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Size influence on shape of handwritten characters loops

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Abstract

In the practice of forensic handwriting experts, the size of the writing on a questioned document may be different from that of known samples. In this study, the hypothesis of shape invariance of handwritten closed loops across size increasing was tested. A Fourier methodology was applied to 2325 small letters (591 *a* loops, 547 *d* loops, 596 *o* loops and 591 *q* loops) and 692 enlarged letters (162 *a* loops, 173 *d* loops, 173 *o* loops and 184 *q* loops), in a population of 13 writers who were asked to write letters in their usual size and about three times larger. Most of the writers presented similar modifications when increasing the size of the loops; they produced enlarged loops significantly more round and less slanted towards the right or the left. Furthermore, a discrimination was demonstrated between the writers on the basis of the enlarged loops, with a correct classification rate superior to 90%, whatever the letter (*a*, *d*, *o* or *q*). A classification of the enlarged loops in their corresponding writer was then possible. On the contrary, when comparing the enlarged loops to the small ones, almost one half of the enlarged loops were allocated to a wrong writer. Shape invariance was thus not supported for this particular application. Consequently, when comparing documents with a different writing size, differences in loops shape should be interpreted cautiously because they may be due to a different writer, but they may also be due to an enlargement of the loops. Therefore, reference material of similar writing size to that of the questioned writing should be requested for the comparison of handwritten loops.

Keywords: Handwriting; Shape analysis; Discriminant analysis; Size; Fourier descriptors

1. Introduction

In the practice of forensic handwriting examiners, the size of the writing on a questioned document may be different from that of known samples. This difference in size can be explained by a difference in surface available on the support, or by a disguise purpose; the author can modify the size of his handwriting in order to make believe that someone else wrote his text. The point consists then to determine whether handwriting samples of the same person that notably differ in size show an invariance of their features.

Several researches have been conducted to test the hypothesis of spatial invariance of handwriting features across size ranges [1–3]. These studies provided quantitative information supporting the assumption of a space invariance of some handwriting features, and demonstrated that variation of other features were proportional to the variation of the writing size, and increasing the size of the writing generally implied greater changes in measurements of the vertical parameters than of the horizontal ones. Furthermore, the characteristics proven to be not invariant could vary differently according to the writers. All these studies were based on metric characteristics. Hereafter, based on a Fourier methodology [4], it is intended to test the assumption of the shape invariance of the loops of handwritten characters when size is increased.

- In a first step, the shape between small and enlarged loops of letters *a*, *d*, *o* and *q* will be compared to determine if a global difference can be shown for each letter and each writer, in a population of writers;
- then, the various aspects of the shape which are represented by the first four pairs of Fourier descriptors [5] will be tested separately to show the ones which remain constant across change in size;
- finally, after testing if discrimination between writers is possible through analysis of enlarged loops, it will be

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investigated if the enlarged and the small loops of one specific letter can be treated together when comparing handwritten documents of the same person.

2. Material and methods

2.1. Sampling

On each one of five documents (see [5]), 13 individuals – those showing closed loops among a larger population of writers – were asked to write 10 times a series of alphabet letters in their usual way, and 3 times by increasing the size of their usual writing by a factor three. The total number of observations was 2325 for the small loops (591 *a* loops, 547 *d* loops, 596 *o* loops and 591 *q* loops) and 692 for the enlarged loops (162 *a* loops, 173 *d* loops, 173 *o* loops and 184 *q* loops). Note small refers to the usual writing size of a writer.

2.2. Features extraction

Calculation of the surface enclosed in the loops, extraction of the skeletons of the handwritten loops, as well as size normalization of these skeletons and Fourier analysis of their shape, were carried out according to the methodology described in detail in [4,5]. Each contour (i.e. the skeleton) was characterized by the first four Fourier harmonics [4], each harmonic being mainly described by two parameters: amplitude and phase. The first harmonic is the ovate contribution to the shape, the second one is its elliptic contribution, the third one is its triangular contribution, and the fourth one is its quadrangular contribution. Amplitude is the importance of the contribution to the original shape of the contour, and phase represents the orientation of the contribution [4].

