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AN EXPERT VISION SYSTEM FOR ANALYSIS OF HEBREW CHARACTERS AND AUTHENTICATION OF MANUSCRIPTS

LAURENCE LIKFORMAN-SULEM,* HENRI MAÎTRE* and COLETTE SIRAT†

* École Nationale Supérieure des Télécommunications, Image Laboratory, 46 rue Barrault, 75013 Paris, France; † Institut de Recherche et d'Histoire des Textes (CNRS), 40 avenue d'Iéna, 75016 Paris, France

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Abstract—This paper describes a knowledge based system that helps scribes to authenticate Hebrew manuscripts for which accurate laws of calligraphy have been given to the scribes. Paleographic expertise is also included in order to characterize the size of the document and the writing. When used for authentication purposes, the system shortens the task of the scribe by pointing out the parts of the document or the characters where problems arise for the machine (low contrast, breaks, ambiguous shape). The scribe will then operate on a restricted part of the document and decide whether it has to be corrected or not.

In order to be close to human mechanisms of interpretation, the system structure includes several analysis levels. This system uses some principles of intelligent vision systems that can set up image and document analysis strategies as well as interactions between the high level and low level procedures. It works directly on grey level pictures.

Expert systems Vision systems Strategies Writing analysis Hebrew characters

1. INTRODUCTION

Pattern recognition methods applied to character recognition have given birth to reading machines which have been successfully developed for several years. But if good results are obtained for the recognition of printed fonts, machines are more limited when dealing with handwriting. However, several methods for the recognition of handwritten characters have been developed both for the Latin alphabet(1–4) and for the non Latin ones.(5–9)

These studies are usually devoted to O.C.R., their main goal being to reach a high recognition rate at a high reading speed. Besides these studies, other works exist, also dealing with writing but where character recognition is not the primary goal. They may provide useful information about the makeup of the text (margin, paragraphs, line spacing, etc.),(10,11) the writing style (and especially the geographic localization or the historic dating,(12–14) or even the writer (mainly for authentication purposes).(15–18) They may concern forensic document analysis,(19) verification of signatures, writer identification(20) or the general study of texts in a paleographic sense.(21) Most of these studies are concerned with Latin(13) or Hebrew(12,14) alphabets. The system presented here aims at giving paleographic information on Hebrew documents described in Section 2.

O.C.R. techniques mainly concern low level picture processing, data analysis, classical and structural pattern recognition. Interpreting the structure of a document, extracting information about the writer and the writing material, authenticating a text, involve using other techniques based mostly on the introduction of knowledge, i.e. contextual information, provided by various experts. The different kinds of knowledge we exploit are presented in Section 3.

Expert systems provide a way to embody such knowledge and control mechanisms. Expert and knowledge based systems are widely used in the field of picture processing, for instance in aerial imagery,(22–25) satellite imagery,(26,27) segmentation,(28–30) object classification,(31) and for the interpretation of medical images, image sequences(32,33) and seismic data.(34) Expert and knowledge based systems have to cope with both low level procedures near the image and high level interpretation procedures. In Section 4 we present the vision expert system we use for investigating Hebrew manuscripts: its architecture and the different analysis levels.

Exploiting different types of knowledge within a system involves working out reasoning and image analysis strategies.(35) To work out document strategies and provide control mechanisms, meta rules are embodied in the system as described in Section 5. Section 6 gives examples of how the system interprets images and verifies the conformity of a document.

Interactions between low and high level procedures were also implemented to locally re-examine the image if problems arise at the interpretation level. Section 7 describes such an interaction. Results are presented in Section 8 and the paper concludes with the various possibilities of extension of this system for use for other studies on writing.

2. ANALYSED DOCUMENTS

We study manuscripts reproducing the biblical text of the Pentateuch. They are calligraphed by skilled scribes with a quill or a calamus, on scrolls of leather or parchment. These documents are written in Hebrew, in a so-called squared writing as most characters are made up of horizontal and vertical strokes. Only a few characters have slanted strokes. The Hebrew alphabet consists of 22 letters, five of which have final forms used when those letters appear at the end of a word (Fig. 1). The scrolls must be fit for liturgical use and hence must be perfect according to canonical rules which we call calligraphic rules, given to the scribes. It is for this reason that the scrolls are inspected by scribes whenever a new scroll has been completed or if a flaw is noticed while reading the manuscript at the synagogue. The scribe will then inspect the whole scroll by verifying that the text is correctly spelt, no letter distorted, adding or missing, that characters and words are properly separated, that the page setting is respected, that the shape of each character is correct according to the rules of calligraphy and that characters are not broken because of loss of ink. This authentication task is lengthy and tedious: it takes several weeks for a scribe to inspect a whole scroll. A system(36) already exists that recognizes characters by classical O.C.R. techniques: it can only verify that the text is correctly spelt, without taking into account the actual form of the letter. One purpose of our system is to perform the authentication task automatically, pointing out to the scribe the deteriorated parts of the documents and the characters that are not consistent with the rules. But our system is not limited to the authentication of characters, its purpose is also to give some information about these documents and to achieve tasks such as the extraction of intrinsic characteristics of the writing and the document (style, dimensions of the quill, variations of the writing, etc), and the extraction of image processing parameters (contrasts, average height of characters, interline distance, etc).

At first, the text has to be digitized. A compromise has to be found between a high fidelity of reproduction and a low storage and processing cost. A reasonable sampling has been found at a resolution of about $30 * 30$ points for each squared character.(37)

א	aleph	ט	tet	פ	peh	ץ	tsadi*
ב	bet	י	yud	צ	tsadi	ף	peh*
ג	guimel	כ	kaf	ק	kuf	ך	kaf*
ד	daleth	ל	lamed	ר	rech		
ה	he	מ	mem	ש	shin		
ו	vav	נ	nun	ת	tav		
ז	zayn	ס	samech	ן	nun*		
ח	het	ע	ayn	ם	mem*		

Fig. 1. The Hebrew alphabet consists of 22 letters, five of which have final forms. In this squared handwriting, horizontal strokes are predominant.

Fig. 2. Samples of Ashkenazic (a) and Sephardic (b) documents. Character resolution is about $30 * 30$ pixels. The Ashkenazic style is characterized on characters by vertical strokes thinner than horizontal ones, curved upper bars, straight downstrokes, because of using a quill. Drawn with a calamus, strokes of Sephardic characters are more homogeneous, downstrokes may be rounded at their end, bars are straight.

On a $512 * 512$ picture, we were able to digitize 10 lines of text with about 20 characters per line (Fig. 2).

3. KNOWLEDGE INCLUDED IN THE SYSTEM

The system exploits four kinds of knowledge described below: a set of calligraphic rules, knowledge provided by a paleograph, knowledge about the content of the text and knowledge related to the properties of picture processing routines (Fig. 3).

A set of rules of calligraphy is given to the scribes. This knowledge is directly available in reference books[38,39] that indicate all the rules necessary for page setting, margins, minimal distances between words and characters. Calligraphic rules also precisely describe for each character the shape of its components. All dimensions are relative to the width of writing implement (quill or calamus) which is an important writing parameter. This width corresponds to the width of horizontal strokes such as the upper bar which is the most significant stroke in Hebraic handwriting. Moreover visual examples of permitted and forbidden shapes are provided that make possible the construction of the character models, i.e. their shapes with their permitted deviations. In addition, according to the rules of calligraphy, characters must not be broken because of loss of ink: breaks are sometimes found inside components of characters or between components.

