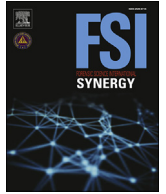




Contents lists available at ScienceDirect

## Forensic Science International: Synergy

journal homepage: <https://www.journals.elsevier.com/forensic-science-international-synergy/>

## Interpol review of questioned documents 2016–2019

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## ARTICLE INFO

## Article history:

Received 6 January 2020  
 Accepted 16 January 2020  
 Available online 12 April 2020

## Keywords:

Questioned documents  
 Ink  
 Paper  
 Forgery  
 Interpol

## ABSTRACT

This review paper covers the forensic-relevant literature in questioned documents from 2016 to 2019 as a part of the 19th Interpol International Forensic Science Managers Symposium. The review papers are also available at the Interpol website at: [https://www.interpol.int/content/download/14458/file/Interpol\\_Review\\_Papers\\_2019.pdf](https://www.interpol.int/content/download/14458/file/Interpol_Review_Papers_2019.pdf).

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## 1. Introduction

This paper is an exhaustive review of the latest technical advances and latest developments concerning documents examination, including handwriting comparison, since the 18th INTERPOL Forensic Science Symposium in 2016. This review is based on articles mostly published in the major forensic or generalist science journals, but also on presentations at international forensic meetings during the period 2016–2019.

The aim of this work is to identify all the relevant work in the field of document over a 3 years period, going from the second half of 2016–2019. This is to improve existing technologies, but also to implement new developments in the forensic laboratories working on documents. This work can also help determine future axes of research that would try to answer real cases problematics. Although every effort has been made to cover all developments about document examination in this review, some omissions might occur.

It is important to notify that in this paper, two different kinds of publications are referenced: forensic and generalist publications. For this work, only forensic publications are commented upon, the others are included as background information only.

The different areas of analysis concerning questioned documents being numerous, it was decided to group the results of bibliographic research around key topics: handwriting comparison, ink composition, inkjet and laser print analysis, crossing lines,

analysis of paper, indented impression, altered documents and security documents.

## 2. Sources of references

References presented in this work and listed below, come either from the scientific literature (forensic or not), or publications from various international meetings. Posters are not included.

## 2.1. Specialised references in forensic science

- Australian Journal of Forensic Sciences
- Canadian Society of Forensic Science Journal
- Egyptian Journal of Forensic Sciences
- Forensic Science International
- International Journal of Digital Crime and Forensics
- Journal of the American Society of Questioned Document Examiners
- Journal of Forensic Sciences
- Science & Justice

## 2.2. Other references

- Acta Chimica Slovaca
- Analyst
- Analytica Chimica Acta
- Analytical and Bioanalytical Chemistry
- Analytical Chemistry

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- Analytical Letters
- Analytical Methods
- Applied Intelligence
- Applied Physics a-Materials Science & Processing
- Applied Sciences-Basel
- Applied Spectroscopy
- Arab Journal of Nuclear Sciences and Applications
- Chemical Papers
- Chemometrics and Intelligent Laboratory Systems
- Egyptian Journal of Chemistry
- Electrophoresis
- Experimental Mechanics
- Expert Systems with Applications
- Forensic Chemistry
- Ieee Access
- Ieee Transactions on Information Forensics and Security
- Iet Biometrics
- Image Analysis and Processing
- Image and Vision Computing
- Information Processing & Management
- International Journal of Corpus Linguistics
- International Journal of Critical Infrastructure Protection
- Journal of Analytical and Applied Pyrolysis
- Journal of Analytical Chemistry
- Journal of Central South University
- Journal of Chromatography A
- Journal of Electronic Imaging
- Journal of Information Processing Systems
- Journal of Information Security and Applications
- Journal of Molecular Structure
- Journal of Raman Spectroscopy
- Journal of the American Society for Mass Spectrometry
- Journal of Visual Communication and Image Representation
- Law Probability & Risk
- Materiale Plastica
- Microchemical Journal
- Multimedia Tools and Applications
- Optical Engineering
- Pattern Analysis and Applications
- Quimica Nova
- Radiocarbon
- Rapid Communications in Mass Spectrometry
- Scientometrics
- Security Journal
- Sensors
- Signal Processing-Image Communication
- Spectrochimica Acta Part a-Molecular and Biomolecular Spectroscopy
- Spectroscopy Letters
- Talanta
- Trac-Trends in Analytical Chemistry
- Vibrational Spectroscopy

### 2.3. Meeting, symposium, forums

- Iapr International Conference on Document Analysis and Recognition
- Iapr International Workshop on Document Analysis Systems
- Ieee International Conference on Collaboration and Internet Computing
- Ieee International Conference on Image Processing
- Ieee International Conference on Multimedia & Expo Workshops

- Ieee International Conference on Software Engineering and Service Science
- Ieee International Joint Conference on Biometrics
- Ieee Winter Conference on Applications of Computer Vision
- International Conference of the Chilean Computer Science Society
- International Conference on Availability, Reliability and Security
- International Conference on Emerging Security Technologies
- International Conference on Enterprise Information Systems
- International Conference on Frontiers in Handwriting Recognition
- International Conference on Health and Social Care Information Systems and Technologies
- International Conference on Intelligent Computing and Control Systems
- International Conference on Pattern Recognition
- International Conference on Project Management
- International Conference on Signal Processing and Integrated Networks
- International Rais Conference on Social Sciences and Humanities
- International Workshop on Arabic Script Analysis and Recognition
- National Academy of Sciences of the United States of America
- Sibgrapi Conference on Graphics, Patterns and Images

### 3. State of the art of the equipment

To start with this study, it is crucial to identify the whole array of equipment, old and new, that are used, or have been used in documents forensic analysis.

