TEMPORAL FEATURES OF HANDWRITING: CHALLENGES FOR FORENSIC ANALYSIS

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Abstract. *This paper looks at handwriting as a multi-stage motor process which develops over time and leaves its time-bound marks in the writing trajectory. It explains some of the time-based research methodology and points out a number of 'dynamic' features with potential relevance for forensic application. The final sections of the paper contain suggestions for research leading to the re-establishment of temporal features in the static trace, which could support the handwriting expert's effort to decide on a document's authorship and on the circumstances at the time of writing. Some of these suggestions present challenges for prolonged interdisciplinary research co-operation.*

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1. Introduction

Over the past two decades, considerable progress has been made in the science and technology of handwriting. The scientific advances are related to the development of theoretical models of handwriting and the simulation of the human writing process by means of computers, in which aspects of these models are implemented. The technological advances include the development of hardware (especially digitizers) and computer software, which allow the human handwriting and drawing processes to be recorded and analysed. The latter development was literally instrumental to the former: modem recording and analysis facilities have given a huge impetus to the international community of behavioral and computational scientists studying the graphic tasks of writing and drawing. Among behavioural scientists, those focusing on motor control have shown the greatest interest and achieved the most notable results.

This paper presents some of these results. It concentrates on hand writing as a process, with orderly sub-processes which take place over time, within seconds and even fractions of seconds. The act of writing proceeds in time, not only in the movement sequence that actually leaves a permanent trace, but also in the preparatory stages and movements above the writing plane that precede the physical production of visible strokes, letters and words. We will show that a wealth of precise information is indeed available in the temporal aspects of the writing trajectory. We will also demonstrate that it is worthwhile, especially from a forensic point of view, to look into the time-based features of questioned documents, even if they are available only as finished products. The presence of pauses, hesitations, and particular speed distributions in a sample of writing may be of great significance in questioned document examination. In order to take advantage of the current knowledge about aspects of the time-bound process, and to find ways to re-establish the temporal features of the graphic marks on paper as they were generated in the questioned documents, it may be necessary to join forces across disciplines.

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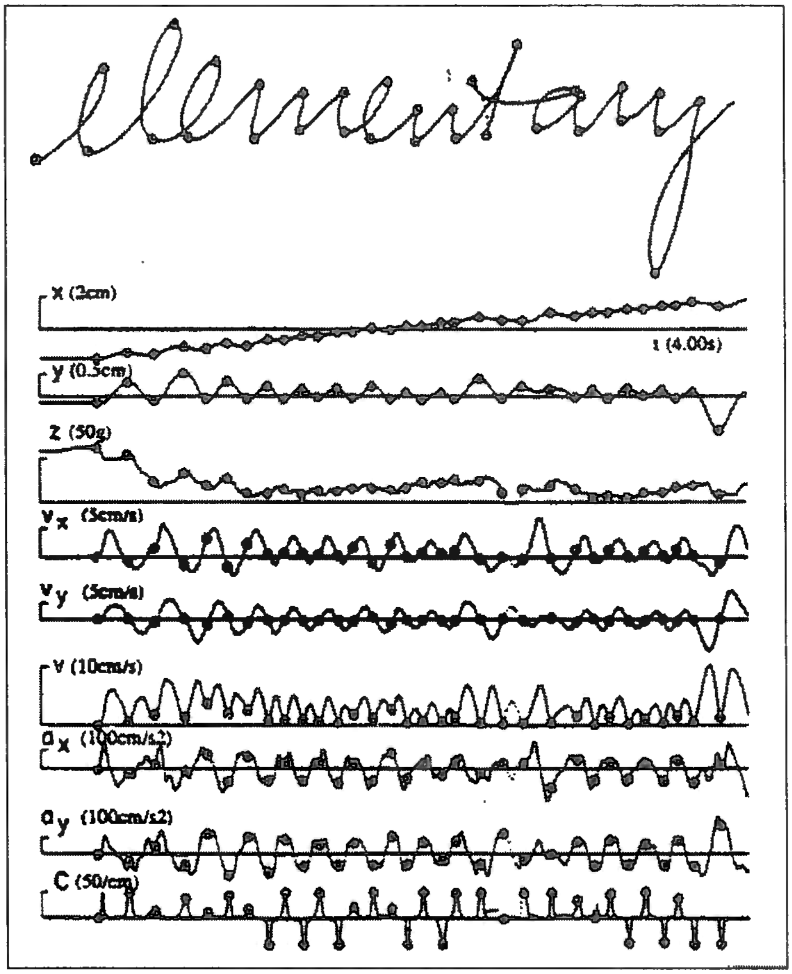

Figure l. Time functions of pen-point displacement (x,y), axial pen pressure (z), velocity (vx, vy, v), acceleration (ax, ay), and curvature (c). From Thomassen and Teulings (in press).

