Forensic Science International: Reports 1 (2019) 100021

Contents lists available at ScienceDirect

Forensic Science International: Reports

journal homepage: www.elsevier.com/locate/fsir

In situ examination of handwritten blue ballpoint inks using video spectral comparison with chemometrics

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ARTICLE INFO

Keywords:
Forensic science
Questioned documents
Video spectral comparator
Visible spectroscopy
Chemometrics

ABSTRACT

Video spectral comparator (VSC®) workstations are routinely used for visual examinations of pen inks on handwritten documents. Current VSC® models also permit spectral acquisition, which can be combined with chemometric techniques to statistically determine ink similarity. However, there is a lack of research comparing such an approach to typical examinations by forensic experts. This preliminary study compares the analysis of handwritten blue ballpoint inks using visual and spectroscopic analysis. Both approaches were successful in detecting simulated additions or alterations on paper documents. These approaches could thus complement each other as an integrated workflow; providing quantitative data to support expert opinions.

1. Introduction

Forensic examination of pen inks; whether for identification, comparison or dating purposes; can be central to cases involving suspected document fraud [1–3]. Whilst microscopy is used to examine morphological features such as striations or gooping, analytical techniques may be required to chemically profile the ink components. Spectroscopic methods are particularly suited to this purpose as they enable *in situ* non-destructive analysis, preserving the document's integrity.

Previous work by the authors used diffuse reflectance visible spectroscopy to examine the variability and ageing of blue ball tip inks on paper [4,5]. Chemometric analysis effectively distinguished the majority of inks based on their colour, presumably due to different dye composition. This approach also detected chemical changes due to ageing, attributed to the demethylation of triarylmethane dyes, within as little as one week. However, this approach required large ink spots unrepresentative of typical handwritten documents, as well as specialised instrumentation that may not be readily available within a questioned document laboratory.

Conversely, video spectral comparator (VSC®) workstations are routinely used by forensic document examiners for specialised lighting inspections [6,7]. The workstation houses a digital imaging system, tuneable light sources and optical filters that allow magnification and visualisation across the visible to near-infrared range [8,9]. Selected models also contain a high resolution grating spectrometer, allowing *in situ* spectral acquisition at high magnification [10,11]. Within an Australian context, this spectral capability is largely under-utilised in forensic casework.

Similarly, there are few reported studies of ink analysis using VSC® spectroscopy. Reed et al. carried out hyperspectral imaging on blue, black and red gel inks using a VSC®6000/HS [8]. Visual comparison of the spectra distinguished over 80 % of all possible pairs for blue and red inks, but only 38 % of black ink pairs. Weyermann et al. obtained a similarly low discriminatory power of 49 % for black gel inks based on Pearson correlation coefficients; less than microspectrophotometry or laser desorption ionisation-mass spectrometry [12].

Recent work by da Silva et al. applied chemometrics to VSC®6000 spectra of blue and black inks [13,14]. The use of chemometrics is ideal for revealing latent trends within a large dataset, and also provides objective data assessment for more transparent decision making. Partial least squares discriminant analysis (PLS-DA) modelling enabled accurate discrimination and classification of the ink type and brand, but required the construction of several independent models, which may be time-intensive. Furthermore, it would be of interest to directly compare the results obtained through spectral and chemometric analysis to standard examinations by forensic practitioners, to assess whether they could complement each other within a single workflow. To the best of our knowledge, no such studies exist in the reported literature.

This preliminary work highlights the rapid discriminating power of VSC spectroscopy with principal component analysis (PCA) for handwritten blue ballpoint inks. The proposed method was validated against blind test samples representing 'authentic' and 'fraudulent' documents, and the results compared to visual inspections by forensic document examiners. This approach has the potential to supplement existing analysis schemes by providing quantitative data to support expert examinations.

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http://doi.org/10.1016/j.fsir.2019.100021
Received 26 June 2019; Received in revised form 5 August 2019; Accepted 8 August 2019
Available online 28 August 2019

Table 1
Models and assigned numeric identifiers for pens examined. (*) denotes pens used for substrate and blind validation testing.

