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Spectral reflectance and transmission properties of a multi-layered camouflage net: Comparison with natural birch leaves and mathematical models

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ABSTRACT

With improved specifications and capabilities of modern sensors and detectors, concealment is an increasingly challenging endeavor. Concealment from modern sensors requires advanced camouflage material that can provide low background-contrast over a wide range of spectral wavelengths. Multi-layer material (i.e. textile fibers) allow for advantageous camouflage abilities such as improved heat transfer and modification of spectral signatures. In this study, we investigate the effect of multiple layers on the reflectance properties of a camouflage net. Camouflage nets provide protection against visual, thermal and radar threats, and can be tailored to offer effective concealment in various natural backgrounds and climate zones. By utilizing a simple mathematic model, we predict multi-layered reflectance properties of the camouflage net from single-layer reflectance data. The model is in good agreement with measurement data for multi-layer net material, and the materials in the study behaves similar to partly transmitting leaves. We also find that 2-3 layers of the materials is sufficient to hinder reflectance contributions from the background. At certain wavelengths, the required number of layers is even lower and reveals that the transmission and reflectance are wavelength dependent.

Keywords: Camouflage, concealment, signature control, reflection, transmission, spectral imaging, leaves

1. INTRODUCTION

From the beginning of human civilization, humans have always been using camouflage (in various forms) to blend in with their environment, hide from predators or enemies and to increase chances of survival. In the visible spectrum (e.g. eye or optical camera), the effectiveness of a target's camouflage depends on its physical properties (i.e. shape, size, color, texture, pattern, shadow) and how it mimics the background in which it is located [1, 2]. With time, advancements in technology have developed sensors providing detection threats in a wide range of electromagnetic spectrums, ranging from ultraviolet to radar wavelengths. To conceal a person or an object has thus become increasingly difficult and encouraged counter measures, e.g. the development of multi-spectral camouflage material. Camouflage nets are advanced materials that provide protection against visual, thermal and radar threats [3-5]. Camouflage nets are routinely used to conceal persons or vehicles, and their properties can be tailored to offer effective camouflage in various natural backgrounds and climate zones [5, 6].

Many camouflage nets comprise fabrics arranged in multiple layers, e.g. a background covered with leaf-like patches. Compared to fabrics composed of a single layer, multi-layer fabrics offer several favorable properties, for instance suppression of thermal contrast [7], improved thermal comfort [8], advanced electromagnetic signature control [9], increased shadowing effects and absence of flat, non-natural ("two-dimensional") surfaces, as well as the possibility to combine additional performance properties. In the literature, there are several methods for testing camouflage net effectiveness [3, 10], but to the authors' knowledge, there are no studies on their spectral properties related to layers or thickness of the material constituting leaf-like patches of a camouflage net. However, there are some relevant publications on transmittance and reflection properties of textiles or fibers [11-14].

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The main motivation for this paper is to investigate how multiple layers of camouflage material affect the spectral properties of camouflage nets, and to model multiple-layer reflectance of camouflage nets, yielding a deeper, basic knowledge of light transmittance in perforated layers. Understanding the reflectance and transmittance properties of multiple-layered camouflage material will be valuable for further improvements and development of advanced camouflage. These properties are also of interest for comfort qualities of fabrics, especially at high temperatures [15, 16].

Camouflage nets with good thermal properties are transparent (with perforations or patterns) to allow adequate airflow. The spectral (i.e. reflectance and transmittance of light) properties of a single-layer of the camouflage net material can thus be modeled by a transparent plate where the reflective and transmittance properties of the layer are known through measurements or calculations. There are several approaches for calculating the spectral properties of a multi-layered stack of plates, including the method of Stokes [17], Tuckerman [18], Kubelka and Munk [19], and Schaich et al. [20]. Some of these methods have also been tailored and improved to describe textile fibers [11, 21], or applied to light interactions in plant canopies [22, 23]. Motivated by similarities in spectral properties between the net material and birch leaves, we here use the simple mathematical model presented by Lillesæter [22] to model the spectral properties of a multi-layer camouflage net. From reflectance measurements of the camouflage net, we find that the model is adequate to predict multiple-layer reflectance properties of the net material. Moreover, we find that 2 – 3 layers of material are sufficient to stop reflection from any background behind the net (e.g. uniform in different color) over all wavelengths, while over certain wavelength bands, fewer layers of material are necessary.

2. THEORY AND MODEL

2.1 Simple mathematical model

The camouflage net studied here was a generic camouflage net (“3-D structured with backing material underneath leaf-like patches), consisting of woven fibers. When an incoming light beam illuminate the material, some of the light beams reflect from the fiber surfaces. Other beams refract or pass through individual fibers. Some beams will also be absorbed by the fibers and transformed to thermal energy. In the simple model for reflection of multi-layered textiles used here, absorption is indirectly incorporated in the transmittance and reflectance of the sample and background, i.e. absorption is not calculated. We also neglect lateral scatting, i.e. we assume that reflection and transmission of light is primarily in a direction perpendicular to the textile. It is challenging to describe the transmittance and reflectance through textiles quantitatively, especially through several layers of fibers. It is therefore helpful to use transparent plates to describe the problem. Stokes developed a model for calculating the reflected light from a pile of parallel glass plates [17]. The model uses single-plate spectral properties (determined by measurements or calculations) to calculate the spectral properties of multi-layered plates and do not consider a background under the plates. Stokes’ model was derived with a different approach by Tuckerman [18] and further developed by Wilhelm et al. [11] to also include the effect of base material reflectance. In this paper we use the simplified approach that was derived by Lillesæter [22] to model spectral reflectance of partly transmitting birch leaves. The derivation of the model follows reference [22].