2. Handwriting analysis techniques

Before expanding on empirical results and theoretical claims we will outline the most representative, current technique for the analysis of graphic behavior which focuses on the movements of the pen point in and above the writing plane. The recording of these movements is in accord with the idea that the motor system organizes movements in terms of spatial trajectories in the writing plane rather than in joint space[3]. Commercially available digitizers are suitable for this purpose, although some adaptations may be required. A digitizer is a flat board which detects the pen position when it is in contact with the paper placed on its surface. The electronic pen is similar to a normal ball point pen of about average size. The writing trajectory is sampled at a high frequency (100 or more times per second, the position of the pen tip is determined, recorded and stored for computation and analysis) with great accuracy. The vertical projection of the pen point, when it is lifted above the writing plane, can also be recorded; accuracy here is slightly less, however. With a properly adapted pen, axial pen pressure can also be determined accurately with the same sampling frequency. The electronic handwriting signal, which contains the spatial and dynamic features of the moving pen, thus consists of a time series of planar coordinates (X,Y) and pressure estimates (Z), which are normally transmitted to the computer at frequencies of 100 to 200 Hz or more, with a spatial resolution of 0.025 cm or better.

The most relevant data, derived from the above coordinate values by means of special software, concern:

- Reaction time (RT= the length of the delay before the onset of writing following the instruction to start; this delay is sometimes called movement initiation time);
- Movement time (MT= the duration of the actual writing trajectory);
- Various velocity measures such as velocity in the horizontal and vertical directions (vX, vY), tangential, or absolute velocity (vabs), local velocity, peak velocity (vmax), and mean velocity;
- Dysfluency, or the number of velocity peaks per stroke;
- Acceleration and deceleration;
- Jerk, or the number of accelerations per unit time.

Of major importance also is:

- The occurrence of pauses between strokes, letters, and words.

Finally, a special analysis technique which involves the fine-grain characteristics of handwriting in the time domain[4] is concerned with

- The distribution of energy in the power spectrum (see below, Power spectral density functions).

These characteristics, illustrated in Figure 1, are derived from time functions sampled while the writing instrument is in the graphic plane (on paper). However, as stated above, relevant data are also obtained when the pen is above that plane. Other measures of great significance in handwriting research are:

- Trajectory length and size, or the horizontal and vertical extent of strokes, letters and words;
- Slant, or the inclination of strokes and letters;
- Slope, or the angle of the baseline of writing
- Local curvature, expressed as the radius of the current segment of a curve.

3. Reaction time, movement time, and processing stages

The human brain, with its 100 billion neurons, possesses an enormous capacity for the processing of information. Nevertheless, each mental action, whether it is perceiving an object, making a decision, or speaking a word, takes a measurable amount of time. An interesting fact that has been established by experimental psychologists is that the more aspects a task has that need to be performed, the longer it takes to prepare that task mentally. When asked to speak two given words following a “go” signal, for example, the human subject will take longer to start responding than when asked to speak just one word. Similarly, to name the colour of a green object takes longer than just to say the word “green”. The duration of the delay (RT or reaction time,) is an index of the amount of internal (mental, cognitive) processing. The systematic effects on RT are generally small, ranging roughly from only about 3 ms to 300 ms. This basic idea has been elaborated and widely exploited in human experimental psychology. It gave rise to a body of sophisticated experimentation in which the principal interest was in the duration of reaction times (RTs). This research has led to the assumption of a series of processing stages in the performance of all kinds of tasks, in the laboratory as well as in everyday life. Some stages have been assumed for sensory information processing, others for memory search and retrieval, and still others for recognition, response selection, and response execution.

This research design, which was initiated by Sternberg (1969), has also been applied to the area of graphic behaviour. It has helped us to identify the processing modules involved in the tasks of writing and drawing. These modules are responsible for the transformation and transmission of information in the cognitive system. Each module is dedicated to its special function. It operates at a specific stage in the processing sequence from perception to action, where it passes its product on to the next stage for further processing. The processing sequence may be as

