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Why Two Genuine Signatures are never identical in Practice: Evidence and Scientific Explanation

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Abstract

Empirical evidence that two genuine signatures are never identical in practice has been available for more than 120 years, but a scientific explanation for this phenomenon is lacking. The authors present a detailed explanation based on the latest research in biomedical sciences, identifying four reasons: 1) The "strokes" of each signature last 1/10 of a second, while the visual reaction time in humans requires at least 2/10 of a second, so the "strokes" cannot be corrected by visual feedback. 2) Each time a signature is written, different motor units of the corresponding muscles are quasi-randomly activated, resulting in slightly different movements and thus a non-identical signature. 3) In writing a signature, muscles of the forearm and the rest of the upper limb are used, which are less controllable from the motor cortex than the intrinsic muscles of the hand. 4) It is implied by electromyogram studies and kinesiology that a unique sequence of muscle movements is required to produce a specific signature or handwriting, so if a person tries to repeat the same movement, the two actions will never be identical. In addition to the above, people usually sign "by heart" without seeing a model of their signature, using their "muscular memory", thus producing non-identical signatures.

***Keywords**: identical signature, visual feedback, motor units, proprioception, kinesiology*

1. Introduction

A common misconception still held by many – even highly educated – people is the belief that an individual can reproduce an identical version of his/her handwritten signature. However, for several decades Forensic Document Examiners (FDEs) worldwide have found that, in practice, two genuine signatures are never identical. Empirical evidence shows that two signatures of the same person may be similar, but never identical: and this is taught as a fundamental principle in FDE training courses.

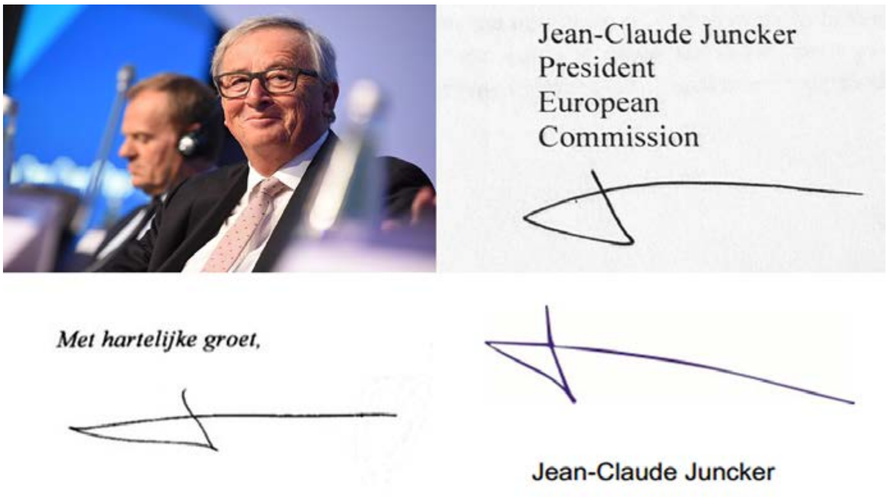

Fig. 1. Photo of Jean-Claude Juncker with three initialled signatures

Sources
https://upload.wikimedia.org/wikipedia/commons/6/69/EPP_Congress_in_Malta%2C_29-30_March_2017_%2833700140116%29.jpg
https://twitter.com/juncker_jc/status/489388420792614912

https://www.dailymail.co.uk/news/article-4546980/Handwriting-expert-reveals-personalities-G7-leaders.html
https://twitter.com/junckereu/status/842313962595201024

When two signatures show various suspicious similarities – sometimes exhibiting an identical shifted base – this is considered a likely case of superimposition rather than free-hand forgery. Even signatures of simple form are never identical. This is illustrated in Figure 1 by examples of the simply formed signatures of a well-known person, Jean-Claude Juncker, former President of the European Commission. Jean-Claude Juncker wrote on Twitter: “My signature has always secretly been the number 4 on its side. When you're PM for 18 years, nobody questions you” (https://twitter.com/juncker_jc/status/489388420792614912). This basic signature, simple initials, is clearly a mirror image of the number 4 sideways; there is also a more complex version of his signature, which is displayed in the Wikipedia article on Juncker.

The samples of the simple signature in Figure 1 are similar, but they do not coincide at any point. In his latest book, Mike Wakshull, a well-known FDE, includes a relevant section with the title “No person writes exactly the same twice”: he gives the definition of intra-writer variability, as “the differences in the way a person writes among sessions” (Wakshull 2019: 67). Although this principle is universally accepted by FDEs, to the best of the authors’ knowledge there is no published scientific explanation: the only written guidance is that “we are humans, not machines”. However, this explanation is not satisfactory. The 2009 publication *Strengthening Forensic Science in the United States* – authored by the National Academy of Sciences and known worldwide as “The 2009 NAS Report” – stated that opinions in handwriting examination were based too much on subjective analysis rather than objective, science-based analysis (NRC 2009). Moreover, court rulings nowadays require use of a scientific approach for the development and presentation of the opinions of FDEs (Wakshull 2019: 1).

Humans are capable of performing some manual tasks highly accurately, the degree of precision being much less than a 1/10 of a millimeter: such tasks require far more precision than the production of handwriting and signatures. Thus, there is a need for a scientific explanation: why two genuine signatures are never identical in practice, in spite of the fact that humans can accurately perform manual tasks that are more demanding in precision.