The incoming light illuminates a single-layer sample with irradiance I, while the reflected radiation R_1 (the subscript denotes number of layers) is made up of two components: the inherent leaf reflection R (reflected by the material on an ideally black background) and radiation $\hat{R}$ reflected from the (non-black) background after transmitting through the material with a transmittance τ. We can express the reflected radiation as:

$$I_R = R + \hat{R} = rI + \hat{r}\tau^2 I \tag{1}$$

Here r and $\hat{r}$ are the reflectance of the sample and background, respectively. The intensity of the reflected light is:

$$r_1 = I_R/I = r + \hat{r}\tau^2 \tag{2}$$

where r is the reflective component from the sample and $\hat{r}\tau^2$ the background component. Note that r, $\hat{r}$ and τ vary with the wavelength. If the same background is used, $\hat{r}$ is the same for different measurements. By performing spectral measurements of the sample placed on a light (L) or dark (D) background, we get the following relationships:

$$r_{1D} = r + \hat{r}_D\tau^2 \tag{3}$$

$$r_{1L} = r + \hat{r}_L \tau^2 \tag{4}$$

If we assume that the sample transmittance is the same in both directions, we find an expression for the two-way transmittance τ^2 by combining Equations (3) and (4):

$$\tau^2 = \frac{r_{1L} - r_{1D}}{\hat{r}_L - \hat{r}_D} \tag{5}$$

r_{1L} and r_{1D} are found by spectral measurements of the sample on light and dark backgrounds, while $\hat{r}_L$ and $\hat{r}_D$ are determined from spectral measurements of the backgrounds without a sample. When the sample transmittance τ and the reflectances r_{1D} and $\hat{r}_D$ are known, the sample reflectance can be calculated from Equation (3):

$$r = r_{1D} - \hat{r}_D \tau^2 \tag{6}$$

Equation (4) can also be used to calculate r in a similar manner. For two layers where each layer has the same spectral properties, Equation (2) transforms to:

$$r_2 = r + r\tau^2 + \hat{r}\tau^4 = r[1 + \tau^2] + \hat{r}\tau^4 \tag{7}$$

N number of layers give:

$$r_N = r\left[1 + \tau^2 + \cdots + \tau^{2(N-1)}\right] + \hat{r}\tau^{2N} \tag{8}$$

Because $\tau < 1$, the sum of this geometric series yield:

$$\lim_{N\to\infty} r_N \equiv r_\infty = \frac{\tau}{1 - \tau^2} \tag{9}$$

2.2 The model used on leaves

The model in Section 2.1 was used by Lillesæter [22] to predict multiple-layer reflection of birch leaves. For comparison with our results in Section 4 and validation of the model, we here include some of Lillesæter's results on birch leaves. The inherent reflectance and two-way transmittance of single birch leaves used in his study are largest between 750 and 1300 nm (Figure 1). Also, note that τ^2 is close to zero for wavelengths below 700 nm.

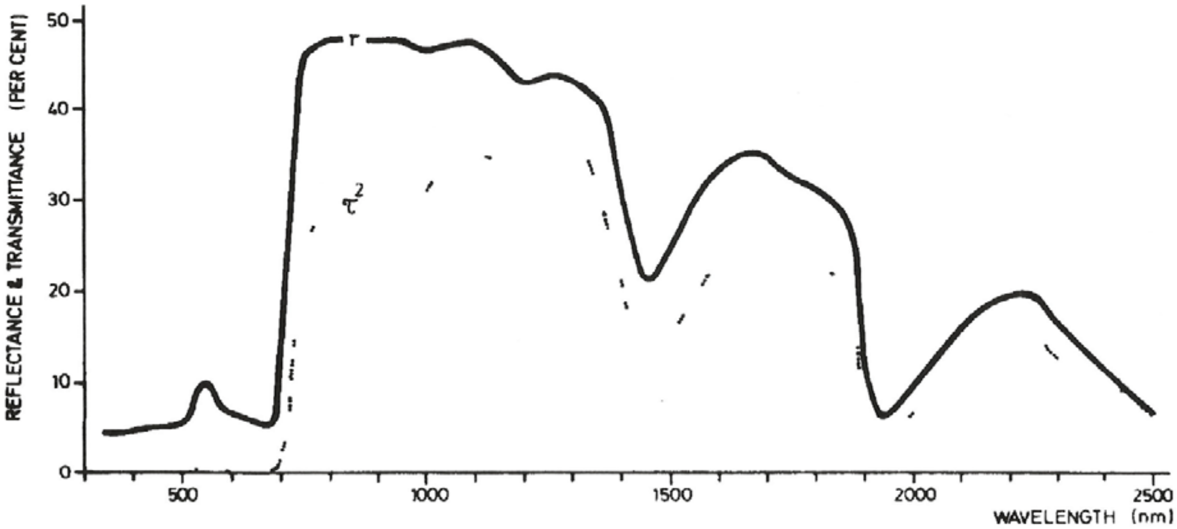

Figure 1 Inherent reflectance $r(\lambda)$ and two-way transmittance $\tau^2(\tau)$ of single birch leaves. Values are derived from reflectance measurements. Adapted from [22].

