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Luminescent Wearables for Low-Light Visibility of Children

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Abstract

This study explores the development of luminescent wearables using machine embroidery with phosphorescent threads to enhance the visibility and safety of children in low-light environments, addressing the need for improved child protection in urban settings. Five embroidery designs incorporating sports, animal, celestial, and typographic motifs were created using Digitizer MBV 2.0 software and produced on a Janome MB4 embroidery machine with phosphorescent threads on black woven fabric for optimal contrast. The luminous performance was evaluated through photographic documentation and lux meter measurements in a controlled light-tight chamber, assessing light emission intensity and decay over time after UV activation. Results demonstrate that designs with higher stitch counts and densities exhibit stronger initial illuminance and longer persistence, with exponential decay curves highlighting rapid initial intensity loss. Variations in design size and stitch density showed linear correlations with illuminance. The study demonstrates the feasibility of luminescent embroidery as a scalable and child-friendly approach to enhancing low-light visibility and safety, combining functionality with aesthetic appeal.

Keywords: luminescent wearables; child visibility; low-light safety; machine embroidery; phosphorescent threads; textile engineering; smart textiles; design optimization; luminous performance

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1. Introduction

Ensuring the safety and visibility of children in traffic environments is of particular importance in urban areas, where the high concentration of vehicles, complex traffic patterns, and the presence of vulnerable road users make effective protective measures essential for preventing accidents and saving lives. Research consistently shows that driver fatigue impairs concentration and slows reaction times, posing significant risks in low-visibility conditions (e.g., inadequate or absent street lighting) and markedly increasing the likelihood of accidents involving children [1–3]. The situation becomes even more critical for those who attend school in alternating shifts or return home during late evening hours [4]. Their shorter stature, combined with rows of parked vehicles along the streets, considerably reduces their visibility to approaching drivers. In Bulgaria, numerous tragic incidents involving children on the road have been reported, many with fatal outcomes [5]. According to a European Commission report, vulnerable road users such as cyclists and motorcyclists remain among the most at-risk groups, while children are particularly exposed to danger in urban traffic [6]. These statistics highlight the urgent need for effective

measures to improve the visibility and protection of children under low-light and heavy-traffic conditions. Although educational programmes targeting different age groups have been implemented [7,8], in accordance with the National Road Safety Strategy [9], the need to enhance visibility remains pressing.

Despite the implementation of national road safety strategies, the problem of ensuring adequate visibility for children in low-light conditions remains insufficiently addressed. In particular, standardized requirements such as EN 1150:1999 for high-visibility clothing for children [10] emphasize the need for innovative, practical, and child-friendly design solutions that combine safety with everyday wearability. Nowadays, increasing attention has been focused on the integration of additional functionalities into children's clothing, aiming to combine aesthetic appeal with practical benefits such as safety, comfort, and enhanced visibility in low-light environments [11]. Reflective textile materials available on the market have been widely studied and are commonly incorporated into garments to enhance visibility [12–15]. These materials are typically classified as retroreflective or diffusely reflective, each offering distinct advantages and limitations. Retroreflective types offer excellent visibility under direct light but are angle-dependent, whereas diffuse reflectors provide broader light dispersion but lower overall reflectivity [12].

Reflective textiles are often woven and, in the form of stripes, are widely used in workwear, sports, and personal protective equipment [16]. Weaving typically allows for a high density of reflective threads, which increases surface coverage and, consequently, enhances the overall light-reflective performance of the strips [17]. However, a primary disadvantage of reflective textile materials is the limited variety in design, which can restrict their aesthetic appeal and adaptability across different garment styles. As noted in [12], most retroreflective materials used in visibility or safety clothing are applied in simple shapes, such as stripes or bands, with limited colour and pattern flexibility, which may reduce their acceptability among specific user groups, particularly children and teenagers. This limitation has encouraged research into alternative approaches that combine functional visibility with aesthetic value, especially for children's clothing intended for everyday use. Machine embroidery technology enables the creation of highly customized designs on a wide variety of textile products and offers significant potential for integrating both decorative and functional features. It allows for personalization even after the items have been fully manufactured, as demonstrated in a study of smart textiles and wearable applications using computer embroidery machines [18]. This flexibility makes it possible to adapt patterns, incorporate logos, or add decorative and functional elements to garments, home textiles, and accessories, thereby enhancing both aesthetic appeal and practical functionality. In the context of children's clothing, embroidery also provides an opportunity to integrate safety-related features, such as luminescent or reflective threads, without compromising visual attractiveness. Recent advances in the field of luminescent and light-emitting textiles have opened new opportunities for both functional and decorative applications in clothing and wearable design. Phosphorescent, fluorescent, and reflective threads are now commercially available and can be applied in machine embroidery to create visually distinctive and safety-enhancing textile elements [19]. Luminous substances containing luminescent pigments or dyes absorb light and gradually emit it, thereby enhancing the wearer's visibility and safety in low-light conditions [20]. Luminescent materials are classified into chemiluminescent (including bioluminescent), photoluminescent, thermoluminescent, triboluminescent, crystalloluminescent, and electroluminescent groups based on their excitation source [21]. Specifically, the group of photoluminescent materials is divided into fluorescent and phosphorescent types, which differ primarily in the duration and mechanism of light emission: fluorescent materials emit light only during the excitation, while phosphorescent materials store energy and release it gradually over time [21]. Such

materials offer promising possibilities for children's clothing, where continuous visibility and engaging visual design are equally important.

Among the various luminescent materials, phosphorescent threads are particularly suitable for wearable applications due to their ability to store light energy and emit it gradually over time, thus improving visibility and recognition of the wearer in low-light environments [19–21]. These threads can be integrated into garments through machine embroidery—a versatile technique that allows for post-production customization and the creation of visually engaging, design-rich elements [18]. Recent research explores the application of photoluminescent threads in embroidery, demonstrating their potential to enhance the visibility, functionality, and aesthetic appeal of textiles [22,23]. However, limited attention has been given to their use in children's garments or to the quantitative evaluation of their luminous performance, which represents an important gap in current research.