2. Evidence and literature review

Empirical evidence that two genuine signatures are never identical in practice has been available for more than 120 years. In 1894, William E. Hagan wrote in his famous book about disputed documents, that based on his and other experts’ experience:

> Where two signatures of the same person exactly coincide when one is laid over the other in parallel arrangement with a strong light behind them, this condition of their appearance is very positive evidence that one of them was traced from the other, and is a forgery, as it is impossible for such a circumstance to occur in the writing of two signatures produced habitually. In the Silvania Ann Howland case there were found to occur as added to a will three codicils each of which had affixed thereto what purported to be the signature of the testator, and which three signatures when examined as transparencies were found to exactly coincide in all respects as to form and general appearance. A calculation made by Prof. Pierce, a learned and well-known mathematician of his day, as to how often it was possible for such a circumstance to happen with habitually produced signatures, he gave it as his opinion under oath, from actual calculation, it could only happen once in two trillion, eight hundred and sixty-six billion times. (Hagan 1894: 91-92)

Also in the U.S.A., Albert S. Osborn wrote in 1910 in his book *Questioned Documents*, a worldwide known book, that “No two genuine signatures can be exactly alike” (Osborn 1910: 281). In many other countries, FDEs came to the same conclusions. In Italy, in 1924 Salvatore Ottolenghi wrote in his book about writing expertise and handwriting identification, that it is impossible for two handwritten words to coincide exactly (Ottolenghi 1924). In the succeeding years, worldwide nearly all the books and articles about Forensic Document Examination stated the same empirical principle, based on the innumerable cases treated by FDEs.

In 2018, Professor James E. Girard, in his widely known book *Criminalistics*, a book for the different forensic disciplines concerning crime, wrote in chapter 7 about questioned documents, that "a person's signature is never identical on two different occasions" – showing that this principle is recognized by scientists in other forensic disciplines. The same principle is repeated in the most respected, recently published books about forensic document examination (Morris 2021, Angel and Kelly 2021, Wakshull 2019), but without any scientific explanation.

The first author of this article, a professional FDE (the other two authors are medical practitioners) contributes to the further verification of this empirical principle with his personal experience; he, too, concludes from the empirical evidence that it is impossible for two authentic signatures to be identical. These empirical data consist of more than 700 cases in Greece, Italy and other countries as a professional FDE over the last 20 years, along with several hundred cases examined for theoretical or educational purposes in his duties as an instructor in a private university and a private school of Forensic Document Examination and Forensic Grapho-Pathology in Italy. Thus, for more than 120 years, two signatures that are identical will immediately arouse a FDE's suspicion of forgery.

The explanation advanced for this empirical fact –that we are humans – is totally inadequate, as humans can perform manually much more difficult tasks with remarkable precision. A classic example of fine hand movements is the threading of a needle, but humans can perform much more impressive tasks, as explained below.

Holding, in the dominant hand, a micro-pipette with an inner diameter of less than 10 μm (i.e., less than 1/100 of a millimeter), aided by a microscope, humans can manually suck a nucleus, having approximately the same diameter with the micro-pipette, out of the cell to be cloned. This is a standard procedure for "somatic cell nuclear transfer" (SCNT), performed successfully in thousands of successful procedures for the cloning of cells over more than two decades, in many countries of the world. Cloning is the process of replicating individual organisms with identical or near-identical DNA – either naturally or artificially through asexual reproduction. The cell to be cloned, the ovum, has a diameter of approximately 0.1mm, and the nucleus has a diameter of about 0.01 mm: the nucleus is sucked out manually, using a micro-pipette, as shown in Figure 2.

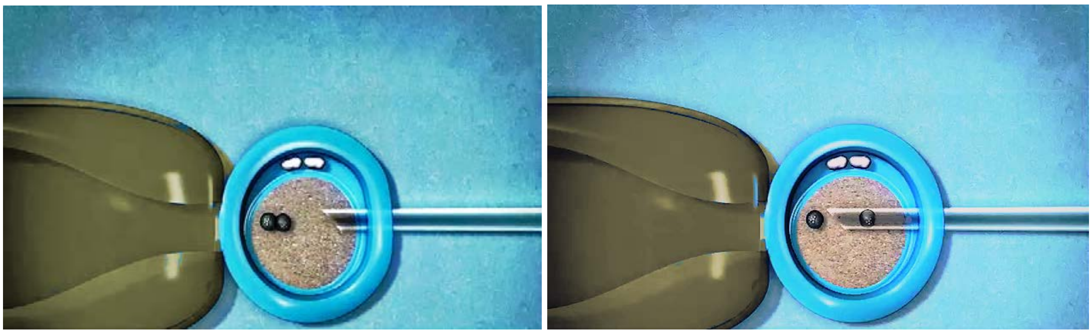

Fig. 2. Schematic representation of SCNT. The inner diameter of the micro-pipette (on the right) is less than 0.01mm.

Source: third author's personal archive

The first mammal cloned from adult somatic cells using SCNT was a female domestic sheep born in Scotland on 5 July 1996; she was named "Dolly" by the scientists who performed this successful procedure, which became very famous worldwide (Wilmut et al. 1997). Since the birth of Dolly, many other species, such as cloned mice, cloned dogs, cloned cows, cloned rabbits, cloned horses, etc., have also been born through SCNT. The standard nuclear transfer procedure is divided into two sub-procedures: the enucleation of an oocyte and the implantation of a donor nucleus from a somatic (body) cell in the oocyte. The enucleation of the oocyte is performed by the micro-pipette tearing apart the genetic material and the cytoplasm in the oocyte: this is the most difficult step in somatic cell nuclear transfer, as shown in Fig. 2. Yet, the main step of oocyte enucleation is still performed manually (Zhao et al. 2021, Liu et al. 2018). This task – performed manually for more than two decades – is much more demanding in precision than the writing of a signature. Only very recently has it been proposed to replace the procedure done manually – to improve the operation's efficiency and success rate – with a robotic, precise oocyte blind enucleation method (Zhao et al. 2021).

Another example of a manually performed task requiring great precision is the writing of many letters on a grain of rice. This is illustrated in Figure 3, below.