2.3. Statistical analysis

The statistical analysis was performed by using SPSS® 12 (SPSS Inc.). A multivariate analysis of variance (MANOVA) was applied to each writer and each letter, to see if there was a difference in means of populations of small and enlarged loops. By doing so, the influence of the size on the shape parameters of the loops could be tested. These multivariate analyses were completed by univariate comparisons based on the Mann–Whitney *U*-test (nonparametric) on each variable (on each writer and on each letter) to determine which aspects of the shape of loops were modified when increasing the size of the loops.

Quadratic discriminant analyses were carried out on the enlarged loops of all the writers, considering all the letters separately and all together, in order to see if discrimination between the writers was possible with the enlarged loops. Then, a classification of the enlarged loops in the groups established on the basis of the small loops was undertaken, in order to see if enlarged and small letters could be considered to form a unique group for each writer.

3. Results

The statistics of the surface and the Fourier descriptors (amplitudes and phases) of the enlarged handwritten characters

Table 1
Surface and Fourier analysis of the enlarged handwritten loops *a* of the writers W1–W13: summary statistics[a] (Stat.) of the surface and the first four Fourier amplitudes (A_1–A_4) and phases (θ_1–θ_4)[b]

Writer	Stat.	Surface	A_1	A_2	A_3	A_4	θ_1	θ_2	θ_3	θ_4
W1	$\bar{X}$	0.17	0.15	1.06	0.26	0.23	342.92	76.58	111.42	74.10
	S.D.	0.05	0.05	0.32	0.12	0.14	14.50	9.94	12.24	16.21
W2	$\bar{X}$	0.17	0.08	0.56	0.25	0.09	354.15	75.07	102.66	63.86
	S.D.	0.04	0.02	0.16	0.07	0.05	12.79	16.54	8.77	17.94
W3	$\bar{X}$	0.10	0.06	0.80	0.25	0.15	278.98	77.75	75.11	61.80
	S.D.	0.02	0.04	0.39	0.16	0.06	61.86	18.68	9.45	19.57
W4	$\bar{X}$	0.30	0.07	1.34	0.21	0.25	347.89	74.97	132.30	76.81
	S.D.	0.12	0.05	0.29	0.12	0.10	49.44	7.66	16.61	9.20
W5	$\bar{X}$	0.14	0.05	1.88	0.17	0.49	291.40	52.39	139.59	51.93
	S.D.	0.03	0.03	0.13	0.06	0.10	101.28	6.58	15.40	6.01
W6	$\bar{X}$	0.14	0.09	2.06	0.12	0.63	360.50	68.45	117.51	69.15
	S.D.	0.05	0.05	0.25	0.08	0.14	23.87	4.98	19.34	3.64
W7	$\bar{X}$	0.19	0.07	1.84	0.11	0.45	276.27	59.71	127.08	59.95
	S.D.	0.06	0.02	0.21	0.06	0.13	54.57	4.99	22.17	4.52
W8	$\bar{X}$	0.23	0.05	1.65	0.17	0.47	357.30	60.29	136.53	61.70
	S.D.	0.05	0.04	0.18	0.10	0.05	74.13	4.51	10.51	3.64
W9	$\bar{X}$	0.20	0.03	0.74	0.27	0.16	225.48	75.05	74.60	56.23
	S.D.	0.03	0.03	0.31	0.09	0.05	49.72	8.34	5.29	5.35
W10	$\bar{X}$	0.63	0.06	1.44	0.17	0.24	354.51	82.71	104.09	79.78
	S.D.	0.21	0.04	0.26	0.09	0.09	70.10	6.15	23.78	7.68
W11	$\bar{X}$	0.41	0.06	0.76	0.13	0.10	351.41	39.39	88.68	37.71
	S.D.	0.14	0.02	0.24	0.10	0.06	24.51	14.57	21.50	22.68
W12	$\bar{X}$	0.07	0.15	1.78	0.21	0.49	358.20	73.31	109.94	70.34
	S.D.	0.01	0.04	0.20	0.08	0.05	27.39	7.20	14.60	4.87
W13	$\bar{X}$	0.04	0.09	1.62	0.15	0.39	348.69	78.72	127.86	79.84
	S.D.	0.01	0.04	0.16	0.07	0.09	29.74	5.26	24.16	5.58

[a] $\bar{X}$, mean; S.D., standard deviation.
[b] Surface is given in cm^2 and phases are given in degrees.

a, *d*, *o* and *q* contours of each writer are summarized in Tables 1–4 (these statistics are given in [5] for the small loops). Since importance of enlargement could not be controlled, all the writers did not produced enlarged loops with a same increasing factor; on average, all letters and writers together, the ratio of surface between the enlarged and small loops amounted to 3.48 (Table 5), in reference to the surface values of the small loops given in [5].

