SWGFAST

Scientific Working Group on Friction Ridge Analysis, Study and Technology

SWGFAST Response to The Research, Development, Testing & Evaluation Inter-Agency Working Group of the National Science and Technology Council, Committee on Science, Subcommittee on Forensic Science

Preamble: This report aims to provide a consolidated list of annotated bibliographic references of published research related to latent print analysis in response questions forward by the Research Development Testing & Evaluation Interagency Working Group (RDT&E IWG) in their letter to the chair of SWGFAST dated September 9, 2011.

This group reply has been prepared by a dedicated task force established at the University of Lausanne (forensic science department of the Faculty of law and criminal justice) under the direction of Professor Christophe Champod. It was composed of academic staff, researchers and last year MSc students in forensic science. The Lausanne team was composed of: Alexandre Anthonioz, Lea Bassil, Andy Becue, Christophe Champod, Nicolas Crettaz, Nicole Egli, Marcela Espinoza, Maya El-Charbaji, Merwan El'Khoury, Thomas Fitzi, Éloïse Forest-Allard, Aline Girod, Laetitia Maddalena, Sébastien Moret, Marieve Rocque, Céline Schürch, Sabrina Wenger.

A core group of SWGFAST members including: Lenny Butt, Christophe Champod, Melissa Gische, Scott Hecker, Glenn Langenburg, Alice Maceo and Maria Roberts served as editorial advisors to the task force.

The report was circulated for review by all SWGFAST members.

This report will not provide an exhaustive list of references that can be found in relation to friction ridge skin impressions and their examination, but will focus on key scientific published papers that address, to some degree, the questions raised by the RDT&E IWG.

Papers providing examples, case studies or anecdotal evidence have not been considered. The selected papers often provide reviews and also a set of references that constitute material for further reading.

This report is structured following the list of questions put together by RDT&E IWG in a column format: the left column recalls the questions put forward by the working group and the right column gives the consolidated and annotated bibliography.

1.1. Underlying Fingerprint Characteristics	
1.1.1. What scientific literature describes how distinct or similar fingerprints are across: ● The overall population? ● Related individuals? ● Identical twins?	We suggest that we break down according to levels of features: **Level 1 features:** *(1) In the general population:* [Mavalwala, J., 1977] The book provides an extensive bibliography on the subject of dermatoglyphics, including over 3000 references. It covers all areas where dermatoglyphics are used except identification work as used by law enforcement agencies. The time frame spans the end of the 19th century and concludes in 1973. It is an extremely valuable resource for research dealing with the distribution of level 1 features (essentially classes of general pattern and metrics of ridge counts) on both fingers and palms in a range of populations (small tribes to large ethnic groups). [Kumbnani, H. K., Anthropology Today: Trends, Scope and Applications, 2007] This article offers an etymological review of dermatoglyphics which shows the valuable implications, applications and utility of the work carried out in this area. It is based on more

	than 220 references covering the years 1891 to 2005. More specifically, the author covers published work on the frequency of various patterns for fingerprints in different communities and populations. Studies on palm, sole, and toe prints as well as on middle and proximal phalanges are covered, showing their strong and weak points. A review of work relating to inheritance and to the correlation between dermatoglyphics and diseases is also presented. The role of dermatoglyphics for personal identification, disputed paternity, and diagnosis of monozygotic (identical) versus dizygotic (fraternal) twins is also reviewed. (*2) Data on level 1 features acquired in the context of law enforcement:* Extensive datasets of fingerprints and palmprints have been acquired by law enforcement agencies and classified according to general pattern (using various classification systems - see [Hutchins, L. A., The Fingerprint Sourcebook, 2011]). This data is not generally part of the public domain (apart from a few generic summaries or data available in the Internet: www.dermatoglyphics.com) with one exception in relation to palmprints. [Tietze, S. and Witthuhn, K., Bka - Polizei + Forschung, 2001] A large amount of information concerning the general characteristics of palms is given in this book based more on experience rather than structured research. However, a large amount of statistical data as to the ridge flow in different parts of the palm is presented. This data comes from operationally acquired palmprints. Observations are presented by palmar area (interdigital area, thenar and hypothenar, left and right hand). As an example of the type of data presented, general patterns present in the interdigital area are detailed as to their shape and placement, allowing the determination that based upon the observation of classifications of 34375

	interdigital areas between the index and middle finger on right hands, 2138 loops have been observed; also, the data reveal that such loop patterns in the interdigital area were more frequently observed in right than in left hands, and that among the loop patterns observed in the right hand, most are between the middle and the ring finger, followed by the space between the ring- and the little finger and finally between the index and middle finger *(3) Specifically among related individuals and twins:* [Loesch, D. Z., Oxford Monographs on Medical Genetics, 1983] A topological system to describe papillary surfaces is presented. A series of dermatoglyphic measurements are associated with this system, such as ridge counts or ridge breadth. The system then allows interpreting the relationships between pattern elements and combinations thereof. The book is divided into three parts and covers the subjects of the classification of dermatoglyphic patterns and their topology, the variability within and between human populations of topologically significant pattern elements, their heritability and diagnostic application. [MacArthur, J. W., Human Biology, 1938] In order to state the degree of similarity in dermatoglyphic features between individuals and between hands and feet of one individual, a quantitative and objective method was developed and is presented in this paper. Comparisons were made bilaterally (hands of one person), homolaterally (same side hands of pair), and heterolaterally (opposite side hands of pair)

	between parents and children, siblings, mono- and dizygotic twins, and left and right hands of individuals. Differences in terms of ridge count, finger pattern, palmar digital and axial triradii, and palm patterns were accounted for. Averages and ranges of differences for all pairwise comparisons are given and suggest that the method developed has potential in distinguishing identical pairs or sets. [Colletto, G. M. D. D., *et al.*, Brasil. J. Genetics, 1987] This paper proposes the use of dermatoglyphic analysis to determine twin zygosity. The study sample consists of 120 same sex twin pairs, of which 66 are monozygous and 54 are dizygous. Numerical values were given to 35 dermatoglyphic variables in order to calculate a dermatoglyphic index. A discriminant analysis was then applied to within-pair differences of these dermatoglyphics variables. 15 of these variables were selected to be used in a function allowing the proper classification of 100% of the twin pairs in this study. Other methodologies are recommended for cases in which the probability of mono- or dizygosity is below 90%. [Steinman, G., The Journal of Reproductive Medicine, 2001] The author observed 250 fingerprints to examine the role of genetics and environmental factors affecting the general pattern of finger prints in uniovular triplets, quadruplets, and quintuplets. Results suggest that as the monozygotic set increases, the concordances in finger print pattern decreases within the set; twins were shown to have 88% concordance, 84% in triplets, 74% in quadruplets and only 71% concordance in quintuplets. These differences may be explained by a higher potential for mutation, as well as increased local dissimilarities within the uterine

	environment in larger sets. [Reed, T., *et al.*, American Journal of Medical Genetics Part A, 2006] The authors analyzed 2,484 twin-pairs to estimate the genetic and environmental influences on the presence of an arch pattern on any fingertip. This estimate is based on the comparison of monozygous and dizygous twin pairs. The results of this study agree with previous studies in relation to overall frequency of arches (4.3%) and to difference in frequency of arches by sex with a higher frequency in females than males (5.5% in females and 3.2% in males). In terms of heritability, the results of this study suggest a very high heritability (91%) and therefore suggest searching for the genetic locus responsible for the arch pattern. A discussion of previous genetics studies and the formation of dermatoglyphic patterns is given in order to suggest possible loci to consider. **Level 2 features: see section 1.2 below**

	Level 3 features: [Ashbaugh, D. R., La gazette de la Gendarmerie Royale du Canada, 1983] Locard and Wilder & Wentworth's work on poroscopy is discussed and the author examines their findings. It was found that the dimensions of pores are variable between fingerprints but relatively similar within fingerprints. Regarding pore shapes, different shapes exist and they vary within fingerprints. Pore position, being the most interesting characteristic, was found to be misaligned from the center of the ridge at times. Also, pores can be grouped or scattered along the ridges depending on the area considered. A statistical explanation to Locard's recommended 20-40 pores necessary for identification as well as recommendations for distorted or missing pores are also given. The author argues that the pores are permanent and unchangeable but also variable between prints and that poroscopy is a valid method for identification. However, due to pore shape variation in inked prints Ashbaugh suggests focusing on the location of pores for comparison. [Roddy, A. R. and Stosz, J. D., Proceedings of the IEEE, 1997] This paper explores statistical behavior of pores on fingerprints and how the performance of biometric systems can be improved by adding the use of pores to the use of minutiae. The model described estimates for the probability of finding a given configuration of pores under various conditions among which are the environmental conditions, the matching algorithm