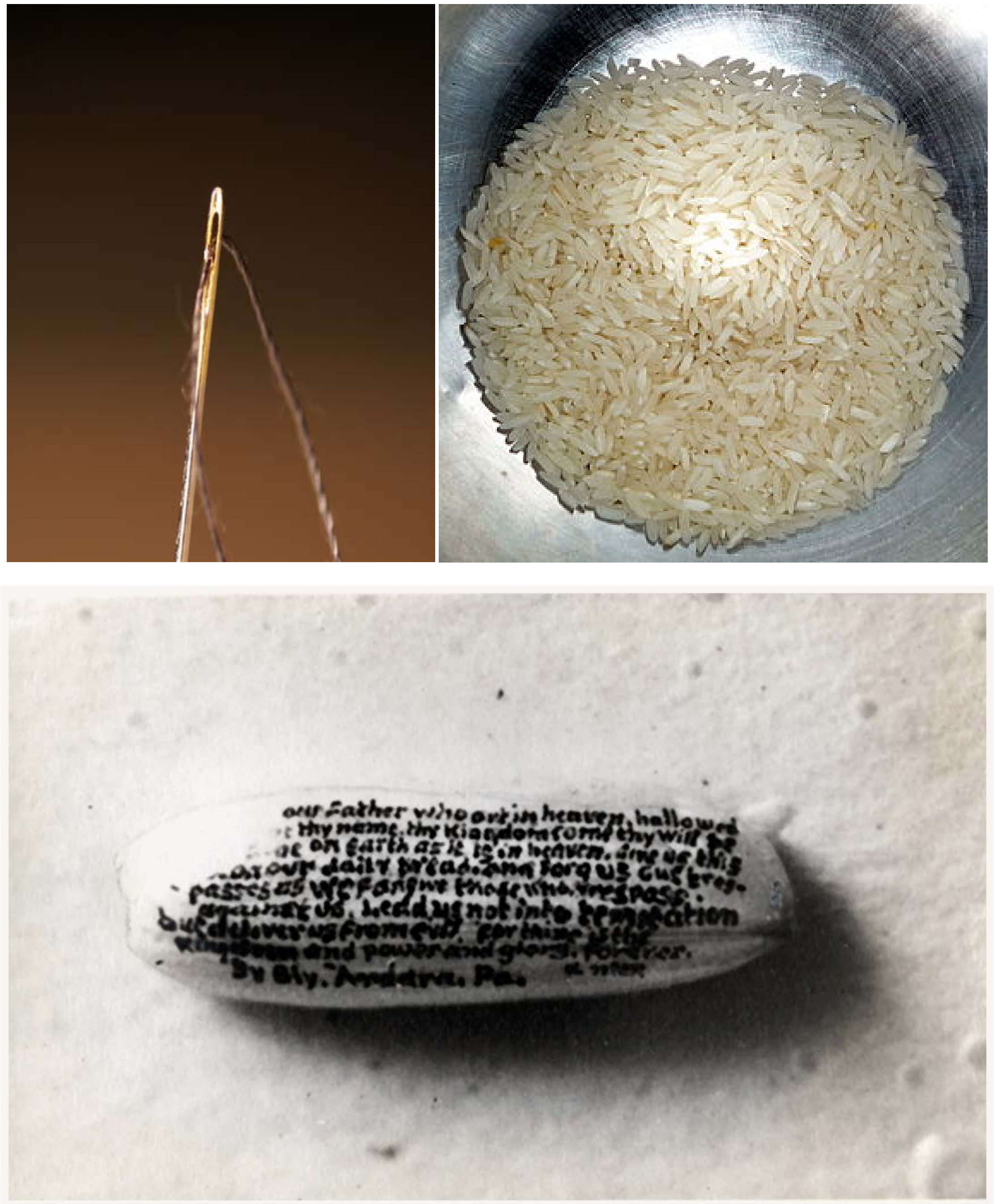

Fig.3. Threading a needle. Plate with rice grains. A single grain of rice on which is written the prayer "Our Father who art in Heaven".

Sources
https://commons.wikimedia.org/wiki/File:Sewing_needle_eye_with_thread.jpg
https://commons.wikimedia.org/wiki/Rice#/media/File:Ricegrains1500ppx.jpg

On the 6th of June, 1991, an article appeared in the *Los Angeles Times* with the title "New World Record in Tiny Writing Reported", announcing that "an Indian has broken his own world record for tiny writing, inscribing 1,314 characters on a grain of rice." Surendra Kumar Apharya, who has been mentioned twice in the Guinness Book of Records, wrote the names of 168 countries and regions on a single grain of rice (L.A. Times 1991). More recently, Mr Surendra Kumar Apharya of Jaipur, Rajasthan wrote 1,749 characters on a single grain, 249 characters on a human hair and a long speech on a small postal stamp. He got his name registered seven times in the Guinness Book of World Record. (Youtube 2020; HISTORY TV18 India; online resource).

Rice writing originated in ancient Anatolia in Turkey and India. Many rituals and rites use rice as a medium, but at some point in ancient Anatolia artisans who were skilled in making miniature paintings decided to turn their skill to making art with what had always been an ancient symbol of prosperity, the oldest example of which lies in Topkapi Palace in Istanbul, Turkey. The artisans would inscribe messages or names on a single grain of rice after it was treated and polished. Apart from Turkey, also India had a large number of artisans skilled in making miniature art, including rice art (Wikipedia: Rice writing).

The above tasks demonstrate the ability of humans to perform miniature works. However, consultation of PubMed (a database of over 32 million citations of biomedical literature) with the key words "rice" and "writing" yields no articles on rice-writing. This is remarkable, considering the importance of human manual accuracy as a crucial component of high-profile research by medical doctors and scientists in biomedicine. We can assume that the reason for this is that scientists know the history of science, but they do not know adequately the rest of the history of the world: thus, many facts which are extremely important for science remain unknown to them for a long time. Moreover, from 1997 there are very many articles cited in PubMed for "somatic cell nuclear transfer" (SCNT), but only in journals for cell biology and/or topics related to fertilization. There is not a single citation of SCNT in journals of experimental psychology, or journals on human movement and motor control. Given that it has been performed successfully thousands of times, and is indisputable evidence of the extreme ability of motor control of very fine movements of fingers, its absence is remarkable. Of course, the thousands of successful experiments of SCNT did not take place in laboratories of experimental psychology, which is the primary explanation for its absence from the disciplinary field. The ability to control the movement of muscles of the hand, by the "feelings" of the position of fingers and articulations of the hand, is named "proprioception".