3.1. Comparison of the shape between small and enlarged loops

The MANOVAs applied on the groups of small and enlarged loops on each writer showed there was a significant difference in the shape parameters of the loops among most of the writers, whatever the letter (*a*, *d*, *o* or *q*), according to the Hotelling's Trace at $p < 0.05$. The shape of letter *a* was significantly modified in every writer. Writers W1, W2, W10 and W12 did not present a significant modification for the letter *d*. Absence of significant modification was most frequently noted in letter *o*; that was the case in writers W3, W5, W7, W9, W10 and W13. Finally, the shape of the loops of the letter *q* was significantly modified in every writer, except in writer W1 (Table 6).

Importance of difference between small and enlarged letters, i.e. of size influence, was depending on the writer and on the letter, according to the values of the Hotelling's Trace. For instance, this influence was highly marked for the four letters *a*, *d*, *o* and *q* in writer W6 and for letters *a*, *d* and *q* in writer W7, as demonstrated by the large values of the Hotelling's Trace for these sets (Table 6).

Univariate analyses by Mann–Whitney *U*-tests provided results showing main trends when the size of the loops increases. When differences in shape parameters between small and enlarged letters were statistically significant (at $p < 0.05$), a reduction of the amplitudes values was often observed. This means that the shape of the enlarged loops was often less ovate, elongated, triangular and quadrangular compared to the small loops. An increase in the phase values was also observed with the enlarged loops, particularly for the second and fourth phases. The main orientation of these aspects of shape was therefore closer to the axis perpendicular to the writing line, i.e. more vertical (Fig. 1).

The general abovementioned trends were not present in every writer. Some of them showed different kinds of modifications, sometimes only for one letter, or for such and

Table 2
Surface and Fourier analysis of the enlarged handwritten loops *d* of the writers W1–W13: summary statistics[a] (Stat.) of the surface and the first four Fourier amplitudes (A_1–A_4) and phases (θ_1–θ_4)[b]

Writer	Stat.	Surface	A_1	A_2	A_3	A_4	θ_1	θ_2	θ_3	θ_4
W1	$\bar{X}$	0.12	0.14	0.90	0.28	0.21	351.72	67.77	110.77	76.98
	S.D.	0.04	0.04	0.46	0.13	0.11	12.77	17.91	8.98	15.80
W2	$\bar{X}$	0.14	0.08	0.27	0.35	0.12	368.53	105.69	107.71	82.66
	S.D.	0.02	0.03	0.16	0.10	0.05	23.65	40.80	7.51	16.75
W3	$\bar{X}$	0.06	0.10	0.69	0.26	0.15	296.86	35.41	131.38	99.60
	S.D.	0.01	0.03	0.22	0.09	0.07	32.95	32.61	18.21	15.17
W4	$\bar{X}$	0.16	0.11	1.75	0.28	0.30	408.66	71.25	139.62	75.80
	S.D.	0.08	0.04	0.36	0.07	0.14	42.72	3.78	6.27	9.06
W5	$\bar{X}$	0.12	0.07	1.87	0.27	0.46	268.70	52.15	137.40	50.34
	S.D.	0.02	0.04	0.19	0.07	0.13	103.12	5.28	6.74	5.28
W6	$\bar{X}$	0.10	0.10	1.83	0.26	0.38	391.78	61.27	133.97	64.24
	S.D.	0.03	0.04	0.46	0.07	0.24	30.77	5.16	7.27	7.77
W7	$\bar{X}$	0.08	0.07	2.37	0.22	0.73	325.29	54.57	136.37	53.86
	S.D.	0.02	0.05	0.31	0.05	0.20	98.07	3.88	8.90	4.54
W8	$\bar{X}$	0.10	0.08	2.00	0.30	0.46	447.99	56.63	140.43	56.67
	S.D.	0.01	0.04	0.33	0.09	0.17	58.02	3.45	6.02	5.19
W9	$\bar{X}$	0.17	0.05	0.49	0.15	0.08	298.76	75.88	67.97	33.80
	S.D.	0.02	0.02	0.24	0.06	0.03	39.36	19.89	31.61	27.85
W10	$\bar{X}$	0.41	0.04	0.80	0.18	0.16	382.59	74.56	89.25	60.69
	S.D.	0.15	0.02	0.19	0.09	0.07	84.46	10.19	18.72	13.99
W11	$\bar{X}$	0.30	0.10	1.24	0.27	0.24	417.02	5.81	78.15	70.60
	S.D.	0.08	0.05	0.33	0.10	0.08	66.16	15.52	22.30	21.40
W12	$\bar{X}$	0.05	0.11	1.23	0.34	0.21	356.80	66.00	126.81	75.89
	S.D.	0.01	0.05	0.26	0.11	0.12	26.02	7.00	12.00	14.78
W13	$\bar{X}$	0.03	0.06	1.83	0.26	0.38	275.00	66.39	151.06	67.90
	S.D.	0.01	0.03	0.34	0.08	0.15	73.29	6.28	7.85	10.00