Our study aims to explore the feasibility of using phosphorescent threads in machine embroidery to enhance the visibility and safety of children in low-light environments. The research focuses on the development and evaluation of luminescent embroidered emblems featuring child-friendly and visually attractive motifs, examining how design parameters (e.g., stitch density and motif size) influence luminous performance. Through controlled measurements and visual analysis, the study seeks to establish practical guidelines for optimizing luminescent wearable designs intended for children's clothing. By combining functional illumination with engaging aesthetics, our research contributes to the advancement of customizable textile solutions that support child visibility and protection, particularly in conditions where traditional materials may be limited in effectiveness or user acceptance.

2. Materials and Methods

2.1. Design Methodology

The transformation of a conceptual embroidery design into a machine-executable pattern requires a structured approach supported by specialized software tools. In this study, the designs were created using Digitizer MB v2.0 and translated into stitch patterns compatible with the Janome MB4 embroidery machine (JANOME Corporation, Tokyo, Japan). The design process is organized into six clearly defined stages, illustrated in Figure 1:

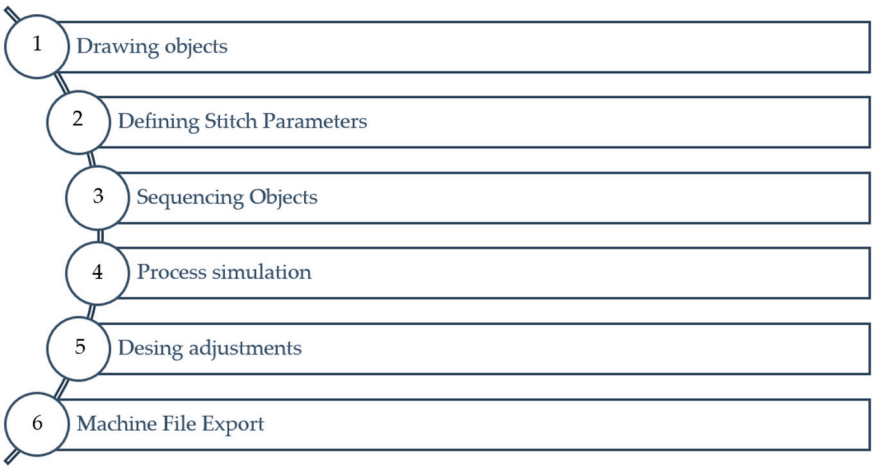


Figure 1. Main stages of creating a new project.

- Drawing Objects—The initial stage involves creating graphical representations of the design elements using appropriate shapes and colour palettes. This step defines the intended appearance of the final embroidery.

- Defining Stitch Parameters—Each object is digitized into stitch rows, where the stitch type (e.g., running, satin, fill) and technical parameters such as stitch length, density, and angle are specified. These settings directly influence the texture and durability of the embroidery.
- Sequencing Objects—The digitized components are then arranged in a logical production order. This sequencing minimizes machine downtime by reducing thread trims and colour changes and ensures optimal stitch continuity.
- Process Simulation—A software-based simulation of the embroidery process is performed to visualize the design in motion. This stage helps identify technical issues such as overlapping stitches, high-density areas, unintentional gaps, or improper sequencing of the objects.
- Design Adjustments—If inconsistencies or inefficiencies are detected during simulation, adjustments are made to the design parameters or object arrangement to improve stitch quality and overall execution.
- Machine File Export—Once finalized, the design is exported as an embroidery machine file (e.g., .DST, .PES, .JEF), which contains all necessary control data for automated production.

This structured approach enables the precise translation of artistic concepts into machine-executable stitch patterns, ensuring high quality and production efficiency in machine embroidery.

2.2. Materials

Five embroidery designs were developed using a simplified two-colour scheme: white (luminescent thread) and black (polyester thread). The use of black as the base colour was chosen to ensure maximum visual contrast, as black absorbs all visible wavelengths and reflects none. Thus, it creates a strong visual contrast with the luminescent elements and enhances the perceptibility of the luminescent areas under low-light conditions. Table 1 summarizes the technical characteristics of the threads used to produce the embroidery samples (as provided by the manufacturers).

Table 1. Characteristics of the threads used for the embroidery samples provided by the producers.

Threads	Composition	Count, dtex	Tensile Strength, cN	Elongation, %
Regular thread in black colour, Isacord, Amann group	Polyester 100%	135 × 2	-	-
Luminous thread Luna, Madeira	Polybutylene terephthalate 60%, Polypropylene 40%	150 × 2	580	40

The used luminous thread employs strontium aluminate-based pigments, known for their characteristic green emission with a peak at approximately 520 nm (FWHM ~100 nm, range 450–650 nm) and broad excitation spectrum spanning 250–450 nm, with optimal absorption at 365 nm [20,21,24]. In the literature [19,24], the cyclic luminescent stability of the thread over 10–20 cycles has been reported, indicating a retention of 90–95% of the initial luminance after 20 cycles of UV charging, which is attributed to its robust polymer encapsulation.

The Luna thread complies with OEKO-TEX Standard 100, Class I, ensuring safety for direct skin contact in children's products, free from harmful substances such as heavy metals or azo dyes [25].

2.3. Methods

2.3.1. Machine Embroidery Techniques for Creating Luminescent Wearables

The creation of luminescent wearable elements was achieved using machine embroidery technology, enabling precise integration of phosphorescent threads into textile surfaces. The Janome MB4 embroidery machine used in this study has four needles and a maximum operation speed of 800 rpm. A view of the machine setup is shown in Figure 2.



Figure 2. View of the used Janome embroidery machine MB4.

The production workflow follows the methodology outlined in Figure 1, with pattern digitization and programming performed using the Digitizer MB V 2.0 software by Janome. All designs were embroidered on black woven fabric with a tear-away stabilizing backing, applied on the reverse side. Black woven fabric was selected as the base material due to its ability to provide maximum contrast, thereby enhancing both the perceptibility and the measured intensity of the phosphorescent threads' luminous effect under dark conditions. The high absorptivity of black surfaces minimizes unwanted light reflection, allowing for more accurate evaluation of emitted light from the embroidery samples in subsequent testing. The woven substrate is a 100% cotton twill 3/1 fabric, with mass per unit area of 250 g/m^2 and thickness of 0.56 mm.

2.3.2. Development of Embroidery Designs

The embroidery designs included sports motifs, animals, celestial bodies, and typographic elements, reflecting a range of interests commonly observed among children. Athletic themes were emphasized due to their broad appeal. These designs were chosen to align with gender-based preferences in preliminary user observations, aiming to increase engagement and emotional connection with the final product.

