing mechanisms (Figure 1): visual, auditory, motor, cognitive accessibility.

According to WCAG 2.2, the accessibility of digital content is not limited to color correction alone, but includes requirements regarding contrast, text scaling, alternative ways of presenting information, and accompanying text descriptions of multimedia content. For users with color vision impairments, visual adaptation methods are particularly important, including the safe selection of color palettes, increased contrast, duplicating color cues with text or graphic markers, and algorithmic color transformation.

Unlike static design solutions, algorithmic color adaptation allows for the type of color vision impairment to be taken into account and automatically adjusts the image representation. However, modern approaches have two typical limitations: either they do not preserve local contrast and natural colors, or they prove to be too computationally intensive for practical use in FHD and 4K interfaces. This is why combining a physiologically grounded color model with specific contrast restoration techniques and GPU-based acceleration is a promising approach.

Given the aforementioned classes of approaches, this paper examines a subset of methods pertaining to visual chromatic adaptation of user interfaces for individuals with CVD. The subject of further analysis is algorithmic color conversion techniques, as they specifically enable targeted image modification depending on the type of color perception disorder. Three algorithms were selected for the study: pixel-based, matrix-based, and a hybrid algorithm based on the Machado model with CLAHE. These approaches cover basic, optimized, and combined levels of implementation, which allows for a valid comparison in terms of adaptation quality and performance.

The main characteristics of the studied algorithms are summarized in a block diagram, which clearly illustrates the differences between basic and physiologically grounded approaches (Figure 2).

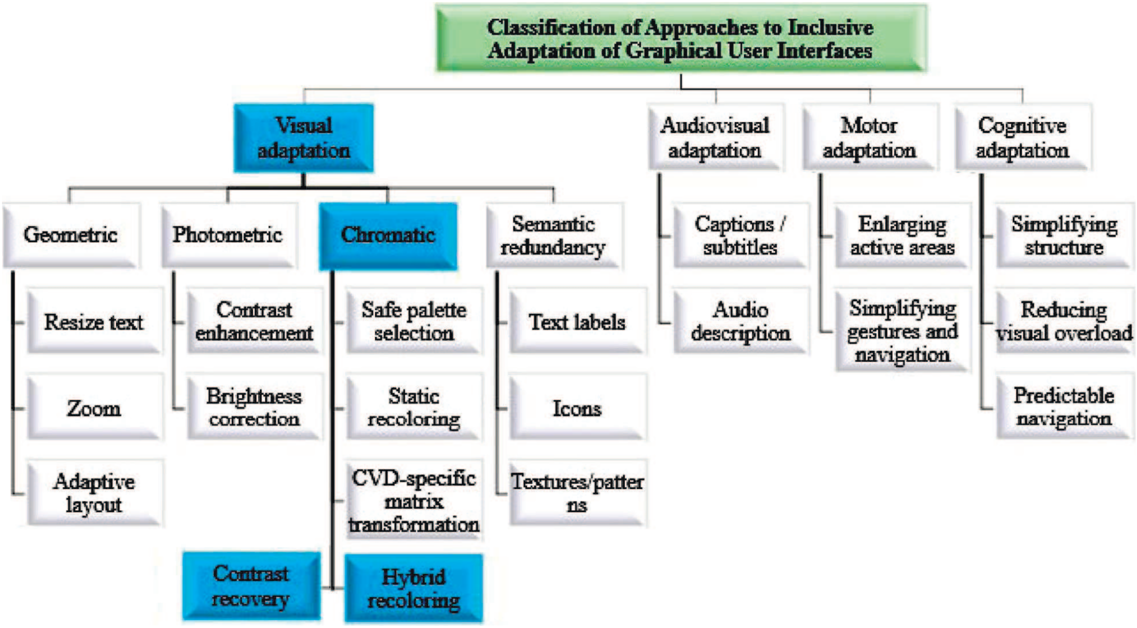

Fig. 1. Classification of approaches to inclusive adaptation of graphical user interfaces / Класифікація підходів до інклюзивної адаптації графічних інтерфейсів користувача