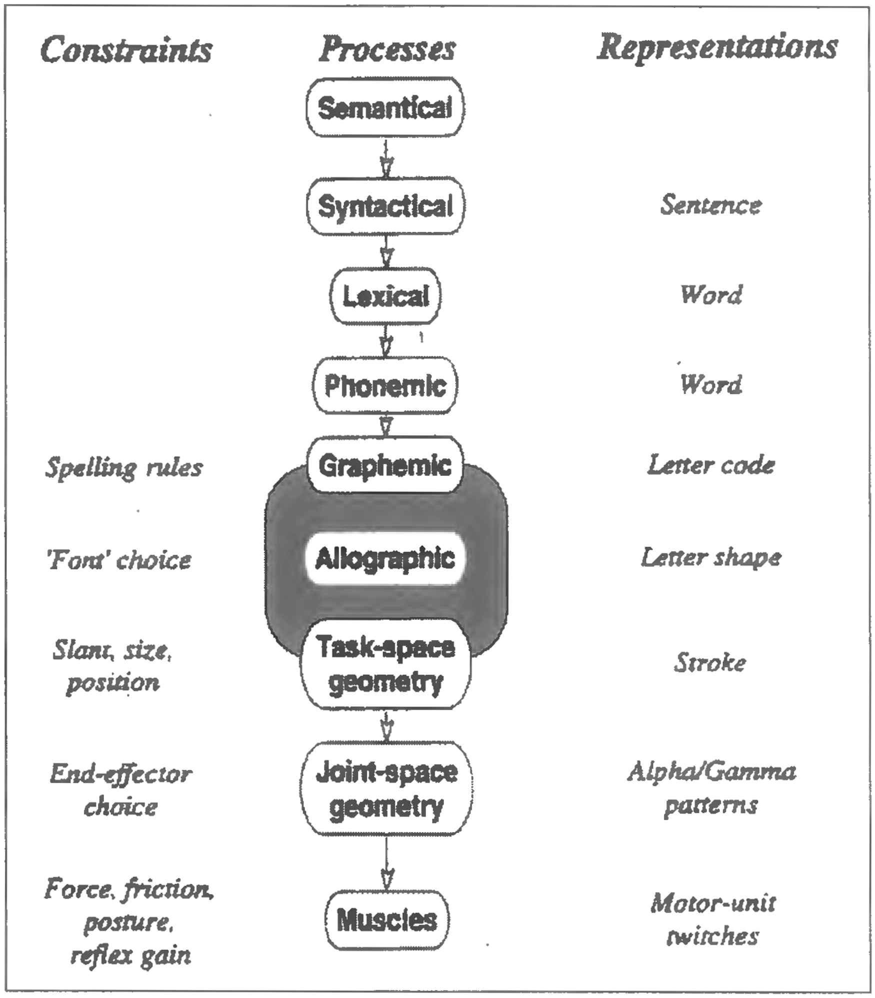

Figure 2. The modular model of handwriting, as proposed by Van Galen. The processing modules (central column) deal with representations (right-hand column) and are subject to various constraints (left-hand column). The dark area indicates the part of the processing chain on which the model focuses most. From Schomaker and Van Galen (1996).

depicted in Figure 2, which is taken from Schomaker and Van Galen. (1996). Together, the modules make up a fairly complete model of hand writing. In the strictest interpretation of the model, the processing modules in the central column perform their specific tasks exclusively in the serial order given, from top to bottom. The output of a module constitutes the input for the next-lower module. In a more lenient interpretation, certain internal and external conditions may call for a slightly different route.

The reaction-time (RT) design works well with relatively simple tasks of short duration such as pressing a button or speaking a word, where the whole performance can be prepared at once. In a relatively slow, complex, and longer-lasting task like handwriting, however, only the first part of the response sequence is likely to be prepared in advance, while later parts are prepared in parallel with the execution of the earlier parts. Due to the limited capacity of the information-processing system, however, such parallel activity results in competition with the current activity, that is to say, the production of writing movements. The effect is a slowing down of the pen in its trajectory, resulting in increased movement time (MT). This allows the use of an MT research model, introduced by Klapp and Wyatt (1976), which studies motor programming within a lengthy sequence of responses.

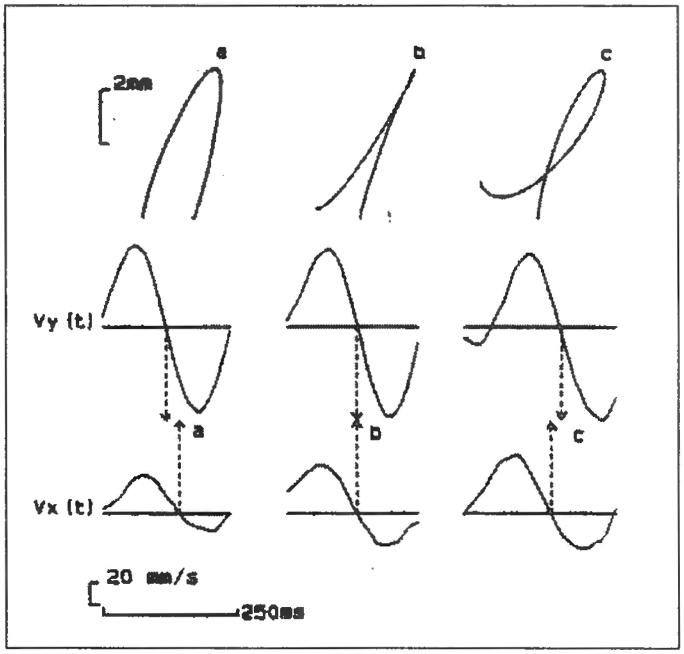

Figure 3. Three stroke pairs (a,b,c) with their relative timing in the velocity domain (vx, vy), resulting in differently shaped strokes and stroke endings. (Schomaker andvVan Galen (1996).

4. A modular model of handwriting

In this section we follow the macro-process of writing down a message, using the model proposed by Van Galen (1991; Thomassen & Van Galen, 1992; cf. Schomaker and Van Galen, 1996).