	used, and the resolution of the scanned fingerprint. Analyses carried out in this study indicate that the probability of two random people having an identical configuration of pores is sufficiently low to avoid a false inclusion even if it exists when using an automated system. Parameters such as plasticity and distortion were also considered in order to lower false rejects, which in turn, may increase the rate of false accepts. [Chen, Y. and Jain, A., Advances in Biometrics: Third International Conference, ICB 2009, Alghero, 2009] The authors propose a model to quantitatively measure the rarity of fingerprints which incorporates all three levels of fingerprint features and their distribution: fingerprint class (general pattern), position and direction of minutiae, ridge period, ridge curvature, and pore spacing. For the evaluation and validation of this model the theoretical probability of random correspondence was computed and compared to that of empirical values obtained from the NIST Special Database 4. Higher probabilities of matching impostor fingerprints are observed for same class fingerprints than for different classes, and this probability is reduced, both theoretically and empirically, when information on ridge features and pore spacing are included. [Parsons, N. R., *et al.*, Law Probability and Risk, 2008] The authors suggest using an automatic and quantitative measure of pore configuration to supplement expert judgment associated with a match. Inked prints were compared to each other using a method of grey-level extraction based on principal components analysis (PCA) of a large class of pores. The statistical properties of configurations of the matching pores from prints of the same finger are compared to those of prints taken from different fingers. Although results from this study indicate that analysis based on configurations of centroids of pores

	works quite well under linear realignment, the authors recommend a large-scale survey.
1.1.2. What scientific literature describes the theoretical or biological basis for the distinctiveness of fingerprint characteristics? **1.1.3. What scientific literature describes the permanence of fingerprint characteristics?** ● How much, if at all, does aging affect latent fingerprint characteristics? ● How much, if at all, do fingerprints change as individuals age? ● How much are fingerprint characteristics altered by particular physical activities (e.g., masonry)?	**Morphogenesis of friction ridge skin:** [Babler, W. J., Dermatoglyphics – Science in Transition, 1991] This chapter provides a full overview of the studies in the relation to the embryologic development of friction ridge skin starting around 10 weeks postfertilization. The understanding of the prenatal morphogenesis of dermatoglyphic traits is fundamental to the understanding of the relationship between dermatoglyphic features and birth defects. A full account is given of the development of the hand, the volar pads, the epidermal ridges (their proliferation on the dermis surface leads to the formation of minutiae) and dermal papillae. The process of ridge formation is not an event occurring simultaneously across the whole surface, but initiates at several points on the surfaces and spreads out until these fields of ridges finally meet. The factors affecting ridge configuration are discussed, including growth stress, topography of the volar pads, the surface distribution of nerves and bone development. [Wertheim, K. and Maceo, A., Journal of Forensic Identification, 2002] The authors studied the anatomical structure and development process of human friction ridge skin with the aim of explaining why friction ridge skin is unique and permanent. The authors discuss how the complexity of the histological arrangements through the biological development of the volar skin enforces individuality and how the cellular junctions ensure permanence. Extensive bibliographic material is provided.

	[Kücken, M. U., Forensic Science International, 2007] The paper offers an extensive literature review in relation to the morphogenesis of friction ridge skin. Three potential processes are covered: the folding hypothesis, the nerve hypothesis and the fibroblast hypothesis. A mathematical model is then proposed suggesting that the general pattern arises as the result of a buckling (folding) process in a cell layer of the epidermis. Essentially in relation to level 1 features, the study confirmed that (1) primary ridges are formed as the result of a buckling process, (2) ridges form perpendicular to the lines of greatest stress, (3) volar pad geometry influences the fingerprint pattern and (4) the nervous system influences ridge formation. [Wertheim, K., The Fingerprint Sourcebook, 2011] Wertheim discusses in detail how the basis of uniqueness lies in embryology and how the late embryological and early fetal development periods are crucial in the pattern formation of friction ridge skin. The author shows using an extensive bibliography that even though genetic information directs cellular function and determines someone's appearance, so many steps and factors are involved between the genesis of the DNA-encoded protein and the final development of the body that even identical twins would develop distinguishable friction ridge skin patterns. **Permanence of friction ridge skin:**

	In addition to the biological foundations covered in the papers in relation to the morphogenesis of friction ridge skin, we draw attention to: [Galton, F., 1892] In addition to setting up a classification for fingerprint files, Galton, in 1892, confirmed the three basic tenets of the science of friction ridge skin examination: immutability (based largely on data provided by Herschel), uniqueness, and inalterability. His studies established that fingerprints were stable from their formation during fetal life until death and even after. They therefore grow as the body grows and are sharply defined until an advanced age when incipient ridges appear as the skin becomes thinner. He also attested that fingerprints were, in severe cases, obliterated by some injuries that could leave permanent scars (hard labour, use of peculiar tools, severe cuts, etc.) and therefore make the ridge at that part undecipherable. He concluded that though the general pattern of volar skin may be altered through time, the number of ridges, their embranchments and other minutiae remain unchanged. [Stücker, M., *et al.*, Journal of Forensic Sciences, 2001] The authors studied the morphologic features of interpapillary ridges (also known as incipient ridges) at the skin surface with the aim of evaluating their frequency of occurrence and quantifying the difference between these lines and the papillary ridges. Hundreds of inked prints were examined and the authors concluded that these ridges are present in a large proportion of the population and that they develop or manifest throughout life. Also, a study on prints of twins and unrelated individuals seems to indicate a degree of heredity for these features.

	[Modi, S. K., *et al.*, Automatic Identification Advanced Technologies, 2007 IEEE Workshop on, 2007] Skin quality changes over a lifetime and can influence fingerprint quality, and consequently, the quality of an image obtained by a fingerprint sensor. This article deals with the influence of quality on recognition performance as a function of age. The authors considered four age groups and showed that there was a statistical difference in image quality and minutiae count for fingerprints from these different groups (with the greatest impact on performance for the group over 62 years old). The author therefore concluded that quality is not the only factor that influences performance rates. Those other factors have to be considered in further researches. [Maceo, A. V., The Fingerprint Sourcebook, 2011] This chapter provides an extensive account of the anatomy and physiology of friction ridge skin building on an extensive biological literature. It describes the biological processes leading to the permanence of friction ridge skin. The effects of aging (flattened ridges and wrinkles) are explained. A full section also deals with the wound healing process and its effect on scar morphology. **Abnormalities and effects of activities on friction ridge skin:** [Haylock, S. E., Fingerprint Whorld, 1987] Abnormalities in finger and palm prints can be congenital or acquired. The author, divided

	these modifications into 3 groups: malformation of digits, disturbances in the epidermal ridges and traumas and diseases. These alterations may make the print's pattern unreadable, and the author explains how some traumas can momentarily alter the quality of a print (minor cuts, contact with rough surface, etc.), and how some other alterations can be permanent (deep cuts, severe burns, etc.). This article contains a list of possible alterations and their effects on fingerprints. [Olsen, R. D., Scott's Fingerprint Mechanics, 1978] Part of this book (p. 80-82) explains how professional occupations (such as glazier, plasterer, labourer and battery worker) or other physical activities can result in temporary or permanent damages to the ridge structure of skin. These injuries can lead to minor or total obscuration of ridges and can sometimes interfere with classification, which is to be remembered by experts. The author provides a list of several physical injuries (like creasing, scars) and examples of altered inked prints.
1.2. Minutiae Sample Sufficiency	
1.2.1. What scientific literature describes the likelihood that observed minutiae originate from the same or different fingerprints? ● What is known about the underlying distributions of	**Underlying distributions of minutiae in the general population:** Importance is given here to studies engaged in a systematic acquisition of statistical data in relation to minutiae where the sample description and the acquisition mechanisms are fully disclosed. In his review chapter [Stoney, D. A., Advances in Fingerprint Technology, 2001]

minutiae in various populations? ● Does variation in minutiae frequencies (e.g., within a fingerprint class) influence the reliability of fingerprint comparisons? ● How does the number of minutiae required to achieve high likelihood vary with number of fingerprints being compared or the quality of the fingerprints? ● How does the likelihood differ when comparing two exemplars vs. a LP and an exemplar?	(see summary hereinafter), Stoney referred to other early attempts to acquire systematic data on fingerprint minutiae (work of Amy, Santamaria Beltran, Kingston, Gupta and Osterburg). However these studies all suffered from a lack of disclosure of the exact fingerprint samples studied or from a very limited sample size. [Koristka, C., *et al.*, Kriminalistik und forensische Wissenchaften, 1979] Based on a sample of 102 ulnar loops and 102 whorls which were chosen from the right middle fingers and right thumbs of 204 individuals, the authors present the results of minutiae relative frequencies and surface densities on the finger. The 102 whorls came from 76 people, and the 102 ulnar loops from 57 people. Minutiae were counted on a grid, which was overlaid on the inked impressions. In total, 9590 minutiae were counted. Twelve different types of minutiae were taken into account (including ending ridges, bifurcations and hooks, all of them considered iin two directions). 5425 of the minutiae came from whorls, corresponding to 53.2 minutiae per fingerprint. On whorls, 2328 ridge endings, and 1603 bifurcations were counted; other types of minutiae were much less frequent. On ulnar loops, 4165 minutiae were counted, corresponding to 40.8 minutiae per fingerprint. From these minutiae, 2062 were ridge endings, and 1155 bifurcations. The authors then present maps of minutiae, where the relative frequencies of the different minutiae types are shown. [Dankmeijer, J., *et al.*, Acta Morphol. Neerl.-Scand., 1980] The question of how many minutiae are necessary for identification when comparing fingerprints is explored in this paper. Samples obtained from 100 Dutch males have been analyzed with respect to finger, general pattern and hand. The statistical analyses showed that