Lillesæther used the mathematical model to calculate the spectral reflectance for 1 – 8 stacked birch leaves on a light or dark background (Figure 2). Below 700 nm, there is no notable difference in the calculated reflectance of the leaves (1 – 8 layers), while above 700 nm, the difference in reflctance between leaves with 4 and 8 layers is small. The result suggests that four layers of leaves is sufficient to suppress $\hat{r}$, the spectral contribution from the background.

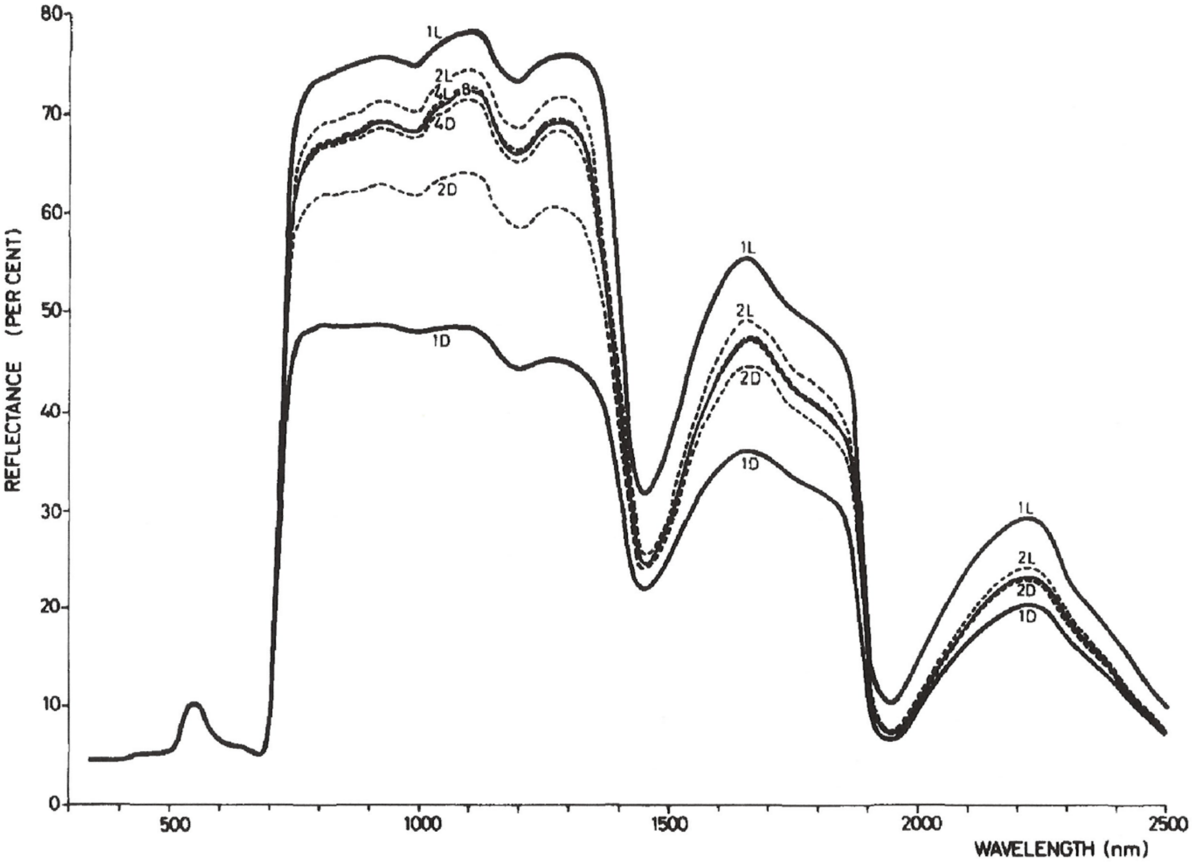

Figure 2 Calculated spectral reflectance for 1, 2, 4 and 8 stacked birch leaves with light (L) or dark (D) background.

Adapted from [22].

Figure 3 compares the measured and calculated reflectance values of leaves at four representative wavelengths. The predicted values based on single-leaf measurements is in good agreement with the measurements performed on several leaves.