Some techniques such as Thin Layer Chromatography have been in use since the beginning of ink analysis. Some of them were improved while new technologies were developed. They can be used in the study of ink composition (dye or other compounds such as volatile solvents used in dating), ink discrimination or in the study of paper.

Although non-destructive techniques such as the Raman spectroscopy are still the preferred ones (damages to the document should be kept at a minimum as much as possible).

In addition to the techniques routinely used by FDEs such as Microscopy, the Video Spectral Comparator which does not need to be presented, the analytical techniques available to us are listed below:

- Accelerator Mass Spectrometry (AMS)
- Atomic Force Microscopy (AFM)
- Desorption Electrospray Ionization Mass Spectrometry (DESI-MS)
- Diffuse Reflectance UV–Vis–NIR Spectroscopy
- Direct Analysis in Real Time Mass Spectrometry (DART-MS)
- Direct Sample Analysis Mass Spectrometry (DSI-MS)
- ElectroSpray Ionization Mass Spectrometry (ESI-MS)
- Field Emission Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (FE-SEM-EDS)
- Fluorescence Microscopy
- Focused Ion Beam (FIB)
- Fourier Transform Near-Infrared spectroscopy (FT-NIR)
- Fourier Transformed Infrared spectroscopy Attenuated Total Reflectance (ATR-FTIR)
- Fourier Transform-Raman spectroscopy (FT-Raman)
- Gas Chromatography Mass Spectrometry (GC/MS)
- High Performance Liquid Chromatography (HPLC)
- High Performance Liquid Chromatography with photoDiode Array Detection (HPLC-DAD)

- High performance Thin Layer Chromatography (HPTLC)
- Hyperspectral imaging
- Laser Ablation coupled with Direct Analyte-Probed Nano-extraction coupled to NanoSpray Ionization Mass Spectrometry (LA-DAPNe-NSI-MS)
- Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)
- Laser desorption Laser postionization time of flight Mass Spectrometry (L2MS)
- Laser-Induced Breakdown Spectroscopy (LIBS)
- Liquid Chromatography Diode Array Detection Orbitrap Mass Spectrometry (LC-DAD-Orbitrap-MS)
- Liquid Chromatography Mass Spectrometry (LC-MS)
- Liquid Chromatography tandem Mass Spectrometry (LC-MS/MS)
- Liquid Chromatography-High Resolution Mass Spectrometry (LC-HRMS)
- Magneto-optical visualizer
- Matrix-Assisted Laser Desorption Mass Spectrometry (MALDI-MS)
- Micellar Electrokinetic Capillary Chromatography (MECC)
- Micellar Electrokinetic Capillary Chromatography with Laser Induced Fluorescence detector (MECC-LIF)
- MicroSpectroPhotometry (MSP)
- Microstructured-Capillary Electrophoresis
- Near-InfraRed spectroscopy (NIR)
- Paper Spray Mass Spectrometry
- Pyrolysis Gas Chromatography Mass Spectrometry (Py-GC/MS)
- Raman spectroscopy
- Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDS)
- Surface Enhanced Resonance Raman scattering (SERS)
- Surface Enhanced InfraRed Absorption Spectroscopy (SEIRAS)
- Thermal Desorption Gas Chromatography Mass Spectrometry (TD-GC/MS)
- Thermogravimetric analysis
- Thin Layer Chromatography (TLC)
- Time-Of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS)
- Time-Resolved Luminescence spectroscopy (TRL)
- UV-Vis Spectroscopy
- X-Ray Diffraction (XRD)
- X-Ray Fluorescence (XRF)
- X-Ray Powder Diffraction (XRPD)

#### 4. Overview about INK and paper analysis, including datation and crossing lines

An overview of the instrumentation and working methods used in the questioned document laboratories around the world demonstrated that it is relatively consistent [1]. This survey could be useful for laboratories to consider new instrumentation or examination methods.

#### 5. Ballpoint, gel, fountain, markers, felt-tip, pen INKS and stamp INK

Several studies [2–31] have been published concerning the analysis and discrimination of writing inks with several kind of instruments. Some papers focused on only one analytical method while others compared a method to another, or combined them to find a methodology to discriminate inks.

##### 5.1. Methods development/improvement [2,9,11,13,15,20,26–28,30–32]

As well as microscopy and VSC, TLC is one of the oldest methods available to a FDE and it is still studied and used by forensic laboratories. The effects of the quality of solvents on the separation of dyes and the repeatability of the TLC results was demonstrated by Barker J. and al [9]. Therefore, the grades and manufacturers of solvents must be consistent when two samples are compared or when a database is created and used.

Raman spectroscopy is a useful non-destructively method to identify dyes and some other components in inks [32], requiring no sample preparation, hence its increasing use in forensic laboratories.

Lee L.C. and al [15] focused on the analysis of ballpoint pen inks by Raman and found a discriminating power of 94% for blue inks and 95% for black inks.

For the data analysis of Raman spectra, Asri M. and al [6] used a chemometric approach, and ballpoint pens of different brands were differentiated while pens of the same model were grouped.

Some papers focused on the discrimination of blue and black pen inks by hyperspectral imaging as a non-destructively method [2,11,13,20].

Suzuki M. and al [28] analysed 18 black inks by TRL spectroscopy to discriminate them. They separated them into 15 groups.

To detect and identify potential acid and basic dyes in blue writing inks, a LC-DAD-Orbitrap MS method was established by Sun Q. and al [27]. 30 blue pen inks were analysed, and they found 10 known dyes and 4 unknown.

Gładysz M. and al [30] analysed nine stamp pad inks in three different colours by micellar electrokinetic capillary chromatography method. The authors concluded that almost all examined samples were differentiated based on the obtained electrophoretic profiles.