	both pattern and finger factors influence the number of minutiae. In particular, whorls have the highest minutiae counts followed by loops and last are arches; Thumbs have the highest minutiae counts then in decreasing order, ring fingers, middle fingers, little fingers and indexes. There is no correlation however between the right/left hand and the number of minutiae. The authors conclude that the number of minutiae needed for identification, therefore, may vary according to finger and general pattern as well as sex and population group of individuals. [Loesch, D. Z. and Martin, N. G., Annals of Human Biology, 1984] The authors present a multivariate analysis of several characteristics of ridge patterns in the middle and ring fingers of the right hand including relationships between minutiae and general characteristics. Descriptive statistics for fingerprints obtained from 38 females and 63 males of European origin are presented. Six different variables have been taken into account: (i) the ridge count, (ii) ridge density, (iii) the total number of ridge endings and bifurcations, (iv) ridge/furrow width ratio, (v) convexity of pattern and (vi) pattern intensity index. Ridge groove width and ridge breadth are the two factors reported to show the most differences between males and females. Correlations between the variables of one finger, as well as between adjacent fingers on a lower level, have been found; factor analysis further describes the relationships between these variables related to the general pattern and minutiae. Negative correlations between ridge ends and ridge breadth has been found, as well as between junctions and pattern intensity (and therefore ridge count). [Champod, C., Institut de Police Scientifique et de Criminologie, 1996] On a large sample of inked fingerprints from male subjects (321 right loops on right index fingers, 365 right loops on right middle fingers, 118 left loops on left middle fingers and 173

	whorls on right index fingers), the author investigates different links between minutiae and other variables. General pattern, finger number, ridge count, minutiae type, minutiae position, minutiae direction, minutiae density and the distance between several points making up a combined minutia are all investigated. The results obtained were as follows: – The number of minutiae depends on the location of the fingerprint area being studied (Delta and the center being the most dense) – The presence/absence of a delta and center influences greatly the number of neighboring minutiae. – The top parts of fingerprints show the least variation in terms of minutiae number – Minutiae distribution in the studied areas mainly follows a Poisson distribution. When comparing two fingerprints using the model presented in this thesis, results tend to support the proposition that individualizing a fingerprint requires more than a fixed number of minutiae that should be in agreement (without discrepancy) between two impressions. On the other hand this probabilistic estimate for a given configuration of minutiae depends on the anatomical position of the area under comparison. [Gutièrrez, E., *et al.*, Forensic Science International, 2007] The authors analyzed the fingerprints of 200 index fingers (100 from males and 100 from females). They studied the general patterns (arches, loops and whorls) and counted the total number of minutiae as well as their type. The most common type of minutiae was ridge ending,

	followed by opening and closing bifurcations; all the others appeared with a frequency lower than 5%. The distribution of the minutiae was not homogenous for the area of the fingerprint; the density of minutiae was greater in the center and delta than in the periphery. There is also a correlation between the general pattern and the total number of minutiae found; whorls showed the highest number, followed by loops and arches. Finally, males present a higher number of minutiae, especially in the periphery. [Seweryn, P., Problemy Kryminalistyki, 2005] Study of the statistical distribution of minutiae observed on 400 fingerprints (right and left index) from 200 individuals (178 males and 22 females) held on police files from Southern Poland. Minutiae were manually counted and classified according to their types (ridge ending, bifurcations and a set of combined minutiae). Relative frequencies are given, showing the large relative abundance of ridge endings (opening and ending) and bifurcations compared to the other types of minutiae considered. One main outcome is the observation that the density of minutiae in the index varies according to the general pattern of the fingerprint (arch, loop or whorl). A rounded mean number of minutiae of 86 minutiae was counted on whorls, 80 on loops and 72 on arches. [Cabanyes Cordero, D. E., Ciencia policial, 2010, Gómez Marín, J., *et al.*, Ciencia policial, 2010] The study sets three main goals: (1) Establishing the frequency of minutiae given general pattern, orientation and position on the fingerprint; (2) Studying if there are any differences in minutiae frequency between sexes, minutiae type, finger position or area under study; (3) Completing the “empirical method” used in fingerprint identification by calculating the

	discriminating power, the error rate, thus providing a scientific basis required by the judiciary. The population of interest grouped 5000 women's fingers and 5000 men's fingers from the Spanish detainees archives, divided equally among their pattern (125 per finger and pattern/1250 for each of the 4 pattern types for each sex). The entire fingerprint is divided into four square sectors by placing a cross on the center. The sectors are numbered in a clockwise fashion, with sector 1 being the top left. Eighteen types of minutiae types were taken into consideration; 4 different types of endings and bifurcations (to the left, right, top or bottom of the print) as well as different combined minutiae. No significant difference between male and female was reported. In all sectors, there was a majority of ridge endings, followed by bifurcations; combined minutiae were much rarer. This was true for all general patterns. To conclude the study, frequency calculations for combinations of minutiae are proposed and carried out based on the hypothesis of independence between features. In the appendix, frequencies of general patterns based on a large sample, for all fingers and for male and female subjects separately, are provided. [Gutièrrez-Redomero, E., *et al.*, Forensic Science International, 2011] A sample of inked prints from 100 males and 100 females of the Spanish population (2000 fingerprints) has been used in order to describe the distribution of minutiae on the fingers. 145,794 minutiae were analyzed in this study. Analyses were carried out by dividing the finger in four sectors, as well as separating the inside from the outside of a circle with a radius of 15 ridges. Twenty different types of minutiae are defined and counted in the 8 different areas defined by the circle and the sectors. Correspondence analysis has been used for the analysis of different relationships such as that between general pattern and finger number (which is significant), between minutiae and finger number (which is significant as well), as well as sex and minutiae by area and by finger. Differences in the frequency of minutiae were found not only between the sexes and the different fingers, but also between the different areas defined;

	endings have a lower frequency in the central area of the fingerprint than in the periphery, while the contrary is true for bifurcations and convergences. More complex relationships are also explained. **Spatial densities of minutiae:** Distributions of minutiae on the surface have been explored by [Champod, C., Institut de Police Scientifique et de Criminologie, 1996] (see above summary). It is reported that core and delta are richer zones in terms of number of minutiae compared to the periphery of the pattern. Hence spatial distribution of minutiae positions depends on the general pattern (more generally on the ridge flow: level 1 features). Similar observations were made by [Chen, Y. and Jain, A., Advances in Biometrics: Third International Conference, ICB 2009, Alghero, 2009], [Gutièrrez-Redomero, E., *et al.*, Forensic Science International, 2011] (see above summaries) and to a limited extent by [Ross, A., *et al.*, Pattern Analysis and Machine Intelligence, IEEE Transactions on, 2007]. **Minutiae distribution among relatives and twins:**

	[Okajima, M., American Journal of Human Genetics, 1967] Individual differences in minutiae were investigated among one population and on the heel of the foot. One hundred seven (107) pairs of Japanese twins between 12 and 17 years old were included. The sole prints were investigated, since in this area, the minutiae frequency cannot be dictated by the turns of ridges. A circular area with a radius of 18 ridges was used for counting. Each end, fork, island or short break counted as 1, enclosures, long breaks and minutiae composed of three ridge terminals counted as 2. The mean count of minutiae thus obtained is higher for males than for females. The differences between means of right and left feet are small (1.0 for males and 2.6 for females). An analysis of the correlation coefficients between the number of minutiae of homologous feet of twins results in larger correlation in monozygotic than in dizygotic twins. This shows that there is a genetic component to the variation of the frequency of minutiae in the calcar area of the feet. [Okajima, M. and Usukara, K., Human Heredity, 1984] Data concerning the total minutiae count and the proportion of bifurcations from the palms of 20 pairs of monozygotic and 20 pairs of dizygotic twins is presented. The correlation of the total minutiae count and of the proportion of bifurcations is larger for monozygotic than for dizygotic twins. The authors conclude that this shows a genetic determination both of total minutiae count and proportion of bifurcations. The study also demonstrated that females showed significantly fewer minutiae than males. [Jain, A. K., *et al.*, Pattern Recognition, 2002] This paper relates to the distinctiveness of biometric characteristics in order to establish the

	performance limits of biometrics-based verification systems. It focuses on fingerprints and briefly reviews the genetic influence and intrauterine forces which affect the general characteristics of the fingerprint pattern and minutiae. The study was performed by comparing, based on minutiae, fingerprints from a population of twins (94 couples) and fingerprints from unrelated people. The study confirmed that a large class correlation exists between identical twin fingerprints. Based on minutiae, twin-twin fingerprints are generally more similar than twin-non twin fingerprints but results of the same order are obtained when comparing fingerprints with different general pattern from unrelated people to fingerprints with same general pattern from unrelated people. It is concluded that twin fingerprints can be distinguished using an automatic fingerprint identification system even if the accuracy is slightly lower than for non twins. [Srihari, S. N., *et al.*, Journal of Forensic Identification, 2008] This study of twins (298 twin-pairs, 42 of which are fraternal twins) shows that twins' fingerprints are more likely to show the same general pattern for a given finger (56.92% for identical twins, 39.44% for fraternal twins and 31.76% for non-twins). After minutiae extraction and matching, the false positive rate obtained for twins is 6.17%, and 2.91% for non-twins. Testing of the distributions of match scores shows that the distribution for twins is different than that for comparisons between impressions from the same finger. The distribution for fraternal twins does not differ from that of identical twins, and the statistical test used does not formally show a difference between the distribution for twins and non-twins; it is concluded however that the similarity of fingerprints of twins is different from the similarity between arbitrary fingers. [Sarkar, N. C., 2004] Based on different tests carried out on a sample of 2010 fingerprints from 201 males and 2020