The message content is first conceptualised semantically, and then cast into a grammatical sentence frame. The elements of the precise phrasing, (the words), are found in the mental lexicon, from which they are given their implicit sounds (phonemic and phonetic features). Using the spelling rules of the language, the word's phonemes are translated into graphemes, which are abstract letter codes. Now their transformation to actual letter shapes or allographs, can take place.

Allographs are the specifications of graphemes in terms of their font (cursive, printed, etc.) and case (capital, upper and lower, etc.). They must be retrieved from an allographic long-term memory store where they are represented in a predominantly spatial format which includes the temporal sequence of their strokes. Therefore, if the sentence in the message is 'We look forward to your arrival", its first word is "we", and its first phoneme is /w/. The corresponding grapheme is <w>, and in this orthographic context the appropriate allograph to be retrieved is [cursive, capital W]. Before this letter can be written, specifications are required of the position where, and the size and slant at which it must be produced; this occurs in the next module. These specifications allow the selection of the best suited end-effector whose precise joint involvement depends on this spatial context. Finally, taking into account the required forces in the current mechanical (paper friction, writing stylus) and biomechanical (limb size and mass, viscosity, elasticity) context, the number of motor units which are needed can be recruited in the sequence dictated by the shape of the first stroke of the particular [W], which is then generated (Figure 3).

Inherent in the model is the fact that the modules at the subsequent processing stages deal with units of different size which tend to decrease as the sequence proceeds. The first module handles the content of an entire message, while the last module deals with the muscles involved in a single stroke. The output of one module, therefore, may constitute the input of several units to the next-lower module. This is one reason for the requirement of a buffer store at the entrance of each module. Another reason is that no matter how quickly and efficiently the modules perform their tasks, all of these sub-processes take time. Because the modules operate independently, they may deliver their products at inappropriate moments. As a result, they need to be put in short-term buffers for temporary storage, even if for a few milliseconds only.

Higher modules process their larger units of the written message earlier than lower modules deal with their smaller units, with the result that the former complete their task on a certain part of the message before the latter. This enables the higher modules to tackle the next part of the message sooner, so that at higher and higher levels, information is being processed further and further ahead of the part of the message that is currently being written. Application of this principle over all modules from high to low results in a system which processes information sequentially, but deals with different parts of the message in parallel at different levels (*ordered parallelism*).

Evidence for this architecture comes from experiments in which the difficulty of tasks at specific levels is increased. The rationale is that the effort spent on the manipulated, more difficult aspect of the task will require additional processing capacity. lbis is expected to result immediately in a retardation of the current movements, even if these movements have not yet reached the place where the increased difficulty occurs in the text. The results show that handwriting movements are affected (slowed down) earlier in time when the increased difficulty is associated with a higher-level module. An example is the introduction of difficulty at word level, which reduces writing speed earlier (before the difficult word is being written) than difficulty at allograph level, which leads to speed reduction only in one or two letters in advance. Difficulty at stroke level, finally, results in increased movement time merely of the current stroke itself (Van der Plaats & Van Galen, 1990).

In addition to these temporal effects, it should be noted that some spatial effects are evident as well, similarly caused by specific processing demands. For example, Van der Plaats, Van Galen, Thomassen, and Schomaker (in preparation) observed increased trajectory lengths and longer spacing distances (movements above the writing plane) in cases of processing difficulty. It appears that inter-word spaces and inter-letter connection strokes are located where spatio-temporal effects of further planning are likely to be found.

Following Schomaker and Van Galen (1996), three interrelated, central issues in handwriting research over the past period were concerned with:

- The kind and number of processing modules involved;
- The size of the basic units of handwriting; and
- The serial or parallel nature of the process.

The first issue resulted in an architecture like the one depicted in Figure 1. The second issue at first seemed to yield the allograph (rather than the word or the stroke) as the exclusive processing unit (feulings, Thomas sen, & Van Galen, 1983) . A more satisfactory conclusion, however, is that each level (processing stage) deals with units of the appropriate size (see above), and that the size of the unit can increase with practice (Hulstijn & Van Galen, 1988). The third issue was resolved in the way just indicated by assuming ordered parallelism.

5. Temporal constraints on the handwriting process

In the review of the above model, some temporal features of the handwriting process were discussed in global terms. It has become clear:

- that the advance preparation of a longer or more complex writing sequence leads to longer movement initiation times, or reaction times; and
- that the on-line preparation of further elements in the sequence leads to a local slowing-down of the pen displacement (increased movement time), where the location of the retardation is determined by the level of the processing module involved.