Proprioception, or kinesthesia, is the sense that lets us perceive the location, movement, and action of parts of the body. It encompasses a complex of sensations, including perception of joint position and movement, muscle force, and effort. These sensations arise from signals of sensory receptors in the muscle, skin, and joints, and from central signals related to motor output (Taylor 2009, Proske et al. 2012). A 2018 review article states that "The ability of proprioception of humans is remarkable, and this is shown by threading a needle, a task which uses the visual feedback to change the extremely fine movements of the fingers, which are controlled by proprioception" (Tuthill et al. 2018). In the cited article, the latest scientific studies are reviewed, but there is no mention of procedures that prove the range of ability of motor control of very fine movements of the fingers, on a scale of 1/100 of an mm, such as the procedure of SCNT performed manually, and the process of rice writing. Only the threading of a needle is mentioned, which is a much less demanding task. We can assume that this omission occurred because writing on a grain of rice is not cited in PubMed; moreover, although PubMed contains over 3,200 articles related to the procedure of SNCT, none of these articles refers to SCNT as a proof of the motor control of very fine movements of human fingers. In the conclusion of a recent article of 2019 on proprioception, the authors write that "angle and torque perception are highly precise" (Prendergast et al. 2019); however, the scale of precision proven with the experiments in the above article is far away from the precision proven by both SCNT procedure and writing on a grain of rice. This lacuna exists because it is not at all easy to perform experiments studying proprioception in psychology laboratories, requiring the participants to perform extremely difficult tasks (rice writing and the SCNT procedure) which also demand much time, and in the case of SCNT also require costly laboratory equipment.

The role of touch in proprioception has been studied in recent articles, which have extended the classical view that touch is mainly devoted to the perception of the external world. In an article of 2019, Moscatelli et al. present their study for testing the hypothesis that touch provides auxiliary proprioceptive feedback for guiding actions. These researchers used a well-established perceptual phenomenon to dissociate the estimates of reaching direction from touch and musculoskeletal proprioception. Participants slid a fingertip on a ridged plate to move toward a target without any visual feedback on hand location. Tactile motion estimates were biased by ridge orientation, inducing a systematic deviation in hand trajectories in accordance with their hypothesis. Results are in agreement with an ideal observer model, where motion estimates from different somatosensory cues are optimally integrated for the control of movement. These outcomes shed new light on the interplay between proprioception and touch in active tasks (Moscatelli et al. 2019).

In contrast to proprioception, the extreme limits of tactile perception are studied by numerous researchers. Skedung et al. (2013) present a study proving that there are two perceptual dimensions directly linked to surface physical properties – the finger friction coefficient and the wrinkle wavelength of the surface. The lowest amplitude of the wrinkles of a surface thus distinguished was approximately 10 nm (10/1,000,000 of a mm), demonstrating that human tactile discrimination extends to the nanoscale. From all the above, it is proven that humans can perform very difficult tasks, requiring much more precision than the writing of a signature, a task for which proprioception is needed to perform it, too. The central role of proprioception for the storage, updating and maintenance of skilled motor programs, as with the signature and/or handwriting procedure, is well established (Hepp-Reymond et al. 2009).

3. Advancing scientific explanations for signature non-replicability

The manual tasks of rice writing and SCNT are much more demanding in precision than the writing of a signature. Here, we propose a scientific explanation why two genuine signatures are never identical in practice, despite the fact that humans can perform much more difficult tasks requiring much greater precision. We suggest that, apart from the reason that people sign in most cases without seeing a model of their signature, there are four other main reasons related to the physiology of humans, having the result that two genuine signatures are never identical in practice. These reasons are derived from different medical disciplines.

People sign in most cases without seeing a model of their signature, so they sign using their "muscular memory", they sign "by heart". This is an obvious reason, why the signatures of a person do not coincide. However, even when someone is asked to sign multiple times on a document, and so she/he sees other samples of her/his signature, she/he cannot produce in practice two identical signatures: this is confirmed by empirical studies of FDEs over more than 120 years.

3.1 Reason no. 1: no possibility of visual feedback

The first reason, other than writing without seeing a model of the signature to be replicated, is that a handwritten signature (and handwriting in general) is produced in adults by sequences of muscle contractions, resulting in "strokes" – i.e. fast movements of the thumb and index finger holding the writing medium (pen, pencil, etc.). These strokes last about 1/10 of a second in adults trained in handwriting from childhood (Teulings 1996), and cannot be controlled or corrected by visual feedback, because more than 2/10 of a second (200ms) is required for Visual Reaction Time (VRT) of young people, and even more for older persons. The reaction time is the time taken for the appearance of a rapid, voluntary reaction by an individual following a stimulus, either auditory or visual. In its simplest form, visually-mediated reaction time can be defined as the time taken to respond to the sudden appearance or change of a visual stimulus. This is referred to as 'simple' reaction time, to distinguish it from 'choice' reaction time. Unlike simple reaction time, choice reaction time requires a choice to be made regarding how to respond – e.g., by pressing one out of four keys with a specific digit depending on which of several stimuli was presented. Simple reaction time (SRT), the minimal time needed to respond to a stimulus, is a basic measure of processing speed. SRTs were first measured by Francis Galton in the 19th century, who reported visual SRT latencies below 190 ms in young subjects. However, recent large-scale studies have reported substantially increased SRT latencies that differ markedly in different laboratories, in part due to timing delays introduced by the computer hardware and software used for SRT measurement. Also, the time lost for saccades, smooth pursuit eye movements, and for blinking of the eyes was incorrectly not taken into consideration in the first studies of VRT.

Saccade refers to a rapid, jerky movement of the eyeball, redirecting the visual axis to a new location. Primates perform saccadic eye movements in order to bring the image of an interesting target onto the fovea. Saccades and smooth pursuit eye movements are two different modes of oculomotor control. Saccades are primarily directed toward stationary targets whereas smooth pursuit is elicited to track moving targets. Eye movements are the most common of all human actions: every second of our waking life we make approximately three of the rapid, stereotyped movements that are saccades (Carpenter 2004). Specialization of the foveal region of the human retina necessitates a sophisticated ocular motor system to translate an image appearing on the peripheral retina onto the fovea: this is achieved by the generation of saccadic eye movements which effect rapid fixation of the target. The saccadic latency, which is the time from the presentation of the target to the commencement of the saccade, consists of the transmission times in the afferent and efferent pathways and the central processing time which is likely to be appreciable due to the complexity of the pathway (Darrien et al. 2001).