	fingerprints from 202 females, concerning both level I and level II features, and integrating familial analysis, the author concludes on the following trends on level 2 features (*the work offers in depth data on other dermatoglyphics traits*): – The distribution of total finger ridge counts and total finger minutiae count are non-Gaussian and characterized by flat peaks. Deviation from normality is not statistically significant for both total ridge counts and total finger minutiae count. – Ridge endings, out of eight minutiae types that were considered, show a preponderance over other types, and the least frequently occurring minutia is the connecting ridge. Two minutiae types, ridge endings and forks, together represent more than 80% of the total minutiae count while the remaining six types represent only about 20%. – Maximum occurrence of minutiae has been noted in the thumb followed by the ring finger, while minimum occurrence has been noted either in index or little finger. – For total ridge counts and total minutiae count, fingers could be classified into two groups: (a) thumb and ring finger, (b) index, middle and little finger. Both total ridge count and total minutiae count also bear high hereditary significance. – Mean minutiae count in males is significantly higher than that in females. – Values of correlation for familial combinations except parent-parent are positive and most of them are statistically significant. The values of correlation for bifurcation and ridge ending are similar to each other and are at par with correlation values for total minutiae count, but higher than those of other minutiae types. – Two minutia types, bifurcation and ridge ending along with a total minutiae count bear strong hereditary significance. These two minutiae types, out of eight different minutia

	types, show very high heritability. Because of this high hereditary significance, fork and ridge ending may be useful as marker characters in genetical analysis as well as in personal identification – Mean values of total ridge counts and total minutiae count for whorls are significantly higher than those for loops. – The values of the ratio between mean minutiae count and mean ridge count is maximal in thumbs and decreases gradually from radial to ulnar fingers and finally reduced to its minimum in little fingers, irrespective of pattern type, hand and sex. [Liu, Y. and Srihari, S., Computational Forensics, 2009] A quantitative analysis of the discriminability of both identical and fraternal twin fingerprints on a new data set (227 pairs of identical twins and fraternal twins) using a state of the art fingerprint verification system is presented. Comparisons are based on the ridge flow and the minutiae. The analysis of level 1 characteristics suggest that fingerprint class in twins is highly correlated and therefore observing the same type of ridge flow between twins is more probable than in non-twins. Furthermore, results show that the minutiae pattern is more similar between twins than between unrelated individuals. Nevertheless, the twin fingerprints are discriminable with a slightly higher error rate than for non-twins, and the error rate for identical twins is slightly higher than that for fraternal twins.

	Probabilities associated with minutiae configurations: For research before 1995, we refer to the review chapter by Stoney [Stoney, D. A., Advances in Fingerprint Technology, 2001], the additional research that followed is added hereinafter. [Stoney, D. A., Advances in Fingerprint Technology, 2001] A review of models measuring the rarity of fingerprint features from 1892 to 1999 is proposed. Out of the fifteen models presented, six are grouped together in a single class since they approach the question in the same way; 10 different approaches are therefore presented. All approaches are explained concerning the characteristics used and their description/measurement, as well as the probabilistic approaches employed and the results obtained. All of these approaches concern minutiae described using type and position, or only one of these two elements. Furthermore, some of these models address only the rarity of a given configuration, while others include a consideration of the correspondence observed during a comparison, or rather, a consideration of differences that are allowed during the comparison. All of the models yield numbers that highlight the variability of fingerprints. After this description of the data and approach used, the models are critically discussed. Finally, the author's conclusion highlights the weakness of the scientific foundation of fingerprint individuality, based on the fact that there while a number of models had been proposed, these were in general established on the basis of little data (with one exception), and in 2001, none of the models had been tested.

	[Pankanti, S., *et al.*, Pattern Analysis and Machine Intelligence, IEEE Transactions on, 2002] The authors quantify the amount of information available in minutiae features to establish a correspondence. An expression for the probability of a false correspondence is derived, taking into account minutiae-based representations. The results obtained using this expression are then compared to typical fingerprint matcher accuracy results. Results show that automatic fingerprint matching is not infallible, and thus led to some false associations. The strength of the evidence was highly influenced by the noise in the input fingermark. The theoretical limit of an automatic fingerprint verification system, as represented by the theoretical expression for the probability of a false correspondence, has not been reached by the systems in use. It would be of interest to explore additional complementary representations of fingerprints for automatic matching, as the systems that are based solely on minutiae generally use only a part of the discriminatory information available in the fingerprints. [Neumann, C., *et al.*, Journal of Forensic Sciences, 2007] A model, taking into account minutiae configurations which are described using their relative orientation and position, as well as the type of the minutiae, is proposed. A means of modeling within-finger variability is proposed, and computations of likelihood ratios (LRs) are shown. Large databases are used for the establishment of the model, and it is tested on simulated cases where the ground truth is known. These tests show in particular that large LRs can be obtained for small numbers of minutiae. Also, as the number of minutiae in a configuration increases, the LRs overall increase. However, large differences in the order of magnitude of LRs are obtained for a given number of minutiae, highlighting that a given number of minutiae is not a sufficient indicator of rarity when dealing with low volumes of minutiae (i.e. 3 to 12) in latent prints..

	[Su, C. and Srihari, S., Computational Forensics, 2009] The authors present a model of the distribution of fingerprint features (ridge flow and minutiae) and use it for estimating the individuality of fingerprints. To this end, three metrics are used: (i) probability of random correspondence (PRC) of 2 individuals, (ii) PRC between two individuals among a group of n individuals (nPRC) and (iii) PRC between a specific individual among others (specific nPRC). The model is tested using these metrics against data obtained from the NIST4 database. Results show that the modeled values follow those obtained empirically. Furthermore, these results also show that PRCs are reduced when more features are used. [Dass, S. C., *et al.*, Encyclopedia of Biometrics, 2009] This paper gives an overview of the problem of fingerprint individuality, while focusing on challenges, models, and methods developed to study the extent of uniqueness of a fingerprint. Two previously published fingerprint individuality models are presented, and it is shown how fingerprint individuality estimates can be obtained. Then, these models are extended to a population of fingerprints, and experimental results, comparing probabilities of random correspondence based on database searches and based on the two models. The empirical results show that in some instances, one of these models provides estimates of probabilities of random correspondence that are close to the observed ones.

	[Egli, N. M., Faculty of Law and Criminal Sciences, 2009] The model is established based on AFIS scores, thus taking into account minutia position and orientation, for groups of minutiae. A very large background database (over 600,000 fingerprints, from over 60,000 ten-print cards) was used, for establishment and testing of the model. Within-finger variability is based on repeated impressions of a given finger, then the scores obtained are modeled (rather than modeling the characteristics directly); impressions from the finger of one donor are used for the establishment of the model, and impressions from a different finger are used for testing. Between-finger variability is extracted by confronting the crime-scene mark to the entire database. Testing using same source and different source comparisons (where the 'different source' reference prints were chosen randomly) showed low rates of misleading evidence. [Neumann, C., *et al.*, Journal of the Royal Statistical Society, 2012] Using the descriptors of fingerprint minutia configurations as in the previous paper (Neumann et al 2007), a new model is proposed. Not only is distortion now modeled completely, and used to generate data for the numerator of the likelihood ratio (LR) expressing the weight of the evidence, but it is also used to generate repeat impressions for assigning the denominator of the LR. Furthermore, for the first time, examiner influence is taken into account – i.e. the differences that will occur if different annotations of the same characteristics are carried out are explicitly modeled, and included in the numerator and denominator. Then, the model is submitted to a 'hard test'. Real cases have been selected, the marks and corresponding prints encoded, and then, the best match for the mark has been searched in the IAFIS database. These triplets (mark-print from presumably same source-closest non-match in large database)

	were then used to test whether the measure computed indeed supported the hypothesis known to be true, or the alternative hypothesis. While the evidence obtained during this test is misleading in a percentage of cases that is not negligible, diagnostics of the measure that allow a large reduction in this percentage are proposed.