Contrasting visual elements were used to support intuitive recognition and enhance aesthetic appeal under varying lighting conditions. The Chicago Bulls logo was included for research purposes only, as it is copyrighted material and cannot be used without permission.

All designs are presented in Figure 3. They were embroidered using weave stitch lines, except for Sample 3, where satin and triple run stitch lines were applied. With weave stitches, the shapes are fully filled and form a continuously embroidered surface. Stitch parameters for each design are summarized in Table 2.

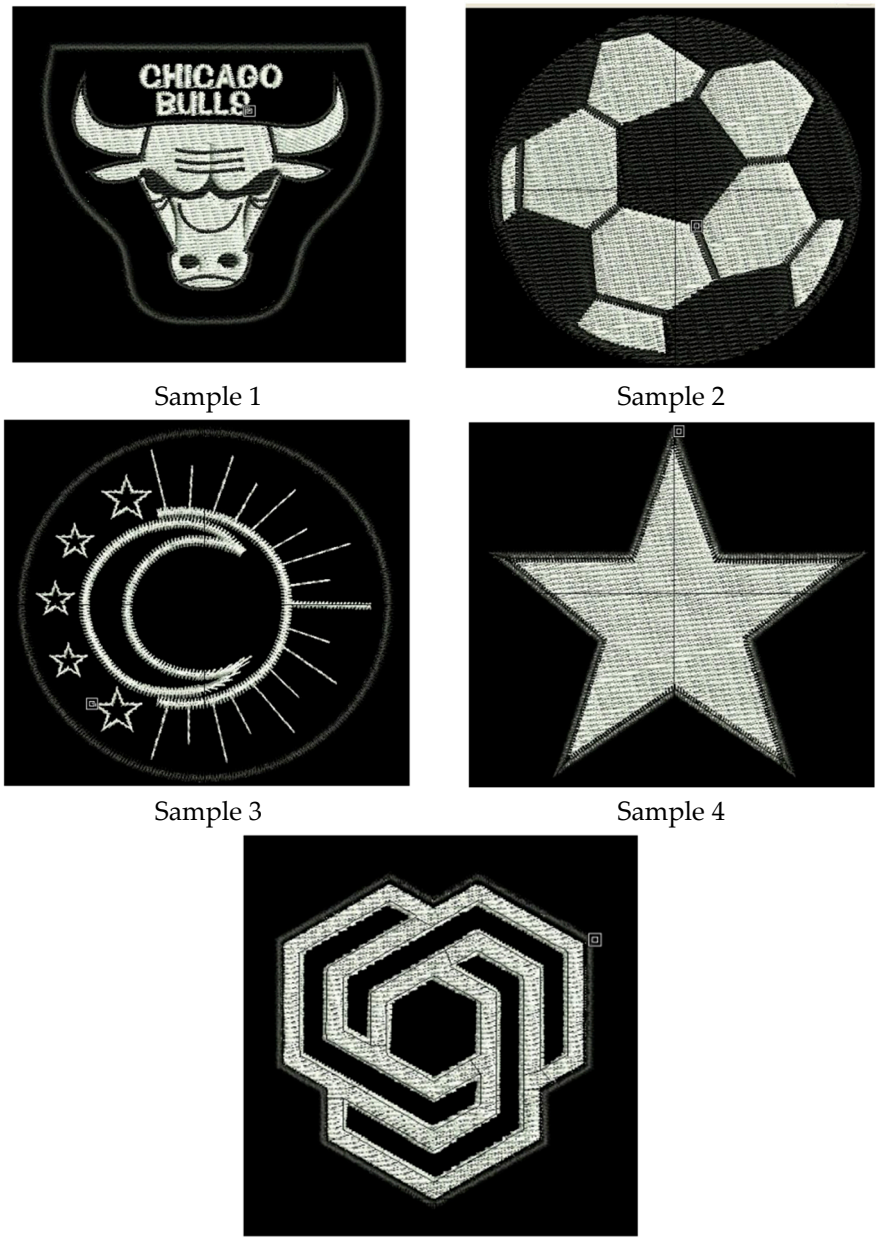


Figure 3. The developed designs. The Chicago Bulls logo is included solely for research purposes and educational illustration (copyrighted material, not used for commercial purposes).

Table 2. Parameters of embroidery samples.

Embroidery Designs	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Overall dimension, mm	77 × 65	60	50	49 × 46	50 × 54
Consumption of luminous thread, m	19.79	18.9	6.23	10.34	16.88
Number of stitches with luminous thread	3901	3240	1648	1702	3318
Stitch type	Weave	Weave	Satin and triple run stitch	Weave	Weave
Underlay stitches	Edge run + weave	Edge run + weave	Center run	Edge run + weave	Edge run + weave
Stitch density, mm	0.4	0.4	105% for satin	0.4	0.4
Stitch length/width, mm	4.2	4.2	1.0 for satin 2.00 for tripple run	4.2	4.2

All designs are suitable for the creation of embroidered emblems, which can be either sewn or heat-applied onto various types of garments and textile products such as jackets, backpacks, caps, and many others.

Additionally, to explore the effect of stitch density and object size on luminous performance, two sets of four variations of Sample 4 were developed. The remaining parameters were unchanged. The first set, featuring variations in stitch density, is presented in Figure 4.

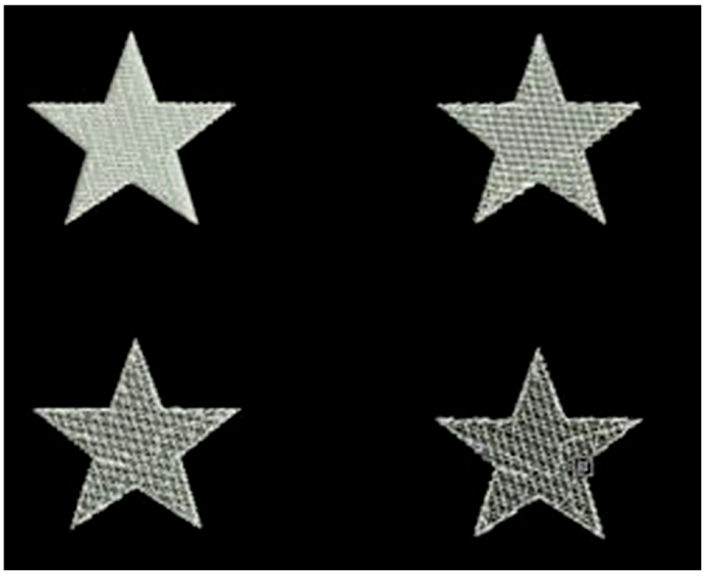


Figure 4. Four additional samples of Sample 4 showing variations in stitch density.