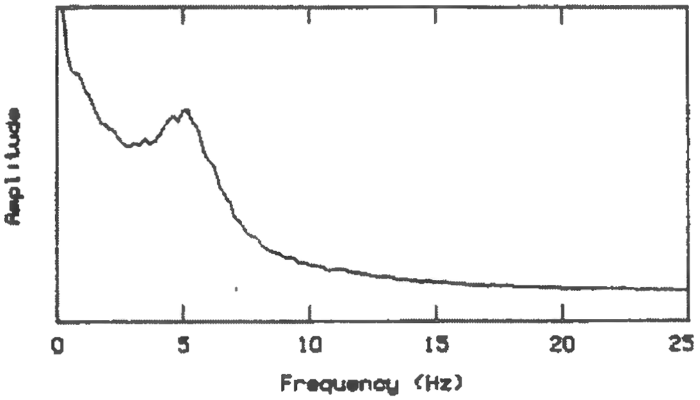

Figure 4. Average frequency spectrum of the velocity-time functions of a large sample of handwriting. From Teulings and Maarse (1984).

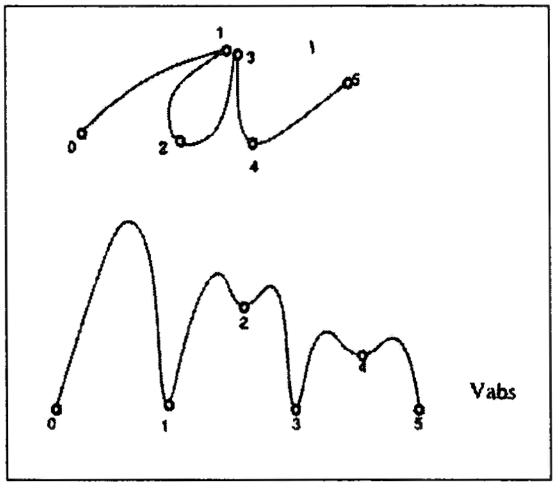

Figure 5. Strokes, defined as segments bounded by velocity inversions (vy), and characterised by a single velocity peak.

There are a number of additional time-based handwriting constraints which deserve mention. The smallest unit of handwriting is the stroke, which is normally defined as a writing segment bounded by inversions in its vertical velocity. Individual cursive letters of the Latin alphabet are composed of two to six such strokes, which are defined roughly as up strokes and downstrokes, and the letters are joined by additional connecting strokes, usually upstrokes. The typical duration of a stroke is 100 to 150 ms, so that on average about 8 strokes, or 2 letters, are produced per second in spontaneous script by an experienced, adult writer. Of course the actual rate depends on many factors such as the age, practice, development, and skill of the writer, and on text complexity, spelling difficulty, letter shape, and stroke sequence. If we regard the production of stroke pairs as a cyclical event, we observe a preferred cycle frequency of about 4 Hz. This is clearly reflected by Figure 4. An essential feature of stroke production is that it is normally generated by just one coordinated agonist-antagonist activation, resulting in a unimodal (single-peaked) bell-shaped velocity profile (Figure 5).

Related to these temporal constraints is the finding that-within a certain size range-a circle, regarded as a stroke pair, will take about 1/4 second to be completed. Consequently, it should take a fixed amount of time to produce a certain angular displacement along a curve, the rate being 4 x 360 degrees per second. This is known as the ‘isogony principle’ (Viviani & Terzuolo, 1980). It is in fact an extension of the more general ‘isochrony principle,’ which holds that the duration of the well-practised graphic production of a shape tends to be independent of its size. Given the above angular velocity, irrespective of size, one may conclude that the absolute, tangential velocity of the pen along a curved trajectory is directly proportional to the local radius of the curve. A general, very common finding which is of great significance in handwriting, is indeed that local (tangential) pen speed is much higher in parts of the trace with only shallow curves than in parts with tight curves (Figure 6).

More precise predictions of velocity and duration in handwriting can be made if we distinguish between macro-context (letter size of an entire word), meso-context (relative letter size within a word), and micro-context (local curvature within a stroke). Some of these predictions require too much detail for this purpose (see Thomassen & Teulings, 1985; Teulings, 1993). However, a general principle, operating at micro-context level, cannot be omitted here. It is an elaboration of the above relationship between pen speed and curvature. The principle holds that angular velocity is not exactly constant, but proportional to the curve radius-to-the-power 2/3. It is appropriately called the ‘two-third power law’ (Lacquaniti, Terzuolo, & Viviani, 1983). The law appears to hold fairly well for freely drawn, smoothly flowing ellipse-like curve sequences, but much less so for normal handwriting (Thomassen & Teulings, 1985).

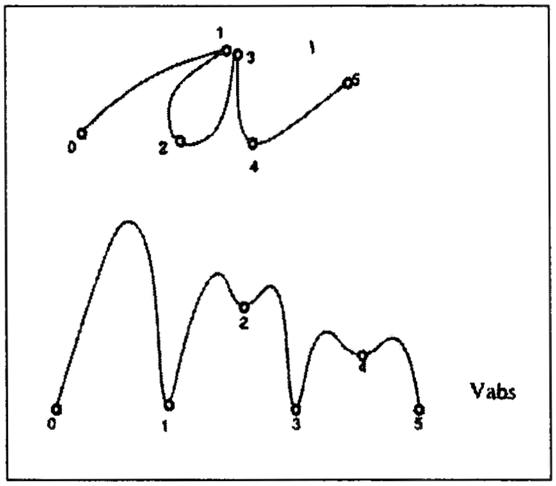

Figure 6. Relationship between local curvature and local pen speed (tangential, or absolute velocity).