1.3. Fingerprint quality	
1.3.1. What scientific literature describes how LP quality affects the probability of correctly matching (e.g., individualization or identification) or excluding fingerprints? ● How is LP quality currently assessed? ● What are the pertinent metrics? ● How do analysts accommodate print quality/ surface during comparison and how effective are the current approaches? ● What methods can enhance images without risking bias in results (e.g., due to altering image)? ● What is the effect of aging and environment on print quality? ● What is the effect of print development (and/or lifting) on print quality?	**Quality metric:** [Hicklin, R. A., *et al.*, Journal of Forensic Identification, 2011] The authors of this paper conducted a survey to determine how fingerprint examiners evaluate the quality of latent and exemplar fingerprints. Eighty-six (86) latent print examiners were asked to perform the assessment of local and overall quality of a series of fingerprints. Examiners were asked to base their assessments on their fundamental understanding of friction ridge impressions with no operational goals or legal consequences. The results of this study are as follows: to an extent, consistency was observed between examiners in value determination, relationships between the overall perceived quality of a print and the size of clear ridge detail were highlighted, as well as relationships between quality, size and correct pattern classification. An analysis of the examiner's subjective assessments of fingerprint quality revealed useful information for the development of guidelines, metrics and software tools for assessing fingerprint quality. [Li, Z., *et al.*, Computational Intelligence and Software Engineering, 2009. CiSE 2009. International Conference on, 2009] In this paper the authors present a novel method for the evaluation of the quality and the validity of the fingerprint image. This method is based on the extraction of 10 features from the fingerprint image including foreground area, global image quality, local orientation certainty and ridge and valley clarity measures. The Fuzzy Relational Classifier (FRC) then classifies these

• What are effects of positive/negative images or reverse latent prints (e.g., color reversal due to fuming with superglue)?	features. This classification includes unsupervised clustering and supervised classification approaches. Their results show that the method is effective for the assessment of fingerprint image quality. [Alonso-Fernandez, F., *et al.*, Biometrics: Theory, Applications, and Systems, 2007. BTAS 2007. First IEEE International Conference on, 2007] The authors of this paper compared several metrics for assessing the quality of fingerprint images using an optical and a capacitive sensor. Image quality is assessed by measuring one of the following fingerprints properties (features): (1) ridge strength or directionality, (2) ridge continuity, (3) ridge clarity, (4) integrity of the ridge-valley structure or (5) estimated verification performance. The following metrics were tested: (1) orientation certainty level, (2) ridge frequency, (3) local clarity score, (4) local orientation quality, (5) energy concentration in the power spectrum and (6) matcher performance. The main results of this study are as follows: (1) all quality algorithms are capable of rejecting images of bad quality for both sensors, (2) several fingerprint image quality measures are suitable for optical and capacitive devices but in general, the discrimination capability is lower for the optical sensor than for the capacitive one and (3) the most discriminative measures with one sensor are the least discriminative ones with the other sensor, in particular with measures relying on grey level features being the most discriminative with the optical sensor and the worst with the capacitive one. [Alonso-Fernandez, F., *et al.*, Information Forensics and Security, IEEE Transactions on, 2007] Existing approaches for fingerprint image quality estimation are first state, and then a number of fingerprint image quality estimation algorithms are tested. The authors divided the existing

	approaches for fingerprint image quality estimation into 3 different classes: (1) Use of images' local features (Local Direction, Gabor Filters, Pixel intensity, Power Spectrum), (2) Use of images' global features (Direction Field, Power Spectrum) and (3) Use of classifiers (prediction of the matcher performance). The authors mention the ISO/INCITS-M1, which established a biometric sample-quality draft standard in which a biometric sample quality is considered from three different points of view. (1) the character (quality attributable to inherent physical features of the subject), (2) the fidelity (degree of similarity between a biometric sample and its source) and (3) the utility (impact of the individual biometric sample on the overall performance of a biometric system). In a second part, the authors studied the effect of rejecting low-quality fingerprint images using quality estimation algorithms. As a result they found a large improvement in the false rejection rate. [Changlong, J., *et al.*, Electronic Commerce and Security, 2009. ISECS '09. Second International Symposium on, 2009] The influence of fingerprint sample quality on minutiae-based fingerprint recognition systems is examined. In a first step the authors evaluated the factors that influence the performance of the matching system and defined the absolute (Quality of Ridge-Valley Texture) and the relative (Common Area and Deformation) fingerprint sample quality. Then five different quality measures were selected and applied. The results show that these quality measures are correlated but sensor independent. It was also highlighted that the rejection of the samples with the lowest quality has a positive influence on the matching performance by decreasing the error rates of recognition systems.

	Impact of quality: [Blomeke, C. R., *et al.*, 42nd Annual IEEE International Carnahan Conference on Security Technology, 2008] The relationship between skin characteristics and fingerprint image quality is investigated. The studied skin characteristics are: moisture content, oiliness, elasticity and temperature. The authors collected fingerprint images from individuals over the age of 18. Measurements were recorded with nine commercially available fingerprint sensors, four capacitance sensors, four optical sensors, and one thermal sensor. The main results are as follows: (1) No correlation between the different characteristics was observed and (2) No significant correlation was observed between the different characteristics (variables) and the obtained quality scores. [Dass, S. C., Information Forensics and Security, IEEE Transactions on, 2010] The author studied the effect of noise in minutiae detection and localization due to poor image quality and its effects in fingerprint individualization. The problem is approached in two main steps: (i) the creation of a flexible class of statistical models for noisy minutiae, in order to derive the random correspondence probability (PRC). (ii) Those PRCs were then modeled as a function of the quality of the fingerprint pair via a log- linear random effects model. Empirical results showed the PRC increases as image quality becomes poorer. The methodology for the estimation of unknown parameters was developed in a Bayesian framework. Empirical results on two databases, one in-house and another publicly available, demonstrate how number of instances of misleading evidence increases as image quality becomes poor. The measure corresponding to the “12-point match” with 26 observed minutiae in the query and template fingerprints increases by several orders of magnitude when the fingerprint quality degrades

	from “best” to “poor.” This study cautions the use of poor quality fingerprint images for the purpose of identification. **Image processing:** [Reis, G., 2007] George Reis presents in the first chapter of his book the principles and fundamentals of image processing. These principles ensure that images are processed according to the rules of evidence and avoid the risk of bias in image processing. In chapter five of the book the author presents a list of valid image enhancement methods, which do not risk bias in the results. Finally, in the sixth chapter, it is described how the metadata of the image can be used and how to keep track of all the image enhancement methods which were applied. **Effects of aging and environment** [Modi, S. K., *et al.*, Automatic Identification Advanced Technologies, 2007 IEEE Workshop on, 2007] The authors state that aging of skin results in loss of collagen and that aged skin is looser and dryer than younger skin. A decrease in skin firmness and some medical conditions such as arthritis may thus affect fingerprint quality during the capturing process necessary for automated system recognition. This research examines the effects of fingerprints from different

	age groups (18-25, 26-39, 40-62, 62 and above) on quality levels, minutiae count, and performance of a minutiae-based matcher. The results showed a significant difference in fingerprint image quality across age groups, the elderly group (62 and above) had the worst quality; the overall quality score decreased with increasing variance as the age increased. Average minutiae counts, however, were within a similar range for all age groups, with only the variance increasing with age. [Popa, G., *et al.*, Romanian Journal of Legal Medicine, 2010] The authors studied the evolution of the fingerprint aging process both indoors and outdoors, focusing on the pores, ridge thickness, valley width, number of minutiae and number of epithelial cells. They observed the disappearance of pores, minutia and epithelial cells as an effect of aging, caused by the dehydration of papillary lines resulting in shrinking of the ridges and an increase in valley width. These processes were faster on fingerprints left outdoors, because of environmental factors (not precisely identified in this paper). Fingerprint quality was of course affected by these degrading factors, presenting less detailed ridge contours and decreased number of minutia. **Effects of development techniques:** [Lee, H. C. and Gaensslen, R. E., Advances in Fingerprint Technology, 2001] The authors discuss in chapter four of the “Advances in Fingerprint Technology (2nd Ed.)”

	book various physical, chemical and illumination methods that are used for the detection of latent fingerprints. They explain which fingerprint detection method can be used on which type of surface to obtain the best results. The quality of the obtained prints is thus not directly dependent on the print development methods because those methods are chosen to obtain the best possible results. The quality of the detected prints is thus rather dependent on the latent fingerprint itself, on the type of surface and on the altering of the latent fingerprint due to environmental factors. [Gupta, A., *et al.*, Forensic Science International, 2008] The authors of this paper conducted a study concerning the reproducibility of friction ridge pore detail in latent fingerprints. The two fingerprint development methods used in this study are cyanoacrylate fuming and ninhydrin. The authors used several fingerprints from the same donor and compared the quality of the pores of the detected fingerprints, aiming at learning more about the reproducibility of friction ridge pore detail. The authors concluded that the fingerprints detected by the two methods present big variations and friction ridge pore detail is not reproducible; friction ridge pore quality is thus mainly dependent on the quality of the fingerprint itself, before any enhancement techniques have been applied. [Anthonioz, A., *et al.*, Journal of Forensic Identification, 2011] In this paper, the authors studied the reproducibility of the following third-level characteristics: pores, ridge edges and particular shapes of minutiae. The reproducibility of these features is examined on several recordings from the same finger, first acquired using only optical visualization techniques and second on impressions developed using the following common fingermark development techniques: DFO, ninhydrin, cyanoacrylate and powdering. The prints