The overall dimensions and the consumption of the luminous thread, specified for each design, are shown in Tables 2 and 3. The stitch density is expressed as a percentage for the satin line, whereas for the other stitch types it is reported in millimetres.

Table 3. Parameters of the additional samples of Sample 4.

	Size 1	**Size 2**	**Size 3**	**Size 4**
Overall dimension, mm	59.7 × 56.3	49 × 46	39 × 36.8	34.9 × 32.9
Number of stitches	2368	1702	1181	1011
Consumption of luminous thread, m	14.9	10.34	6.92	5.73
	Density 1	**Density 2**	**Density 3**	**Density 4**
Stitch density, mm	0.4	0.7	1.0	1.5
Number of stitches	1011	663	616	491
Consumption of luminous thread, m	5.73	3.76	3.2	2.55

Among all samples, Sample 1 had the largest dimensions and the highest consumption of the luminescent thread, while Sample 3 had the lowest values for both characteristics.

2.3.3. Measuring the Luminous Effect

The luminous effect was evaluated using two methods. The first method employs a digital camera to capture images of the samples in a darkened environment. It provides a practical approach for visual comparison and detailed examination, as well as offers a reliable basis for qualitative assessment. This technique, consistent with approaches adopted in prior studies [26–28], was employed to additionally evaluate the planar uniformity of the emitted light across the embroidered wearables using ImageJ (Fiji distribution, version 1.54g, National Institutes of Health, Rockville, MD, USA). The acquired photographs were first converted to 8-bit grayscale, and a thresholding procedure was applied to iso-

late the luminescent areas from the background. Key parameters, including the mean gray value, standard deviation of gray values, and minimum/maximum intensity values, were extracted. The second method involves measuring the light intensity of the embroidered samples using a lux meter, which offers quick and direct readings of illuminance in lux [21,24]. The lux meter assures objective comparison between different thread types, exposure durations, and design densities. Its application is advantageous due to its simplicity, portability, and real-time response; however, it is limited to measuring total illuminance and does not provide spectral characteristics. A lux meter, model LX1010BS, was used in the study.

To eliminate the influence of ambient light and ensure high accuracy and repeatability of results, the measurements of the light emission were conducted in a controlled environment. For this purpose, a custom-built light-tight chamber (Figure 5) was used, with anti-reflective coatings on the internal surfaces to minimize reflections and improve measurement accuracy. The embroidery sample, along with the lux meter sensor, was placed inside the chamber. The distance between the sensor and the sample was adjustable and set to 100 mm, as indicated in Figure 6.

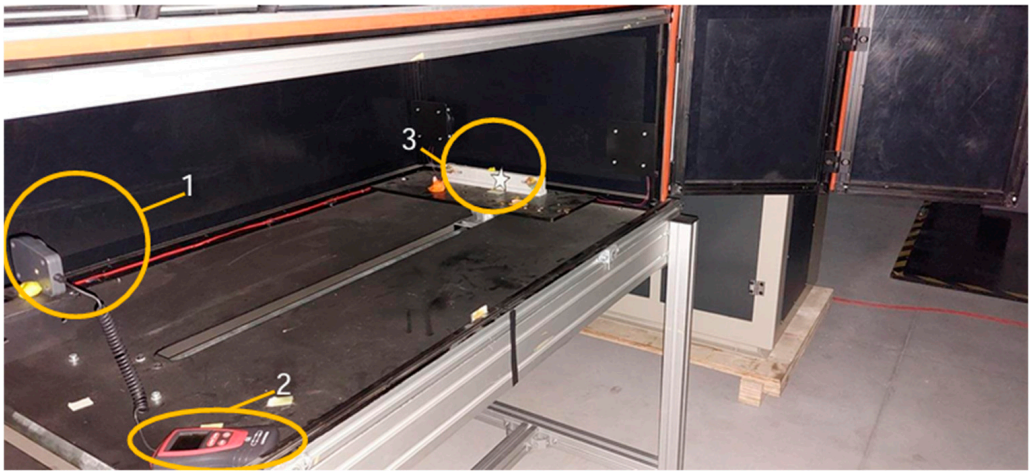


Figure 5. Experimental chamber with anti-reflective coating: 1—sensor, 2—measurement device, 3—sample.

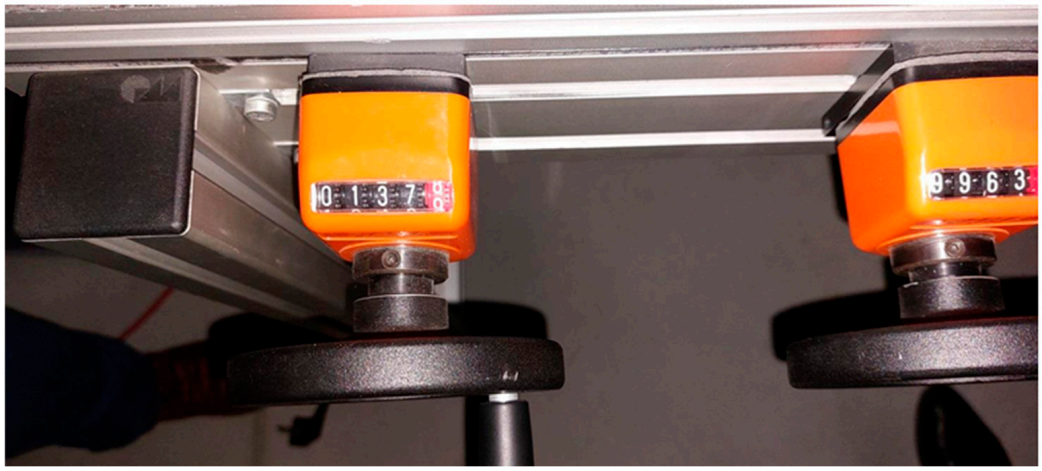


Figure 6. Indicator for the distance between the sensor and the measured object.