This first level of knowledge is completed by a visual and paleographic expertise provided by a paleograph, i.e. an expert in handwritings. The paleograph completes the rules of calligraphy by selecting significant features that enable a reader to recognize characters and distinguish between them. For instance, the rules of calligraphy specify that for the letters Mem Sofit and Samech whose shapes are very similar, the left and right corners of the lower horizontal bar must be rounded for the letter Samech, and straight for the letter Mem Sofit. But in practice, the paleograph advises us to examine also the shape of the internal part of the letter (whether it is squared or not), or the inclination of the right contour (Fig. 4). The paleograph can also extract a great deal of information from a document. For instance he knows how to characterize the style of a document and compare different handwriting.[40] In this study we separate documents into two styles: the Ashkenazic style which originated in East Europe and the Sephardic style which originated in North Africa. According to experts, the Ashkenazic style is characterized on characters by vertical strokes thinner than horizontal ones, curved upper bars and straight downstrokes due to the use of a quill. Being drawn with a calamus, strokes of Sephardic characters are more homogeneous, downstrokes may be rounded at their end, bars are straight (Fig. 2).

We are also interested in reproducing the mechanisms of interpretation used by a paleograph. An expertise may be separated into three different levels of vision corresponding to the three levels of vision when analysing a manuscript.[41] During global vision analysis, the manuscript is seen as if at a distance: some global features may appear such as page setting, style characteristics, density of writing, internal height of characters . . . Closer to the manuscript, pages contain characters of a specific alphabet which can be recognized: this is the near vision. If we now look at the manuscript with a magnifying

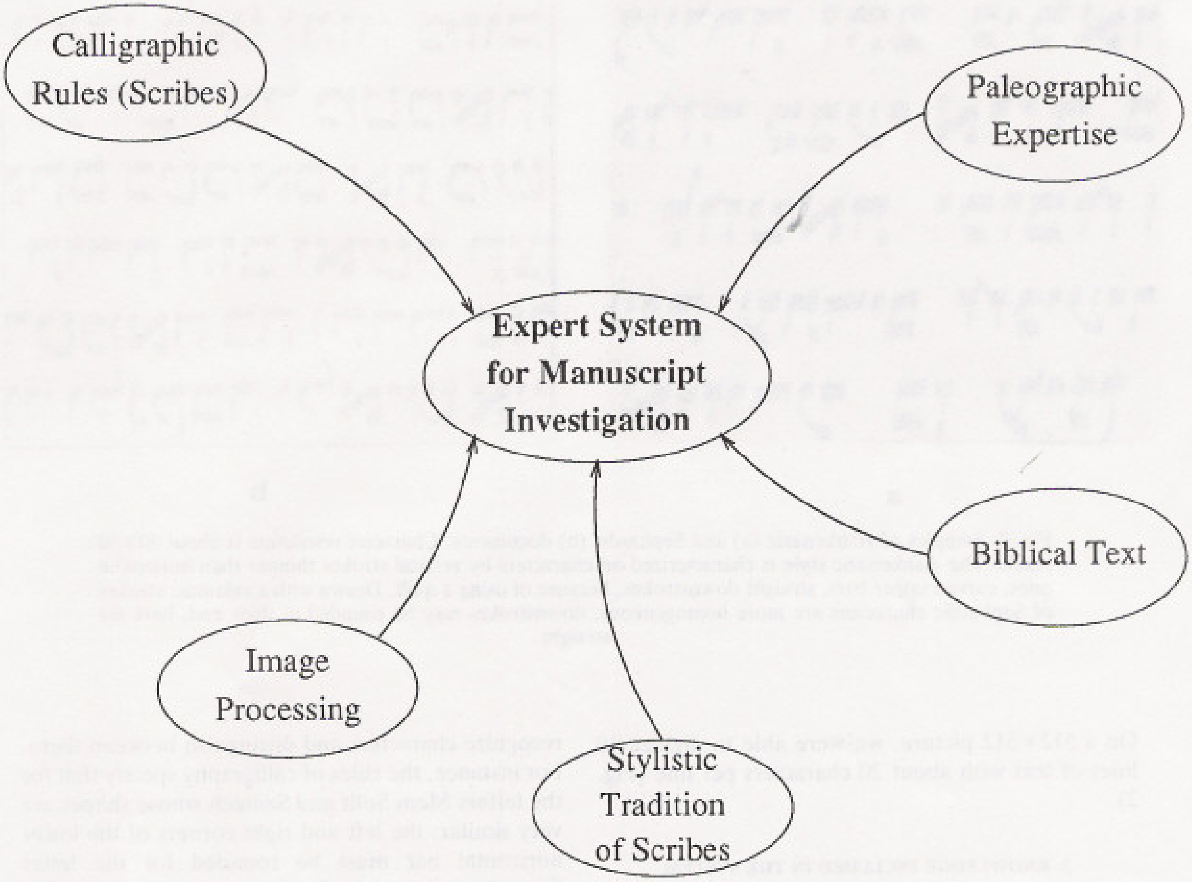

Fig. 3. The different kinds of knowledge exploited by the expert system.

glass, very fine details will appear on characters such as the shape of a contour: this is magnified vision (Fig. 5). When analysing a manuscript, the paleograph can change from one level to another to confirm or deny his hypotheses. But two levels of vision cannot coexist at the same time: once focused on a particular level, the other ones temporarily vanish. Questions such as when the system has to change to another level, which actions must be performed at one particular level, must be answered in order to work out document analysis strategies.

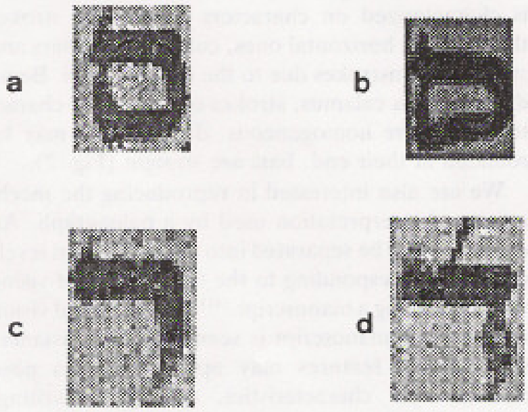

Fig. 4. Examples of similar shapes. For characters Mem Sofit (a) and Samech (b), the main difference lies in the lower right corner. For characters Rech (c) and Daleth (d), it lies in the upper right corner.

Other kinds of knowledge are also embodied in the system. First the content of the well known text of the Pentateuch is used in order to be sure that no letter is added or missing in the text under analysis. This information may also be used for learning purposes, to direct the expert system to a specific part of the text. Finally, some knowledge of picture processing is used, for instance to detect a feature (component, curvature, etc) or to enhance the contrast of some very thin strokes, etc.