Blinks and saccadic eye movements both have the capacity to disrupt visual perception. Vision is temporarily occluded during blinks which typically last for around 200 ms; saccadic eye movements, whose duration ranges from 20 ms to more than 100 ms depending on the amplitude of the movement, result in rapid retinal image motion. Thus, the current estimation of the minimum Visual Reaction Time (VRT) for young adults, including the latency (delay) due to eyeball movements and blinking, is more than 200 ms (Barrett et al. 2020; Prabu Kumar et al. 2020, Hülsdünker et al. 2019, Bremmer et al. 2016, Woods et al. 2015, Eckner et al. 2010, Galton 1890). According to a review article of 2015, typically, an adult skilled in handwriting performs the strokes so rapidly that there is no possible role of visual feedback in the form or dynamic characteristics of writing a particular letter of the alphabet or other symbol. Visual feedback is used only for the “topocinetic” component of handwriting – the spatial layout of the text in the graphic space, the spacing between letters and words and the placement of punctuation. Thus, the form of the letters cannot be controlled by visual feedback (Danna 2015). In the above-mentioned article, the current estimation of VRT (more than 200 ms) is not included. Furthermore, the article does not mention the fact that strokes are performed so quickly, that the form of the letters cannot be controlled by visual feedback, and so the form of the signature too cannot be controlled and corrected by visual feedback. Nonetheless, this review article of the field of experimental psychology, combined with the other articles, implies that one of the reasons that two genuine signatures are never identical in practice, is that the strokes in signatures and handwriting are faster than VRT, so the form of the signature and the letters cannot be controlled and corrected by visual feedback. In contrast to this, SCNT and rice writing are performed with slow movements, both of which can be corrected using visual feedback.

3.2 Reason no. 2: quasi-random motor unit activations

The second reason comes from the discipline of physiology of muscles. Recent research supports the model of quasi-random motor unit recruitment of a muscle which performs a specific task. The recruited motor units are suitable to perform the required task. When the muscle performs the same task many times, each time different motor units are recruited, quasi-randomly, and this results in a slightly different torque and a slightly different movement, although the order sent from the central nervous system (CNS) to the muscle is to perform the same task. (Hudson et al. 2019, Sartori et al. 2017, Peng et al. 2017, Dean et al. 2014, Dideriksen et al. 2013, Heckman et al. 2012, Hodson-Tole et al. 2008, Jubeau et al. 2007, Romaiguère et al.1993, Heckman et al. 1993).

One of the most common features of human movement is its variability. Human movement variability can be described as the normal variations that occur in motor performance across multiple repetitions of a task. This variability is intrinsic to all biological systems and can be observed quite easily. If a person tries to repeat the same movement twice, the two actions will never be identical, and this is proved by many experiments in laboratories studying human movement (Stergiou et al. 2011). Thus, one of the reasons for this variability is the quasi-random motor unit recruitment of a muscle which performs a specific task. Skeletal muscle contains many muscle fibres that are functionally grouped into motor units. Every skeletal muscle fibre must be innervated by the axon terminal of a motor neuron in order to contract. Each muscle fibre is innervated by only one motor neuron. The actual group of muscle fibres in a muscle innervated by a single motor neuron is called a motor unit (as illustrated in Fig.4). The size of a motor unit is variable depending on the nature of the muscle. A small motor unit is an arrangement where a single motor neuron supplies a small number of muscle fibres in a muscle. Small motor units permit very fine motor control of the muscle. A large motor unit is an arrangement where a single motor neuron supplies a large number of muscle fibres in a muscle. Large motor units are concerned with simple, or “gross”, movements, such as powerfully extending the knee joint. There is a wide range of motor units within many skeletal muscles, which gives the nervous system a wide range of control over the muscle. The small motor units in the muscle will have smaller, lower-threshold motor neurons that are more excitable, firing first to their skeletal muscle fibres (which also tend to be the smallest).

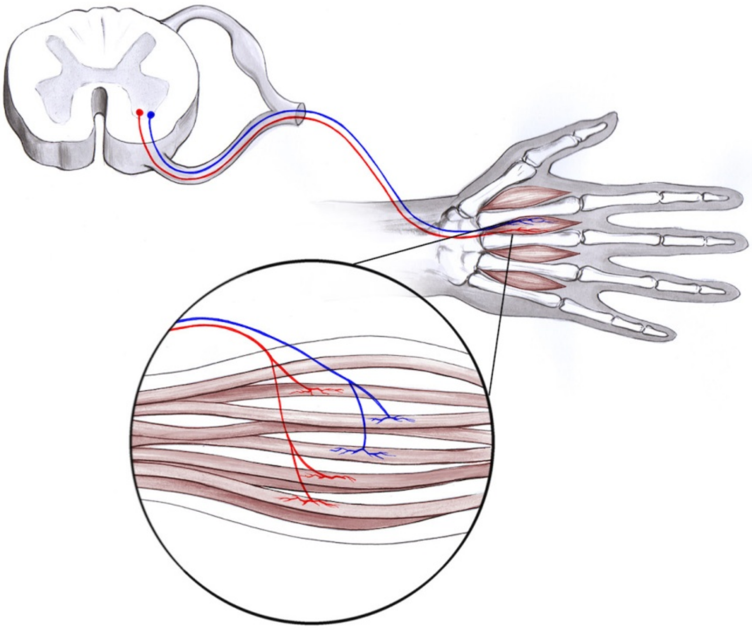

Fig. 4. Two motor units, red and blue, in the second dorsal interosseous muscle. The actual group of muscle fibres in a muscle innervated by a single motor neuron is called a motor unit.