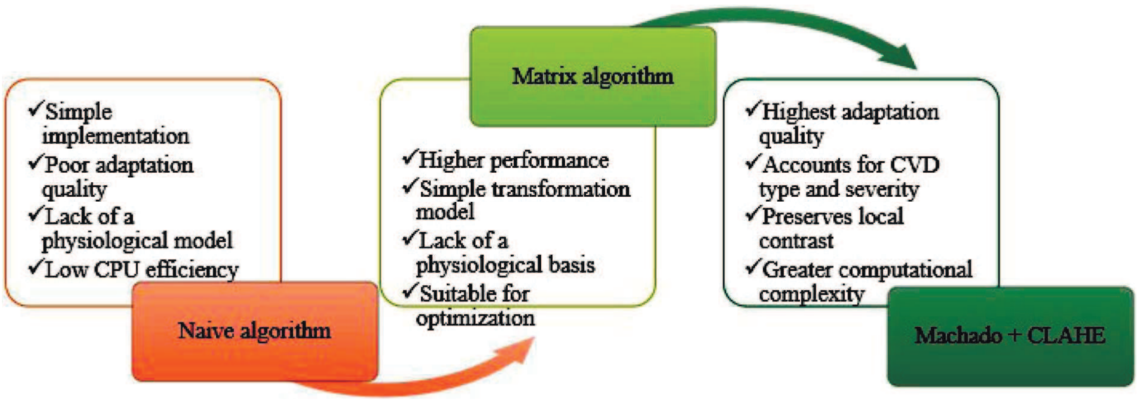

Fig. 2. Color conversion algorithms for implementation in a graphical user interface adaptation system / Досліджувані алгоритми кольорової конверсії для імплементації в систему адаптації графічних інтерфейсів користувача

To address the challenge of developing an accelerated GPU pipeline for color conversion of graphical user interface elements, a generalized and decomposed model of the software system for color adaptation of the graphical user interface was developed. At the top level, the system receives the input image, the CVD type, and the selected algorithm, and returns the adjusted image. In more detail:

- image preprocessing (linearization – only for the Machado algorithm);
- performing color transformation using the selected algorithm on the CPU or GPU;
- applying CLAHE (only for the Machado algorithm) and returning to the standard color space.

Figure 3 shows the generalized model, and Figure 4 shows a detailed view with decomposition into GPU pipeline blocks.

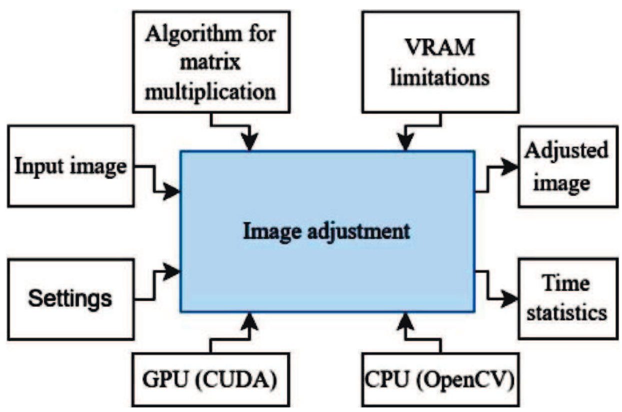

Fig. 3. Generalized model of the image adaptation system / Узагальнена модель системи кольорової адаптації зображення

The generalized diagram (Figure 3) illustrates the top-level function – image adaptation to a given type of color vision deficiency. The input data consists of an image in PNG or JPEG format, the type of CVD, and its severity. The control inputs are the matrix multiplication algorithm and VRAM limitations. The execution mechanisms are a CUDA-enabled graphics processor and a central processor with the OpenCV library. The system returns the corrected image and execution time statistics.

The detailed diagram (Figure 4) illustrates the internal GPU processing pipeline. The first step involves preprocessing – the image is converted into an array of normalized values, and the transformation matrix is loaded into video memory along with the input data. The second step is mass parallel transformation: the image is divided into blocks of pixels (the number of blocks depends on the resolution), and each block is processed independently on a separate GPU compute core. After the parallel computations are completed in the third step, the result is synchronized and transferred from video memory back to RAM. In the final fourth step, if the hybrid algorithm is selected, the central processor applies CLAHE adaptive histogram equalization to restore local contrast, after which the result is saved along with time statistics.