4. SYSTEM OVERVIEW

4.1. *Architecture*

Our system is supervised by a rule based expert system to which we added a set of image processing routines working directly on pictures (Fig. 6). Classically the architecture of an expert system consists of a set of facts (symbolic objects), a set of rules (rules and sometimes meta-rules) and an inference engine. These elements belong to an OPS 5 environ-

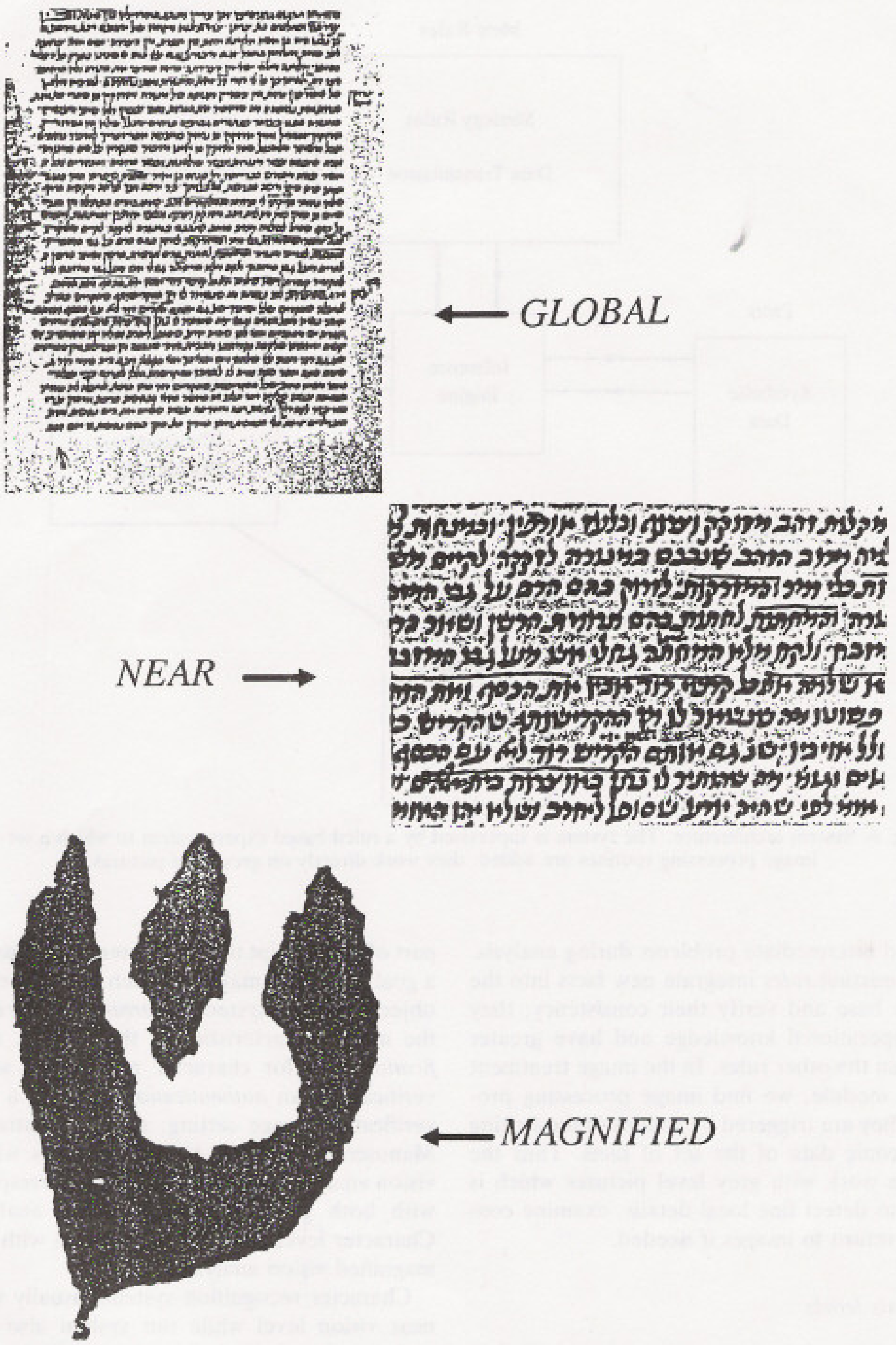

Fig. 5. A human analysis may be separated into three levels of vision. (a) During global vision analysis, the manuscript is seen as if at a distance: global features may appear (page setting, style, density of writing, etc). (b) At the near vision level, characters can be recognized. (c) Magnified vision corresponds to looking at the manuscript through a magnifying glass: fine details may appear.

ment (from Digital Equipment Co), which provides a language to describe objects and write rules, and a forward chaining inference engine enabling the use of variables[42] (level 1 engine).

Here the set of facts consists of symbolic elements that describe the situation under analysis, and of iconic data which are document images (columns of text, characters, etc). The set of *writing rules* represents general knowledge and expertise about manuscripts, hebraic handwriting, and includes the character models. Meta-rules control the use of writing rules through the inference engine. By means of meta-rules, we work out a *general strategy* for analysing a document and *specific strategies* to solve

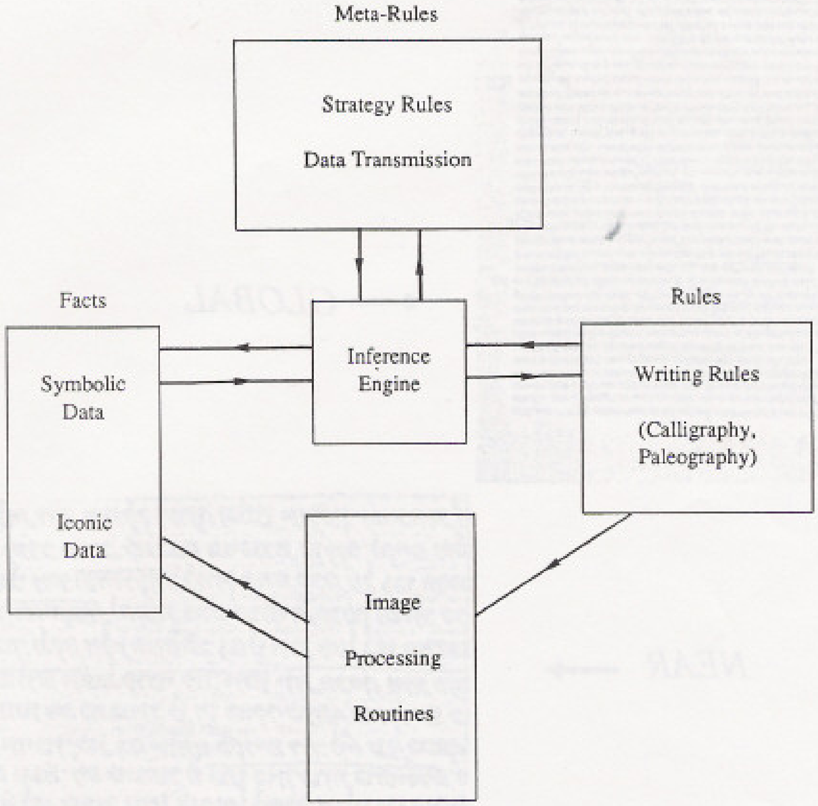

Fig. 6. System architecture. The system is supervised by a ruled based expert system to which a set of image processing routines are added: they work directly on grey level pictures.

specific and intermediate problems during analysis. *Data transmission rules* integrate new facts into the knowledge base and verify their consistency; they form an operational knowledge and have greater priority than the other rules. In the image treatment procedure module, we find image processing procedures. They are triggered by actions of the writing rules on iconic data of the set of facts. Thus the system can work with grey level pictures which is necessary to detect fine local details, examine contrasts and return to images if needed.

4.2. *Analysis levels*

The structure of the system must be adapted to the human mechanisms of an expert. We showed in Section 3 how an expertise may be separated into different levels of vision and that only one level could be present at a given moment. To reproduce this scheme of interpretation, we include in the system four levels which are: a *Root level*, a *Manuscript level*, a *Page level* and a *Character level*. Each of these levels represents the environment (data structure, writing rules, meta-rules) in which the system works at a given time (Fig. 7).