Krol M. and al [31] also analysed stamp inks by MEKC but with a LIF detector and obtained a discriminating power of 87.3%.

Valderrama L. and Valderrama P. analysed blue pen inks using iPhone. After digital image analysis combined with chemometric analysis, the identification of the pen inks types is tested [26]. The method could be interesting for field application, but it must be improved and many parameters should be taken into account.

##### 5.2. Comparison of methods [4,12,19,21–23]

Raman spectroscopy and SERS were used for dye identification in ballpoint inks and the results of these two methods were compared. SERS provided enhanced spectral features and quenching of fluorescence [4]. Saviello D. and al [21,22] found the same conclusions for felt-tip pen inks.

Sharma V. And Kumar R [23]. discriminated 57 blue ballpoint pen inks by ATR-FTIR and HPTLC. The discriminating power of ATR-FTIR is 97.93% by visual comparison and of 99.69% with chemometric analysis, while the discriminating power of HPTLC is 93.8%.

Drury N. and al [12] compared DART-MS and DSA-MS to analyse writing inks. They concluded that the spectra are similar between the two techniques, the DSA-MS spectra are little less noisy, but the quantity of sample used for DSA-MS analysis is more important than for DART-MS.

Liu R. and al [19] analysed gel pen inks of different colours by L2MS and LD-MS. The characterisation and the discrimination of the samples are better with L2MS analysis.

##### 5.3. Methods combination and methodology [4,22,25]

In Sun Q. and al [25], 18 blue ballpoint inks were examined by microscopy, VSC, TLC, GC/MS and LC-MS/MS. They suggested that

all the methods must be applied to discriminate the inks. However, they used the microscopy as the last step and the combined methods VSC, GC/MS and TLC or VSC, GC/MS and LC-MS/MS gave the same results as the combination of the four methods.

Alyami A. and al [4] showed that UV–vis spectroscopy and TLC complemented Raman/SERS.

The complementarity of SERS and UV–vis spectroscopy was also highlighted by Saviello D. and al [22].

#### 5.4. Data analysis [3,5–8,11,14,16–18,20,23,24,26,33]

Multivariate data analyses or chemometrics are one of the most studied fields. Concerning pen inks, 15 papers refer to this topic [3,5–8,11,14,16–18,20,23,24,26,33]. A chemometric approach is primarily used to classify samples or to discriminate them. In view of the studies, the use of a chemometric approach increase the discrimination power of analytical methods. However, the intra-variability of the samples is rarely presented in the chemometric results.

Asi M. and al used a chemometric approach (Pearson's Product Moment Correlation or PPMC and Principal Component Analysis or PCA) to compare an unknown sample to a database of Raman and FTIR spectra to determine the original pen. This approach was tested on gel pens [7] and ballpoint pens [8].

Lee L.C. and al focused on the use of chemometrics on FTIR spectra and discussed the pre-processing effects and the choice of parameters on the data classification by PLS-DA (Partial Least Squares-Discriminant Analysis) [17,18]. They also tested the influence on the PLS-DA performances of the distribution of samples between the training set and the test set [16]. They separated 1361 ink strokes that originated from 273 blue gel individual pens (IPs) of 23 pen models and 10 pen brands in two sets (training and test) using two different principles: all the strokes of a particular IP was in the same set or, the strokes of a particular IP could be spread between the two sets. The authors noticed no differences between the two approaches. However, strokes of pens of the same model could be spread between the two sets; a new study considering only one pen by model could be interesting.

Chlebda D. and al analysed 35 black gel pen inks (10 pairs were repeated) by hyperspectral imaging coupled with chemometric analysis to discriminate them [11]. Three chemometric methods were used in this study: Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA) and Spectral Angle Mapper (SAM). The method is interesting, however some replicates was not grouped together and were differentiated.

Pereira J. and al [20], also focused on the analysis of black pen inks by hyperspectral imaging combined with Projection Pursuit and PCA.

Kumar R. and Sharma V. compared the discriminating power of UV–Vis spectroscopy (destructive method) to diffuse reflectance UV–Vis–NIR spectroscopy (non-destructive method) combined to a chemometric approach [14]. The use of chemometrics improve the discriminating power of the diffuse reflectance UV–Vis–NIR spectroscopy from 69.67% to 99.46%.

## 6. Inkjet and toner printing

### 6.1. Ink/toner analysis [34–48]

The black inkjet inks [34–37] and black toners [38–43] analysis is a current challenge for FDEs and some researches were published on this topic.

Oravec M. and al [34] used FT-NIR to classify black inkjet inks in two groups depending on the ink type: Carbon black or black colorant.

In another study, Oravec M. and al [35] analysed black inkjet

inks by SEIRAS, corresponding to a surface-enhanced ATR-FTIR using silver colloid. The results were not convincing, the paper significantly affected the spectra.

SERS was used to improve the information obtained by Raman spectroscopy analysis on black inkjet ink and on black toner, with interesting results [37].

Von der Kall V. and al [36] analysed the main volatile components of 5 pigmented black inkjet inks by GC/MS with a thermic-desorption system to classify them.

Materazzi S. and al [39] analysed and discriminated 10 black toners by FT-NIR coupled with chemometrics. Their results suggested that it is also possible to discriminate toner printed with different quality settings (low and high quality) and with low percentage of toner in the cartridges.

To complement FTIR analysis, Biedermann A. and al [43] analysed the magnetism by a magneto-optical visualizer of black toners on documents printed. To interpret the results, a Bayesian approach using parametric distributions was presented. One condition of the analysis was an identical text area to obtain comparable results. To overcome this problem, Polston C. and al [40] determined that the toner area was correlated to the magnetic flux.