6. Power-spectral density functions

As we saw above, the recorded writing signal may be regarded as having a cyclical form. This allows its analysis in terms of the frequencies of the components that together make up the signal. In this way we showed that the preferred frequency in adult handwriting is of the order of 4 Hz. In the frequency spectrum of the displacement signal, the band encompassing this value is clearly dominant, showing proportionally high energy or power. A further application of spectral analysis has recently been developed in the area of handwriting (Van Galen, Van Doorn, & Schomaker, 1990) in order to assess the level of noise in the handwriting signal. By providing estimates of the energy contained especially in the higher-frequency bands (up to 49 Hz; bandwidth 3 Hz) of the velocity signal, the analysis makes it possible to detect altered biomechanical features in the end effector (see footnote 5). The method involves the determination of a deviation spectrum, which is the frequency spectrum of the difference between the actual velocity signals and the average velocity signal of the same task. The resulting spectral density function reveals the noise components of the performance of the task. This spectral distribution can, in turn, be expressed as a proportion of the distribution of the total energy contained in the original function, resulting in the relative noise spectrum (Figure 7).

This procedure has been applied by Van Galen and Van Gemmert (1996; Van Gemmert & Van Galen, 1996) in the context of experimental forensic research. These authors observed not only some striking differences between normal writing and forged script in variables such as reaction time, movement time, fluency, and pen pressure, but also in increased energy in the higher-frequency bands of the spectrum. In earlier research by Van Gemmert and Van Galen (1994) the latter effect had been observed as well. It was concluded that in graphic movements under stress, subjects use a biomechanical strategy of enhanced limb stiffness to neutralise (filter out) the neuromotor noise effects induced by psychological and physical stress. The assumption by Van Galen and Van Gemmert (1996) is that forgery in handwriting imposes specific processing demands (stress) on the motor system. These demands are not necessarily reflected by the spatial features of the finished product, but are expected to become manifest in the kinematics and dynamics of the movements, that is to say in the time domain. Thus, on theoretical grounds these authors argue that simulating another person's writing should (apart from increased reaction times, movement times, dysfluencies, and pen pressure) result in similarly dynamic effects due to increased limb stiffness as a biomechanical factor affecting the end effector. In the power spectral density function of the velocity signal, the latter effects should once more appear in the form of increased relative energy in the higher-frequency bands of the velocity signal (see also Van Galen et al., 1990). And this is what Van Galen and Van Gemmert (1996) observed in their samples of forged writing.

7. Re-establishing temporal features in the static trace

In our overview, which focused on the writing process as evolving over time, we mentioned a number of time-based handwriting features. Although these were studied in an entirely different context, it appears to us that some of them have direct relevance for forensic analysis. For the handwriting expert, in his effort to verify the authenticity of a document, identify its author, or assess the circumstances under which the writing took place, it will often be essential to know whether a delay was involved in the continuation of a written passage, or at which speed a word or letter was produced. In certain cases it may indeed be possible to

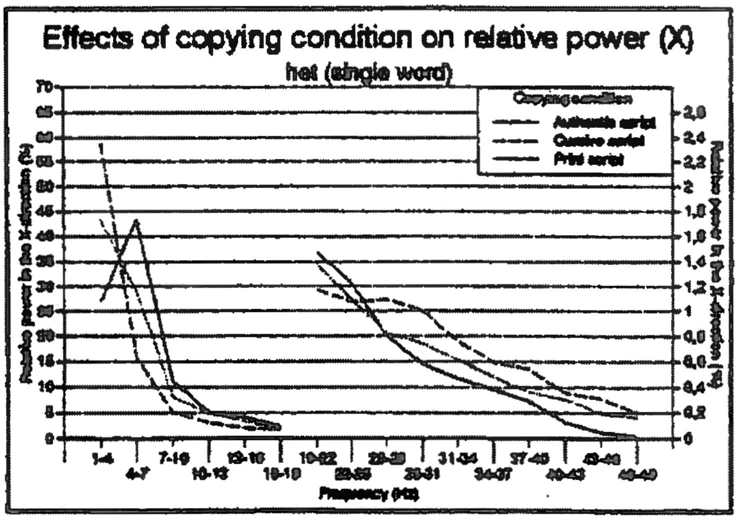

Figure 7. Relative power spectrum of the noise contained in hand written words under normal conditions (writing authentic script), and two conditions of forging (forging cursive and print script). Only the horizontal (X) dimension is depicted here. (Van Galen and Van Gemmert, 1996).

recover this ‘dynamic’ information by re-establishing some of the temporal aspects of the writing trajectory from the finished trace.