The Root level is used for initializing the system and has no correspondence with any vision level. At the Root level, the user chooses a manuscript or a part of manuscript that the system must analyse, and a goal. The goal may be chosen between one of the objectives of the system: a *learning* task for extracting the main characteristics of the writing, an *identification* task for character recognition and shape verification, an *authentication* task for a complete verification (page setting, shapes, contrasts, etc). Manuscript level has correspondences with global vision analysis while Page level has correspondences with both global and near vision analysis, and Character level has correspondences with near and magnified vision analysis.

Character recognition systems usually work at a near vision level while our system also works at global and magnified vision levels which enable the extraction of useful characteristics of documents and characters.

This multi-level structure involves a partition of the data structure and of the actions the system performs since different types of actions are applied to documents, pages and characters. In a manuscript, the different columns of text can be distinguished and the margins examined, page setting may give style indications, the general contrast of the document—if uniform—can be found, and it is possible to focus on one specific column (page) of text. On a page of a document we may get information about its own contrast, distinguish words and characters

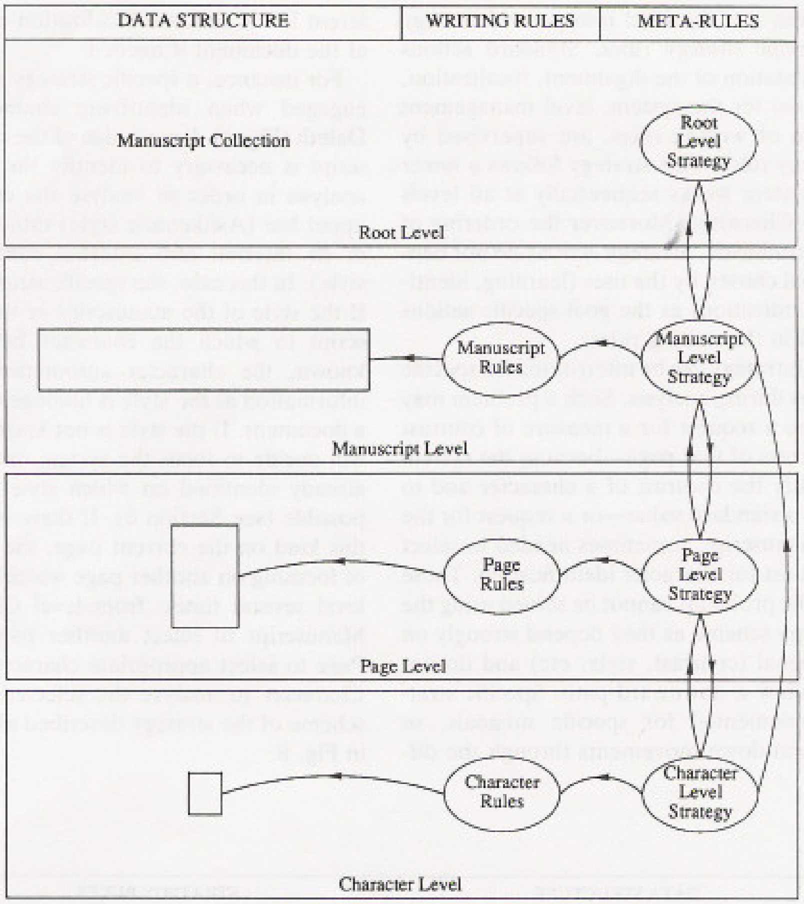

Fig. 7. The different analysis levels in the system, Root, Manuscript, Page and Character. They represent the environment in which the system works at a given time. This involves a partition of the data structure and of the actions the system performs.

and control their spacing, find the interline distance, the internal height of characters, the dimensions of the quill or the calamus, the typical contrast of characters and focus on a specific character. From a character, general, structural or morphometric features are extracted (position and dimensions of components, average contrast, etc) as are fine details such as the shape of a contour, a junction or a head curvature. As we mentioned previously, level classification involves a partition of the data structure whose principal objects are the manuscript object, the page object and the character object, each one specific to one level. Writing rules as well as strategy rules are also classified into levels. Writing rules corresponding to one level can only process objects belonging to the same level.

5. META-RULES

Meta-rules are control rules with higher priority than writing rules. Meta-rules consist in this system of strategy rules and data transmission rules. Strategy rules are of major importance as they control the document analysis. The subset of strategy rules corresponding to one level controls the activation of the writing rules corresponding to the same level. Moreover, strategy rules control changes from one level to another. Data transmission rules are in charge of the integration of new facts and the verification of their consistency.

5.1. *Strategy rules*

Document analysis strategy consists of deciding which kind of action must be activated at a given state of the analysis, whether it is necessary to change from one level to another one and to choose this new level. It also decides where on the document must the system focus according to the present state. Applied in the system it will principally consist of deciding when to invoke the subset of writing rules associated with one level, which actions must be performed at a given level, when to change level and on which manuscript, page or character to focus. Strategy rules are classified into the four levels described in part 4.2 and each subset of strategy rules can only invoke the corresponding subset of writing rules.

Strategy rules are classified into *general strategy* rules and *specific strategy* rules. Standard actions such as segmentation of the document, focalization, choice of a goal for the system, level management and activation of writing rules, are supervised by general strategy rules. This strategy follows a linear path as the system works sequentially at all levels from Root to Character. Moreover the ordering of actions is deterministic. Strategy actions do not depend on the goal chosen by the user (learning, identification, authentication) as the goal specific actions are embodied in the writing rules.

The general strategy can be interrupted if a specific problem arises during analysis. Such a problem may for instance be a request for a measure of contrast for the characters of that page—because the system needs to qualify the contrast of a character and to compare it to a standard value—or a request for the style of the manuscript, sometimes needed to select the right features for character identification. These kinds of specific problems cannot be solved using the general strategy scheme as they depend strongly on a specific subgoal (contrast, style, etc) and do not necessarily follow a downward path. Specific strategies are implemented for specific subgoals, so enabling up-and-down movements through the different levels and also focalization on different parts of the document if needed.

For instance, a specific strategy related to style is engaged when identifying characters Rech and Daleth (Fig. 4). Knowledge of the style of the manuscript is necessary to identify the character under analysis in order to analyse the curved part of its upper bar (Ashkenazic style) rather than the shape of its internal and external contours (Sephardic style). In this case, the specific strategy is as follows. If the style of the manuscript or the page of manuscript to which the character belongs is already known, the character automatically inherits this information as the style is homogeneous throughout a document. If the style is not known, strategy rules will decide to focus the system on other characters already identified on which style determination is possible (see Section 6). If there is no character of this kind on the current page, the strategy consists of focusing on another page which implies changing level several times: from level Character to level Manuscript to select another page, then to level Page to select appropriate characters, then to level Character to analyse the selected characters. The scheme of the strategy described above is presented in Fig. 8.