[a] $\bar{X}$, mean; S.D., standard deviation.
[b] Surface is given in cm^2 and phases are given in degrees.

Table 3
Surface and Fourier analysis of the enlarged handwritten loops *o* of the writers W1 to W13: summary statistics[a] (Stat.) of the surface and the first four Fourier amplitudes (A_1–A_4) and phases (θ_1–θ_4)[b]

Writer	Stat.	Surface	A_1	A_2	A_3	A_4	θ_1	θ_2	θ_3	θ_4
W1	$\bar{X}$	0.15	0.12	0.99	0.30	0.22	339.54	63.54	96.72	76.43
	S.D.	0.03	0.04	0.35	0.14	0.08	24.84	9.70	10.08	15.84
W2	$\bar{X}$	0.19	0.06	0.47	0.31	0.12	367.51	27.72	92.21	87.52
	S.D.	0.03	0.03	0.28	0.15	0.05	60.07	37.64	10.33	20.49
W3	$\bar{X}$	0.07	0.05	0.55	0.33	0.17	306.41	134.06	90.50	82.90
	S.D.	0.02	0.03	0.26	0.15	0.08	74.12	30.18	21.86	22.55
W4	$\bar{X}$	0.34	0.09	1.27	0.14	0.24	338.61	75.42	122.94	72.00
	S.D.	0.11	0.03	0.33	0.06	0.11	21.65	7.59	18.74	8.98
W5	$\bar{X}$	0.16	0.07	1.17	0.11	0.28	287.16	59.48	116.10	57.25
	S.D.	0.03	0.02	0.25	0.04	0.10	36.60	7.71	37.41	6.16
W6	$\bar{X}$	0.15	0.08	1.20	0.14	0.27	343.06	76.63	106.31	75.80
	S.D.	0.06	0.03	0.23	0.10	0.07	16.75	7.80	22.80	5.35
W7	$\bar{X}$	0.13	0.14	1.75	0.22	0.41	338.86	57.64	97.89	59.75
	S.D.	0.03	0.05	0.29	0.06	0.14	23.90	5.59	5.87	6.42
W8	$\bar{X}$	0.16	0.11	1.20	0.20	0.24	350.59	75.05	118.96	76.71
	S.D.	0.03	0.05	0.31	0.10	0.12	16.27	7.11	18.16	6.75
W9	$\bar{X}$	0.18	0.04	0.39	0.20	0.09	285.28	98.19	58.21	58.89
	S.D.	0.03	0.02	0.32	0.14	0.06	73.42	36.42	30.39	18.92
W10	$\bar{X}$	0.29	0.09	1.04	0.20	0.15	347.37	80.25	106.15	74.36
	S.D.	0.07	0.03	0.19	0.07	0.07	17.88	10.62	15.61	16.27
W11	$\bar{X}$	0.32	0.07	0.51	0.23	0.11	369.25	40.41	102.53	110.25
	S.D.	0.08	0.02	0.28	0.09	0.04	17.15	24.88	9.24	19.77
W12	$\bar{X}$	0.09	0.09	0.80	0.14	0.15	351.63	49.61	122.07	58.66
	S.D.	0.02	0.03	0.32	0.09	0.08	15.88	12.70	18.65	16.84
W13	$\bar{X}$	0.05	0.08	0.87	0.17	0.16	309.59	83.79	102.74	85.59
	S.D.	0.01	0.03	0.30	0.09	0.09	24.81	11.30	29.22	17.56