Buzzini P. and al [44], discriminated coloured inkjet inks of different cartridge models using Raman spectroscopy. They also discriminated inks of two printers of the same model. However, no information on the cartridges was available for one of the printers, and could be cartridges refilled or not original ones.

Corzo R. and al [45], Johnson C. and al [46], Williamson R. and al [47], and Trejos T. and al [48] analysed the same set of samples by different analytical methods, compared their discrimination powers and developed a searchable database. LA-ICP-MS seemed to have the highest discrimination power.

### 6.2. Physical analysis [49]

Hofer R [49], established a horizontal profile of letter's blank area of pdf text file printed on 25 laser printers and compared the measures to each other. Significant differences were found between the toner printers, in some cases even within the same brand and the same model. The author recommend further research on this topic.

### 6.3. Printer identification [50–58]

Nine papers [50–58] were published on this topic and they are all based, not on chemical analysis to identify a printer but on physical features (as banding artefacts, local texture patterns, microscopic structure and texture information) with sometimes the use of deep learning system.

This type of research is still in its beginning, and some parameters that can influence the results were not discussed.

Escher S. and Strufe T [50], analysed an identification scheme that uses the halftone texture of colour laser image prints as an intrinsic signature. The results showed the halftone textures were dependent on driver settings and could be manipulated.

## 7. Dating

For many years now, this topic has been one of the most important challenge for FDEs, either in absolute dating especially in ink dating, as in relative dating by the determination of writing and/or printing sequence.

## 7.1. Absolute dating

### 7.1.1. Ink dating [36,59–73]

Ink dating remains a challenging task for FDEs despite the several studies that have already been published. However, ink dating remains controversial, especially regarding the reliability and repeatability of results. In addition, the document storage conditions remain a hugely influencing factor in the methods currently in use. Several analytical approaches may be employed, such as solvent evaporation or dye degradation. The most studied method is the analysis by GC/MS of phenoxyethanol (PE) of ballpoint inks.

A review of the main existing dating methods used in forensic laboratories for pen inks was presented and tested by Díaz-Santana O. and al [59]. These methods are based on determining solvents and dyes using GC/MS and HPLC-DAD respectively. The most reproducible results was obtained for the combined methods (both solvents and dyes analysis).

Sharma V. and Kumar R [60]. analysed by UV–Vis spectrophotometry the decrease in absorption of dye with respect to time during 9 months, and ink aging curves was created by statistical methods. The results obtained show that the method is not efficient, the error rate is important, and to create the ink aging curves, only one analysis per sample by month seems to have been done.

Sauzier G. and al [61] studied the potential of Vis-spectroscopy combined with statistical analysis for ink dating of blue ball tip inks. The predictive accuracy was found to improve for long term ageing.

Hofer R. and Yahaya Bako A.S [62]: used the diffusion of luminescent components of some inks for a dating estimation.

Aginsky V [63]. focused on rollerball pens and their gradual loss of 2-pyrrolidone (2-PD) that may correlate with the age of the inks during up to 12 months following the application of the inks to paper.

Grechukha N.M. and al [64] compared the use of Raman and a combination Raman GC/MS to estimate the ink dating by taking into account dyes and solvents presented in ballpoint pens.

Díaz-Santana O. and al [65] analysed dyes and solvents present in two types of ballpoint pen inks by GC/MS and HPLC-DAD and regression models was developed for each ink type for a 45 months period.

TOF-MS was used to provide dye composition and document dating information [66]. By the determination of the dye formulation of a sample and by comparison with a database of ink formulation over time, Costa K. and al estimated the date on which manuscripts were launched on documents but with important dating errors (8–15 years).

Five studies [67–71] focused on the analysis by GC/MS of phenoxyethanol (PE) of ballpoint inks and, its decrease over time.

Koenig A. and Weyermann C [67,68]. tested different parameters to monitor ink ageing and found 3 ageing parameters promising (the PE quantity, the ratio and the difference of quantities of PE extracted from both natural and heated samples). In a second part, they tested 3 interpretation models to date ink entries in a legal perspective: the threshold model, the trend tests and the likelihood ratio calculation.

De Carvalho C. and al [69] tested firstly the main parameters involved in the reliability of the method (linearity, repeatability, limits of detection and quantification, accuracy and robustness). In a second part, they tested the paper influence on the quantity of PE from ink. The authors determined that the results showed a method linear, precise, accurate and robust and an influence of kind of paper in PE quantification.

Andrasko J. and Lagesson-Andrasko L [70]. also focused on the analyse by GC/MS of phenoxyethanol of ballpoint inks but with a thermal microdesorption unit.

Sun Q. and al [72] analysed by LC-HRMS the PEG oligomers in carbon-based black gel inks and their degradation over time. They showed that the relative amount of low molecular weight oligomers increased over time and suggested further studies on this topic.

Cantú A [73]. discussed about the methods that are based on the analysis of ink solvent and the ink aging curve resulting. From his point of view, some problems occurred in aging curves could be partly due to the parameter values that were improperly determined such as when a measurement is made of an ink solvent that is not completely extracted from an ink sample.

Most of the ink dating research concerned pen inks, yet Von der Kall V. and al [36] studied the decrease of volatile compounds (2-Pyrrolidone, TEGBE) of black inkjet inks over time.

### 7.1.2. Paper dating [74–77]

Few researches have been done on this topic due to the weak usefulness in forensic science as the dating correspond to the paper fabrication period. However, in the historical field or works of art, paper dating can be important to detect forgeries and fraud.

Risoluti R. and al [74] developed a method by NIR spectrometry associated with statistical analysis, presented as efficient to characterise paper and to date it. Silva C.S. and al [75] also present a method to date paper based on FTIR analysis and statistical analysis. However, the variability in the spectra for each year was important and another approach could be considered.