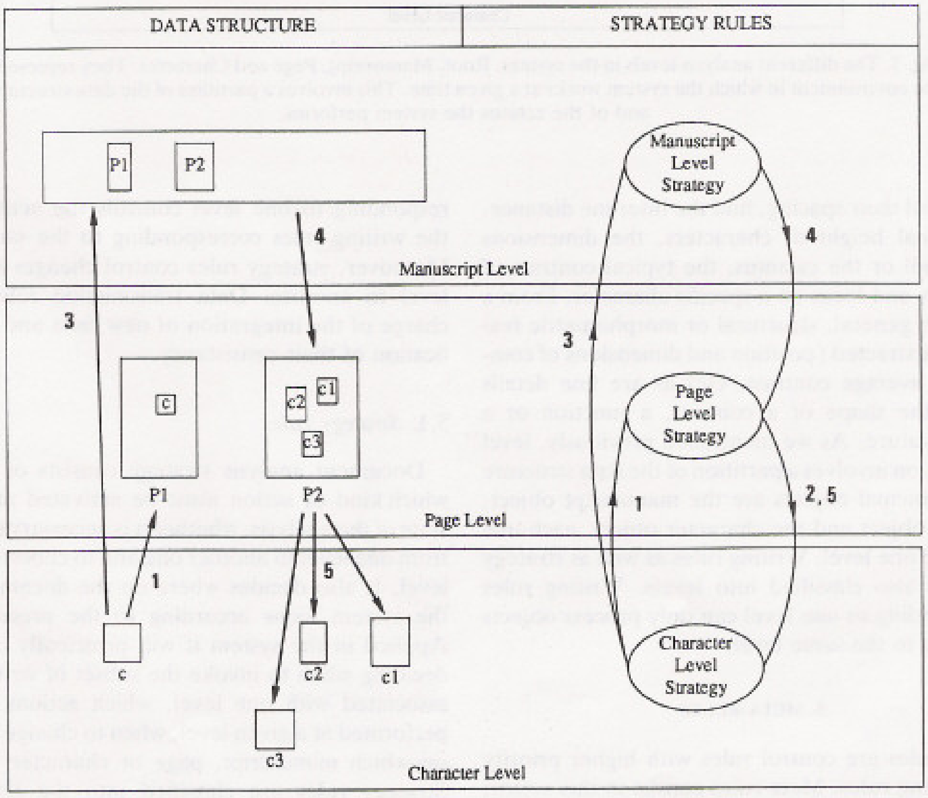

Fig. 8. Specific strategy related to style identification: (1) attempt of identification at Page level; (2) answer and return to Character level; (3) if style identification is not possible at Page level, attempt at Manuscript level; (4) attempt at Page level (on another page); (5) attempt at Character level.

5.2. *Data transmission rules*

Data transmission rules belong to the set of control rules but are of a different kind to strategy rules. These rules are operational knowledge and are activated by demon objects[42] produced by writing rules. Demons are control objects that immediately invoke an associated set of rules when created in the set of facts. One of these rules will actually fire and will afterwards destroy the demon objects. Moreover, data transmission rules are not associated with a specific level as are strategy rules. On the contrary, they transmit information from the current level to a superior or an inferior one and can modify symbolic objects that belong to a level other than the current one. The two possible modes of transmission are an *indirect mode* and a *direct mode* with consistency verification.

The indirect mode consists in incorporating a new information from one level to another after some computation. For instance the width of the writing implement in a particular page of text is an important writing parameter which is computed from the width of strokes in certain characters (Bet, Daleth, He, etc) belonging to the page in question. When extracted from a character, the width of its upper bar is used to update the value already set at the Page level using previously analysed characters, by calculating the average value. Other level specific features which are computed from objects belonging to other levels are the standard contrast of the document (at level Manuscript from different pages), the average dimensions of squared characters, the width of the writing implement, the standard contrast of characters, the variations of dimensions within each class of character (at level Page from characters).

Image analysis is characterized by a great deal of uncertain data which implies that results often are erroneous and must be checked in several different ways. Direct transmission occurs when new information does not need any computation to be incorporated to another level but has to be accepted with care because of possible errors. The scheme of transmission is as follows. The information will first be transmitted to the immediate next level (superior) only. If this information is already known at this level and is consistent with the information extracted, it will be transmitted to a level of higher rank. On the other hand, if these two pieces of information (extracted and at the immediate next level) are not consistent and if no information is available at higher levels, we monitor these two pieces of information by incrementing a flag. When it reaches a certain value (chosen empirically), the information is reconsidered at both levels and marked as undetermined. Table 1 summarizes how the style attribute is transmitted after determination on a character. The result of transmission depends on the style attributes already known for the manuscript and the page to which the character belongs.

6. WRITING RULES

Knowledge about writing, paleography and authentication of documents is embodied in production rules called writing rules. They are divided into three classes, related to the last three levels, according to whether the rule's actions apply to a manuscript, a page or a character. The condition part of these rules expresses conditions on symbolic objects of the knowledge base. The action part modifies symbolic elements or engages an image treatment procedure on iconic data of the set of facts: the result of the procedure is then stored in symbolic elements.

Two sets of writing rules cannot be invoked at the same time as they belong to different levels. Strategy rules only can decide when to activate at a given level the corresponding set of writing rules. Once invoked, the set of writing rules will be applied until no more rules match their conditions on the set of

Table 1. Consistency verification and transmission of character's style attribute. A flag (c) is incremented to monitor inconsistencies. If the style is undetermined on a particular character, no information is transmitted

Before transmission			After transmission		
Character	Page	Manuscript	Character	Page	Manuscript
Ashkenazic (Sephardic)	nil	nil	Ashkenazic (Sephardic)	Ashkenazic (Sephardic)	nil
Ashkenazic (Sephardic)	Ashkenazic (Sephardic)	nil (Sephardic)	Ashkenazic (Sephardic)	Ashkenazic (Sephardic)	Ashkenazic (Sephardic)
Ashkenazic (Sephardic)	undetermined	Ashkenazic (Sephardic)	Ashkenazic (Sephardic)	Ashkenazic (Sephardic)	Ashkenazic (Sephardic)
Ashkenazic	Sephardic ($c < C0$)	nil	undetermined	Sephardic $c = c + 1$	nil
Ashkenazic	Sephardic ($c \geq C0$)	nil	undetermined	undetermined	nil
Ashkenazic	Sephardic	Sephardic	undetermined	Sephardic	Sephardic
Sephardic	nil	Ashkenazic	undetermined	nil	Ashkenazic

Table 2. Possible actions of the writing rules at each level

Manuscript Level	Contrast (Manuscript) Page setting (Margins) Style identification (Column organization)
Page Level	Page setting (Words and characters) Global identification of style Contrast (Page) Average dimensions of characters Slant direction of writing Density of writing
Character Level	Local contrast of characters Width of the quill Curvature analysis (style) Component extraction Accurate details analysis Recognition (Character) Contrast verification (Character) Breaks within components Validation (Character)

facts. Then control returns to strategy rules which decide of the next level. Premises of writing rules include conditions on the analysis level, the initial goal chosen by the user, the part of manuscript that must be analysed and the state of the analysis. Table 2 summarizes for each level the possible actions of the writing rules. The rules are not extensively described here. Our purpose is to present the way the system analyses documents and characters. The whole set of rules can be found in reference (43).

6.1. *Extraction of writing characteristics*

During the learning task such writing parameters as the width of the quill, the style of document, the dimensions of squared characters are extracted from document and character images. A learning task applied to a restricted part of the document may precede an identification or authentication task. Results obtained after a learning task are more reliable and obtained more quickly, as contextual knowledge about the writing under analysis is already present in the system. For instance, all dimensions are relative to the width of the writing implement as we consider proportions rather than absolute values. When analysing a character, if this width parameter is not known from a precedent learning task, the default value we take for this parameter is the width of the horizontal stroke of the character itself. Of course, this value is less reliable than a value extracted from several characters but to avoid mistakes we invoke extra image procedures to guarantee the quality of this measure.