Source
http://backyardbrains.de/experiments/MuscleSingleunit (Creative Commons)

Activation of these smaller motor units results in a relatively small degree of contractile strength (tension) generated in the muscle. As more strength is needed, larger motor units, with bigger, higher-threshold motor neurons are enlisted to activate larger muscle fibres. This increasing activation of motor units produces an increase in muscle contraction, known as recruitment. As more motor units are recruited, the muscle contraction grows progressively stronger. In some muscles, the largest motor units may generate a contractile force of 50 times more than the smallest motor units in the muscle. This allows a feather to be picked up using the biceps brachii arm muscle with minimal force, and a heavy weight to be lifted by the same muscle by recruiting the largest motor units. When necessary, the maximal number of motor units in a muscle can be recruited simultaneously, producing the maximum force of contraction for that muscle, but this cannot last for very long because of the energy requirements to sustain the contraction. To prevent complete muscle fatigue, motor units are generally not all simultaneously active, but instead some motor units rest while others are active, which allows for longer muscle contractions. The nervous system uses recruitment as a mechanism to efficiently utilize a skeletal muscle (OpenStax, Human Anatomy). For any motor task there are many possible combinations of motor units that could be recruited and it has been proposed that a simple rule, the 'size principle', governs the selection of motor units recruited for different contractions. Motor units can be characterized by their different contractile, energetic and fatigue properties and it is important that the selection of motor units recruited for given movements allows units with the appropriate properties to be activated (Hodson 2008).

The central nervous system is responsible for the orderly recruitment of motor neurons, beginning with the smallest motor units. Henneman's size principle indicates that motor units are recruited from smallest to largest based on the size of the load. For smaller loads requiring less force, slow twitch, low-force, fatigue-resistant muscle fibres are activated prior to the recruitment of the fast twitch, high-force, less fatigue-resistant muscle fibres. Larger motor units are typically composed of faster muscle fibres that generate higher forces. Motor units recruited at low force (low-threshold units) tend to be small motor units, while high-threshold units are recruited when higher forces are needed and involve larger motor neurons.

For handwriting, low force is needed, so the recruited motor units are a small percentage of all the motor units of the muscles contributing to handwriting. Each time a person produces a signature, different motor units are quasi-randomly recruited from the muscles used for the production of the signature, resulting in slightly different movements – "strokes" with slightly different torque. So, a signature is never identical with a previous one. The following example in Figure 5 illustrates the variation of a stroke, due to quasi-randomly recruited motor units. A person produces a signature like the signature of Jean-Claude Juncker. To form the horizontal-oblique line of the signature, using the right hand with a stroke from left to right, clockwise, she/he must rotate the wrist clockwise using the muscle extensor carpi ulnaris (shown in Figure 5). This fact is confirmed by EMG studies (Chihi 2020). There are also other muscles contributing to this movement, but to make the example simpler we mention the most important for this stroke.

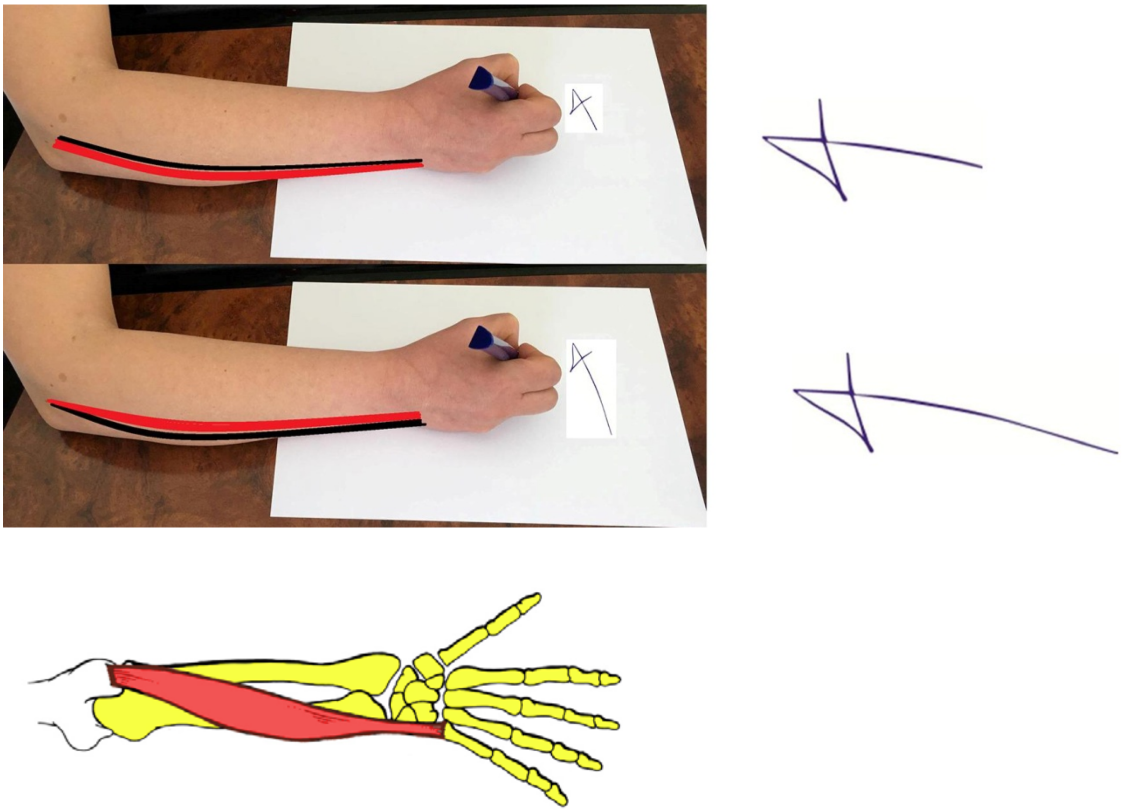

Fig. 5. Schematic representation of the activated motor units of ECU coloured black and the non activated red. Left, middle: The activated motor units are nearer the little finger and so they produce a bigger rotation and bigger horizontal-oblique part of the signature. The difference in signatures is exaggerated. Below the photos a sketch of the muscle right extensor carpi ulnaris (ECU).

Source
https://commons.wikimedia.org/wiki/File:Extensor_carpi_ulnaris.png (modified)

Every time she/he signs, different motor units are activated, and slightly different torque and angle of rotation are produced, so the horizontal-oblique part is bigger in the second photo. Here, the activated motor units are nearer to the little finger, producing a larger movement of the wrist and a bigger movement of the pen, resulting in a larger horizontal-oblique part of the signature. To demonstrate the difference of the length of the horizontal-oblique parts, the horizontal part in the second photo is drawn much longer (exaggerated) than in the first photo. The activated motor units are painted black, and the non-activated red. The activated motor units are painted black and drawn separately from the non-activated red, which is also a simplification for the purpose of illustrating the phenomenon, while in reality the fibres of the activated motor units are mingled with the non-activated ones.