Pen ID	Pen Model	Pen ID	Pen Model
1	Pentel e-Ball	19	Faber Castell Grip 2022*
2	PaperMate Ink Joy 300*	20	Pilot BP-GP
3	Artline Ikonic*	21	Uniball Power Tank*
4	Pentel Vicuna	22	Pilot BPS-GP
5	Bic Softfeel	23	PaperMate Profile
6	PaperMate Kilometrico	24	Bic Pro Plus
7	Bic ReAction	25	Bic Atlantis Air
8	Pilot Dr. Grip Advance	26	Milan P1 Look*
9	Bic Classic Fine	27	PaperMate Kilometrico Elite
10	Pilot BeGreen Acroball	28	PaperMate Ink Joy 550
11	Keji Ballpoint	29	Uniball Jetstream 3
12	Artline Smoove*	30	Pilot BP-145
13	J.Burrows Ballpoint	31	PaperMate Flexgrip Ultra
14	Bic Ultra Round Stic	32	PaperMate Ink Joy 100
15	Artline Flow	33	Uniball Laknock
16	Artline Clix	34	Pilot BPE-GP
17	Bic Cristal Easy Glide	35	Staedtler 430
18	Bic Economy		

2. Experimental

2.1. Sample preparation

35 blue ballpoint pens were purchased from Officeworks, Western Australia (Table 1). Handwritten entries were produced on ‘standard’ A4 white copy paper (Reflex Ultra White, 80 g/m^2) by writing the name of the pen model using the corresponding pen. Additional entries from six pens (Table 1) were also prepared on recycled copy paper (J.Burrows 100 % Recycled, 80 g/m^2) and silk finish paper (J.Burrows A4 Premium Digital, 100 g/m^2).

‘Blind’ validation samples were produced by offering a volunteer six pens from the sample set (Table 1) and asking them to write five sets of three-digit numbers on standard copy paper. Each number sequence could be written using either:

i A single pen – Simulating an ‘authentic’ document
ii Separate pens for different digits of the sequence – Simulating a document containing fraudulent additions
iii Separate pens for individual ink lines within a single digit – Simulating a document containing fraudulent alterations

Photographs of the validation samples and corresponding pens are presented in Figure S1. The pen(s) chosen by the volunteer for each sample were unknown to the analysts until after the examination, to minimise confirmation biases. All handwriting samples were placed in paper envelopes and stored in a dark drawer away from light when not under examination. Previous work has demonstrated that this minimises spectral changes due to dye photodegradation [5].

2.2. Spectral collection

Visible-near infrared (Vis-NIR) spectra were obtained using a VSC®6000/HS workstation (Foster + Freeman, UK). The instrument was operated in reflectance mode using a standard white tile (Foster + Freeman, UK) as the blank reference. Samples were illuminated under a 100 W halogen lamp and viewed at 30x digital magnification in auto focus mode. Measurements were recorded over the 400 – 1000 nm range at 60 % brightness, using automatic exposure settings