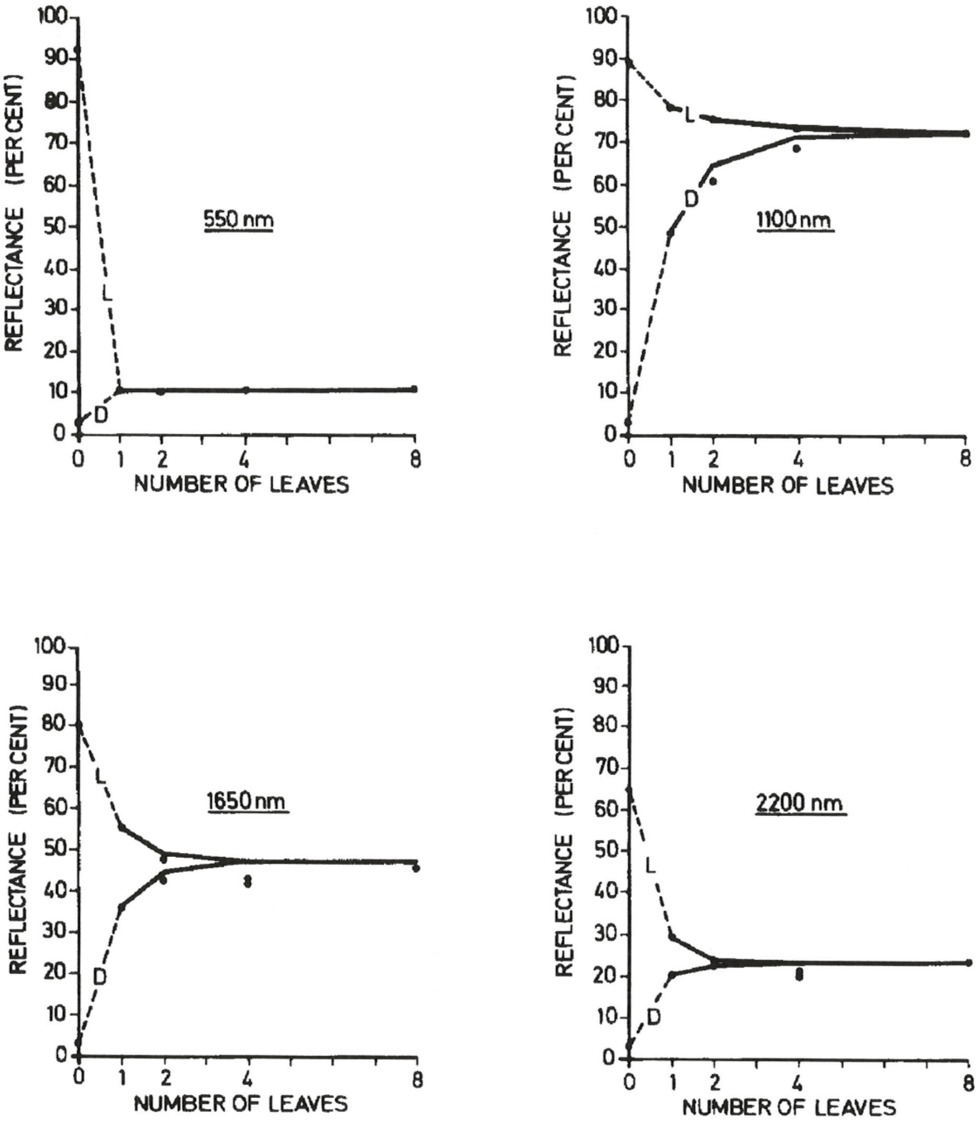

Figure 3 Measured (dots) versus calculated (solid lines) reflectance at selected wavelengths for stacked birch leaves on height (L) or dark (D) background. Adapted from [22].

3. METHODOLOGY

In this study we tested a generic camouflage net consisting of two layers. The front layer of the net was built up with several leaves-like patches of different colors, while the back layer was single-colored. Hereafter we refer to the front layer as material 1, and the back layer as material 2. Both of the materials were perforated (material 2 was more transparent material 1, most likely due to a higher holes-to-solid material ratio). Before measuring the materials, we cut parts of the net to square patches of area 5x5 cm^2. A PerkinElmer spectrophotometer (Lambda 750 UV/VIS/NIR) was used to measure spectral reflectance of the different net materials between 250 and 2500 nm. For the measurements, we chose a CIE Standard Illuminant D65 to mimic relevant and standardized illumination conditions outside in the nature. The illuminant D65 corresponds to average midday light in Northern/Western Europe and comprises both diffused light and direct sunlight. To imitate the diffuse nature of the radiation illuminating the background through the sample, we used a spectrophotometer with an integrating sphere. The test samples were mounted in the spectrophotometer vertically and fasten with a sample holder (see Figure 4). We used the program UV WinLab (v. 6.4.0.973, reflectance scan) to run and control the measurements. Before each measurement series, the spectrophotometer was calibrated by using a white reference background (Lambertian surface). The reflectance data presented in this paper is an average of at least three measurements.