Our current understanding of the handwriting process, and in particular of the intrinsic relationships between its dynamic features and their static consequences in the handwriting trace, is considerable. It is, there fore, at least conceivable that in the future, dynamic features can be reconstructed for questioned documents that are available only as finished products. But obviously much more research is needed before this is possible. In this section, we would like to make some tentative suggestions in this respect. We realise that as laymen in the forensic area we may seem naive, or even amusingly simple. But for the sake of our common goal, which is to join forces to achieve improvements in handwriting expertise, we are prepared to run that risk.

In the psychological literature, at least one attempt to recover dynamic information from the static handwriting trace has been made. Evidence provided by Freyd (1987) indicates that subjects identify ambiguous graphic patterns according to the way in which they were produced. It appears that human recognition of static handwriting takes place by reference to the dynamics virtually contained in the strokes. Unfortunately, the judgments in Freyd’s task were based on stroke order and stroke direction only, and not on more detailed temporal information such as speed, which is our primary interest here.

Obviously, reaction time (RT) as a delay without overt action, is not reflected in the writing trace. With respect to movement time (MT), we noted that certain temporal effects due to experimental manipulation are really very small (a few milliseconds), so that it may be futile to attempt the recovery of these minimal time differences in the static trace. Other temporal effects, however, appear to vary with spatial effects, so that the trace itself may reflect delays or retardation, even though they may be short-lived. This is the case with larger-than-normal spacing, which was observed to result from ‘difficulties’ in the on-line preparation of further items in a sequence. Similarly, increased ‘ pen-down’ 6 trajectory length, and in particular extended connection strokes between letters, may reflect prolonged movement time due to hesitations of the same origin. These effects seem both worthwhile and feasible to follow up and to scrutinise in handwriting expertise.

Trajectories of the pen above the writing plane, which clearly reflect preparatory processes, do not leave any direct traces. But there may be an indirect way to detect them. In normal writing, these ‘pen-up’ movements are highly predictable; when difficulties arise, or when uncertainty or special planning is involved, these invisible trajectories are lengthened in the temporal area and they follow a longer and less predictable path in 3-D space. This should result in the pen landing on the writing plane in a different way and from a different direction than under normal writing conditions. Document examiners may find traces of such deviant 'approaches' in response to non-spontaneous writing conditions.

In the area of computer recognition, Boccignone, Chianese, Cordelia, and Marcelli (1993) developed a method to recover part of the lost script dynamics to assist the process of letter identification. Making use of 'good-continuation' criteria, it reconstructs the most likely trajectory followed by the writer by solving ambiguities at trace junctions and crossings. This may by itself be of significance from a scientific point of view, and useful in the off-line automatic recognition of cursive script. It seems of limited value, however, for our present purpose, certainly since the algorithm neither preserves the width of the strokes, nor determines their actual direction over time.

8. Perspectives and challenges for forensic research

This leads us to the contributions that may be expected from computer science. In many recognition algorithms, the essential information derived from the trace or the trajectory is the identity of the letters which convey the content of the message (what does it say?). Idiosyncratic or condition-specific information is therefore discarded as disturbing noise. Examples to achieve this are the algorithms for thinning the trace down to a skeleton of one pixel wide. In contrast, the aim in forensic analysis is to establish the identity of the writer (who wrote this?), and therefore its interest is to represent precisely these particular features. Here the entire trace needs to be preserved, including its variable width and the many shades of pigment (grey levels) characterising the ink marks on paper, as has been suggested by Doermann and Rosenfeld (1992).

Making these optical features available in digital form, and combining them—in perfect spatial alignment—with the digitized data from the microscopic inspection of the physical indentations in the paper layer, holds promise as the basis for a tool of the future for the sophisticated handwriting expert. Once the required preprocessing and analysis software, and possibly even hardware, for this hybrid combination has been developed, it will enable the expert to re-establish stroke order, stroke direction, pausing, retracing, hesitation, and (relative) speed.

In the above section, we made a few suggestions with respect to the re-instatement of movement dynamics in the static trace. We will now propose some further preliminaries as challenges for investigation in the near future.

In general terms, it would seem advisable to study the writing trace quantitatively and systematically under different speeds. It may appear that, given a certain writing instrument, ink, and paper, standards could be developed for the effects on the paper fibers as well as for the ink distribution, both as a function of speed. If and when they are produced under normal conditions, strokes (taking 100 to 150 ms for a length of 2 to 10 mm) should have the speed characteristics for a range of about l0 to 100 mm per second.

Even if such standards for absolute speed cannot be made available, it seems quite feasible to make relevant comparisons in the time area. One such comparison involves the ballistic nature of strokes. In normal script, each stroke has a single velocity peak, and the marks on and in the writing paper should reflect this speed distribution along the trace. Another relevant comparison could relate to the ink distribution and paper indentation on straight versus curved segments. The isogony principle and-to some extent-the two-third power law, predict relative speed as a function of curvature in spontaneous writing. If ink marks and paper indentation are in agreement with these relationships, the likelihood of uninhibited, spontaneous writing in the document is greater than if these relationships are violated.