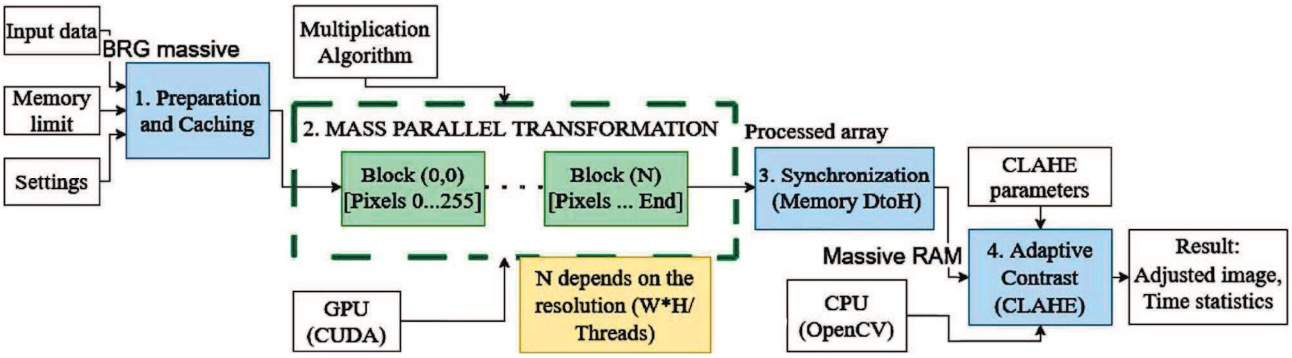

Fig. 4. A decomposed model of a color image adaptation system, adapted for GPUs / Декомпонована модель системи кольорової адаптації зображення, адаптована для ГПУ

A computing system supporting massively parallel computing based on an NVIDIA GeForce GTX 1650 Ti Mobile graphics adapter was used to conduct the experiments. This allowed us to evaluate the effectiveness of GPU acceleration when executing color conversion algorithms on images of various resolutions. The hardware specifications of the test bench are given in Table 1. The NVIDIA GeForce GTX 1650 Ti Mobile (launched 2020) is a mobile GPU based on the Turing architecture (TU117 or TU116 core) that provides decent entry-level capabilities for parallel processing. It was designed for laptops, often within a 35W–55W (up to 80W) power range, making it suitable for moderate computational experiments rather than extreme high-performance computing (HPC) workloads.

Table 1. Hardware specifications of the computers used / Апаратні характеристики використаних обчислювачів

Component	Characteristic	Value
Computing platform	System type	Laptop
Central processing unit (CPU)	Model	AMD Ryzen 5 4600H
	Number of cores / threads	6 / 12
	Base clock frequency	3.0 GHz
	Maximum clock frequency (Boost)	up to 4.0 GHz
Random access memory (RAM)	Capacity	16 GB
	Type	DDR4-3200
Graphics adapter	Model	NVIDIA GeForce GTX 1650 Ti Mobile
	Architecture	Turing (SM 7.5)
	Number of CUDA cores	1024
	Video memory capacity	4 GB
	Video memory type	GDDR6
	Memory bus width	128-bit
	Memory bandwidth	192 GB/s
	TDP	50 W

For the GPU versions, the CuPy library was used, which is essentially an analogue of NumPy but for graphics cards with CUDA. The naive algorithm on the GPU is implemented via a dedicated CUDA kernel, where each pixel is processed by a separate thread. The matrix and Machado algorithms are implemented via CuPy array operations.

To visually assess the performance of the algorithms, a comparative processing of a test image for the CVD protanopia type was performed at the maximum severity level on the GPU. This comparative processing involves using GPU acceleration (e.g., CUDA-based approaches) to simulate how individuals with severe Protanopia (red-blindness) perceive visual content. Such tests are designed to evaluate the efficiency and accuracy of simulation models like Brettel, Viénot, or Machado, which often struggle to distinguish between red and green colors at high severity.