[a] $\bar{X}$, mean; S.D., standard deviation.
[b] Surface is given in cm^2 and phases are given in degrees.

such variable. These peculiarities will be described below for amplitudes first, then for phases.

The second amplitude of the loops of every letter of writer W10 was significantly higher for the enlarged loops than for the small ones; this means that increasing the surface of the loops was accompanied in this writer by an increase in their elongation (see an example of letter *a* in Fig. 2). The same kind of modification was observed in writer W9; in a significant way for the letter *q* only. Writers W6 and W13 presented enlarged loops with a higher fourth amplitude compared to that of the small letters; i.e. quadrangularity of their enlarged loops was more important. Lastly, writer W4 produced enlarged loops with higher second and fourth amplitudes and with lower first and third amplitudes than the respective amplitudes of the small letters.

The phase of the first harmonic was sometimes decreased when increasing the size of the loops. This phenomenon was particularly pronounced in writer W5, and was also present in writers W6, W7, W9 and W11. In writer W9 (Fig. 3), a significant reduction was revealed in the values of the second and the third phases of the loops of the letter *o*. This writer was greatly distinguished from the other writers, since his changes in Fourier descriptors were clearly different from the tendencies encountered in other writers.

3.2. Discrimination between the writers from the enlarged loops

The discriminant analysis performed on the Fourier descriptors of the loops of letters *a*, *d*, *o* and *q* showed that the most discriminating shape features for the examination of enlarged loops were the same ones as those highlighted through the analysis of small loops [5], namely the amplitude of the second harmonic and the phase of the second and the fourth harmonics.

The correct classification rates of the enlarged loops amounted to 96.3% for letter *a*, 97.1% for letter *d*, 92.5% for letter *o* and 94% for letter *q*. This rate amounted to 64% when all the letters were considered simultaneously. When comparing these results with those obtained on the basis of the small letters (74.8% for letter *a*, 82.4% for letter *d*, 69.7% for letter *o* and 81.4% for letter *q*, see [5]), letter *d* still provided the

Table 4
Surface and Fourier analysis of the enlarged handwritten loops *q* of the writers W1–W13: summary statistics[a] (Stat.) of the surface and the first four Fourier amplitudes (A_1–A_4) and phases (θ_1–θ_4)[b]