Style information is presently extracted from particular characters: Kaf, Rech, Lamed, Mem Sofit, Samech. On a paleographic suggestion, we tested the correspondence between the head curvature of these characters and the style of the document. For this purpose we developed an image procedure that determines the *Cup* parameter, i.e. the proportion of the curved part of the upper bar. Figure 9 shows the results obtained from a training set of characters. We were able to select two ranges, deliberately not too near, to separate Ashkenazic from Sephardic characters. The undetermined zone is large enough to obtain reliable results. Moreover, if the style is found undetermined on a character, the system has the possibility to extract style information from many other characters.

6.2. *Shape analysis*

Character shape analysis and verification is performed during the identification task by writing rules belonging to the Character level. The rules work directly on character images to extract the components and analyse accurate details of the shape. Some characters may easily lead to confusion with another letter since their shapes are very similar. We present here the case of the letter Bet which resembles the letter Kaf (Fig. 10) in order to illustrate how the system proceeds during shape recognition and verification. The structural components of the character Bet are its upper and lower bars and a right inter-bar downstroke. We suppose here that these components have already been extracted and that they are correctly formed according to criteria of dimension, height and width so that we will not mention them in the conditions of the following rules. The other attributes that may be used are those which represent and quantify the extension of the lower bar, the shape of the lower right corner of the lower bar, the internal shape of the character and the shape of the lower bar–downstroke junction. Writing rules extract the attributes when needed from grey level pictures by the means of image procedures. This extraction is guided by the character models. In the rules dealing with the character Bet, all of these attributes are not necessarily used as conditions at the same time: just as the eye ident-

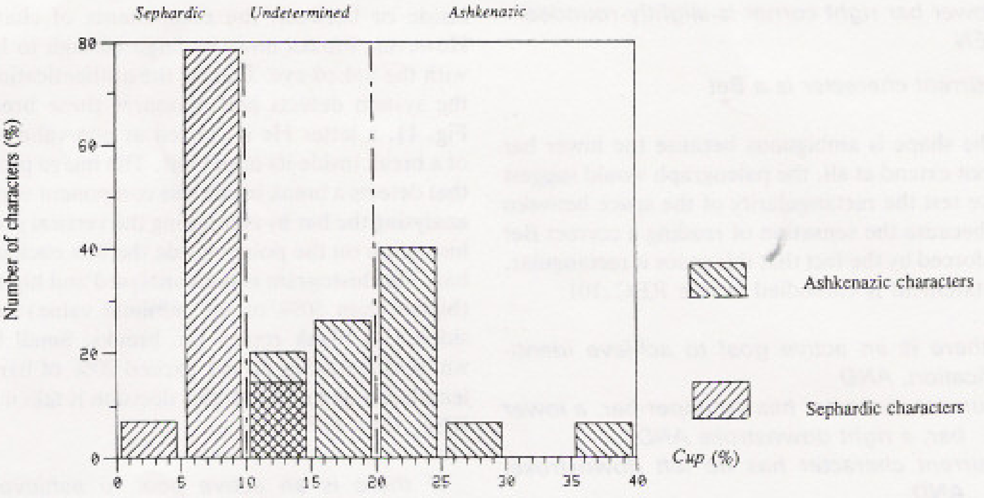

Fig. 9. Ashkenazic and Sephardic character distribution versus Cup. Ashkenazic characters can be characterized by a Cup < 10%, Sephardic ones by a Cup > 20%. For a Cup between these two ranges for a character, the style is considered as undetermined for that character.

ifies a shape by association of only certain attributes. This association depends on the degree of ambiguity of the shape. Four rules were written to describe a shape as a correct Bet. The values of the attributes expressed in rules are usually relative to some parameters of the writing (width of the quill . . .). If not, they are chosen empirically but include a range of undetermination.

According to calligraphic rules, the ideal Bet is supposed to be characterized by its lower bar extending beyond the vertical alignment with the upper one, and by the right-angled corner of the lower bar. Conditions of rule REC_96 perform this test:

```
IF there is an active goal to achieve identi-
    fication, AND
  current character has an upper-bar, a lower
      bar, a right downstroke AND
  current character has no left downstroke,
      AND
  its lower bar is extended, AND
  lower bar right corner is very right-angled
THEN
  current character is a Bet
```

But in practice, the right corner of the lower bar may be slightly rounded if the extension of the bar is more significant (REC_99):

```
IF there is an active goal to achieve identi-
    fication, AND
  current character has an upper-bar, a lower
      bar, a right downstroke AND
  current character has no left downstroke,
      AND
  its lower bar is significantly extended, AND
```

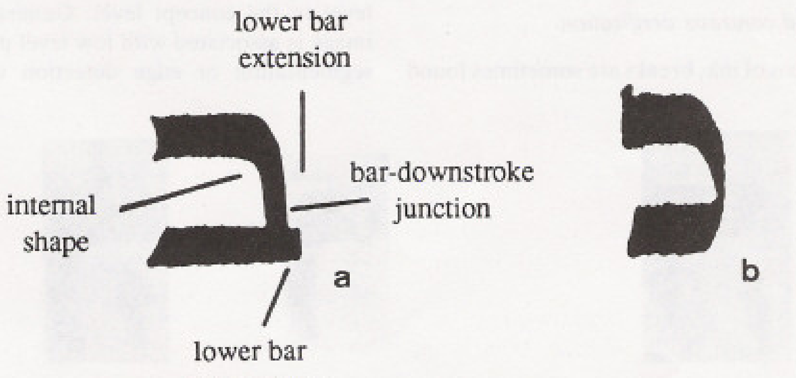

Fig. 10. (a) Character Bet (b) Character Kaf. The ideal Bet has a lower bar extended. The lower right corner of an ideal Kaf is rounded. For non-ideal shapes, features such as the internal shape or the shape of the lower bar-downstroke junction must be tested.

lower bar right corner is slightly rounded
THEN
current character is a Bet

If the shape is ambiguous because the lower bar does not extend at all, the paleograph would suggest that we test the rectangularity of the space between bars, because the sensation of reading a correct Bet is reinforced by the fact that this space is rectangular. This statement is embodied in rule REC_101:

IF there is an active goal to achieve identification, AND
current character has an upper-bar, a lower bar, a right downstroke AND
current character has no left downstroke, AND
its lower bar is not extended, AND
space between the two bars has a rectangular shape, AND
lower bar right corner is right-angled
THEN
current character is a Bet

When the shape does not match any model previously proposed, rule REC_102 tests if the lower bar-downstroke junction is oriented inwards:

IF there is an active goal to achieve identification, AND
current character has an upper-bar, a lower bar, a right downstroke AND
current character has no left downstroke, AND
space between bars is undetermined, AND
lower bar right corner is right-angled, AND
lower bar-downstroke junction is oriented inwards
THEN
current character is a Bet

6.3. *Breaks and contrasts verification*

Because of loss of ink, breaks are sometimes found inside or between the components of characters. However, breaks must be large enough to be seen with the naked eye. During the authentication task, the system detects and measures these breaks. In Fig. 11, a letter He is classed as non-valid because of a break inside its upper bar. The image procedure that detects a break inside this component consists of analysing the bar by computing the vertical projected histogram on the points inside the box enclosing the bar. This histogram is then analysed and high values (higher than 50% of the minimal value) are considered as blank zones, i.e. breaks. Small breaks, whose dimensions do not exceed 20% of bar's total length can be tolerated, this decision is taken by rule REC_159:

IF there is an active goal to achieve authentication, AND
current character has an upper-bar, AND
we do not know whether the bar is valid, AND
relative length of the broken zone has already been computed and is less than 20% of bar's length
THEN
mark the bar as valid

Contrasts also are checked during the authentication task. The average contrast is computed for each character of the current page and compared to the standard contrast value of characters belonging to that page, or by default to the current manuscript. Standard values are for instance computed during a previous learning task and absolute deviations from standard values are tolerated. Figure 11 shows a set of characters marked as invalid because of a too low contrast.