For estimating the age of documents, paper analysis by Py-GC/MS [76] was also conducted. Two approaches were tested: an indirect approach based on the identification of compounds characteristic of the document period and a direct approach using the pyrolytic fingerprints of the paper. The indirect approach could be interested to demonstrate an anachronism for example, but further studies should be done for the direct approach.

Huels C.M. and al [77] have measured radiocarbon concentrations in papers of the last 65 years. From their point of view, the proposed method could potentially enhance the precision of paper production-date estimates for samples made after 1955.

## 7.2. Relative dating

### 7.2.1. Crossed lines [78–95]

The determination of the sequence of crossing ink lines remains a challenging task for FDEs despite the several studies published, demonstrated by the review of Brito L. and al [78]. The difficulties of this task is also highlighted by the several methods that were tested: microscopy [79–82], AFM [83–85], the hyperspectral imaging [86,87], MSP [88], Raman spectroscopy [89], FIB-SEM/EDX [90], TOF-SIMS [91–93], TLC [94], GC/MS [94], HPLC [94], MALDI-MS [94], DART-MS [94], LC-MS [94] and PS-MS [95].

All the researches focused on the determination of the sequence of heterogeneous line intersections, and they determined that the results were mostly positive but it was usually under some conditions.

Some reviews [83–85] presented the usefulness of AFM in different fields of the forensic science including document examinations and crossed lines analysis.

Lunakova M [79]. analysed the sequence of handwritten and printed entries without direct intersection under digital microscope (direct method) and studied the distribution of toner particles on the stroke and in the blank region of the paper (indirect method). For the indirect method, an absence or a reduction in the density of toner particles in the stroke compared to the blank region was expected if the stroke was done before the printing process. To the author, coaxial mode could be helpful in some cases for the direct method.

3D application of confocal microscope was explored by Mann M. and al [80], to determine the sequence of homogeneous line intersections produced using black or blue ballpoint, fountain or gel pens. The authors were able to determine correctly the sequence in 81%.

Observation method of physical characteristics, scraping technique and fluorescence method was used to determine the sequence between laser printing line and inkpad or stamp pad ink seal by Li B. and al [81,82].

The hyperspectral imaging is used by Brito L. and al [86] and by Martins and al [87] on black pens (different types) and blue ballpoint pens respectively. In the first research, the results were inconclusive while the authors of the second studies concluded positively with 63% accuracy.

Li B [88], analysed by MSP heterogeneous line intersections produced using inkpad, stamp-pad ink and ballpoint pens, gel pens, fountain pens, laser and inkjet printers. From the point of view of the author, the MSP could be used to determine the sequence of heterogeneous line intersections under some conditions.

Borba F. and al [89] combined confocal Raman imaging to chemometrics (MCR-ALS) to study depth profiling of crossed lines. Only two cases were investigated, further studies should be done on this method.

Kim J. and al [90] focused on the determination of the sequence of heterogeneous line intersections analysing the FIB exposed region by EDX. The technique was successfully tested on intersections produced using gel pens and red sealing inks.

Lee J. and al [92] used TOF-SIMS to determine the sequence of line intersections. The TOF-SIMS depth profiles seemed to reveal successfully the order of deposition in some cases, as for laser printing and stamp ink. In the same way, Malloy M. and al [91] analysed blue ballpoint pen inks and successfully identified the sequence deposition order by molecular imaging. Goacher R. and al [93] also analysed crossed lines of different black inks using TOF-SIMS but in some cases, incorrect conclusion were made regarding ink deposition order.

Williamson R. and al [94] identified some luminescent components of inks by several techniques and tested unsuccessfully to determine the sequence of crossing ink lines by this way.

## 8. Paper analysis

Since the last review, 8 articles have been published on this topic [96–103].

Jones K. and al [96,97] analysed standard white papers by IRMS to examine the intra and inter-variability for oxygen isotopes measured. The examination of the variability of samples was conducted at the sheet, ream and brand source levels, and a high intra sample variability was found. With a 1.4% discrimination range for the comparison process, 82% of the samples were discriminated. The authors also highlighted the effect of toner on the oxygen isotopes measurements while inkjet printing processes did not seem to have an effect on it.

Kumar R. and al [98] analysed papers by FTIR for characterisation and discrimination. They used chemometrics to increase the discrimination and obtained a discriminating power of 99.64%.

Tino R. and al [100] also analysed and compared papers by FTIR and chemometrics. They found that paper sheets originating from different producers or from various production technology units could be differentiated.

Zieba-Palus J. and al [99] analysed papers by Raman and FTIR. The samples have been artificially aged before new analyses. The authors concluded that they were still distinguishable after this process.

Musgrave N. and Thorne O [101], observed Ultraviolet Line

Patterns (UVLPs) on sheets under UV light and were able to conclusively associate sheets of paper from the same ream. The authors explained that the UVLPs were found to repeat through the ream in a predictable way, while also changing.

Kumar R. and al [103] discriminated 24 different kinds of writing/printing papers by using Thermogravimetric Analysis with a discriminating power of 99.28%.

## 9. Document security

### 9.1. Counterfeit detection [104–109]

Paper analysis could be used to determine if a document is genuine or counterfeit [104] or to determine the methods and techniques used by counterfeiters [105]. Marabello D. and al [104] analysed paper of genuine and counterfeit banknotes by X-ray powder diffraction. The results showed that the papers of genuine banknotes were composed of cotton-based cellulose and TiO<sub>2</sub>, while the papers of counterfeit banknotes were composed of cellulose based on wood pulp and TiO<sub>2</sub> mixed with calcite.

Brandao J. and al [106] determined the authenticity or counterfeiting of banknotes and Brazilian driver licenses by VSC and AFM, using roughness and topographic profiles of the chalcographic region. The usefulness of the AFM analysis could be discussed as the observations by VSC gave the same conclusions.