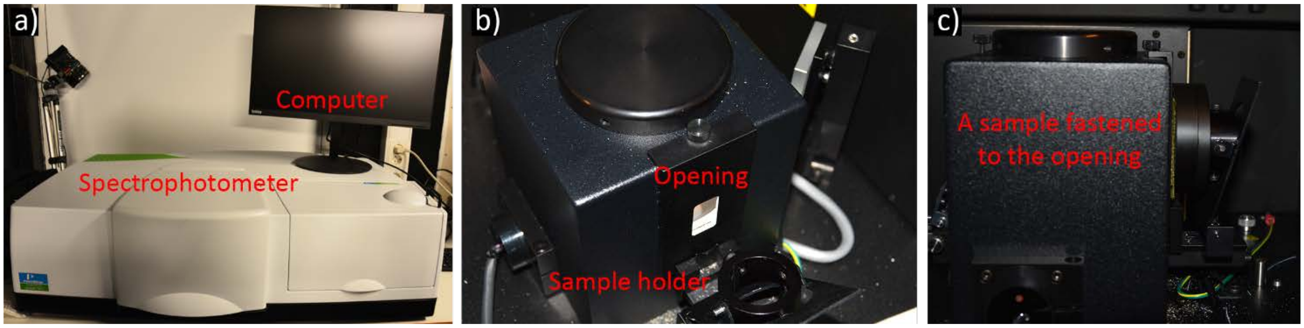

Figure 4 a) A picture of the PerkinElmer spectrophotometer connected to a computer. b) Inside the spectrophotometer. The opening area for measurements was around 13 x x25 mm^2, and the samples were mounted vertically by a sample holder. c) A sample fastened to the opening of the spectrophotometer.

We used two different backgrounds for the spectral measurements: 1) two layers of a white textile, and 2) 10 layers of a black textile (each layer of the black textile was perforated, but when stacked into 10 layers, the layers effectively constituted an opaque background layer). The backgrounds were chosen to mimic a perfect reflector (white) and an ideally black background, in accordance with the theory for calculating transmission and reflectance of the net material (Section 2). The spectral properties of the backgrounds are presented in Figure 5. We measured the spectral reflectance for both materials. Material 1 was measured with 1 – 6 layers, while material 2 was measured with 1 – 10 layers. More than 6 and 10 layers did not have any measureable effect on the spectral properties of the samples. Data from the measurement were saved as .txt files and further analyzed and plotted in Origin (v. 2019b).

4. RESULTS AND DISCUSSIONS

4.1 Measured reflectance of backgrounds and single-layer material

To apply the mathematical model in Section 2.1 to the camouflage net, we performed reflectance measurements of the backgrounds (white and black colored, Figure 5 a)) and a single layer of the two different material of the net placed over each of the backgrounds (Figure 5 b)). As intended, the white background is significantly more reflective than the black background. The black background has low reflectance variation over all measured wavelengths (250 – 2500 nm), while the white background reflectance is nearly constant between 600 – 1600 nm.

Our reflectance measurements of the materials show that the reflectance is strongly influenced by the underlying background (Figure 5 b)), e.g., the materials placed on the white background achieved higher reflectance than the same materials that were placed on a black background. We also find that the reflectance of the materials is wavelength dependent, especially material 1 with a reflectance peak around 800 – 900 nm.