	were deposited on different porous and nonporous surfaces and the digital images were recorded at two different resolutions: 1000 and 2000 ppi. The main results are as follows: (1) the most reproducible features observed were minutiae shapes and pore positions along the ridges, (2) the third-level characteristics show very good reproducibility in high-quality images, directly obtained by coaxial episcopy, (2) the reproducibility of third-level characteristics is very difficult to obtain on marks detected with various detection techniques, particularly on porous surfaces, (3) the lack of reproducibility particularly penalizes small formations, precise shape of ridge edges, shape and size of pores, making it difficult to differentiate between real features and artifacts and (4) the increase in resolution did not result in better feature detection or comparison between images.
1.4. Fingerprint Matching	
1.4.1. What scientific literature describes and justifies the role of automatic software algorithms in the fingerprint matching process? ● Ability of algorithms to operate as a stand-alone tool? ● Application of algorithms to aid a human analyst? ● What is required to integrate algorithms more fully into the comparison process? ● What is the confidence in match results (e.g., Trade-off between	[Bolle, R. M., *et al.*, 2004] This book presents the main aspects related to biometric systems and recognition. Two chapters are dedicated to system errors. The two principal types of errors performed in biometric systems (called false acceptation and false rejection) are presented and discussed in the context both of verification and identification purposes. Since these two types of errors are highly correlated, the choice of the operating point is crucial and application related. This specificity is discussed in this book and various ways of presenting error probabilities are presented. [Dvornychenko, V. N. and Garris, M. D., 2006] The purpose of the test summarized is to assess the state of the art in latent matchers and to

Type I and Type II error probability)? ● How does the accuracy of a human analyst compare to that of automated algorithms?	evaluate the ability of current latent matchers to field "semi-lights-out" latent search systems. All the steps involved in latent matching are described and the concepts of lights-out and semi-lights-out systems are introduced. Due to the important size of current latent databases, there is a need to produce latent search systems which are faster, and more accurate. Since generally it is not possible to process in a full lights-out manner, that is, completely without human intervention, semi-lights-out systems require human intervention exclusively for final verification and are less time-consuming than current latent matchers. [Moses, K., The Fingerprint Sourcebook, 2011] The benefits of the use of automated fingerprint identification systems (AFIS) as an essential tool for law enforcement agencies are presented. A complete description of the system's working principles is given, including AFIS functions and capabilities, system accuracy, and system and image requirements. The algorithm requirements for a successful data acquisition, data enrollment, feature extraction and matching process are also presented. The difference in performance between experts and automated systems is also discussed in this chapter. The authors highlight that "automatic fingerprint-matching algorithms are significantly less accurate than a well-trained forensic expert", but even so they can significantly reduce the work for forensic experts. [Paulino, A. A., *et al.*, Graphics, Patterns and Images (SIBGRAPI), 2010 23rd SIBGRAPI Conference on, 2010] As latent print matching techniques still suffer from limitations in terms of accuracy and speed, and require heavy human intervention, the authors propose a method to improve latent to full fingerprint matching accuracy by combining manually marked minutiae with automatically

	extracted minutiae. "[…] This framework consists of the following steps: (i) reconstruct the orientation field based on manually marked minutiae and singular points, (ii) enhance the latent using median ridge frequency computed in small image blocks and the reconstructed orientation field, (iii) match enhanced latents and rolled fingerprints, and (iv) combining the scores from two matchers using boosted max". It has to be noted that the improvement of the latent matching performance is quality independent. The results presented show a better CMC curve (CMC for cumulative match curve) for the highest rank fusion than for manually marked minutiae. [Indovina, M., *et al.*, 2011] The purpose of this test provided by the National Institute of Standards and Technology (NIST) Evaluation of Latent Fingerprint Technologies - Extended Feature Sets (ELFT- EFS) is to evaluate the current state of the art on latent feature-based matching, by comparing the accuracy of searches using automatic feature extraction and matching alone with searches using different sets of features marked by experienced latent print examiner. The highest accuracy for all participant technology providers was observed for searches that included examiner-marked features in addition to latent image, while image-only search were more accurate than feature-only searches for most matchers. The score-based results provide an indication of how accuracy would be affected by an increase in database size. For most matchers, the addition of new EFS features provides an improvement in accuracy.
1.4.2. What scientific literature	**ACE-V:**

describes and justifies standards regarding formulation and reporting of “Inclusion/ Identification; Exclusion; and Inconclusive” opinions? **1.4.3. What scientific literature describes, justifies and evaluates available mathematical models to assist in evaluating current or potential fingerprint matching methods?** **1.4.4. What scientific literature characterizes the probability that two complete or sampled prints share a common source?** ● What is the basis for the probability assessment? ● How much precision/uncertainty is associated with probability estimates? ● How much does the probability vary with amount of available information? ● How much similarity (particularly with respect to sampled minutiae) is needed to obtain a high probability of	[Scientific Working Group on Friction Ridge Analysis Study and Technology (SWGFAST), 2011] This document details the steps of the ACE-V methodology (Analysis, Comparison, Evaluation and Verification) used for friction ridge examinations. These steps include both qualitative and quantitative aspects. Special attention is given to the evaluation, in which the examiner ultimately decides whether the unknown impression is from a different source or the same source as the compared impression. The possible conclusions reached after the decision-making process are exclusion, individualization and inconclusive. The significance of each of the three conclusions is explained in detail. A flowchart of the entire ACE-V protocol is represented in appendix. [Langenburg, G., The Fingerprint Sourcebook, 2011] Based on Popper’s criteria, the author of this book chapter presents friction ridge principles (i.e. uniqueness and permanence) as appropriate scientific theories and laws, and friction ridge examination is presented as hypothesis testing. He also provides a state of the art (through 2007) regarding scientific work carried out in order to answer questions related to uniqueness and permanence of friction ridge skin. Moreover, a review of available models to assess matching probabilities of a specific configuration of minutiae is provided. Finally, he shows the results of studies performed to test the ACE-V method used by fingerprint examiners to compare fingerprint impressions, such as the benefit of training or the absence of bias during the analysis step.

match or confidence in mis-match? ● How are the three levels of detail accommodated in the analysis?	**Numerical standard for conclusions:** The statistical studies exposed in section 1.2.1 bring support to the view that the strength of the association based on a configuration of minutiae will not solely depends on their number (as a fixed minimum standard may suggest) but also depends on their position, type and orientation. Additional references below address the same issue. [Champod, C., Encyclopedia of Forensic Sciences, 2000] This paper presents the two existing standards of proof, one using a predetermined minimum number of minutiae and one with no numerical standard. The author recommends the use of the latter, because identification process is a global assessment which balances both quantitative and qualitative aspects, rather than being a concept reduced to counting fingerprint minutiae. This statement is supported by the 1995 Ne'Urim declaration, stating that "[n]o scientific basis exist for requiring that a predetermined minimum number of friction ridge features must be present in two impressions in order to establish positive identification". Moreover, arguments are given in favor of a probabilistic approach and the possibility of giving qualified opinion based on dactyloscopic evidence in the decision making process, rather than the use of positive identification. The presented way forward is the adoption of a scheme of total quality management dealing with the various aspects of identification and training, laboratory procedures and audits.

	[Interpol European Expert Group on Fingerprint Identification II - IEEGFI II, 2004] The report recognizes and endorses the basic principles of fingerprint identification. It contains detailed guidelines for analysis, comparison, evaluation, validation and verification of fingerprint details, introduces common terminology, identifies certain areas of risk and advises upon the application of general scientific principles and methodology which can be readily translated to the field of fingerprint identification. This leads to an entirely transparent, rigorous, reproducible, and verifiable methodology and process. Intentionally, no numerical standard for conclusions is proposed. Instead, some criteria are proposed to help assess the strength associated with the findings. [Polski, J., *et al.*, 2011] The main recommendation of the present report states that “[t]here currently exists no scientific basis for requiring a minimum amount of corresponding friction ridge detail information between two impressions to arrive at an opinion of single source attribution.” Another milestone in this report is the recommendation that allows examiner to offer oral or written reports of testimony of probable or likely conclusions concerning source attribution of two friction ridge impressions being from the same source. Note the presence of appendix G referencing a bibliography of available research material.