The phosphorescent sample was placed at the end of the chamber and exposed to a UV light source with controlled intensity to pre-charge the luminescent pigments for 3 s. Afterward, the light source was turned off, and the emission from the sample was measured.

Measurements were recorded over time to analyze the temporal emission (phosphorescence) of the threads, enabling evaluation of both the duration and intensity of the light emitted after the stimulating source was turned off. To determine the maximum intensity of the emitted light, five measurements were taken.

3. Results

3.1. Manufacturing of the Embroidery Patterns

At each startup of the embroidery machine, the hoop positioning system automatically moves to its home (initial) position. Once the design programming is complete, the corresponding machine file is uploaded to the MB4 embroidery machine. The required design is selected using the machine's built-in controller (Figure 7), initiating the production process.



Figure 7. Controller of the embroidering machine.

Each program contains information about the number of objects arranged in the stitching sequence, the colour number assigned to each object, the X and Y coordinates of the hoop positioning system before each needle penetration (i.e., before creating an individual stitch), and other relevant parameters.

The following key settings can be adjusted: reordering the sequence of object stitching, assigning the needle/thread for each object, setting the embroidery speed, and modifying the design size.

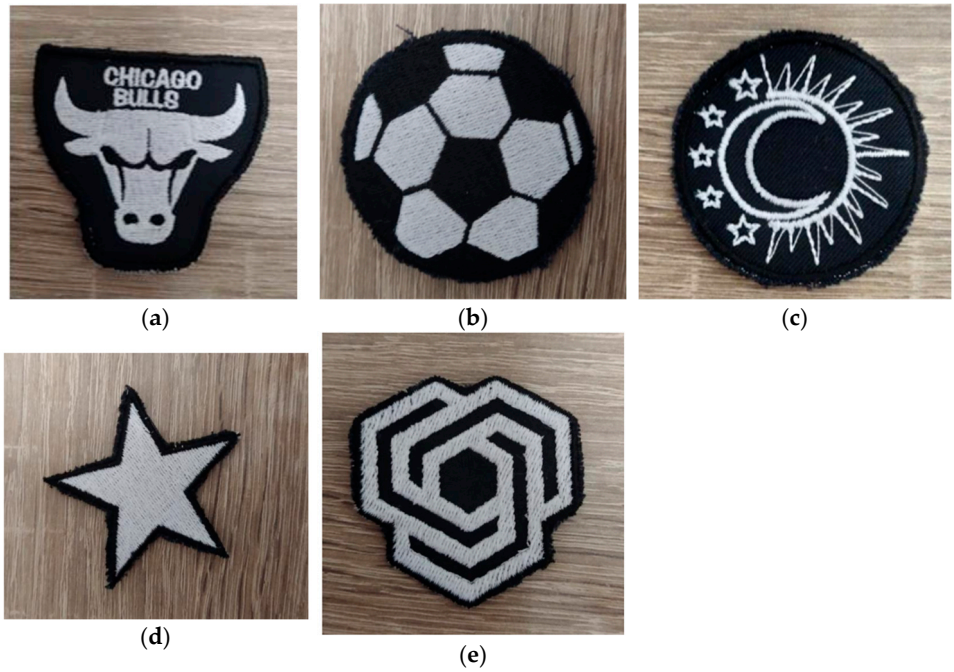
After production, visual quality control was performed. The samples were inspected for conformity with the programmed shapes and dimensions. Any surface irregularities or technical defects were identified at this stage.

The embroidery process was carried out at a speed of 600 rpm, as the stitch length accuracy is ± 0.1 mm. The thread tension was calibrated to achieve balanced stitches, eliminating loose stitches or puckering.

The total production time for each of the five samples is summarised in Table 4, and the completed embroidered samples are shown in Figure 8.

Table 4. Production time.

Embroidery Samples	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Production time, min	22	26	9	11	24

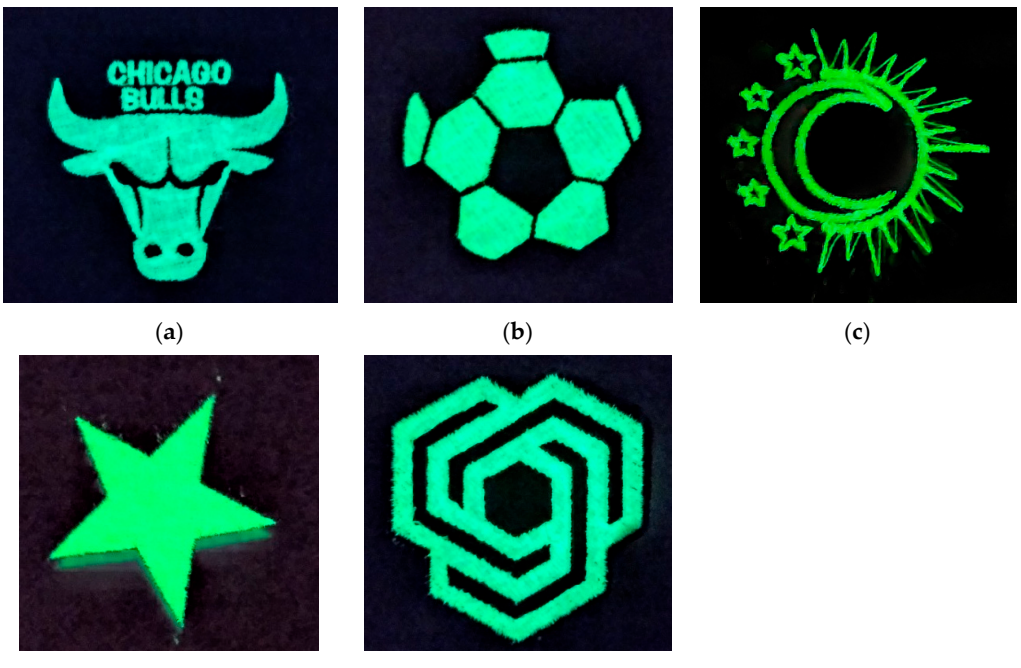


(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 8. The produced embroidered samples: (**a**) Sample 1; (**b**) Sample 2; (**c**) Sample 4; (**d**) Sample 3; (**e**) Sample 5.