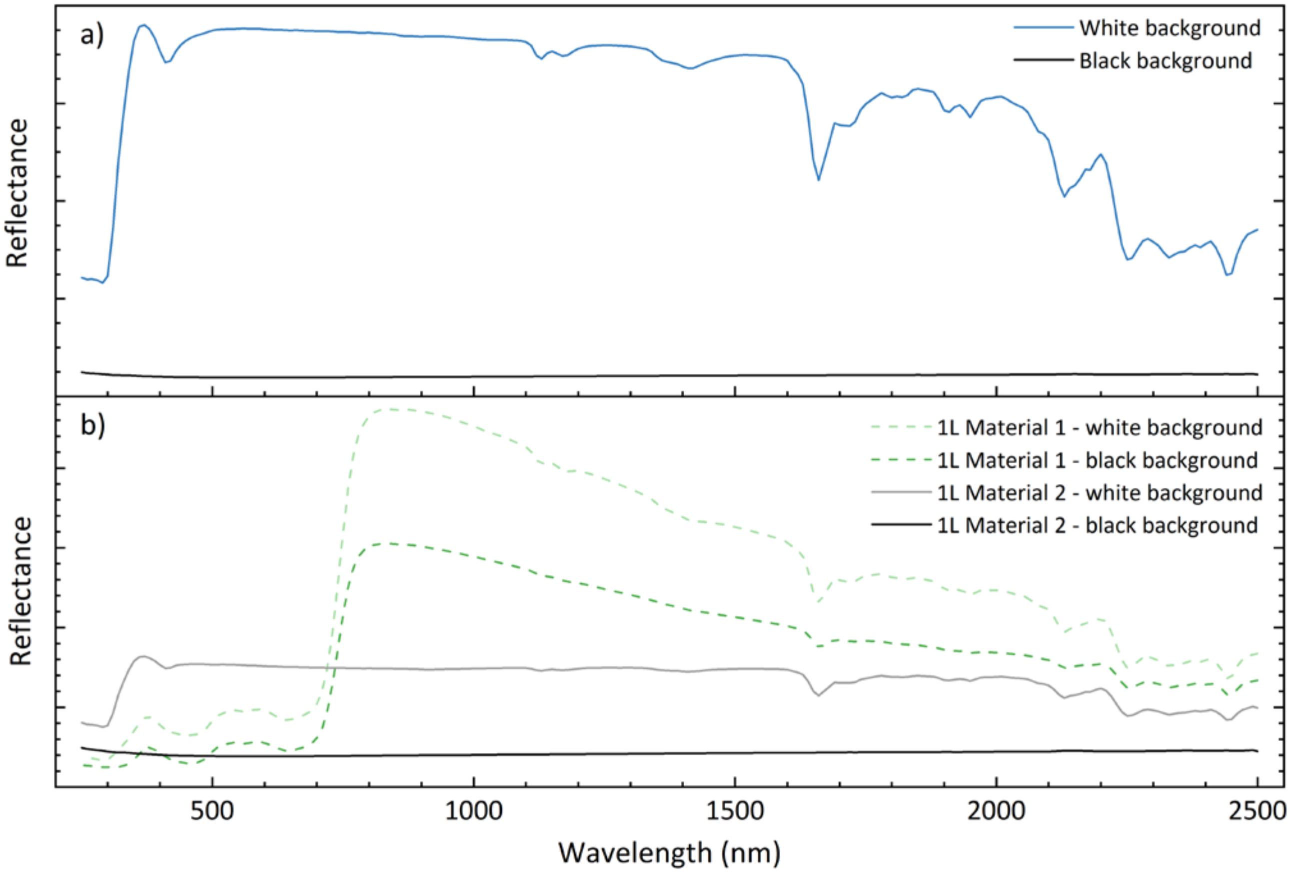

Figure 5 Measured reflectance of a) the white (blue curve) and black background (black curve) used in this study. b) Reflectance of a single-layer sample of net material 1 (dashed curves) and a single-layer of net material 2 (solid curves) on the white and black background.

4.2 Calculated transmission and reflectance of single-layer material

The reflectance data presented in Figure 5 and Equations (5) and (6) were used to calculate the two-way transmission ,τ^2, and reflectance of the net materials (Figure 6). For material 1, the reflectance is higher than the two-way transmission at all measured wavelengths larger than 700 nm (Figure 6 a)). Both of these spectral properties are wavelength dependent, with maximum values around 800 – 900 nm. Interestingly, the spectral properties of material 1 is similar to those of a birch-leaf presented in Figure 1. The two-way transmission of material 2 is higher than its reflectance for all measured wavelengths. The theoretically calculated reflectance values are similar to those measured on single-layered materials on a black background (Figure 5 b)). This similarity is expected because the measured reflectance from the black background is very low compared to the reflectance from the material. If the reflectance from the background is small enough (and/or the transmission is low), the material reflectance can be measured directly.