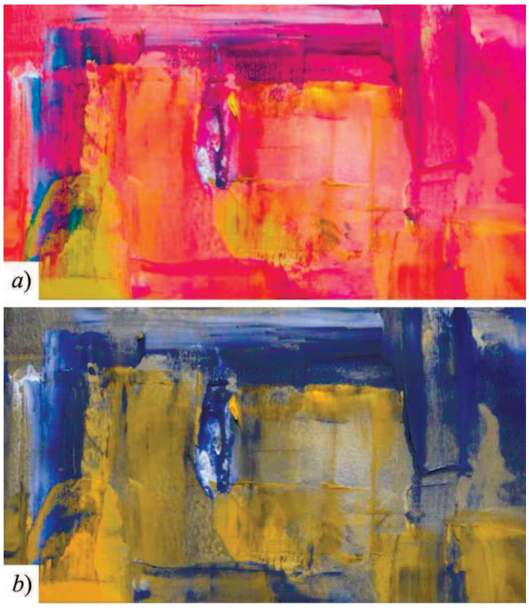

Fig. 5. Result of color conversion based on a matrix algorithm for protanopia on a GPU / Результат колірної конверсії на основі матричного алгоритму для протанопії на ГПУ

Figure 5 demonstrates the result of the matrix algorithm: the color palette has been altered – the warm red-pink tones of the original image have been transformed into a blue-yellow range characteristic of human perception with protanopia. However, in areas with smooth gradients, a partial loss of detail is noticeable due to uniform recoloring without accounting for local contrast.

The hybrid algorithm combining the Machado simulation model with Contrast Limited Adaptive Histogram Equalization (CLAHE) for protanopia (red-green deficiency) produces enhanced, daltonized images that significantly improve red-green contrast and color discrimination while preserving naturalness. When accelerated on a GPU, this approach allows for real-time video processing.

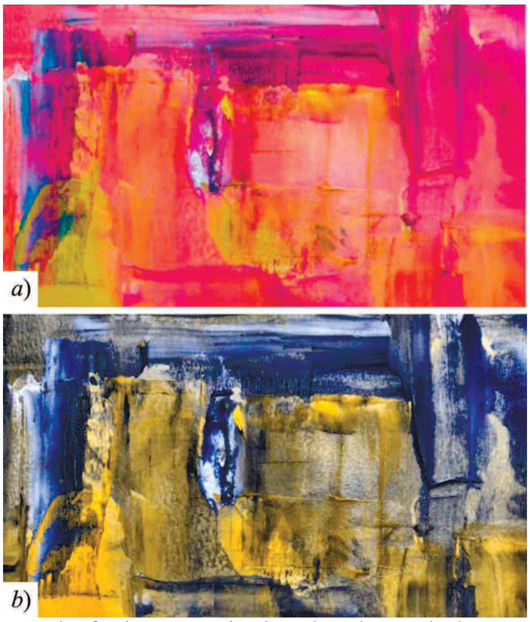

Fig. 6. Result of color conversion based on the Machado + CLAHE hybrid algorithm for protanopia on a GPU / Результат колірної конверсії на основі гібридного алгоритму Machado + CLAHE для протанопії на ГПУ

Figure 6 shows the result of the Machado hybrid algorithm with CLAHE: the color transformation is similar, but textural details and boundaries between zones are preserved much better thanks to additional contrast equalization. This confirms the practical advantage of the hybrid approach when adapting images for CVD users.

The *time.perf* counter function was used to measure the execution time of each algorithm. Testing was conducted on three image resolutions: HD (1280×720), FHD (1920×1080), and 4K (3840×2160). Each algorithm was run 5 times, and the average value was recorded in the table. All three types of color blindness were tested, but the results differed by less than 2 % between them, so Table 2 shows data only for protanopia.

Table 2. Comparison of computation times for protanopia, s / Порівняння часу обчислення для протанопії, с

Method	CPU HD	CPU FHD	CPU 4K	GPU HD	GPU FHD	GPU 4K	Speedup (4K)
Per-pixel	9.12	20.83	81.51	0.215	0.248	0.234	~349×
Matrix-based	0.024	0.051	0.174	0.030	0.054	0.076	~2.3×
Hybrid (Machado + CLAHE)	0.037	0.061	0.226	0.032	0.069	0.133	~1.7×

The table shows that the per-pixel method on the CPU is simply not practical – 80 seconds per 4K image is far too long (Figure 7,*a*). If we move this same algorithm to the GPU, it processes the same image in 0.23 seconds (Figure 7,*b*). This is ~349 times faster, which clearly demonstrates the effect of parallel pixel processing on the graphics card.