So, the quasi-random motor unit recruitment of a muscle which performs a specific task has the result that every time the actual muscle movement is slightly different, although the CNS sends the order to the muscle to perform the same task. Thus, on each occasion the stroke is slightly different, and the corresponding line of the signature is different.

A remarkable example of the principle that if a person tries to repeat the same movement twice, then the two actions will never be identical is the phenomenon that even top basketball players do not succeed every time they perform a free shoot in the game.

Fig.6. Top basketball player Dwyane Wade shooting free throw.

Source
https://en.wikipedia.org/wiki/File:Dwyane_Wade_Shooting_Free_Throws_(2751838793).jpg

3.3 Reason no. 3: controllability of relevant muscles

The third reason is derived from neurology and neuroscience. Among the muscles used for handwriting, there are muscles of the forearm, the arm and the shoulder – which are less controlled by the motor cortex, as depicted in the “motor homunculus”. This is in contrast to the tasks of rice writing and SCNT, which are performed almost exclusively with the highly controllable muscles of the hand, called “intrinsic” hand muscles. A motor homunculus represents a map of brain areas dedicated to motor processing for different anatomical divisions of the body (Marieb 2007, Wikipedia: Cortical homunculus).

The primary motor cortex is located in the precentral gyrus and handles signals coming from the premotor area of the frontal lobes. Along the length of the primary motor cortex, the areas specializing in different parts of the body are arranged in an orderly manner, although ordered differently than one might expect. The toes are represented at the top of the cerebral hemisphere (or more accurately, "the upper end", since the cortex curls inwards and down at the top), and then as one moves down the hemisphere, progressively higher parts of the body are represented, assuming a body that is faceless and has its arms raised. Going further down the cortex, the different areas of the face are represented, in approximately top-to-bottom order, rather than bottom-to-top as before. The homunculus is split in half, with motor and sensory representations for the left side of the body on the right side of the brain, and vice versa. The amount of cortex devoted to any given body region is not proportional to that body region's surface area or volume, but rather to how richly innervated that region is. Areas of the body with more complex and/or more numerous sensory or motor connections are represented as larger in the homunculus, while those with less complex and/or less numerous connections are represented as smaller. The resulting image is that of a distorted human body, with disproportionately huge hands, lips, and face (Saladin 2007, Wikipedia: Cortical homunculus).

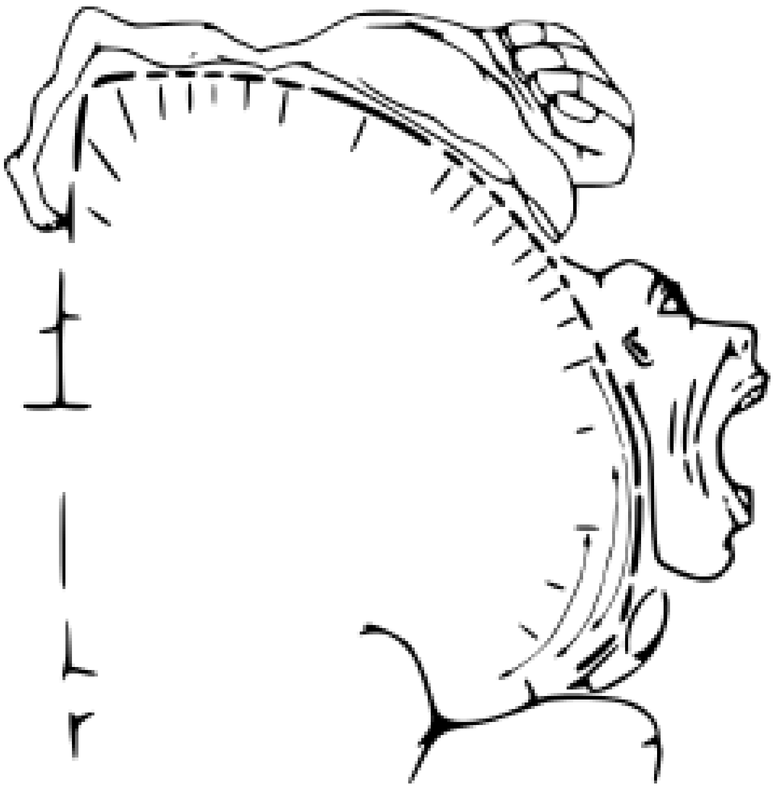

Figure 7. A 2-D cortical motor homunculus

Source: https://commons.wikimedia.org/wiki/File:Motor_homunculus.svg

As we see in Figure 7, the size of the motor cortex dedicated to the muscles of the hand is many times greater than that dedicated to all the other muscles of the upper limb, combined. Handwriting consists of a sequence of coordinated movements of the muscles of the hand and the forearm, but there is also a contribution of the muscles of the arm and the shoulder region: in total, forty-three muscles participate, to a greater or lesser degree, in the act of handwriting, as shown by electromyogram (EMG) studies (Derbel 2020: 71, Mahmoud 2020). For the tasks of rice writing and SCNT, the intrinsic muscles of the hand are the main muscles used, which are highly controllable, as a great proportion of the motor cortex is dedicated to these muscles.

So, this is the third of the main reasons why an individual cannot reproduce two identical signatures. Also, the component letters in the handwriting of an individual are similar but never coincide, for the same reasons. The degree of similarity of strokes in handwriting is not the same for all strokes. Teulings et al. found that:

> Downstrokes were more invariant than upstrokes in terms of vertical stroke size. However, contrary to the vertical stroke size, the horizontal stroke size was not invariant. Both vertical and horizontal sizes showed substantial between-stroke correlations. (Teulings et al. 1993)

We propose that the explanation for this inequality of similarity of strokes is based on the following:

a) The principal muscle generating horizontal strokes in handwriting is the extensor carpi ulnaris (ECU), a muscle of the forearm which shifts the right wrist so that the fingers bend toward the ulna bone. The ECU is controlled by a smaller area in the motor cortex than the intrinsic muscles of the hand, as shown in the “motor homunculus”. Downstrokes are generated mainly by muscles moving the thumb and the middle finger holding the pen, and secondarily by muscles moving the wrist. The muscles moving the fingers are more controllable, as they are controlled by a bigger area from the motor cortex, as depicted in the motor homunculus.

b) Among the muscles contributing to downstrokes are the flexors of the wrist and of the fingers, which are stronger, dominant and more controllable than the extensors. The above explanations are based on study of many relevant articles and books dedicated to anatomy and kinesiology of muscles (e.g., Kapandji 2010).