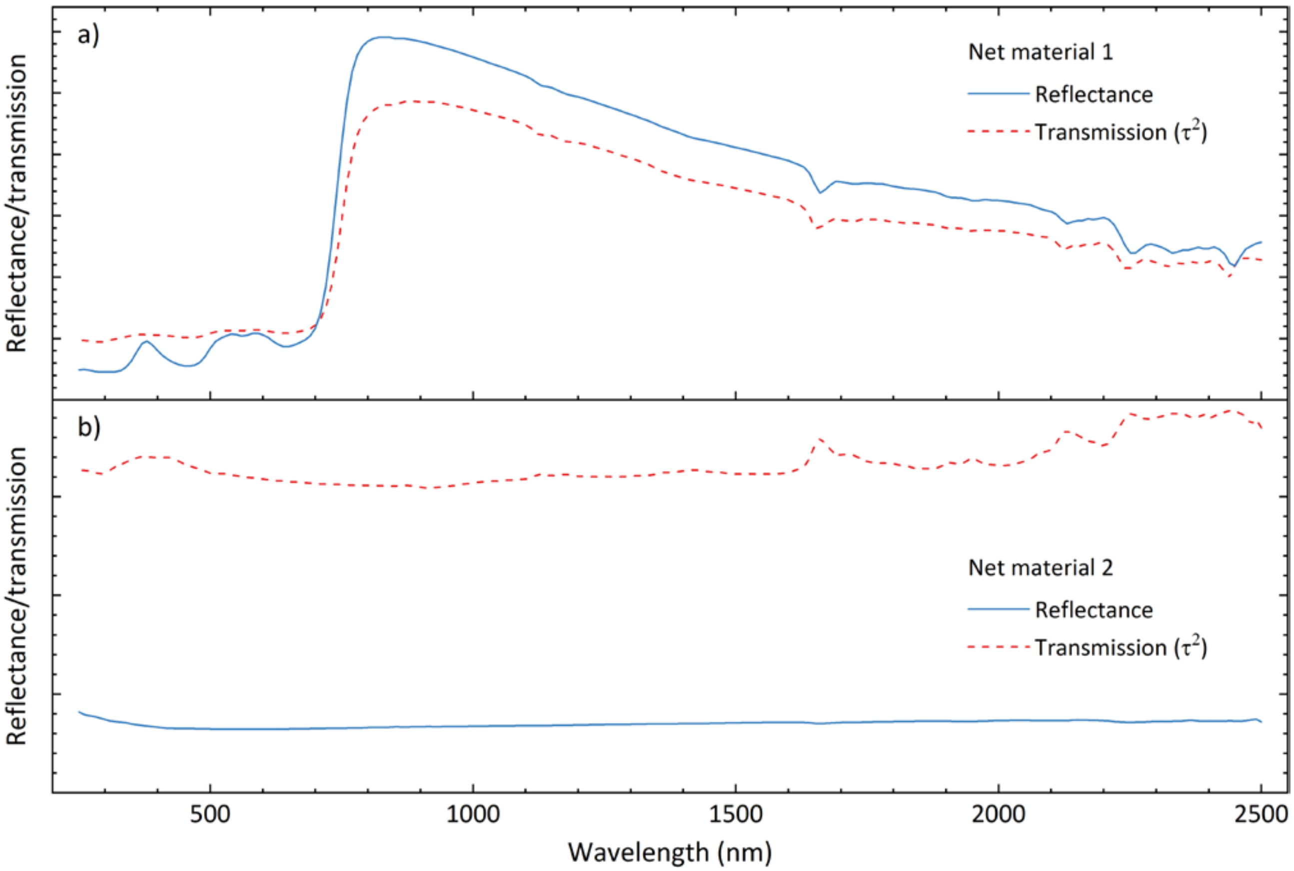

Figure 6 Calculated reflectance (solid curves) and two-way transmission (dashed curves) for a single-layer of a) camouflage net material 1 and b) material 2.

4.3 Reflectance of multi-layered materials

With known reflectance and transmittance values for the net materials, we used Equation (8) to estimate the materials' multi-layer reflectance. The calculated values, based on the theoretical model [22] are presented in Figure 7 (dashed lines) and compared with multi-layer (material 1: 1, 2, 3 and 6 layers, material 2: 1, 2, 3 and 10 layers) experimental data from the reflectance measurements of the materials (solid lines) when stacked on top of a white background. We found that the calculated reflectance is in good agreement with the measured data, especially for net material 1 (Figure 7 a)) where the calculated reflectance values are slightly higher than the measured values. The small dissimilarity between the calculated and measured values might be due to energy absorption, which is not directly included in the model, or differences between forward and backward transmittance. For material 1, the difference between the calculated and measured reflectance is only distinct between wavelengths 800 – 1600 nm. In this wavelength band, we found the maximum reflectance and transmittance of the material (Figure 6). It is therefore reasonable that any dissimilarities between the measured values and the model are enhanced at these wavelengths. Also, note that the single-layer reflectance values of the model and measurements overlap for both materials (light blue lines, Figure 7). That is because the r and τ^2 values of the materials are based on reflectance measurements performed on single-layer materials (i.e. inserting Equations (3), (5) and (6) in Equation (7) yield $r_1 = r_L$).

Consistently, the reflectance values of the net materials decrease when the number of layers increases. Each additional layer of material decreases the reflectance contribution from the white background $\hat{r}$ significantly, which means that more of the incoming light is reflected by the material. The reflectance values of material 1 with 2, 3 and 6 layers are similar at wavelengths between 250 – 800 nm and 1600 – 2500 nm. At these wavelengths and when covered with two (or more) layers, the background behind the material does not influence the measured reflectance. From 800 – 1100 nm, we measured a small reflectance difference between 3 and 6 layers of material 1. This difference is possibly explained by the high material transmission found at these wavelengths (Figure 6). At similar wavelengths, Lillesæter [22] also found a big reflectance difference between 2 and 4 layers of birch leaves (Figure 1).