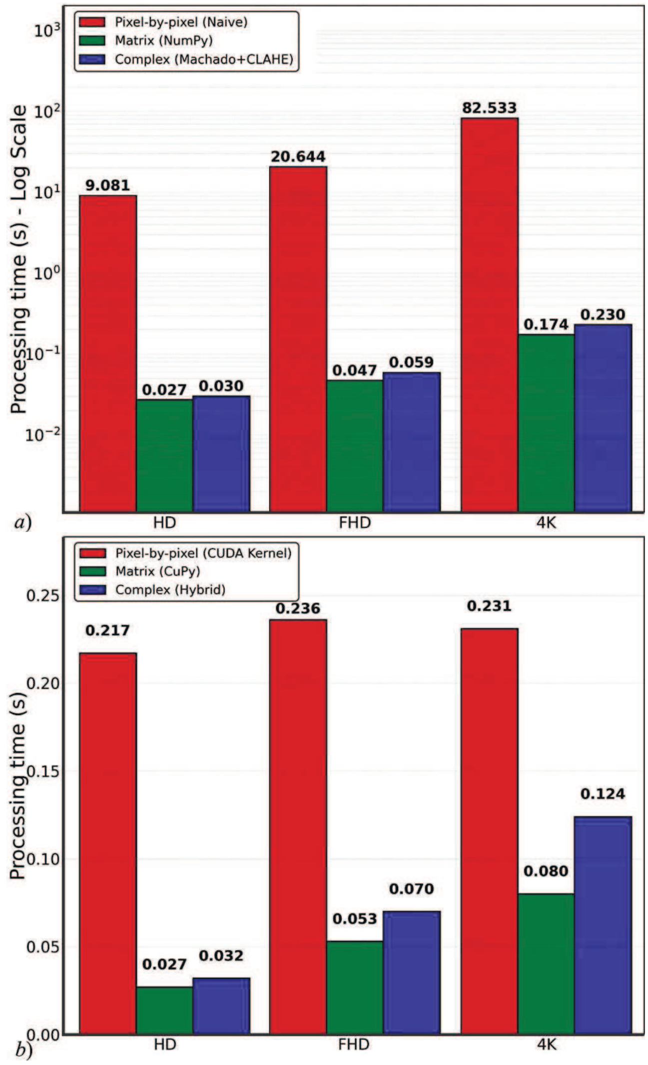

Fig. 7. Algorithm performance on / Продуктивність алгоритму на: a) CPU (logarithmic scale), s / ЦПУ (логарифмічна шкала), с; b) GPU (linear scale), s / ГПУ (лінійна шкала), с

The matrix method is more interesting. On HD images, the GPU is even slightly slower than the CPU (0.030 seconds vs. 0.024 seconds) – this is because copying data to video memory also takes time, and on small images this becomes noticeable. But on 4K, the GPU provides a 2.3x speedup, and the larger the image, the more noticeable the difference.

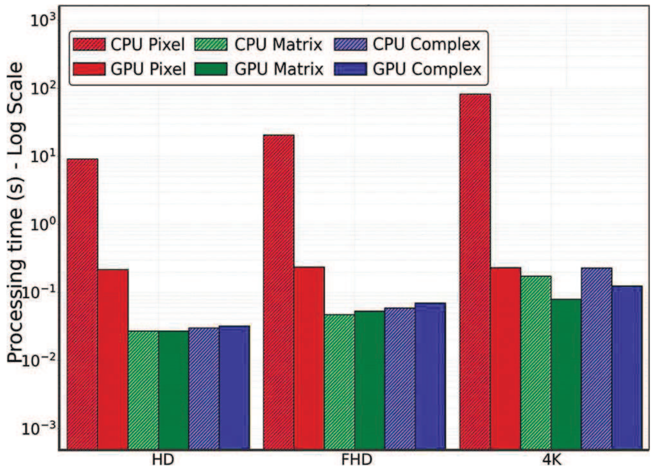

Fig. 8. Overall comparison of CPU vs. GPU for all methods (logarithmic scale) / Комплексне порівняння продуктивності ЦПУ та ГПУ для всіх досліджених методів (logarithmic scale)

The hybrid method on the GPU processes a 4K frame in 0.13 seconds. It is slightly slower than the matrix GPU

(0.076 seconds) because CLAHE is additionally performed on the CPU. However, the image quality is better – contrast is preserved, and interface elements appear clearer and more understandable to a person with color blindness after correction.