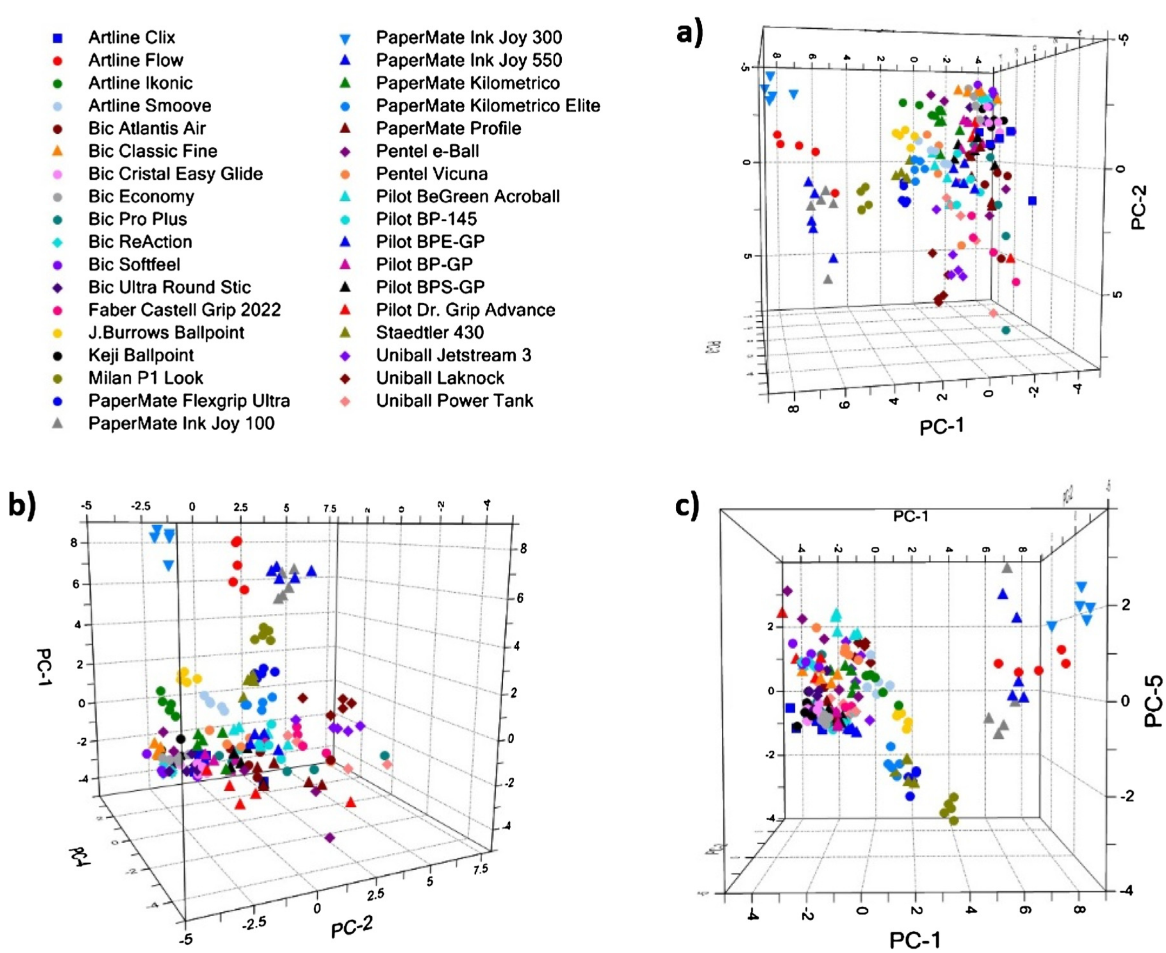

Fig. 1. Three-dimensional PCA scores plots of 35 blue ballpoint inks based on their VSC®6000/HS reflectance spectra, using (a) PCs 1-3; (b) PCs 1, 2 and 4; (c) PCs 1, 2 and 5.