7. KNOWLEDGE HIERARCHY AND INTERACTIONS

An image understanding system includes several kinds of processes and knowledge from the pixel level to the concept level. Generally the physical image is associated with low level processes such as segmentation or edge detection which are inde-

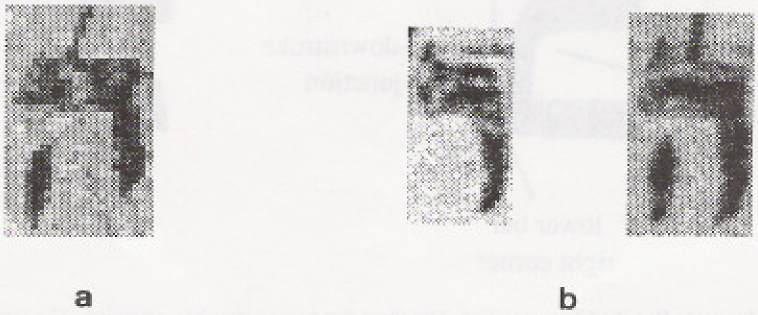

Fig. 11. Non-valid characters. A 4-pixel-long break is detected from the upper bar histogram of the character He (a). Low contrast characters due to loss of ink (b).

pendent of the domain of application and written in an algorithmic language, whereas high level processes deal with interpretation from abstract representation. At the bottom of the knowledge hierarchy we find the image made of pixels, which is then converted into intermediate representations such as lines, edges, regions, primitives, symbolic representations to obtain at the top of the hierarchy an abstract and reduced representation of the scene. Presently most of the systems deal with a restricted set of possible representations. They work either at the low level(29) or at the high level (or from pre-extracted primitives like edges(32)), or at both levels but with a separation of the two stages.(30) The system we have designed works at all levels of the hierarchy, pixel level included. The system can work directly with grey level pictures which are required for the detection of fine details or damaged parts of the document.

Dealing with both low and high level processes implies controlling the interactions between them which means here that the system can return to low level data, i.e. the image, if problems arise at the high level of interpretation. For instance the system automatically modifies the contrast of a character in cases of ambiguity, overthick lines and partial deletion of characters.

A typical problem with our characters is the partial deletion of a thin downstroke because of a too low contrast (this occurs particularly in vertical downstrokes in Ashkenazic manuscripts). For instance the character He is characterized by a detached left downstroke, while for character Het its left downstroke is bound to the upper bar. If there is a slight hole between the upper bar and the left downstroke, ambiguity arises as shown in Fig. 12. Once the system has found such an ambiguity at the interpretation level, it returns locally to the image of the ambiguous zone to restore a possible binding.

8. RESULTS

The system is currently running on a VAX 8550. About 250 rules written in OPS 5 are implemented in the system and are dedicated to learning, identification and authentication tasks (writing rules), con-

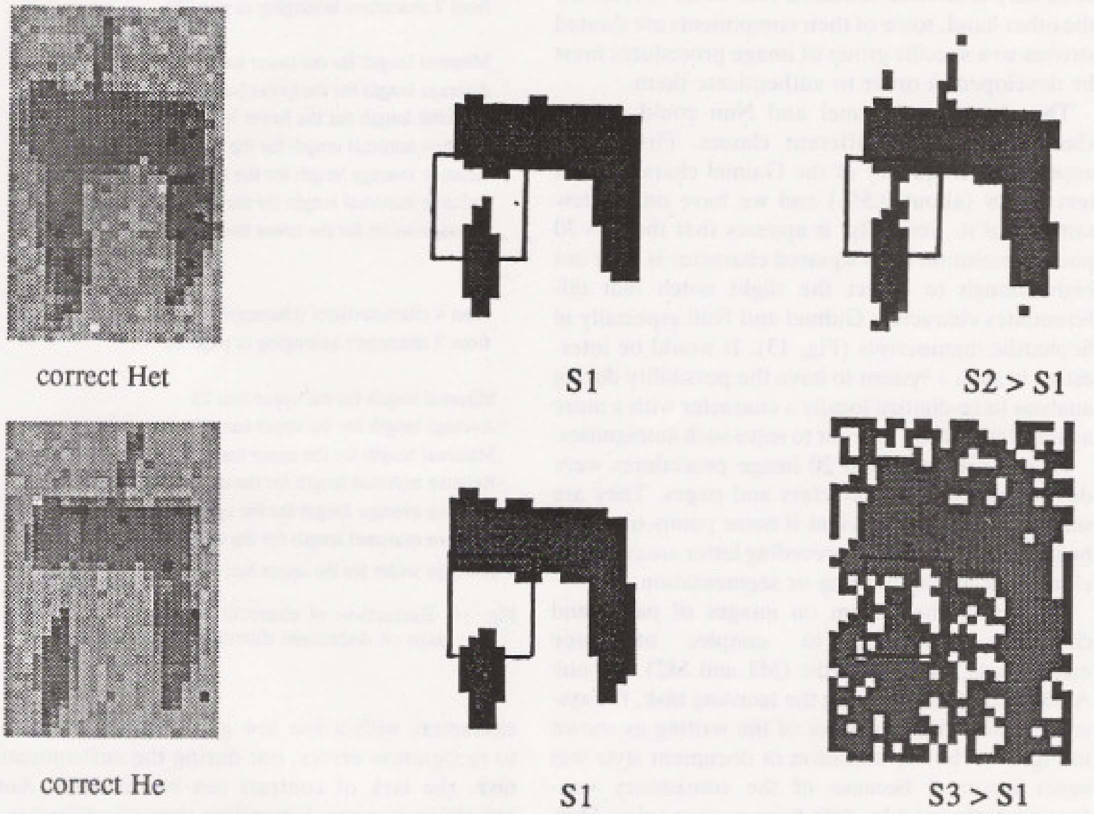

Fig. 12. Interactions between high and low level processes can occur because of binding problems. Here an ambiguity arises for the character Het (a) at threshold S1 as its left downstroke is detached from the upper bar: is the character a broken Het or an incorrect He? The system returns locally to the ambiguous zone to restore a possible binding. The low level procedure of restoration uses mathematical morphology(44) and consists of gradually increasing the contrast until a 4-connex upper bar–downstroke binding is obtained. The homogeneity of the points belonging to this 4-connex binding is tested (by standard deviation analysis) in order to verify whether a real binding is restored or not. If the background points belong to the 4-connex binding, that means that there is in fact a "hole" as shown on the character He (b). Otherwise a real binding was restored in the image and the character is a Het (a).

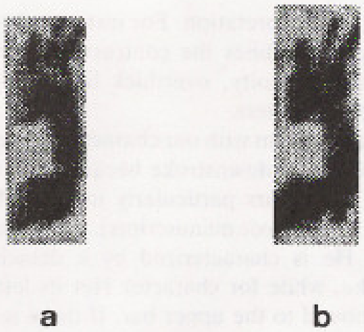

Fig. 13. The slight notch in the lower bar that differentiates characters Nun (a) and Guimel (b) is not detected at the usual resolution.

trol and data communication (meta-rules). Presently the system deals with 21 characters out of the 27 in the Hebrew alphabet, but the knowledge base can be easily extended to the last six characters. These six characters are Aleph, Tsadi, Sofit, Tet, Shin and Ayn which have openings at the top and whose shapes are very specific and thus easily recognized since they cannot be confused with other letters. On the other hand, some of their components are slanted strokes so a specific group of image procedures must be developed in order to authenticate them.