Writer	Stat.	Surface	A_1	A_2	A_3	A_4	θ_1	θ_2	θ_3	θ_4
W1	$\bar{X}$	0.09	0.12	1.08	0.29	0.21	340.93	64.03	98.20	64.03
	S.D.	0.02	0.06	0.44	0.12	0.10	24.34	9.81	13.30	9.59
W2	$\bar{X}$	0.13	0.07	0.44	0.25	0.11	397.55	37.85	101.65	66.55
	S.D.	0.02	0.02	0.22	0.11	0.07	48.49	43.83	12.45	24.24
W3	$\bar{X}$	0.06	0.05	0.66	0.25	0.14	322.03	72.74	72.05	42.15
	S.D.	0.01	0.03	0.30	0.10	0.06	93.75	34.22	18.99	27.09
W4	$\bar{X}$	0.16	0.07	1.66	0.19	0.42	327.32	59.63	103.24	59.56
	S.D.	0.08	0.04	0.35	0.12	0.16	55.84	12.19	28.33	12.54
W5	$\bar{X}$	0.11	0.03	1.34	0.12	0.33	303.01	37.83	124.19	40.14
	S.D.	0.02	0.02	0.24	0.07	0.10	58.86	6.16	27.35	5.77
W6	$\bar{X}$	0.09	0.09	1.44	0.24	0.26	370.14	50.41	112.55	54.73
	S.D.	0.03	0.03	0.33	0.08	0.10	24.16	12.26	12.89	14.99
W7	$\bar{X}$	0.08	0.07	2.04	0.19	0.53	351.90	45.60	114.12	46.54
	S.D.	0.02	0.03	0.29	0.07	0.20	69.05	4.45	16.59	5.61
W8	$\bar{X}$	0.10	0.12	1.95	0.35	0.43	415.47	52.66	129.42	53.35
	S.D.	0.04	0.05	0.30	0.08	0.16	42.99	6.60	7.63	8.61
W9	$\bar{X}$	0.14	0.05	0.72	0.19	0.14	290.61	69.69	55.45	39.70
	S.D.	0.02	0.02	0.28	0.13	0.07	85.49	10.11	22.33	18.71
W10	$\bar{X}$	0.25	0.06	1.18	0.16	0.14	315.55	78.68	89.02	76.08
	S.D.	0.07	0.03	0.23	0.10	0.09	54.43	8.92	18.46	10.52
W11	$\bar{X}$	0.21	0.06	0.94	0.16	0.16	331.58	27.30	57.23	120.36
	S.D.	0.06	0.02	0.39	0.08	0.08	38.13	8.44	23.50	12.14
W12	$\bar{X}$	0.06	0.21	1.88	0.32	0.59	365.26	66.63	105.46	65.31
	S.D.	0.01	0.04	0.16	0.13	0.09	9.59	5.21	11.67	5.07
W13	$\bar{X}$	0.03	0.11	1.29	0.26	0.26	349.40	63.50	115.60	74.67
	S.D.	0.01	0.03	0.43	0.11	0.15	27.53	12.25	25.71	14.12

[a] $\bar{X}$, mean; S.D., standard deviation.
[b] Surface is given in cm^2 and phases are given in degrees.

best classification score and letter *o* still was that which provided the worse results. On the other hand, the letter *a* gave slightly better results than the letter *q* with enlarged loops.

3.3. Classification of the enlarged loops in the small loops groups

Discriminant functions were established on the basis of small loops to discriminate between the 13 writers, and we applied these functions to the enlarged loops to try to classify them correctly. In this case, the correct classification rates were low; practically one half of the enlarged loops were incorrectly classified: 51.2% for letter *a*, 56.6% for letter *d*, 44.4% for letter *o*, 43.4% for letter *q* and finally 43.4% for the simultaneous combination of letters *a*, *d*, *o* and *q*.

Furthermore, whatever the letter, the writer W6 presented the greatest proportion of misclassifications (Table 7). This writer was also that presenting the most manifest changes in shape of the loops when increasing their size (see the highest value of Hotelling's Trace value in Table 6, when considering all the letters simultaneously). Besides, the writers showing atypical shape modifications when increasing the size were not inevitably those whom error rates were the largest (such as writers W9 and W10).

Note, the effect of a different size among small and enlarged loops has been tested by drawing random samples of small loops in order to compare samples of the same size between small and enlarged loops. Results, either for MANOVAs and discriminant analyses reported on this section, did not show relevant differences.

Table 5
Surface ratio between small and enlarged loops for each writer, in considering all the letters *a*, *d*, *o* and *q*, simultaneously

Writer	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13
Surface ratio	2.39	2.29	1.75	4.26	3.46	4.26	5.13	6.12	3.07	3.21	4.30	2.77	2.29

Table 6
Measure of size influence on shape of loops in each writer: Hotelling's Trace (Hot.) and signification (Sig.[1]) values for the comparison between the first four pairs of Fourier descriptors (A_1–A_4 and θ_1–θ_4) of small and enlarged loops of letters *a*, *d*, *o* and *q* considered separately and all together