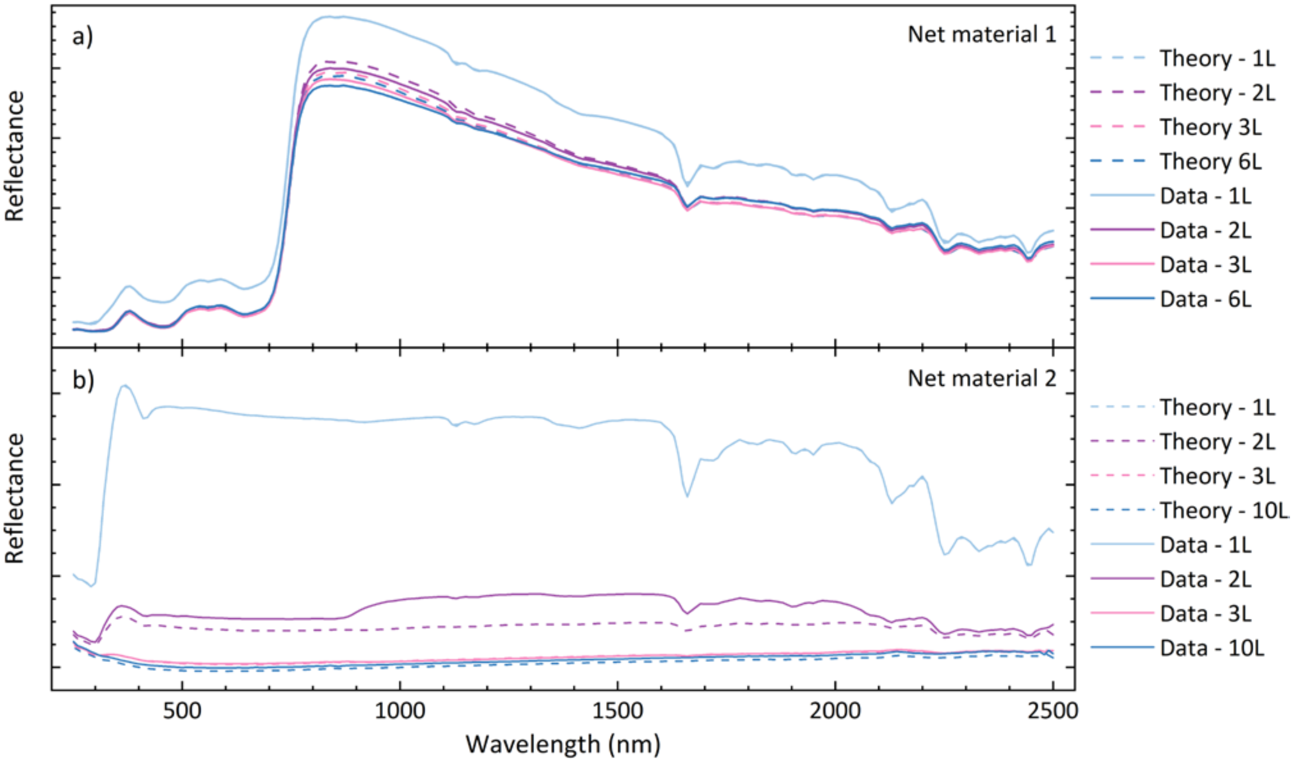

Figure 7 Calculated (dashed lines) and measured reflectance (solid lines) of a) material 1 and b) material 2 of the camouflage net. We performed reflectance measurements on 1 – 6 layers of material 1, and 1 – 10 layers of material 2. A white background was used for these measurements.

Moreover, we observe that three layers of material 2 is sufficient to cancel the reflectance contributions from the background. For most wavelengths, 2 layers of material 2 was sufficient to rule out the contribution from the background on the measured reflectance, slightly higher than for material 1 . This is most likely due to the assumption/fact that material 2 has larger perforations than material 1, as well as a higher hole-to-solid-material ratio. This observation also corresponds well with our calculations of the two-way transmission (Figure 6). The reflectance values measured for 3 and 6 layers of material 2 are similar, indicating that the effect of more than three layers on the measured reflectance is hardly noticeable.

For all measurements, a sample holder pressed the materials together in the spectrophotometer (Figure 4) with more or less the same pressure. We did not observe substantial differences in measured reflectance (larger than 2%) when we repeated the measurements using the same material, the same number of layers (with different configurations amongst the individual net leaf samples or material samples). However, it is important to point out that our test setup is different from how the camouflage net is intended to function. When used, there is usually an air gap between the layers (material 1 and 2) that varies in distance with up to approximately one cm. Based on the results presented in this study, we can only speculate how such a gap will affect the overall spectral properties of the net. We therefore recommend a future investigation of this effect.

5. CONCLUSIONS

In this study, we have investigated multi-layer reflectance of a generic camouflage net by spectral reflectance measurements. We found that one of the net’s materials has spectral properties similar to birch leaves, i.e. similar wavelength dependency with maximum reflectance in the near infrared (750 – 1400 nm). For this reason, we applied a simple mathematical model used by Lillesæther [22] on birch leaves to predict multi-layer reflectance and test its validity on camouflage net materials. The mathematical model requires only single-layer reflectance data as input, and adequately gives an estimate of the multi-layer reflectance of the net materials. Our results suggest that theoretical calculations can reduce the number of spectral reflectance measurements in the lab, as measurement on each distinct number of layer can be calculated mathematically, and consequently save valuable time for other tests. However, we recommend additional studies on multi-layered materials of different fabrics, colors, dyes and backgrounds for further validation of the model. It would also be useful to test wet vs. dry samples, the effect of air gaps between the layers, thermal properties of the material and to examine absorption effects.

The reflectance measurements in this study show that two layers of material 1 is sufficient to cancel the effect of the background at all measured wavelengths except for 800 – 1500 nm. For material 2, more than three layers did not affect the measured reflectance of the material at wavelengths 250 – 2500 nm. These results highlight the importance of opacity when developing effective camouflage material for particular environments and specifications, i.e. if the material is too transparent, the background or military target to be concealed, may affect and compromise the camouflage signature to a high degree. A possible approach to prevent this is using multiple layers of material. When designed properly, reflectance from the background could also be part of the camouflage signature, e.g. to introduce small spectral variations or to slightly increase/decrease the reflectance.

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