	Concerning the addition of level 3 features: [Jain, A. K. and Feng, J., Pattern Analysis and Machine Intelligence, IEEE Transactions on, 2011] The authors implement an algorithm for automated latent fingerprint matching using minutiae as well as extended features, including singularity feature, ridge quality map, ridge flow map, ridge wavelength map, and skeleton. The system was tested by matching 258 latent fingerprints against a background database of 29,257 rolled fingerprints. The benefit of this approach over a baseline minutiae matcher is an increase of performance from 34,9 to 74 percent of rank-1 identification rate. The experimental results indicate that singularity feature, ridge quality map, and ridge flow map are the most effective features in improving the matching accuracy. The accuracy mainly depends on the latent fingerprint quality, and taking into account secondary features (level 3 features) will not lead to obvious improvement in the matching accuracy. [Jain, A. K., 2011] In this study, the author develops algorithms for encoding and matching extended features, develops fusion algorithms to combine extended features with minutiae information to improve fingerprint matching accuracy, and shows the contribution of various extended features in

	latent fingerprint matching. An improvement in latent fingerprint matching accuracy on automated fingerprint identification systems (AFIS) is reached when taking into account extended features, such as ridge flow map, ridge wavelength map, and ridge quality map. Although the accuracy improvement is the highest with level 1 extended features, low quality latent fingerprints benefit the most from the use of level 3 extended features. In light of theses results, the author concludes that: "All extended features at Level 1 and Level 2 should be incorporated into AFIS […]". **1.4.3 and 1.4.4: See section 1.2 above regarding level 2 features.**

1.5. Analyst Considerations	
1.5.1. What scientific literature characterizes the effect of analyst qualifications/ experience on fingerprint matching accuracy? ● What processes are used and what support is there for each process? ● What are the current methods and associated benefits of qualifying analysts? ● What on-going certification or training procedures are or should be used and what justification is there for the recommended methods? ● Does variability in analyst background/ experience materially affect accuracy (e.g., probability of correct match/ mis-match decisions)? ● What is an appropriate proficiency test and what justification is available for the	[Wertheim, K., *et al.*, Journal of Forensic Identification, 2006] Data were collected during a comparison training exercise open to participants of any skill level, including participants without training or experience. To analyze the data, two separate groups were created: one of participants with more than one year of experience and another one of participants with one year of experience or less. Numerous data were analyzed, leading to important conclusions, among which it clearly appeared that: "participants with one year experience or less made a significantly higher ratio of errors (specifically erroneous individualizations) when compared to participants with more than one year of experience". Moreover, they also noticed that when the level of confidence (for the group of experienced examiners) decreases, the number of erroneous individualizations increases. Finally, the number of errors classified as 'clerical (transcription) errors' remains constant; they are considered as independent of latent print difficulty or examiner ability. [Koehler, J. J., Hasting Law Journal, 2008] The author addresses several questions about current proficiency tests: Are they really efficient? Do they measure what we expect? How can we improve them? Properly designed, proficiency tests may provide a reasonable estimation of the rate at which false discoveries, false positive errors, and false negative errors occur. One conclusion offered by the author is that for a proficiency test to provide reasonable estimates of error rates in real casework, neither the examiners nor their supervisors should know that they are working on a proficiency test. The reason is that examiners performance is likely to improve when they know they are

test?	being tested. Contextual blindness is required to ensure that examiners base their conclusions on the forensic evidence alone. Proficiency test participants should be a representative sample of laboratories and examiners drawn from the population of those who provide fingerprint testimony in court. [Busey, T. A. and Dror, I. E., The Fingerprint Sourcebook, 2011] This chapter is a combination of several studies that were conducted on the forensic expertise. It brings up the importance of experience and perceptual learning which improve the performance of the examiner of a latent fingerprint. It also talks about the configural processing used by the experts to unitize the individual features in a noisy latent print, allowing them to improve the quality of information extracted from this print. In addition to that, it is recommended that training should be with clear images since it develops the processes of external noise filtering and the enhancement of weak stimuli, and afterwards generalize this knowledge to noisy images. Furthermore, the examiners who rely on information that is not easy to verbalize should refine their learning by training on stimulus sets for which the ground truth is known and can be immediately verified. In fact, they create psychological dimension of stimuli, integrate and differentiate them depending on the nature of the task. Therefore, the correct working procedures should minimize the psychological and cognitive interferences in making fingerprint matching decisions. [Busey, T., *et al.*, Journal of Forensic Identification, 2011] The authors of this paper wanted to determine which details fingerprint examiners rely on when conducting an examination. Two groups were considered: one of expert latent print examiners and one of novice participants. The eye positions were recorded while comparing the latent

	print with the inked print. When there was no time limit, the experts spent approximately 50% more time inspecting the images than the novices. When 20 seconds were given to compare the prints, the experts were more consistent than the novices. Moreover, experts had higher accuracy, spent more time inspecting the latent prints, and showed shorter saccades (rapid eye movements during which no visual information can be acquired) than novices. [Ulery, B. T., *et al.*, Proceedings of the National Academy of Sciences USA, 2011, www.pnas.org/cgi/doi/10.1073/pnas.1018707108] The goal of this study was to determine the frequency of false positive and false negative errors, to see if consensus exists between examiners' ability to reach a conclusion, and what are the factors influencing these values. The results indicate as a main outcome that: "False individualizations were made at the rate of 0.1% and never by two examiners on the same comparison. Five of the six errors occurred on image pairs where a large majority of examiners made true negatives. These results indicate that blind verification should be highly effective at detecting this type of error. Five of the 169 examiners (3%) committed false positive errors. False exclusions were much more frequent (7.5% of mated comparisons)". The paper offers a rich analysis of other variables as well. [Dror, I. E., *et al.*, Forensic Science International, 2011] The authors studied the inter- and intra-expert consistency. This study brings up some individual differences between the latent fingerprint examiners, which may be attenuated by a proper training tool that enables the examiners to correctly calibrate their thresholds. This problem might also be decreased by a possible best practice that identifies a priori which

	marks are likely to produce such decision variations, and by applying special procedures such as the use of consensus high confidence minutiae, quality mapping and conservative selection procedures. Therefore, it is suggested to tailor procedures and best practices to difficult marks, since it will allow for higher quality work without requiring more resources, because it wisely and appropriately allocates resources to where they are needed. It is also recommended to isolate and document the initial analysis of the latent mark prior to moving to the other stages of the ACE-V process, in order to minimize the bias effect of the presence of a target comparison print (for further development on bias, see 1.5.5).
1.5.2. What scientific literature describes and justifies current quality control measures? ● Under what circumstances are blind controls routinely processed? ● What are appropriate quality controls on LP matching and what justification is there for the recommended controls?	[Gray, L., The Fingerprint Sourcebook, 2011] This book chapter is a review specifically dedicated to the quality-assurance topic, and proposes information about accreditation and certification organizations. Special reference is given to the SWGFAST standards. [United States Department of Justice and Office of the Inspector General - Oversight and Review Division, 2006, United States Department of Justice and Office of the Inspector General - Oversight and Review Division, 2011] Although these two reports are not published in peer-reviewed journals, they bring a full account of the investigation undertaken by the Office of the Inspector General following the misattribution of a latent mark to M. Brandon Mayfield. It is followed by an assessment of the quality control measures in place further implemented after this incident.

1.5.3. What scientific literature establishes the value of replication by a different examiner? ● How consistent are results by different examiners? ● How much is error reduced by verification? ● How consistent are results of re-examination by same examiner? **1.5.4. What scientific literature examines the range of innate human pattern matching capabilities?** ● General pattern recognition ● LP matching-specific pattern recognition	[Langenburg, G., Journal of Forensic Identification, 2009] This article fully answers this question (as well as the #1.6.3), since it covers the whole ACE-V process, with an assessment of the precision, accuracy, reproducibility, and repeatability of the process. The conclusions were numerous as many aspects of the ACE-V process were considered and tested. Briefly, about the value of replication, it was shown that during the verification every false positive was caught however none of the false negatives were detected. This demonstrated a strong resistance to bias with respect to the identifications but a high degree of bias considering exclusion (during a non blind verification for these participants). Six fingerprint analysts participated in a series of tests which are divided in three principle steps: first analyzing sets of fingerprints with an ACE process, then conducting the verification for a set of fingerprints analyzed by another fingerprint expert, and finally re-presenting a certain number of comparisons to see if they will maintain their initial conclusions. The results can be briefly summarized as follow: 100% accuracy for the trials where an opinion of identification was reported (ACE and ACE-V processes) and 67% (ACE-V)/86% (ACE) for those with an opinion of exclusion; the precision during the ACE-V trials showed higher precision than ACE trials during the verification stage; regarding reproducibility 72% provided a 100% consensus; and the author compared both reproducibility and repeatability in these experiments. [Busey, T. A. and Parada, F. J., Psychonomic Bulletin & Review, 2010] This paper is a review which highlights different points regarding latent fingerprint experts, such as the way they conduct their examinations, the features or sources of information they use, the required evidence, in addition to the best approach for training new examiners. One of the well-known approaches is the ACE-V process. Experience allows the expert to outperform the novice especially when the expert is accustomed to specify which features are essential and of great importance. About training, the best procedure should involve only clear prints not

	corrupted by visual noise since it improves the perceptual representation of the stimulus and helps exclude external noise. The performance and the capability of a correct matching appeared to be related to the level of experience of the examiner, since experts tend to follow a certain configural processing of upright fingerprints and identify the diagnostic features. Their visual perception of the features and their ability of filtering the external noise are improved by the training giving therefore; a better performance result than the novices.
1.5.5. What scientific literature establishes the key sources of bias and characterizes the effectiveness of measures to mitigate the bias? ● Under what circumstances are "Exclusions" and "Inconclusives" verified during ACE-V? ● What knowledge does an analyst have regarding other case evidence? ● How much does such evidence influence accuracy? ● How much is accuracy affected by "blind" or "non-blind" status? ● Under what circumstances do examiners/ verifiers compare several candidate prints versus verifying a single suspect print in comparison to a single crime	[Langenburg, G., *et al.*, Journal of Forensic Sciences, 2009] Context and confirmation biases – respectively the exposure to extraneous information and the expectation of the observer – constitute the potential biases that might influence fingerprint experts during the verification stage of the ACE-V process. The study of these potential biases was the aim of this article which shows that fingerprint examiners can be biased especially during complex comparison trials. Moreover, they are more susceptible to this effect when it prompted towards inconclusive or exclusion conclusions compared to ones of individualization where they are trained to be more conservative; the risk and the penalties of incorrect individualization are far more severe than the other false conclusions. Therefore, in order to mitigate the bias, it is wisely recommended that blind testing verification is conducted during the situations cited above in addition to some random case selection and not in all routine examinations, since it is a waste of time and needlessly consumes significant personnel resources. [Thompson, W. C., Wiley Encyclopedia of Forensic Sciences, 2009] The author focused on the "observer effects" that influence the forensic scientists and hence, affect their interpretations leading to erroneous results. Such effects take place through