Finally, we wish to point out that microscopic analysis may also reveal aspects of the power-spectral density distribution in the static trace. After all, the increased high-frequency oscillations were detected by the digitizer, so there is a chance that they can be made visible by microscopic inspection as well. What is needed here is insight into the mapping of the dynamics underlying the spectral data onto the static results on paper. Furthermore, a comparison baseline may be required for each individual writer under normal conditions. A potentially interesting research

Figure 8. Configuration of 17 infrared-light emitting diodes (IREDs) allowing the accurate recording and analysis of joint angles from elbow to finger tip, as well as of the pen point and its inclination. (Schillings, Meulenbroek, and Thomassen, 1996).

topic would be the investigation of oscillations in the moving pen held by the individual writer's hand. If such oscillations are relatively stable at known frequencies, and discernible not only in the global power spectrum but also in individual writing trajectories, the speed of the trajectory could be derived from the micro-oscillations in the spatial trace, where the waves of constant duration would then provide the time units.

We conclude this paper by pointing out a few areas in which insight may be obtained into the relationship between handwriting features in the finished product, and the transient circumstances under which the specimen of handwriting was produced, as well as the permanent characteristics of the writer. A key concept which has recently received considerable research attention in the handwriting context, is 'stress.' In the above paragraphs we saw several promising examples of research centered around this theme. Moreover, an earlier study which demonstrates the effect of personality characteristics (diagnosis DCD, or developmental coordination disorder) on the dynamic features (noisiness) of the writing trajectory and the spatial features of the writing trace (poor handwriting), was presented by Van Galen, Portier, Smits-Engelsman, and Schomaker (1993). These findings are placed in a theoretical perspective by Van Galen and his co-workers (Maarse & Van Galen, 1993; Van Gemmert and Van Galen, 1997). They propose a systematic description of the relationship between (a) psychological stress in its various forms, (b) the strategies which a writer may apply to adapt his or her movements biomechanically, and (c) the resulting spatio-temporal features of the trajectory in handwriting and other graphic performance.

Handwriting has traditionally been used as an indicator of intoxication and pharmacological and drug effects. The classic study by Watson (1919) on oxygen shortage at high altitude, clearly shows the effect on spatial handwriting features. Other early examples are the study by Hirsch, Jarvik, and Abramson (1956), who evaluated the effects of LSD-25 and six related drugs on handwriting, and the proposal by Legge, Steinberg, and Summerfield (1964) of handwriting as a measure of drug effects. More recently, and more in line with current graphonomic, (quantitative) leanings, Wing and Baddeley (1978) published a brief article in which they analysed off-line the way in which forms were filled out graphically, as a function of alcohol consumption. An overview, in the German language, of the effects of drugs and their interactions on spatial and temporal handwriting features has more recently been provided by Wildt (1989). Moreover, a review in English of about 40 journal articles reporting on the effects of a large variety of drugs on handwriting is available (Wellingham-Jones, 1991). In fact, handwriting is now justifiably regarded as a sensitive measure for the kind and dosage of medication, and computer analysis is being applied to monitor and to assist the prescription adjustment (e.g., Emmen, Kulig, & Sennef, 1993).

A different direction for future research in forensic aspects of handwriting concerns the relationship between the writer's anatomy, the writing process executed by it, and the resulting trace. Since anatomy is constant in adults, this approach may be of considerable value in forensic science. The relevance of the anatomy and biomechanics of the hand for the study of graphic behaviour is by no means a new idea (e.g. see An, 1991). However, although some preliminary results of such biomechanical measurement and modelling have been reported in a forensic context (Hardy, 1992; Hardy & Fagel, 1995), much of this area remains to be explored. But preliminary results are present in the study by Zhang and Macleod (1996). Their pen-hand model of writing movement is based on anatomical writer-dependent features which determine the three-dimensional (3-D) graphic geometry of the written product. Another example is the model by Lelivelt, Meulenbroek, and Thomassen (1996). This model predicts letter shape and size in part on the basis of the writer-specific features such as hand posture and the relative sizes of the limb segments. The application to handwriting of recent 3-D optical techniques (e.g., Optotrak) for recording and analysing the movements made by individual effector joints (Thomassen, Meulenbroek, Schillings, & Steenbergen, 1996; see Figure 8) will undoubtedly stimulate empirical and theoretical approaches along these lines.

It is becoming clear from the challenging suggestions outlined above, that in future the major developments in forensic handwriting expertise will largely depend on the concerted multi-disciplinary action of forensic scientists with physical engineers to dissect and scrutinise the document; with behavioral scientists, in particular from the area of human movement science, to model handwriting production from intention to stroke, taking anatomy, biomechanics, and physiology into account; and with computer scientists to develop algorithms for the storage, selection, and comparison of documents. The sooner such cooperation is accomplished, the greater are the chances for progress in this rich and important area of applied handwriting research.

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