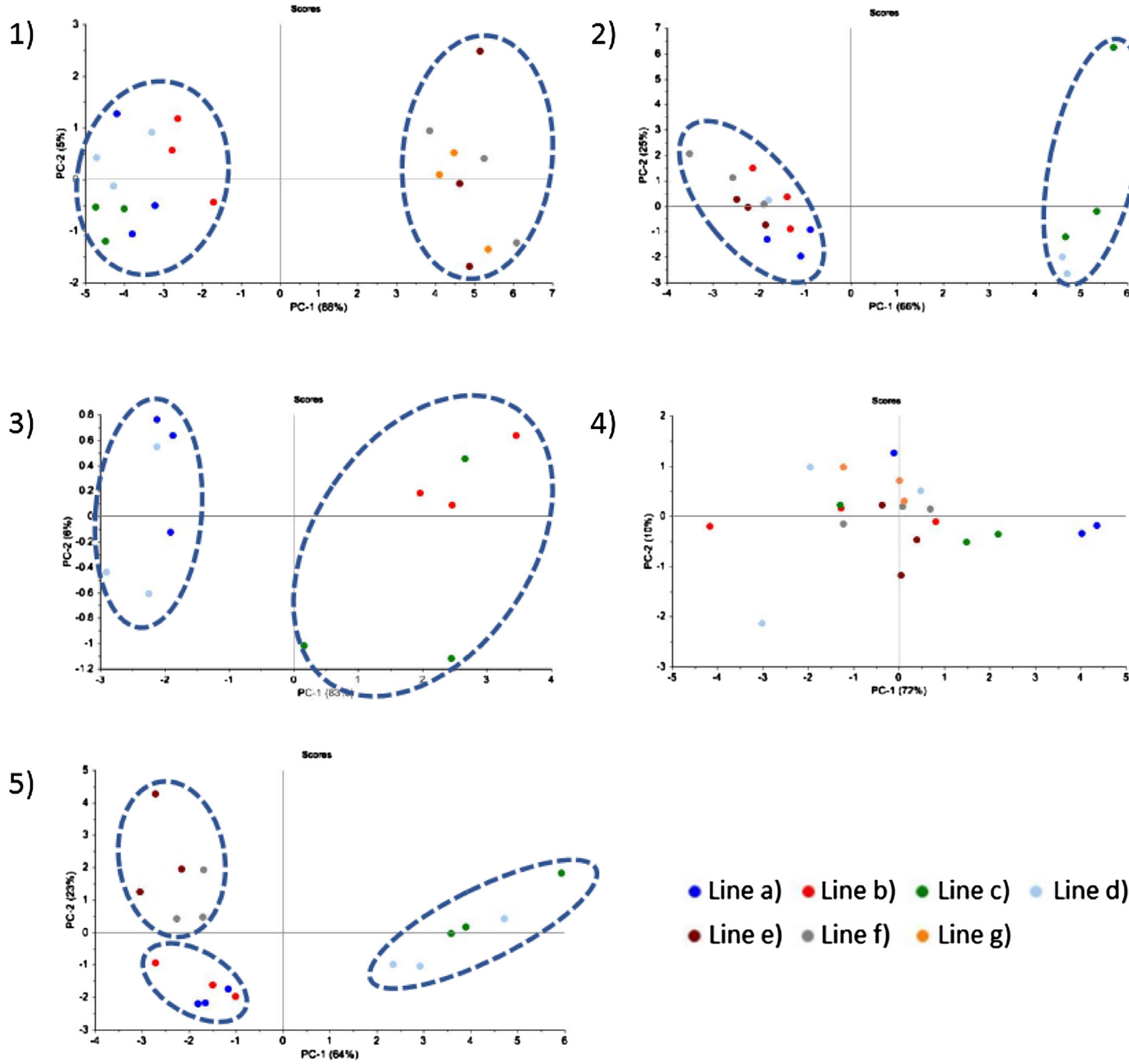

Fig. 2. 2-dimensional PCA scores plots showing the distribution of blue ballpoint ink strokes in blind validation test sets, based on their VSC® 6000/HS reflectance spectra. Dotted circles indicate clusters assumed to represent a single ink.

for integration time and iris width. Five replicate spectra were obtained for each of the 35 inks at different locations along the ink trace. For the five blind validation sets, three replicate spectra were acquired from different locations along each individual ink stroke, avoiding intersections with other ink lines.

2.3. Visual examination

An evaluative examination was conducted on each of the five blind validation sets to determine any visible difference in the ink hue, or the presence of any features indicative of deterioration of the writing implement. Detailed microscopic examinations were conducted to determine the presence of any discrete features of similarity or dissimilarity (such as burr striations) between the ink strokes. The luminescence and/or absorbance characteristics for each of the five sets were then examined under variable lighting and filtration using a VSC® 5000 (Foster + Freeman, UK). After considering the environmental factors associated with the nature and condition of the document substrate, where sufficient discrimination was observed, an opinion regarding the differentiation of the inks was recorded.

2.4. Data analysis

Data pre-processing and chemometric analysis was carried out using the Unscrambler® X 10.5 (Camo Software AS, Oslo, Norway). Spectra were first baseline offset to 0 % reflectance to remove variation due to the amount of ink deposited. A first-order Savitzky-Golay derivative (second order polynomial, 11-point smooth) followed by an extended multiplicative scatter correction (EMSC) were then applied to remove additive or multiplicative effects due to random light scattering. Principal component analysis (PCA) was carried out on the pre-processed spectra using mean-centring and the non-linear iterative partial least squares (NIPALS) algorithm. Each sample was subsequently plotted against combinations of up to the first five principal components (PCs) to determine whether any inks could be visually distinguished.

3. Results and discussion

3.1. Population variability

PCA was carried out on replicate spectra from all 35 pens to assess the level of diversity existing within the total ink set. PCA is a feature