3.2. Luminous Performance of Phosphorescent Thread Embroidery

The samples were initially photographed using a digital camera. Figure 9 shows images of the embroidered samples while exhibiting a luminescent effect after activation with UV light.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 9. Images of UV-light-charged designs: (**a**) Sample 1; (**b**) Sample 2; (**c**) Sample 4; (**d**) Sample 3; (**e**) Sample 5.

Figure 10 illustrates the temporal evolution of the luminous effect. Although the intensity decreased significantly after 8 min, all samples—except for Sample 3—remained discernible for approximately 18 to 20 min.

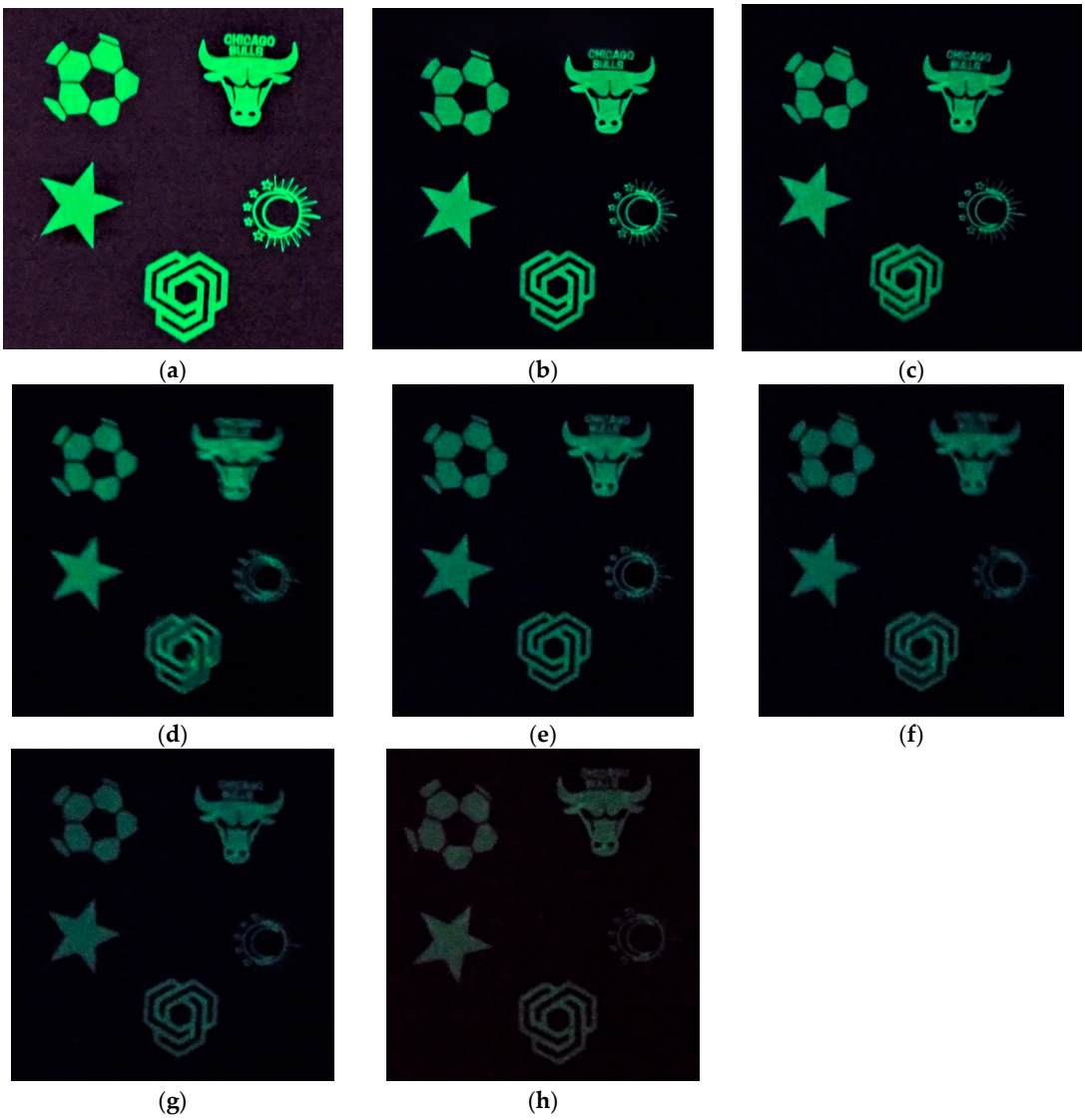


Figure 10. Images of UV-light-charged designs. (**a**) after charging; (**b**) after 2 min; (**c**) after 3 min; (**d**) after 4 min; (**e**) after 5 min., (**f**) after 6 min, (**g**) after 7 min, (**h**) after 8 min.

Table 5 summarises the results of the measurements of light intensity decay immediately after UV activation for all five samples. The data provide a quantitative view of the rate at which the luminescent emission decreases over time. These results are essential for evaluating the persistence of the phosphorescent effect in the tested samples. The corresponding phosphorescence decay curves are shown in Figure 11. All curves have a characteristic exponentially decreasing shape, indicating a rapid decrease in light intensity at the beginning, after which the rate of decline slows. This is typical of luminescence decay processes, in which the energy stored in the threads is gradually released as light.

The analysis of Figure 11 also shows that Samples 1 and 5 maintained the highest illuminance values throughout the entire measurement period. This result can be attributed to their larger stitch count and higher embroidery density, associated with the used weave stitch. In contrast, Sample 3 exhibited the lowest initial intensity and the fastest decay, corresponding to its lower density and the use of satin and triple run stitches. Samples 2 and 4 demonstrated intermediate behaviour with a gradual decrease in illuminance. These results confirm that both stitch density (and the associated thread consumption) and stitch type (weave, satin, etc.) play a crucial role in maintaining visible emission over time.

Table 5. Decay of the emitted light intensity over time.