scene print?	communications between the different people working on a case (such as police, lawyers, experts, etc.), or after being aware of the previous result of an analyst, or even when relying in part on subjective judgment to evaluate potentially ambiguous data. Numerous procedures might be employed in order to decrease this bias such as separating several laboratory functions and assigning them to different people, or performing the analysis and evaluation of various samples in a sequence so that analysis and interpretation of early samples cannot be influenced by knowledge of the later one. Another approach consists of conducting a blind or even double-blind procedure, with a "case manager" who is the only one aware of the broader facts of the case. [Dror, I. E. and Cole, S. A., Psychonomic Bulletin & Review, 2010] Various research studies that assess the different factors influencing the perception and comparison of fingerprint patterns, along with the forensic decision-making are well elaborated in this article. It also highlights some famous erroneous judgments such as the Mayfield case, since it shows the pernicious combination of an AFIS search and cognitive bias such as the explanation and dismissal of the discrepancies, which led to the bias of the subsequent examination. Latent print examination, despite its reputation for accuracy and objectivity, is subject to bias. However, this phenomenon is not observed among all examiners or scenarios, especially if they are analyzing a complete and high clarity print, or if they are aware that they are part of an experimental study. [Dror, I. E., *et al.*, Forensic Science International, 2011] In this paper, the studies performed on actual latent fingerprint examiners revealed the

	potential effect of the presence of a target comparison fingerprint on the analysis of the latent print. This research also reported some inconsistencies between and within experts during the analysis of latent marks. Therefore, it is highly suggested to follow a linear application of the ACE approach by first examining the latent mark, prior to looking at any potential comparison print, especially if the latent mark is of low quality, distorted or contains limited information. Furthermore, proper training can decrease the variation of consistencies among the examiners by developing an appropriate calibration tool that enables them to adjust their threshold so as to meet the standards in the field.
1.5.6. What scientific literature proposes, describes and evaluates alternative methods? • What are the benefits and deficiencies of each method?	[Olsen, R. D. and Lee, H. C., Advances in Fingerprint Technology, 2001] In addition with the conventional method ("based on the ridge characteristics and their unit relationship to one another"), there are seven alternative methods which can be used by latent print examiners for the evaluation and individualization of latent fingerprints (Osborn Grid, Seymour Trace, Photographic Strip, Polygon, Overlay, Osterburg Grid, or Microscopic Triangulation). According to the authors of this book chapter, all of these methods except the conventional one are limited since they only rely on spatial positions of the ridge characteristics; they don't take into consideration the relationship between the characteristics and all the other ridges or even the influence of distortion in the print. In addition, they don't explain the logical decisions that are required throughout the entire identification processes.
1.6. "End-to-End" Process reliability	
1.6.1. What scientific literature describes	It is clear there is relationship between 1.5 and 1.6. We shall only cover additional material

and evaluates current and potential methodologies? ● Under what circumstances are specific methods appropriate and effective? ● How effective are the methods described? ● What future procedures (e.g., DNA confirmation) are under development (e.g., by SWGFAST or SWGDAM)? ● Does the size of the database (i.e., number of comparisons) influence methods?	here. [Dror, I. E. and Mnookin, J. L., Law Probability and Risk, 2010] The authors review the problems and challenges brought by forensic tools such as AFIS. Before the use of databases, experts would generally compare a latent print with a quite limited number of tenprints, most of the time from individuals already suspected. With a system such as AFIS, latent prints can now be compared to many millions of prints stored in huge databases. The chances of finding by pure coincidence a lookalike print is much higher than when comparing a latent print to just a few dozens, hundreds or even thousands of prints prior to the introduction of AFIS. When database size increases, the chances that some print in the database will bear a high degree of resemblance to the latent in question also goes up. Despite this evolution, fingerprints experts have not changed and adapted their criteria for determining what counts as an identification as a result of AFIS.
1.6.2. What scientific literature establishes the basis for appropriate false match vs. missed match probabilities? ● How do the probabilities differ for automatic and manual methods?	
1.6.3. What scientific literature establishes the overall accuracy of current fingerprint analysis methods? ● What is the error performance of	1.6.2 and 1.6.3: See section 1.5 above plus the following contribution in relation to 1.6.3:

individual steps in each method? ● How much does accuracy vary with LP quality? ● How much does accuracy vary with the number of minutiae examined? ● How well does measured accuracy compare with examiner perception? ● How much does the number of comparisons performed in single evaluation influence accuracy? ● How does accuracy vary for automatic versus manual examination? ● How is "ground truth" (i.e., true match/ non-match status) established to support evaluations of examiner accuracy?	[Neumann, C., *et al.*, Forensic Science International, 2011] The purpose of the study is to assess the operational impacts (increase of evidence produced and benefits compared to the current protocols) of implementing a statistical model in fingerprint casework. Following an implementation (in a shadowing process) over 6 months, the study showed that among a total of 3600 additional marks (initially classify by the examiners having no value) but considered by the research team, only a few (38) led to additional evidence. That shows how efficient is the initial triage process carried out holistically by the laboratory. This filtering process is very efficient at maximizing the contribution of fingerprint evidence given time and resource constraints. Among the fingermarks (70) taken through a comparison process but ultimately not used as evidence (reported inconclusive or no value), 20 led to evidence of association with weights quantified using the statistical model. The weights associated with these cases are of similar order of magnitude as the weights associated with the identification decisions reported by the laboratory. The paper provides a full description of the likelihood ratios associated with the reported cases by the laboratory and their relationship with the number of minutiae considered in the model. Finally the researchers have not observed any indication that the examiners were influenced by the number of previously recovered marks or by the presence of control prints when deciding to recover marks or to consider them of value.
1.7. Future Research	
What new technologies and areas of	Focus will be given here on research avenues in relation to the questions raised by the RDT&E

research should be pursued with regard to latent print examination and analysis? (Note- this question does not require a list of references, it is for informational purposes only.)	IWG in this document. Needless to say that other areas such as the management of fingerprint identification activities (including AFIS operations and error management), the detection (and dating) of friction ridge skin marks both at the crime scene and in the laboratory or the preparation of witness statements and testimonies are also of paramount importance in forensic science. Within the above restricted scope, the following lines of research constitute the priorities for SWGFAST (note that the order does not translate any priorities): ● Develop research in relation to the analysis phase of ACE-V with a view to help examiners to **assign a level of complexity to friction ridge skin marks** using dedicated tools such as automatic **quality measurements**. ● Research on **AFIS systems** aimed at (a) measuring the likelihood of observing close non-matches based on marks showing various levels of quantity and quality, (b) increasing accuracy by accounting for the discriminating value of additional features such as minutiae types or other features including level 3, or (c) defining the boundaries of fully automatic operations (i.e. *lights-out*) either on prints or marks. **Interoperability** of systems is also a key research area. ● Develop ways to handle decisions in complex comparisons in a way that reduce examiner variability, for example by taking advantage of a **consensus set of features** provided by a pool of experts. ● Expand the **systematic acquisition of data in relation to friction ridge skin features** on areas such as palms, phalanges or upper fingertips. The acquisition should cover the range of features used by examiners in the comparison process, hence not only minutiae (and their combinations) but also scars, wrinkles, creases, warts, and level 3 features.

	• Develop proper mechanisms to **interpret and assign weights to discrepancies** observed during the comparison process. Research in this area should study the **distortion** of the friction ridge skin when applied with various forces and movements on substrates both qualitatively and quantitatively. • Pursue the research in relation to **statistical models** on large datasets in order to bring to examiners operational tools that can be applied in casework (both during the analysis stage and the evaluation stage of ACE-V). • Study the statistical contribution of **level 3 features** in the identification process. • Provide **integrated technology to support the full examination process** by e.g. an adherence to the steps of ACE-V, restricting case information to domain relevant, offering peer review mechanisms, a full documentation tuned as a function of complexity, automatic assessment of the markings and Q/A alarms. • Research in relation to **decision thresholds of examiners** at the various stages of ACE-V, typically when large-scale AFIS systems are used. • Because probabilities play such an important role in the decision-making process, there is a requirement for a **training program** for examiners covering for example empirical data regarding fingerprint features, models for friction ridge skin variability, inference and decision making. Such a program should allow a transition from the above research avenues to daily casework.

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