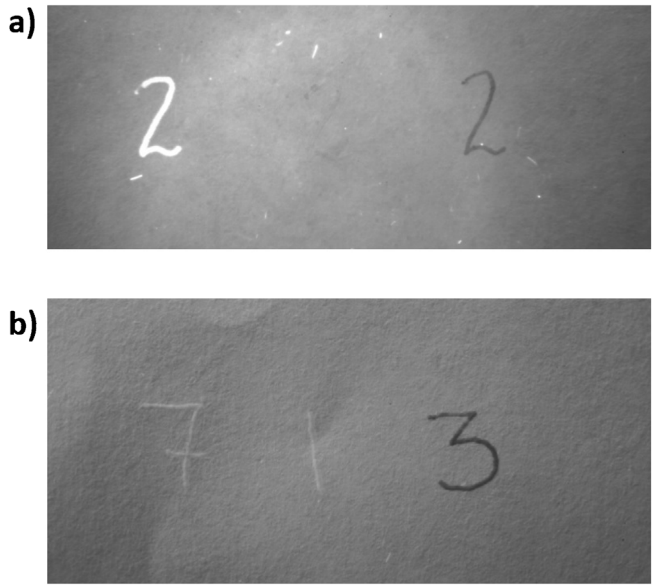

Fig. 3. VSC® 5000 images of blind validation sets showing discrimination of inks based on luminescence and/or absorbance characteristics; (a) Test Set 5, illuminated using a 546-610 nm spot lamp and viewed through a 648 nm longpass filter; (b) Test Set 1, illuminated using a 605-640 nm spot lamp and viewed through a 668 nm longpass filter.

extraction method that reduces the dimensionality of multivariate data, revealing hidden trends or groupings [15,16]. An orthogonal transformation is first applied to the initial variable set of spectral wavelengths to produce principal components (PCs), which describe the most significant contributors to sample variation [17]. The first few components are then used to map the sample set into a lower dimensional space, while retaining the majority of useful information.

Spectra were plotted against combinations of the first five PCs (accounting for 88.3 % of total variation in the dataset) as shown in Fig. 1. Compared to previous work using a conventional ultraviolet-visible spectrophotometer [4], a greater spread was observed between replicate spectra collected using the VSC® 6000. Inspection of the raw spectra showed variations in relative reflectance in the 410–500 nm (blue-violet) and 650–800 nm (red-near infrared) regions (Figure S2). This is potentially due to fluctuations in the detector sensitivity, and could hamper attempts to differentiate inks with very similar optical properties. Nonetheless, several inks were immediately distinctive, such as the PaperMate Ink Joy 300 and Artline Flow, indicating that this approach could assist in comparing ink entries on handwritten documents.

3.2. Effect of paper substrate

A limitation to *in situ* analysis of inks on written documents is the potential for interferences caused by the substrate. Six inks were therefore deposited on different paper types to determine the effect on their resulting spectra and chemometric analysis. Standard and recycled copy papers and silk finish digital paper were chosen for this investigation, as these frequently constitute documents submitted for examination in Western Australia. Spectra from each paper type were acquired using the Foster + Freeman standard white tile as the blank reference.

PCA resulted in a distinct separation of the three paper types, as seen in Figure S3. Comparing spectra from a single ink obtained on each paper type, variations were noted in the peak shape and intensity at ca. 400-450 nm. This is possibly due to each substrate containing different optical brighteners, which absorb light in the ultraviolet region and re-emit in the blue region to produce a 'whiter' appearance [18]. From the spectra, it can be seen that the relative blue reflectance was highest for the silk finish paper and lowest for the recycled paper. This is consistent with the International Commission on Illumination (CIE) whiteness values of each paper, which were advertised as 150, 165 and 170 for the recycled, standard and silk finish papers respectively.

The observed spectral differences due to paper type is relevant to the comparison of inks on separate documents, as substrate interferences may result in false exclusions. In such scenarios, a blank section of the document should ideally be used for the reference measurement rather than the standard white tile, as this has been reported to compensate for the majority of variations associated with background surface [13]. It should be noted that VSC® 6000/HS operating guidelines cite that either the tile or a bare portion of the document may be used as a reference, but do not specifically comment on the suitability of either for different purposes of examination.

3.3. Blind validation

Casework document examinations frequently involve examinations of ink on a single document to detect any additions or alterations. Blind validation was therefore carried out using five handwritten test sets representing both 'authentic' and 'fraudulent' documents. The actual number of inks present in each set were not disclosed to the examiners until after they had drawn their conclusions, in order to avoid confirmatory or other cognitive biases [19–21].

Three replicate spectra were recorded from individual ink lines within each test set, and PCA carried out to estimate the number of inks present. This was done by examining the distribution of spectra against the first two PCs, which accounted for 82–93 % of total variance within each set (Fig. 2). Separation between particular ink strokes was assumed to be indicative of different inks. The spectral analysis was challenging in that it