The characters Guimel and Nun could not be classified into two different classes. Firstly, the appearance frequency of the Guimel character in a text is low (about 0.5%) and we have only a few samples of it. Secondly, it appears that the 30 * 30 points resolution for a squared character is here not high enough to detect the slight notch that differentiates characters Guimel and Nun especially in Sephardic manuscripts (Fig. 13). It would be interesting in such a system to have the possibility during analysis to re-digitize locally a character with a more adapted resolution in order to solve such ambiguities.

At the present about 20 image procedures were developed to treat characters and pages. They are simple, robust and efficient if noise points or points belonging to the next or preceding letter are correctly eliminated during filtering or segmentation.

We tested the system on images of pages and characters belonging to samples of three manuscripts, two Sephardic (M1 and M2) and one Ashkenazic (M3). During the learning task, the system extracts characteristics of the writing as shown in Fig. 14. The identification of document style was never incorrect because of the consistency verification performed by data transmission rules. During the identification task, the error rate fluctuates (between 0% and 3%), according to the state (damaged or not) of the manuscript. The error rate is the percentage of characters incorrectly identified among those the system considers as correct. Errors are often due to points not belonging to the character under analysis (noise or other letters). Damaged characters with a too low global contrast can lead to recognition errors, but during the authentication task, the lack of contrast can be detected. Authentication is more demanding than identification as not only shapes but also breaks and contrasts are checked. During authentication (Table 3), the system marks as valid characters whose shape is correct and which have a good contrast. The system marks as non-valid, broken or poorly contrasted characters, characters with ambiguous shape or those that the system has not recognized because their shapes do

```
****************************************************
General characteristics of Page 20 :
****************************************************

-Average contrast of a correct character: 74
-Width of the pen: 10
-Page style : ASHKENAZIC
(Style of manuscript 3 : ASHKENAZIC )
-Page contrast: 142
-Contrast : good
-Average height of a squared character : 24
-Average length of a squared character : 22

class 2 characteristics (character Bet) :
from 7 characters belonging to page 20

Minimal length for the upper bar : 17
Average length for the upper bar: 18
Maximal length for the upper bar: 19
Relative minimal length for the upper bar: 1.5
Relative average length for the upper bar: 1.8
Relative maximal length for the upper bar: 2.0
Average width for the upper bar: 10

from 7 characters belonging to page 20

Minimal length for the lower bar: 18
Average length for the lower bar: 20
Maximal length for the lower bar: 21
Relative minimal length for the lower bar: 1.8
Relative average length for the lower bar: 1.9
Relative maximal length for the lower bar: 2.1
Average width for the lower bar: 10

class 4 characteristics (character Daleth) :
from 3 characters belonging to page 20

Minimal length for the upper bar: 25
Average length for the upper bar: 25
Maximal length for the upper bar: 25
Relative minimal length for the upper bar: 2.5
Relative average length for the upper bar: 2.5
Relative maximal length for the upper bar: 2.5
Average width for the upper bar: 10
```

Fig. 14. Extraction of characteristics of the writing on a page of document during the learning task.

Table 3. Authentication task: quantitative results. The system is more severe than a human expert but the scribe's task of authentication is considerably shortened

	Valid characters (%)	Non-valid characters (%)	Problematic characters (%)
M1	81.0	19.0	11.0
M2	89.0	11.0	0.0
M3	82.0	18.0	3.0

not correspond to any model, however loose, of the knowledge base, or characters that were erroneously recognized and that the system detects as textual errors. Manuscript M1 is in part damaged and contains a lot of non-valid characters because of their too low contrast. In the Ashkenazic manuscript M3, some characters are detected as being broken because some thin vertical downstrokes have completely disappeared after digitization and filtering. The third column shows the percentage of characters found to be problematic to a human expert. These characters may be considered as valid after being analysed by the scribe, but it is necessary to submit them to human judgement (Fig. 15). These are:

—those which have a low contrast or contain breaks because of loss of ink. The scribe has to decide whether they need ink restoration.

—those whose graphical shape may be correct but does not correspond to any model. For instance the character Bet with a rounded upper bar is different from the usual straight shape, or a drop of ink can modify a shape.

During authentication the system validates correctly and directly 80% to 90% of the characters (first column). These characters do not need to be examined later by a human expert as they are also validated by a scribe. By comparing the second and third columns we deduce that the automatic system is more severe than a human expert but considerably shortens the scribe's authentication task.

9. CONCLUSION

In this study, we have built an expert system that not only recognizes handwritten Hebrew characters but that can also provide information about ancient Hebraic texts. The system investigates in a manner close to that of a human expert and provides information about the style, the writing and the validity of the document. Directed by one principal request given by the user, the system collects heterogeneous information in order to give as much information as possible about the text under analysis.

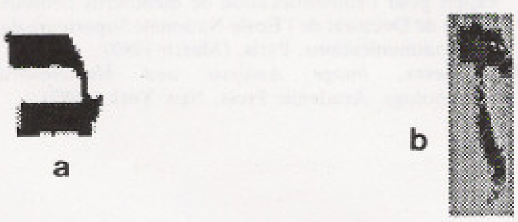

Fig. 15. Examples of characters that must be submitted to human judgement: (a) Bet's upper bar is rounded; (b) the shape of this Nun Sofit is modified because of a drop of ink.

As a vision system, this system works both at a high level of interpretation and a low level with grey level images. It can set up document analysis strategies (general and specific) and interactions between high and low level processes.

The system presented here does not yet perform all the potential operations at each level, especially those that correspond to global vision analysis. Most of the operations presently concern near and magnified vision. However, the structure of this system is complete in that it can work at all levels of vision and new procedures can easily be implemented at their corresponding level. Global vision analysis complements near and magnified vision. In general, global procedures use principles of statistical pattern recognition and would be of great interest to enrich the learning task, to study extensively the page setting and structure of the document or to develop other studies related to writing such as the comparison of scribes or the dating of manuscripts. Using such a system also provides an opportunity to explore, quantify and confirm certain hypotheses about significant or non significant features of writing.

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About the Author—LAURENCE LIKFORMAN-SULEM received an engineering degree in Telecommunications (1984) and a Doctorat in Automatics and Signal Processing from the Ecole Nationale Supérieure des Télécommuications (ENST) in Paris, France, in 1989. Her interests lie in artificial intelligence, image processing, pattern recognition and cognitive science.

Since 1987, she has been a member of the International Graphonomics Society. Her current research activity concerns artificial intelligence and document understanding.

About the Author—HENRI MAÎTRE received the engineering degree from the Ecole Centrale de Lyon, France, in 1971. He received the "Docteur ès Sciences" degree in physics from the University of Paris VI in 1982.

Since 1973 he has taught digital picture processing at the Ecole Nationale Supérieure des Télécommunications (ENST) in Paris. As Head of the Images Department there, his research includes work on image analysis, image understanding and computer vision. He has published more than 40 papers, mainly in image processing and optics.

About the Author—COLETTE SIRAT, "Docteur ès Lettres", teaches at the Ecole Pratique des Hautes Etudes (4th section) at Sorbonne University (Paris).

As Head of Section at the Institut de Recherche et d'Histoire des Textes (CNRS), her research includes work on mediaeval Hebrew manuscripts and the history of writing.