Writer	*a*		*d*		*o*		*q*		*adoq*	
	Hot.	Sig.	Hot.	Sig.	Hot.	Sig.	Hot.	Sig.	Hot.	Sig.
W1	0.516	**	0.216	n.s.	0.516	**	0.315	n.s.	0.207	***
W2	0.503	**	0.138	n.s.	0.361	*	0.860	***	0.088	**
W3	0.741	***	2.277	***	0.316	n.s.	0.596	**	0.323	***
W4	0.632	**	0.620	***	0.434	*	0.470	*	0.166	***
W5	0.810	***	0.796	**	0.210	n.s.	0.551	***	0.154	***
W6	1.714	***	3.517	***	1.248	***	1.032	***	0.707	***
W7	2.738	***	1.043	**	0.150	n.s.	1.356	***	0.288	***
W8	0.996	***	1.408	***	1.035	***	1.785	***	0.476	***
W9	0.461	**	1.132	***	0.222	n.s.	0.366	*	0.124	***
W10	0.380	*	0.294	n.s.	0.253	n.s.	0.376	*	0.146	***
W11	0.542	***	1.087	***	2.151	***	1.071	***	0.376	***
W12	0.747	**	0.119	n.s.	0.577	**	0.955	***	0.210	***
W13	0.630	***	0.523	**	0.111	n.s.	0.475	**	0.160	***

[1]n.s.: $p > 0.05$ (i.e. non significant).
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

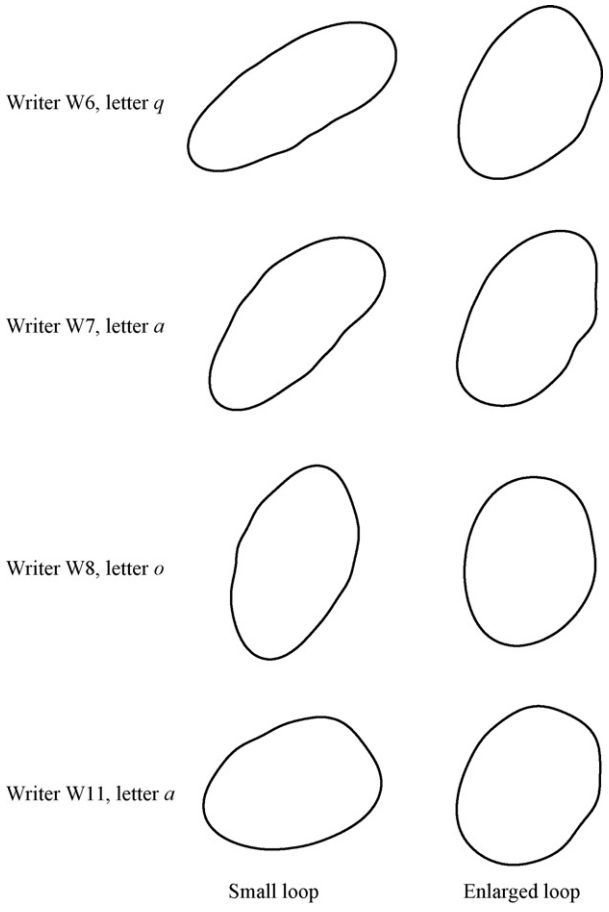

Fig. 1. Examples of small and enlarged handwritten loops illustrating the main tendencies of shape modification (reduction of elongation associated with a more vertical orientation) when increasing the size of the loops, for the writers showing the most visible changes. Note the size of the loops was normalized.

4. Discussion

A global comparison of shape between small and enlarged loops was allowed by applying the MANOVAs, since all the variables of the shape, i.e. the first pairs of Fourier descriptors, were taken into account simultaneously. Multivariate analyses showed that the shape of the loops *a*, *d*, *o* and *q* was modified when increasing their size; these results tend to refute the hypothesis of shape invariance when modifying the size of the writing.