3.4 Reason no. 4: unique sequences of contracting muscles

The fourth reason is related to the specific anatomy and kinesiology of the muscles of the upper limb. The three previous reasons taken together mean that a person cannot perform two movements exactly alike. Thus, the question arises if that is sufficient for the non-reproducibility of a signature: maybe two signatures can be written identically by a person using different muscle movements of the upper limb. There is unanimous agreement that a person holding a pen (or pencil, etc.) has to move the muscles of his upper extremity in such a way that the produced signature or handwriting has the desired form. The issue is whether this can be done in different ways, or if there is a unique way of doing it. To the knowledge of the authors, there is no published scientific answer to this question to be found in FDE journals or books.

Study of relevant articles and books dedicated to the subject (e.g., Kapandji 2010), has led to the conclusion that there is a unique sequence of muscle movements required to produce a specific signature or handwriting. In a recent article, the first author, after having collaborated with the other two authors of this article, has proposed the hypothesis that a specific signature or handwriting is generated by an unique sequence of contracting muscles of the upper extremity; this is supported by recent research on the reconstruction of handwriting and other meaningful arm and hand movements from surface electromyography (sEMG) signals. Using computer algorithms, researchers solved the inverse problem – that is, deducing which specific letter or figure was written, by examining the recorded sEMG signals of the relevant muscles of the hand or forearm. Four facts lead to this conclusion: a) that the forearm rests on the table, b) that the pen is held in a “tripod” manner, c) that the tip of the pen (more generally, the tip of the medium used for writing) moves in a plane, and d) that the signature or handwriting must be produced by moving the pen along a specific trajectory, the same as followed by the other person. These four facts restrict the mobility of the upper extremity. Applying standard knowledge of the anatomy, physiology, and kinesiology of muscles and joints, the conclusion is that there is only one sequence of specific muscles contracting that can produce a particular signature or handwriting. Only rarely is there an equivalent sequence of muscle movements that can accomplish this task (Kipouras 2021).

Thus, genuine signatures produced by the same person, are produced by the same sequence of contracting muscles: on each occasion, the sequence of muscles is the same, but each time the parameters of contraction of every muscle are slightly different, so the signatures produced are similar but not identical. The four parameters of the contraction of a muscle are: the time span required for the muscle to obtain the desired length, measured from the initiation of the contraction; the strength of the contraction (based on how many muscle bundles contract); the duration of the contraction (the time interval that the muscle remains contracted); and the different length that the muscle acquires with each contraction. The length of the muscle may be reduced more or less by the corresponding contraction, which is voluntary (Hall 2010). So, the fourth reason why two genuine signatures are never identical is that there is a unique muscle sequence to produce a specific signature: since a person cannot repeat any muscle movement twice with the same parameters of contraction (as shown in 3.2, above), it is impossible to generate two genuine signatures that coincide completely.

4: Conclusions and discussion

The four reasons for the non-reproducibility of an identical signature by free-hand signing are the causes of the evident intra-personal variability of any individual’s signatures. To the best of the authors’ knowledge, these causes have not been described in scholarly publications on Forensic Document Examination (FDE). These four reasons make it impossible in practice for two signatures to coincide, as the estimated probability of two genuine signatures to be identical by chance is less than one in several millions (Hagan 1894: 91). Of course, there are other factors that can cause the intra-personal variability of the signatures – including illnesses, psychological factors affecting performance of hand movements, drugs, etc. These are well-known to FDEs. A common case, too, is when a person's natural signature dimensions do not fit into the small available space in a document (as on the back of credit cards) or electronic screen, so the person has to modify the signature.

The proposed hypothesis of a unique sequence of muscle movements required to produce a specific signature or handwriting can be viewed as a paradigm shift in Forensic Document Examination. In the latest textbooks of FDE, there are no chapters on the anatomy and kinesiology of muscles and joints of the upper extremity: even experienced FDEs are not well informed on this topic. The cause of this is probably the belief that without exception there are multiple ways, using different muscles, to perform manually the same task. Bernstein proposed in 1967 that there is "motor redundancy" of the hand, so that a hand can perform a motor task in multiple ways (Bernstein 1967). In an editorial of the journal *Motor Control* in 2000, Mark Latash wrote that "There is no motor redundancy in human movements. There is motor abundance (Latash 2000)." Still, according to Latash, there are many ways for a hand to perform a specific task. This is generally true, but not in the case of handwriting and producing a signature, because of the four restrictions mentioned above. This belief, of redundancy-abundance in human movements without exception, created for decades a bias in the study of handwriting, and only recently are there published articles for the specific muscles used in handwriting for specific letters and numbers.

So, given that two genuine signatures are never identical in practice, the question is what FDEs should do to verify that a questioned signature, or handwriting, is genuine. We suggest that, in addition to the examination for similarity of the shape of the questioned signature to the genuine signatures, the FDEs should do a kinesiology analysis of the signatures, analyzing which muscles have generated each part of the genuine and the questioned signatures.

Also, we propose a new test for the verification of authenticity of questioned signatures and/or handwriting – the "proprioception test". This test consists of holding a pencil in a "tripod" grip and following the trajectory of a photocopy of the questioned signature, and then doing the same for the genuine ones. In so doing, we can "feel", by proprioception, if the sequence of muscle contractions is different in the suspect case, compared to the genuine signatures. The ability of human proprioception of very fine movements is indisputably proved by the performance of very difficult tasks innumerable times worldwide (SCNT and rice writing), although there is an absence of experiments of proprioception, with the same degree of difficulty, in laboratories of experimental psychology in universities.

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