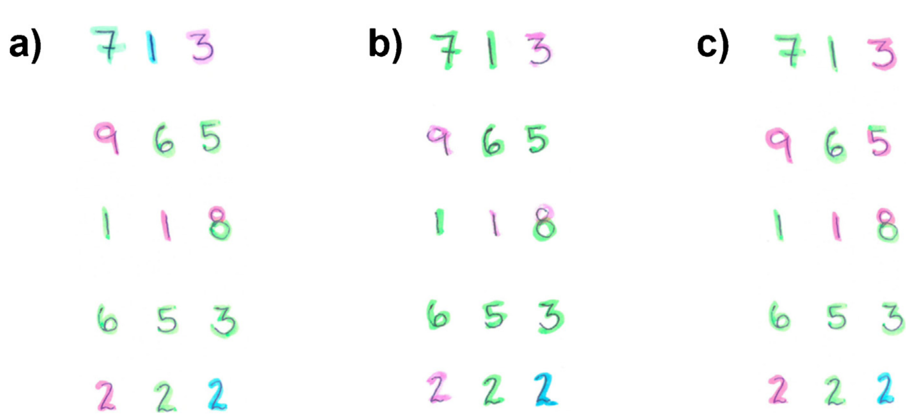

Fig. 4. Colour-coded images of blind test sets representing (a) the number and distribution of inks present in each set; compared to those determined through (b) visual examination and (c) spectral examinations. Colour-coding applies only within each individual test set, and does not indicate any association of inks between different test sets.

was based solely on the optical properties of each ink, without the aid of any visual features. Nonetheless, the findings were largely consistent with the actual number and distribution of inks in each set. All four 'fraudulent' entries were successfully detected as containing multiple inks, and the identified distribution was correct in all but Set 2. In the first 'fraudulent' set, only two of the three different inks present were detected, revealing that inks with very similar optical properties may not be distinguishable through colour alone. However, detection of at least two inks is still sufficient to indicate that a document may be fraudulent and warrants further investigation.

An additional advantage of PCA is the ability to more readily compare *intra*-group variation between replicate spectra to *inter*-group variation between different clusters. This may be used as a statistical measure to assess the reliability of separation. In this case, clusters within the first two test sets were distinctly separated, suggesting that these inks have chemically distinct compositions. In contrast, two of the groupings for the Set 5 were grouped closely together. These inks can be assumed to be more chemically similar, and may not be reliably differentiated. The PCA scores could thus be used by forensic document examiners to support their opinions regarding ink differentiation.

Microscopic and specialised lighting examinations were also carried out using a VSC® 5000, reflecting common approaches taken by forensic document examiners. These examinations were complicated by the limited quantity of handwriting available for comparison. Additionally, as the pens for this study were newly purchased, there were limited pen striations or similar features that might assist in discriminating inks with similar optical properties. Despite this, several inks were again distinguishable based on their luminescence and/or absorbance behaviour under specific illumination conditions (Fig. 3).

The results drawn from the visual examination were largely consistent with those from PCA (Fig. 4). The sole exception was Set 2, in which the same number of inks were detected, but associated with different ink strokes. In this instance, visual examination correctly identified the distribution of different inks within the set. The consistency in results indicates that the two approaches can be considered complementary, with chemometric analysis of spectral data supporting the findings of visual examination. In particular, the use of documented statistical methods provides a quantitative basis for decision-making, addressing the concerns of subjectivity or cognitive bias often highlighted in feature comparison disciplines [22–24].

4. Conclusions

VSC spectroscopy with chemometrics has been demonstrated as a powerful tool for comparing visually similar ballpoint inks on paper documents, performing comparably with visual examinations by an expert examiner. Both approaches were demonstrated to be successful in identifying potentially fraudulent documents containing multiple inks. As this method is rapid, non-destructive and makes use of instrumentation readily available within many questioned document laboratories, this approach could be readily integrated into existing analysis workflows. The resulting data output could provide forensic document examiners with a statistically sound basis to support their results, enabling more confident and transparent decision-making. However, it is of interest to further study how factors such as background substrate or ageing may affect the results, and whether suitable corrections for these factors can be developed. In the case of background substrate, it is recommended that a blank section of the substrate is used for reference measurements in order to minimise spectral interferences.

Future work may expand this proof-of-concept by examining an increased number of complete handwriting specimens. This work may also provide the basis for an inter-laboratory study, to assess how examinations are affected by individual instruments or examiners. Such studies are an important step to validating and standardising feature-comparison methods in forensic disciplines.

Declaration of Competing Interest

None.

Acknowledgements

The authors wish to thank the staff at Reserve Bank Australia and the Digital & Document Evidence Branch; Victoria Police Forensic Services Department for providing access to the instrumentation for this research. This research was supported by the Faculty of Science Research & Development Committee, Curtin University.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fsir.2019.100021.

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