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5	
Illuminance, lux	**Time, s**	**Illuminance, lux**	**Time, s**	**Illuminance, lux**	**Time, s**	**Illuminance, lux**	**Time, s**	**Illuminance, lux**	**Time, s**
0.25	2	0.25	1	0.12	1	0.25	2	0.25	2
0.19	6	0.12	7	0.09	5	0.20	5	0.20	7
0.12	13	0.09	12	0.08	6	0.12	15	0.12	16
0.11	15	0.07	15	0.07	7	0.09	19	0.11	20
0.09	20	0.06	18	0.06	9	0.08	22	0.09	24
0.08	23	0.05	20	0.05	12	0.07	28	0.07	33
0.07	27	0.04	29	0.04	14	0.06	30	0.06	40
0.06	31	0.03	40	0.03	16	0.05	37	0.05	45
0.05	38	0.02	51	0.02	25	0.04	45	0.04	58
0.04	46	0.01	80	0.01	35	0.03	56	0.03	70
0.03	58					0.02	96	0.02	95
0.02	78					0.01	111	0.01	137
0.01	115								

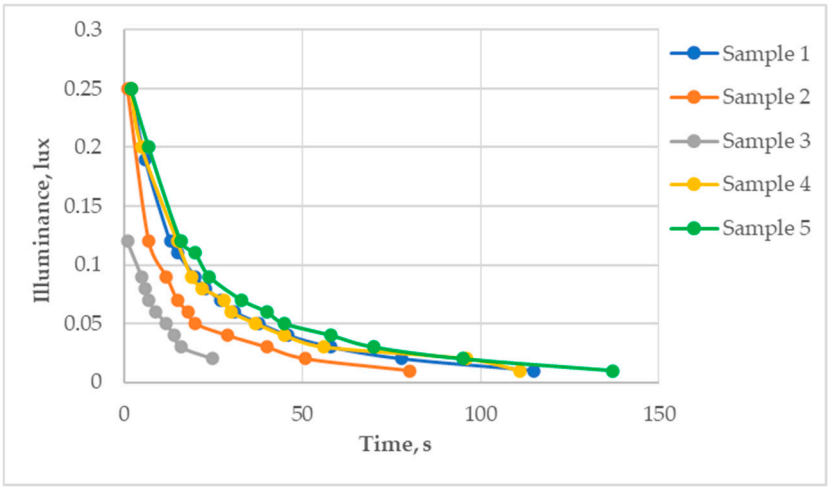


Figure 11. Phosphorescence decay curves.

Figure 12 illustrates the relationship between maximum illuminance and stitch count based on design size variations of Sample 3. The results indicate that larger embroidered areas created with phosphorescent thread produce higher levels of light intensity. This trend confirms the direct influence of design size on perceived brightness and demonstrates that increasing the number of stitches enhances the overall luminous effect.

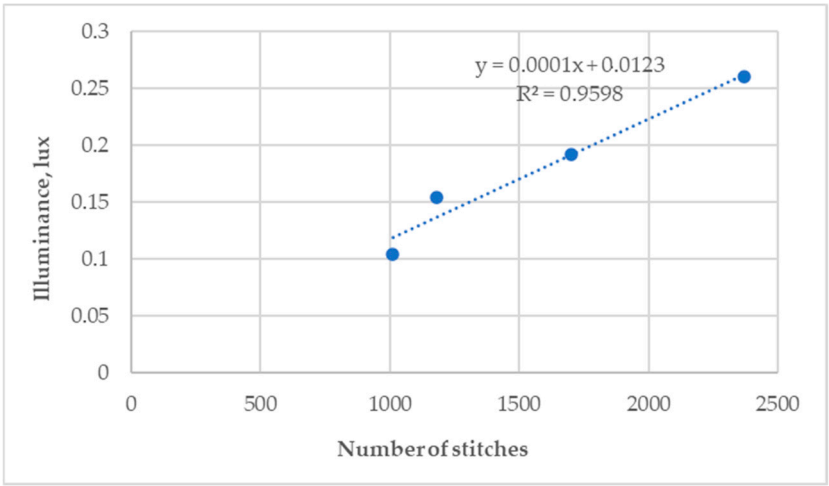


Figure 12. Dependence between the illuminance and the number of stitches by changing the design size of Sample 3.

Moreover, an almost perfect linear dependence was observed between the two variables: the number of stitches (x) and the measured illuminance (y, in lux), with a coefficient of determination $R^2 = 0.96$. The relationship is described by the following linear equation:

$$y = 10^{-5}x + 0.0123 \quad (1)$$

where x is the number of stitches and y is the maximum illuminance (lux).

This model provides a reliable tool for planning luminescent embroidery, allowing for straightforward estimation of the achievable illuminance for a given stitch count. The observed relationship is essential for optimizing design parameters to reach the desired level of visibility and aesthetic appeal.

Figure 13 illustrates the relationship between maximum illuminance and stitch count for variations in stitch density within Sample 3. At a fixed design size and varying stitch densities, a positive linear trend was observed: illuminance increased as the number of stitches rose.

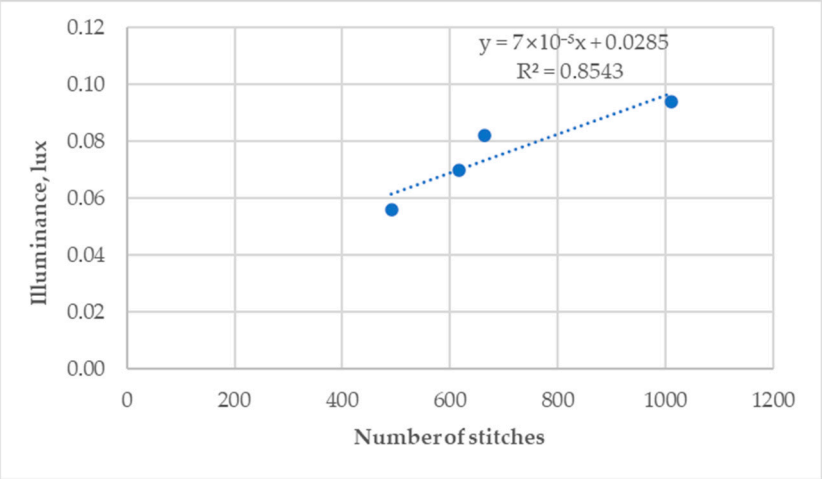


Figure 13. Dependence between the illuminance and the number of stitches by changing the stitch density.