Melendez-Perez J. and al [107] analysed revenue stamps by Energy-dispersive X-ray fluorescence (ED-XRF) coupled with chemometric tools to discriminate between authentic and counterfeit stamps. The authors proposed this method for use by non-specialist operators to screen for counterfeit stamps.

Leonard P [108] used VSC and appropriate reference material to discriminate between authentic and counterfeit postage stamps. Some parts of the philatelist methodology could be compared to the forensic approach.

These last years, several researches focused on the development of automatic fraud detection systems. However, are they really efficient and better than trained human is? Gariup M. and Piskorski J [109], reported the findings of the Document Challenge II performed in Lisbon in September 2013 and organized by Frontex. Some conclusions of the authors are:

- The results of experienced human were better than the results of automated document inspection systems.
- The decision of the automated document inspections systems was not consistent.
- The deployment of automated systems alone or with non-experienced/untrained officers represents an important vulnerability for the detection of false documents and should be studied and analysed thoroughly.

### 9.2. Altered document [33,89,110–122]

Sidere N. and al [110] created a public dataset for forgery detection. The dataset was made of a corpus of 477 corrupted payslips in which near 6000 characters were forged. This dataset could be used to develop or test automatic fraud detection system.

Saini K. and Kaur S [111], examined documents altered by software. The examination procedure usually done on documents was applied on digital documents:

- Spacing between letters or words
- Discrepancies in size, font or design
- Crowding of various letters and words
- Non uniformities in the background

Megahed A. and al [112] proposed a new method to detect the forgery in a text by detecting different ink using image processing instead of conventional methods.

Artaud C and al [113] described the ICPR2018 fraud detection contest and the different methods submitted by the participants to automatically detect fraud on documents. However, the number of participants was weak.

Cruz F. and al [114] analysed inconsistencies on the intrinsic features of the document image and presented a classification-based approach for forgery detection. Discriminant texture features was determined by Local Binary Patterns (LBP) and multiple descriptors were combined from neighbouring regions to model contextual information. Support Vector Machines (SVM) for classification was applied to detect several types of forgeries in a wide range of types of documents.

Several articles focused on the obliterated issue, and the non-destructive methods are preferred.

The VSC is commonly used for this kind of alteration but could be combined with an infrared hyperspectral imaging system [115]. Khan M. and al [116] used the hyperspectral imaging to detect forgery but combined with a deep learning approach.

Suzuki M. and al [117] applied a wide-field time-resolved luminescence (TRL) method with a pulsed laser and a gated intensified charge coupled device (ICCD) for deciphering obliterated documents.

Borba L. and al [89] used confocal Raman imaging coupled with MCR-ALS analysis to examine obliterated texts.

These methods could be interesting if the analysis by Video Spectral Comparator is inconclusive.

In a destructive way, Huynh V. and al [118] removed the ink concealing a text by laser ablation to reveal the original text and to be able to analyse the ink of the original text.

Teixeira C. and Poppi R [33], focused on the analyse of blue ballpoint pens inks by Raman imaging spectroscopy and used a chemometric approach to analyse the data (Independent Components Analysis algorithm). This approach permitted to detect alteration (as addition) on documents when different pens were used and to obtain Raman spectra of each pen.

To alter a document, some part of the text can be erase. Recent inks have the characteristic to remove by friction or by heating. This kind of ink was successfully revealed by using VSC, ESDA [119,120] or by DESI-MS [121]. It is also possible to reveal Thermal inks after cooling the sample in a refrigerator at 0° to -10 °C [122].

### 9.3. Forensic intelligence [123–126]

Few studies focused on this topic even if it is an important field of investigation for the fraud analysis to link cases or to reveal some trends.

Baechler S. and Margot P [123], postulated that “a monitoring approach rooted in the systematic examination and profiling of counterfeit and forged documents using forensic science methods shall provide novel, relevant and useful crime intelligence”. They have developed a method to compare the characteristics of false identity documents.

De Alcaraz-Fossoul J. and Roberts K [124], also highlighted the importance to extract information of counterfeit documents to generate forensic intelligence.

Auberson M. and al [125] developed a systematic computer vision-based method to analyse and compare images of false identity documents to classify false identity documents and highlight links between documents (modus operandi, source ...).

Vieira R. and al [126] also developed an automatic system by comparison a fraudulent document to a database of counterfeit documents to determine if a similar technique or material was already used to forge a document.

### 9.4. Miscellaneous [127]

To prevent falsification of handwriting document, Loc C. and al [127] proposed to use watermarking technique, with Fully Convolutional Networks. On their point of view, this approach achieved high performance regarding such properties as imperceptibility and robustness against distortions caused by JPEG compression, geometric transformation and print-and-scan process.

## 10. Handwriting/signature

### 10.1. General aspect [128–132]

Eggleston C [128], reviewed Huber and Headrick's Handwriting Identification: Facts and Fundamentals, Second Edition. The author in this new edition noted some important updates:

- The chapter on graphology was deleted but some of its text had been relocated elsewhere.
- The discussion under statistical inference in the identification process is badly flawed with respect to Bayes theorem.
- Incorporation of information on online and offline signature/handwriting and automated handwriting verification.

Durina M. and Caligiuri M [129], compared the results of determination of authorship from a homogeneous group of writers by FDEs and Laypersons. The Laypersons determined authorship with average accuracy scores of 76% (98% for FDEs).

### 10.2. Handwriting analysis [133–140]

Dziedzic T [133], studied the influence of lying body position on handwritten and concluded that the comparison was possible between handwriting made in sitting position and in lying position, even if differences could be noticed.