Univariate analyses were then applied to show which aspects of the shape were modified with changes in size. Most of the writers shared similar modifications when increasing the size of the loops; they produced enlarged loops significantly more round and less slanted towards the right or the left; but some writers presented also particular changes, thus confirming the

Table 7
Discriminant analysis of the first four pairs of Fourier descriptors of the handwritten loops of letters *a*, *d*, *o* and *q* taken separately and all together, to discriminate between the 13 writers: percentages of misclassifications of enlarged loops in groups of small loops for each writer

Writer	*a*	*d*	*o*	*q*	*adoq*
W1	54.5	33.3	60.0	60.0	41.1
W2	42.9	6.70	33.3	42.9	36.2
W3	72.7	53.3	36.4	86.7	82.7
W4	61.5	28.6	76.9	60.0	65.5
W5	35.7	40.0	15.4	13.3	28.1
W6	92.3	100	100	73.3	94.6
W7	84.6	83.3	28.6	73.3	70.4
W8	21.4	50.0	66.7	60.0	35.4
W9	30.0	45.5	42.9	46.2	43.7
W10	30.8	11.1	20.0	7.10	34.8
W11	53.3	33.3	92.9	13.3	59.3
W12	25.0	58.3	84.6	35.7	74.5
W13	23.1	21.4	53.3	57.1	67.9

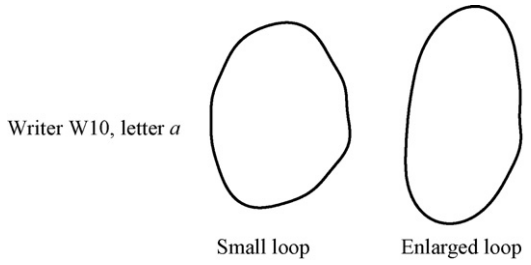

Fig. 2. Example of a typical shape modification: an increase of the elongation was observed when increasing the size of the loops, in writer W10. Note the size of the loops was normalized.

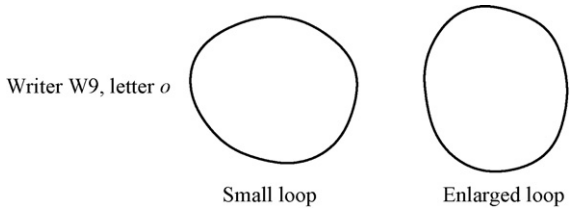

Fig. 3. Another example of a typical shape modification: the orientation of the elongation and triangularity were more vertical when increasing the size of the loops, in writer W9. Note the size of the loops was normalized.

dependence of changes according to the writer [3]. Shape aspects of the loops were not identical between small and enlarged letters. Consequently, these results are in disagreement with principle of shape invariance through modifications in size, which is a part of the traditional approach explaining handwriting processes [6]. From another point of view, we observed that general construction mode of the loops was identical between small and enlarged loops for every writer; differences in shape were thus not caused by a different loop formation when increasing the size.

The general characteristics which allowed the differentiation of the writer groups based on small loops, which were highlighted in a previous study [5] (importance of elongation, orientation of this elongation and orientation of the fourth contribution), were also those explaining most of the discrimination between the writers with enlarged loops. Therefore, the same main shape aspects – importance and orientation of elongation as well as orientation of the quadrangular contribution – should be focused on when comparing enlarged loops between them or small loops between them, since these features are more susceptible to differ between the writers.

The correct classification rates of the enlarged loops were rather high (more than 90%); an objective discrimination between most of the writers was thus completely possible through the shape of enlarged loops. We deduce from these results that it is possible to classify the enlarged loops to their adequate writer. However, if the comparison takes place with small letters, the error risk considerably increases (in this case, about 50% of the enlarged loops were wrongly classified). The significant modifications of shape (demonstrated using multivariate and univariate analyses) were great enough to make difficult the classification of enlarged loops to their adequate writer. Shape invariance was thus not supported for this particular application. Consequently, when comparing documents with a different writing size, differences in shape of loops should be interpreted cautiously because they may be due to a different writer, but they may also be due to an enlargement of the loops. Therefore, reference material of similar writing size to that of the questioned writing should be requested for the comparison of handwritten loops.

In this study, we compared the shape of loops of small and enlarged loops to determine which shape aspects could be modified and if these modifications were similar between the writers. In a further study, we plan to determine the probability of authorship, given the shape parameters of a suspect and those of a questioned document. Further study will thus be done for assessing the value of the evidence in computing multivariate likelihood ratios related to the comparison of shape of loops.

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