The derived relationship is described by the following linear equation:

$$y = 7 \times 10^{-5}x + 0.0285 \quad (2)$$

where x is the number of stitches and y is the maximum illuminance (lux).

The high coefficient of determination ($R^2 = 0.85$) indicates that, within the scope of this experiment, stitch count accounts for a substantial portion of the variation in illuminance. These results highlight that stitch density is a critical factor influencing the luminous performance of phosphorescent embroidery. Understanding this relationship supports the optimization of stitch parameters in the development of luminescent and safety wearables, where designers must balance thread consumption and light output.

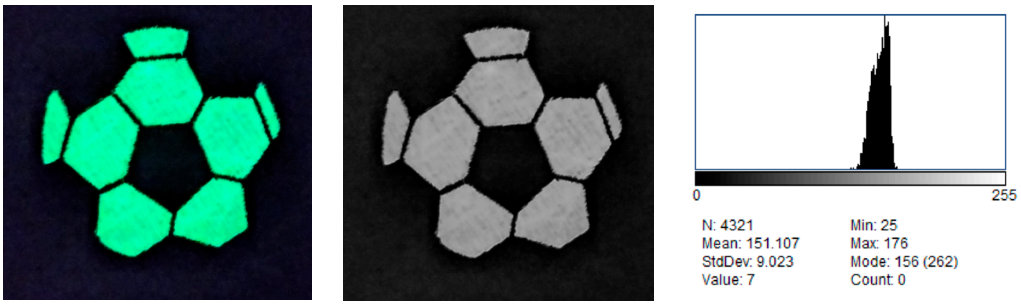
The spatial uniformity of the illuminous effect is assessed by analysing the digital images of the samples using ImageJ software. Some of the processing steps are presented in Figure 14.

To provide a quantitative measure of the luminance distribution, a uniformity index (U) was calculated for each sample according to the following equation:

$$U = 1 - \frac{StdDev}{Mean} \quad (3)$$

where StdDev denotes the standard deviation of gray values within the luminescent region and Mean represents the corresponding mean gray value.

A U value close to 1 indicates higher uniformity of light emission, while a lower U value corresponds to stronger local variations in brightness. The results obtained for all samples are summarized and presented in Table 6.



(**a**) (**b**) (**c**)

Figure 14. Image processing for Sample 2 for quantitative analysis using ImageJ software: (**a**) original image, (**b**) transformed image in grayscale; (**c**) histogram.

Table 6. Quantitative analysis of luminance uniformity for embroidered wearables.

No	Mean Gray Value	Standard Deviation	Min	Max	Uniformity Index
Sample 1	149.765	13.405	11	178	0.91
Sample 2	151.107	9.023	25	176	0.94
Sample 3	123.015	27.024	37	134	0.78
Sample 4	139.629	12.049	5	183	0.91
Sample 5	149.601	10.142	21	174	0.93

The analysis shows that the embroidered phosphorescent motifs have generally uniform illumination, as reflected by the high uniformity index values for all samples (0.91–0.93), except for Sample 3 (0.78). This lower value can be attributed to the applied stitch type, which does not completely cover the areas with phosphorescent thread. As a result, the overall visual consistency of the luminous effect is slightly compromised.

4. Discussion

The integration of phosphorescent threads into machine embroidery presents a promising approach for designing wearables that combine functionality with aesthetic appeal, improving visibility in low-light environments. All the tested samples exhibited a rapid decay in illuminance within the first few minutes after UV activation, consistent with the inherent properties of phosphorescent materials.

Sample 3, which employed satin and triple run stitches, showed the fastest decay and lowest persistence due to its low stitch density and unfilled structure, resulting in a reduced luminescent surface area. Conversely, Samples 1 and 5, featuring fully filled weave stitches and high thread consumption, sustained greater luminance over extended periods, confirming that higher stitch count and density enhance luminous performance.

The ImageJ analysis confirmed that the embroidered wearables exhibited generally high luminance uniformity, with calculated uniformity indices from 0.78 to 0.93, indicating that the luminous effect was evenly distributed across the stitched areas. The variations observed in Sample 3 are attributed to the specific stitch line configuration, which locally reduces the homogeneity of the emitted light.

The determined strong linear correlations (R^2 = 0.96 between design size and Illuminance, and R^2 = 0.85 between stitch density and illuminance) provide actionable design guidelines, enabling precise optimization of visibility while minimizing material costs.

Our research prioritizes child-oriented designs featuring engaging motifs, aiming to increase acceptance and encourage consistent use. This approach effectively overcomes key limitations of traditional reflective materials, such as their restricted design versatility and pronounced angle dependency, which demand direct external light sources for activation.

Using a black base fabric maximized contrast and enabled accurate measurements. However, practical applications may necessitate testing across diverse garment colours and dynamic real-world conditions, including motion and ambient light interference.

The successful integration of Sample 2 onto a children's backpack (Figure 15) demonstrates the adaptability of phosphorescent embroidered emblems for everyday textile items such as jackets, caps, and school bags. To address the brief maximum intensity duration (typically 5–10 s), incorporating intermittent UV recharging mechanisms could enhance functionality. However, further research is needed to ensure safety and energy before implementation in consumer products.



Figure 15. Example of sewing an embroidered emblem (Sample 2) to a children's backpack. In addition, the results of the study indicate potential opportunities for alternative applications, such as interior decoration and child-friendly environments, where photoluminescent wearables may provide both aesthetic value and functional comfort.

5. Conclusions

Our study demonstrated the feasibility of using phosphorescent threads in machine embroidery to enhance the visibility of children in low-light conditions. Five embroidered designs with child-friendly motifs were created and evaluated, confirming that stitch density, stitch count, and design size significantly affect luminous intensity and duration. The results showed a characteristic exponential decay in light emission, highlighting the need for further design optimization and development of effective recharging strategies. To enhance the illumination effect, it is essential to include design elements that are fully filled with stitches, avoiding any gaps between filled areas and run stitches. A stitch density of approximately 0.4 mm is recommended to achieve a dense and effective coverage of at least 90% of the embroidered object.

While the current findings were obtained under controlled laboratory conditions, future research should include durability assessment, user comfort evaluations, and real-world testing in everyday clothing applications for children, as well as the potential integration of smart and sustainable technologies to improve functionality and long-term performance.

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