The overall comparison graph (Figure 8) clearly demonstrates the fundamentally different behavior of the algorithms when scaling resolution. The curve for the per-pixel algorithm on the CPU rises sharply on a logarithmic scale, while the corresponding GPU curve remains practically horizontal – the GPU effectively handles the increase in data volume thanks to massive parallelism. The matrix and hybrid algorithms show a significantly smaller gap between CPU and GPU, but even here the GPU's advantage at 4K is evident. The overall trend confirms: at HD resolution, the difference between platforms is minimal due to the overhead of data transfer, but starting with FHD and especially at 4K, the GPU becomes the only viable solution for practical use in real-time interfaces.

Discussion of research results. In the study [10] was shown that parallel image processing becomes more effective as image size increases, and the speedup for grayscale conversion rose from 1.1623 for 100×100 images to 3.1810 for 1000×1000 images. This agrees with the results of the present study, where the benefit of GPU acceleration was limited for HD images but became much more evident for FHD and especially 4K resolution.

In the paper [11] GPU-based color space conversion was found to be considerably faster than CPU-based execution, with the reported GPU speedup reaching approximately 3.45-9.59 tim12es depending on the mode. These results support the findings of the present study and confirm that color transformation tasks are well suited for massively parallel architectures.

In the study [12] the authors reported that optimized CLAHE improved SSIM by 24.69 %, PSNR by 24.36 %, and reduced LOE by 36.62 % compared with standard CLAHE. This confirms that CLAHE can improve local contrast and preserve important visual details, which is consistent with the results of the present study, where the hybrid Machado + CLAHE method provided better visual quality than simpler conversion schemes.

In the paper [13] was shown that redesigning GUI elements for colourblind users improves task performance, with an average efficiency increase of 1.5 % for desktop tasks and 12.84 % for Device Manager tasks. Although that study considered icon redesign rather than algorithmic color correction, it supports the practical importance of improving the visual accessibility of graphical interfaces for colourblind users.

In the study [14], adaptive interfaces for users with color vision deficiency improved productivity by up to 20 %, effectiveness by up to 85 %, and satisfaction for protanopia users by 40.54 %. These results confirm that color-adaptive interfaces are useful in practice and support the relevance of the present study, which addresses this problem from the standpoint of computationally efficient color transformation.

Thus, the analyzed studies confirm the relevance of the present research. Existing works separately demonstrate the advantages of parallel image processing, GPU-based color conversion, CLAHE-based contrast enhancement, and adaptive interface design for users with color vision deficiency. However, they do not present a combined comparative analysis of naive per-pixel, matrix-based, and hybrid Machado + CLAHE methods on CPU and GPU for HD, FHD, and 4K graphical interfaces. Therefore, the obtained results support the feasibility of GPU-accelerated color correction for inclusive graphical user interfaces.

Future directions for developing this topic involve implementing the developed and refined methods into a real software system, followed by experimental validation under practical conditions. Conducting field studies involving users with various types of color perception disorders is promising, as this will allow for evaluating the effectiveness of the proposed approaches not only in terms of computational metrics but also in terms of actual improvements in the contrast of interface elements. Special attention should be paid to analyzing how the methods perform on different types of screens, as the characteristics of color reproduction, contrast, and brightness of displays can significantly affect the outcome of color adaptation. This approach will enable a transition from laboratory evaluation to a comprehensive assessment of the practical suitability of the developed solutions under real-world operating conditions.

So, based on the results of the work performed, it is possible to formulate the following scientific novelty and practical significance of the research results.

Scientific novelty of the obtained research results – the has been refined of a hybrid method for the color adaptation of graphical user interfaces for users with color vision deficiency, which, unlike standalone per-pixel and matrix-based approaches, combines the physiologically grounded Machado model with CLAHE and is implemented as an accelerated GPU pipeline, thereby reducing the processing time of high-resolution images while preserving local contrast and the visual clarity of interface elements.

Practical significance of the research results – they can be used in the development and integration of inclusive software tools and services for graphical user interface adaptation in desktop and mobile applications, where GPU-accelerated color correction enables practically acceptable processing speed for FHD and 4K images and improves the readability of interface elements for users with color vision deficiency.