Cadola L. and al [134] studied the reliability to compare spray paint writings on walls to conventional reference material. They concluded that the comparison is not conclusive and FDEs need reference material produced under similar conditions.

Saini K and Kaur M [135], studied the effect of age and Parkinsonism on handwriting characteristics. Several variations on the handwriting were observed which made their writing appeared different altogether as compared to their corresponding normal writing.

Even if FDEs examine mostly cursive handwriting, they are able to deal with block hand printing by using the same methods and protocols as in the identification of cursive handwriting, according to Mitchell L. and Merlino M [136].

Yang C. and al [137] studied the handwriting of adolescents in Singapore and concluded that the writing styles and characteristics are different in some points of those observed in previous studies from other countries. They also suggested some factors that could explain these differences.

Rika J [138], determined a correlation between texts by using relative width and height of handwritten letters.

GraphJ is a plugin for ImageJ. It could help FDE in the analysis step of a document and so to the decision process. GraphJ results were determined as compliant to those obtained by FDE using standard manual techniques [139,140].

### 10.3. Signature [141–143]

As the complexity of a handwritten signature is an important factor for FDEs. The perception of this complexity is studied [141]. The results showed that the FDEs perception is repeatable and reliable.

The variation of the signature was studied by Singer K. and Cox N. over an average of four decades [142]. The authors, based on the eight characteristics that they have defined, determined that the variation of the signature was very little over time.

Conlan X. and al [143] introduced a new methodology - the Line-Up method - for the presentation of signatures for comparison. This methodology did not show significant differences in the decision or results compared to the Target methodology for the FDE.

#### 10.4. Online/dynamic/electronic signature [144-153]

Heckerroth J. and Boywitt C [146]. evaluated the ability to compare dynamic signatures.

Linden J. and al published a review of dynamic feature variation and forensic methodology on dynamic signatures analysis [147].

The results of the study of Caligiuri M. and al [148] revealed that several kinematic handwriting features (pen pressure, stroke velocity, straightness variability) were significantly associated with accurate FDE opinions for writer identification.

The new parameters introduced by the dynamic signature are kinematic parameters. The study of these parameters could be used by FDEs, with classical parameter, to determine if a signature is genuine or simulated [149,150].

Linden J. and al [151] studied the reproducibility, the intra-variability and the occurrence of the of correctly simulated features. In their study, the reproducibility is high except for the pressure. The occurrence was low for features such as signature size, trajectory length, and total signature time. These three parameters performed the best result for discriminating genuine from simulated dynamic signatures.

Kinematic parameters were also used to develop a model that explain the variability in FDEs perception of the complexity [152].

Li C. and al [153] used statistical analysis on pen pressure data for dynamic signature verification. They considered that this kind of analysis, with only pen pressure parameter, has a good potential to be developed as a tool for automated signature identification. The other papers on the subject concluded that different kinematic parameters should be used with classical parameters to discriminate between genuine and simulated signatures.

#### 10.5. Automatic systems [148,154-177]

Several studies [148,154-176] focused on the development and test of automatic systems to identify the writer of different available datasets. Some researches were based on deep learning systems and others used basic statistical tools to create a classification method.

Kumar R. and al [154] extracted some features used by FDEs and used statistical tools to create a classification of writers and so a writer identification. However, some parts of their research are not with a FDEs perspective.

Ni K. and al [163] proposed a methodology for denoising handwritten documents to improve the writer identification of noisy handwritten documents (lined, graph paper, coffee stains, stamps ...).

Al-Maadeed S. and al [169] tested different new features (e.g chain-code features, edge-based directional features) that improved the automatic writer identification.

Morales A. and al [170] studied the potential of human interventions to improve Automatic Signature Verification, and concluded that improvement was obtained when human interventions at feature extraction level is done (by manually annotating signature attributes).

Morocho D. and al [171] presented a new semiautomatic signature labelling interface inspired by FDE.

Parziale A. and al [177] presented a study using writer identification on sample with just a few lines of text available in both genuine and questioned documents.

#### 10.6. Interpretation [178-184]

Lewis J [178]. discussed on the cognitive bias in document examination and recommended to minimize them but the FDEs should not work completely blind to information. For the author, training in cognitive bias should be studied during the training of the FDEs.

The application of a Bayesian approach on signature and handwriting results was discussed in some researches. Marquis R. and al [180] presented a practical example of the likelihood ratio approach when the Court asked whether a questioned signature was written, or not, by the suspect and the assessment of the error margin of the signature analysis. They presented advantages of the Bayesian approach and showed that a logical approach for evidence evaluation can be followed even if hard statistical data are not available. Morrison and al [184] gave a response to this article and especially on the lack of hard statistical data and that the evaluation was based on the knowledge and the experience of the examiners.

The Bayesian approach is also discussed by Gaborini and al [182] in questioned handwritten signatures by the use of Bayesian networks. They identified writing features case-specific and more general that are highly discriminant, and easily detectable.

Johnson M. and al [181] studied the occurrence of predetermined characteristic found in handwriting and handprinting samples, while Vastrick T. and al [183] measured the occurrence of handwritten numeral characteristics.

#### 10.7. Miscellaneous [185-198]

Makris J [185]. compared the features made by a tracing guideline and by similar outlines created by the inclination of the writing instrument on a soft writing substrate. If this is due to the inclination of the writing instrument, the indented line is always at a parallel and fixed distance from the inked line.

Liu N. and Zhang L [186]. compared the RTI (reflectance transformation imaging) and CLSM (confocal laser scanning microscopy) results to quantify the 3D details of document surfaces that could be helpful for the analysis of morphological characteristics. Visually, the results produced using RTI were better than with CLSM.