Conclusions / Висновки

The efficiency of color correction algorithms for adapting graphical user interfaces to various forms of color blindness depending on the selected computing architecture was investigated, which made it possible to formulate practical recommendations for selecting color correction algorithms and computing architecture for the development of inclusive graphical user interfaces. Based on the results of the research the following main conclusions can be drawn.

1. Analyzed approaches to the inclusive adaptation of graphical user interfaces made it possible to establish that algorithmic color transformation is the most appropriate direction for adapting interfaces to different types of color vision deficiency under conditions of widespread use of digital systems.
2. Developed accelerated GPU-based implementation of color transformation algorithms made it possible to establish that massively parallel architectures are the most effective for high-resolution image processing, since for 4K images the naive per-pixel algorithm achieved the greatest acceleration, reducing processing time from 81.51 s on the CPU to 0.234 s on the GPU.
3. Established comparative analysis of the naive per-pixel, matrix-based, and hybrid Machado + CLAHE methods showed that GPU acceleration becomes most justified for

FHD and 4K resolutions, whereas for HD images its advantage is reduced due to data transfer overhead.

4. Determined the hybrid Machado + CLAHE method provides the best balance between processing efficiency and visual adaptation quality, since it preserves local contrast and improves the visual clarity of interface elements while maintaining practically acceptable execution time.
5. Confirmed the obtained results demonstrate the feasibility of using GPU-accelerated color correction in inclusive graphical user interface adaptation systems intended for users with color vision deficiency.

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ДОСЛІДЖЕННЯ МЕТОДІВ КОЛІРНОЇ АДАПТАЦІЇ ГРАФІЧНИХ КОРИСТУВАЦЬКИХ ІНТЕРФЕЙСІВ

Проаналізовано підходи до колірної адаптації графічних користувацьких інтерфейсів для осіб із порушеннями кольорового зору. З'ясовано, що для практичного використання найдоцільнішими є алгоритмічні методи, здатні забезпечувати не тільки корекцію кольорів, а й прийнятну швидкодію під час оброблення зображень високої роздільної здатності. На відміну від повної втрати зору, кольорова сліпота не потребує створення нових програмно-апаратних рішень, а вимагає адаптації наявних графічних користувацьких інтерфейсів до конкретних типів порушення кольорового сприйняття, що робить проведене дослідження актуальним. У роботі досліджено особливості реалізації трьох алгоритмів колірного перетворення, а саме наївного попіксельного, матричного та гібридного методу на основі фізіологічно обґрунтованої моделі Machado і CLAHE. Розроблено пришвидшений GPU-конвеєр колірного перетворення елементів графічного інтерфейсу з використанням CUDA та CuPy. Проведено порівняльний аналіз продуктивності реалізацій на CPU та GPU для зображень з роздільною здатністю HD, FHD і 4K за умов протанопії, дейтеранопії та тританопії. Встановлено, що результати для різних типів порушень кольорового зору відрізняються незначно, тому репрезентативні дані подано для протанопії. Показано, що перенесення попіксельного алгоритму на GPU скорочує тривалість оброблення 4K-зображення від 81,51 с до 0,234 с, тобто приблизно у 349 разів. Визначено, що матричний метод забезпечує найменшу тривалість оброблення на GPU для 4K-зображень, однак гібридний підхід, у якому поєднано модель Machado та CLAHE, забезпечує краще збереження локального контрасту та візуальної виразності елементів інтерфейсу. Показано, що для HD-зображень перевага GPU є менш помітною через витрати на передавання даних, тоді як для FHD і особливо 4K використання графічного процесора є доцільним. Запропонований підхід можна використати під час розроблення інклюзивних програмних систем адаптації графічних інтерфейсів. Отже, запропонований гібридний підхід поєднує ефективну корекцію кольору зі збереженням контрасту завдяки використанню адаптивного вирівнювання гістограми CLAHE, що визначає його потенціал для інклюзивних систем дизайну графічного інтерфейсу користувача. Подальший розвиток цієї роботи передбачає інтеграцію результатів у широко використовувані програмні системи для забезпечення більш доступної та ефективної адаптації графічних інтерфейсів користувача.

Ключові слова: кольорова сліпота; пришвидшений GPU-конвеєр; CUDA; CuPy; матриці Мачадо; CLAHE; GUI; інклюзивність.