Dellavalle F. and Frontini S [187]. studied the 3D depth measurement of the grooves and the measure of the relative pressure variation along a graphic pattern by a laser microprofilometer. For any given "writing means" (pens) and "writing medium" (inks), the authors defined the intravariability and intervariability in degree of indentation.

Lanners B [188,189]. studied the ability for a FDE to correctly associate the Dominant-Hand Writing to the trained Non-Dominant-Hand Writing of the same person.

Moszczyński J [190]. studied cases where the same person develop two or more different styles of handwriting. The identification of this kind of writer may pose serious problems if the known sample and the questioned document do not have the same writing style.

Some researches [191-195] using handwriting and statistical tools to determine the gender of the writer than others to determine writer's country of origin [196].

Can handwriting be simulated by robots with the same individual characteristic as a person? Dumitra A and al [197] studied this topic and found several differences between the two handwritings. Some features could be characteristic of a robotic writing (pen pressure, superimposition of letterforms).



Gervais R [198] studied the distortion of signature created by using a photocopier. Copies created distortions and image degradation on the signatures. The kinds of distortion and degradation were photocopier dependant.

## 11. Miscellaneous

15 papers are listed in this section that were difficult to classify in the previous categories.

### 11.1. Indented recovery [199,200]

Roloff B. and al [199] studied the influence of the paper density on the threshold of recovering of indented impressions.

Two methods were compared to reveal indented writing on thermal paper: ESDA and the controlled application of heat [200]. With three sheets of paper above the thermal paper to made the indented writing, the visibility grade was better using the heating method. However, this method alters the document and could have an impact on the fingerprints recovery.

### 11.2. Shredded documents [201–205]

5 researches [201–205] deal with the shredded documents. Reconstructing shredded documents could be important for the investigation but it is time consuming. To perform this task in a limited time interval, several computational techniques have already been proposed but the results needed to be improved. The researches were mostly done on Chinese documents, and the best accuracy is 97.19% [205].

### 11.3. Text analysis [206–211]

The text analysis is field with different topic as the linguistic [206–208], the stylometry [209], and text classification [210].

Faigenbaum-Golovin S. and al [211] mixed a comparison of handwriting text made by machine learning algorithms and textual analysis to identify authors of texts.

### 11.4. Recovering information [212]

One research deals with the thermal ribbon analysis. Stephens J. and al [212] developed and tested a device that scans a wide variety of cartridge formats to recover and preserve the photographic data for analysis.

### 11.5. Methodology [213]

Parsons L. and al [213] studied the impact of DNA analysis and document examination on respective analyses. Firstly, they determined locations on the document that are most commonly touched during writing and handling and given the best results. They described the impact of each techniques on respective analysis. They concluded that care is required when ordering these examination strategies.

## 12. Trends/challenges

The trends concerning document analysis are the use of new technologies to analyse inks and papers and the use of chemometrics to evaluate the analytical data. Researchers are heading towards the development of new methods more sensitive, but these methods may be destructive, time-consuming, expensive and sometimes not useful for a forensic scientist. The forensic scientist is not only a chemist, the results should be evaluated in a forensic

point of view; the forensic information must be helpful for investigators and Courts of justice.

The challenge for a forensic scientist in document examination should reside in the improvement of the evaluation of the results obtained from methods already developed and used in our laboratories, backed with strong researches and databases. The data analysis, the implementation or development of database for the identification (e.g inks, devices) or the estimation of the occurrence of a characteristic in a population could help the forensic scientist in his mission. One of the trends in forensic science is the data analysis by using statistical analysis or chemometric tools to improve the efficiency of a research in a database and to improve objectivity in the comparison process. According to published studies, the use of chemometrics can increase the discriminating power of techniques already in use in our laboratories. Studies on this topic should be encouraged but without forgetting some principles of research in our work, such as the study of the intra-variability or the determination of the limits of the method. Chemometrics should be used as tool to help in the decision process but cannot replace an expert in this field. Any tool used by an expert should be mastered by them to the point they should be able to explain how they work (principles and theory). The use of statistical tools when we do not know how and where the differentiations are made should not be encouraged.

The dating remains a challenge for the forensic scientist. A consensus between different laboratories seems to have been reached, and standardisation has begun. However, ink dating must remain a research topic, especially regarding the reliability and repeatability of results.

Regarding document fraud, two trends seem to exist: Forensic Intelligence and the use of automated systems for the detection of fraudulent documents. The development and application of automated systems are quite researched (as opposed to Forensic Intelligence) even if limits in their use without the assistant of an expert in fraud have been highlighted. Forensic Intelligence seems to be a good way to identify connections between cases at national and international levels in addition to criminal intelligence.

As in the last report, the researches on handwriting comparison have been focused on the use of automated and statistical tools. The fact that these works are still in process is the proof that the implementation of such devices is very challenging. Furthermore, disguised handwriting is not taken into account by these systems despite its crucial importance in the field. Automated systems for handwriting comparison are based on the research and the analysis of similarities between handwritings whereas an expert analyses and compares both differences and similarities.

## Disclaimer

This is a republication in journal form of a conference proceeding that was produced for the 19th Interpol Forensic Science Managers Symposium in 2019 and was originally published online at the Interpol website: [https://www.interpol.int/content/download/14458/file/Interpol\\_Review\\_Papers\\_2019.pdf](https://www.interpol.int/content/download/14458/file/Interpol_Review_Papers_2019.pdf). The publication process was coordinated for the Symposium by the Interpol Organizing Committee and the proceeding was not individually commissioned or externally reviewed by the journal. The article provides a summation of published literature from the previous 3 years (2016–2019) in the field of questioned documents and does not contain any experimental data. Any opinions expressed are solely those of the authors and do not necessarily represent those of their agencies, institutions, governments, Interpol, or the journal.

## Declaration of competing interests

The author declares that they have no competing interests.

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