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Levels of Representation in Word Processing

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Four experiments are described examining the effects of words frequency, orthographic structure, and letter spacing on a range of tasks designed to tap different levels of representation in word processing. In Experiment 1, the task was lexical decision. Effects of both frequency (high-frequency words were recognized faster than low-frequency words) and orthographic regularity (illegal non-words were rejected faster than legal non-words) were found. In Experiment 2 subjects had to detect a rotated letter within the letter strings. Effects of orthographic structure emerged, with a marked disadvantage for illegal non-words with respect to the other types of string. No difference was found among high-frequency words, low-frequency words and legal non-words. In Experiment 3, subjects had to detect a letter elevated above the horizontal plan with respect to the rest of the string. Effects of both spatial arrangement of letters and number of letters were found (spaced strings were responded to less accurately than non-spaced strings and seven-letter extra-spaced strings were responded to slower than the other strings). Neither lexical nor orthograpic variables affected this task. In Experiment 4 subjects had to detect the presence of a bold segment contained in one of the letters in the strings. Performance was unaffected by both lexical and spatial variables. The pattern of results is discussed with reference to a multi-stage model of word recognition in which lexical and spatial variables affect processing at different stages. At a feature map level, in which features are extracted from the discontinuities of light intensities, processing is independent of both spatial and lexical

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factors. At a letter-shape map level, in which spatial relationships between features are coded, spacing between letters affects encoding. At a graphemic map level, in which letter identities and their relative positions within strings are coded, orthographic variables have an effect. Lexicality and frequency affect only subsequent stages of processing, when stored lexical information is retrieved (e.g. for lexical decision).

Visual word recognition probably involves multiple processing stages, which enable semantic and phonological information about words to be accessed from the orthographic input. Perceptual as well as linguistic factors affect such a process, the former mainly in the initial phases. In this paper we report a series of studies on the factors affecting the visual representations mediating word recognition.

The framework within which the studies were conducted is that outlined by Marr (1982; see also Marr & Nishihara, 1978) to account for object recognition. Marr's theory postulates that several types of representation are implicated in visual information processing. Starting from a primal sketch of the primitive features, a series of representations in which the information extracted is increasingly abstract and independent from the local relationships between the object components is constructed. This process ends when a structural description of the object's shape is build, coded relative to an object-centred co-ordinate system (the 3D model).

There are several features that render Marr's proposal interesting and make it appealing for visual word recognition. The parallel between the two domains has already been explicitly discussed by Monk (1985) and by Caramazza and Hillis (1990).

Monk (1985) addressed the issue by proposing potential primitives and potential coordinate systems of the reading process, and by discussing how they might interact to generate a representation of the printed material. Among the primitives Monk considered visual features, letters, graphemes, syllables, morphemes, and words, which are assumed to vary along a dimension of abstractness. Among the coordinate systems, Monk considered a retinal coordinate system, a viewer-centred and a real-word-coordinate system (both considered spatial coordinate systems), a word-centred coordinate system, and a sentence-centred coordinate system. According to Monk, in word-recognition studies empirical evidence is available only for postulating the existence of the first of the three stages proposed by Marr and Nishihara—that is, the primal sketch. This has a retinal coordinate system and primitives just less abstract than words (i.e. letter features or letters) and is computed within a single eye fixation. In contrast, intermediate spatial coordinate systems were not considered necessary in reading. However, Monk argued that there may be a role for a word-centred stage of representation, as this may be particularly useful for accessing stored lexical knowledge. He suggested that word-centred representations consisted of an ordered set of graphemes, anchored either to the initial or the final grapheme, or to both. This proposal departs from models in which descriptions based on position-specific letter information are used to access the lexicon (Johnston & McClelland, 1980; McClelland & Rumelhart, 1981).

The levels identified by Monk for the linguistic domain do not closely correspond to the levels identified by Marr in the object domain. Specifically, the early stages of word analysis proposed by Monk are supposed to operate on all units less abstract than words (including letter features and letters); thus the primitives involved are not specific to that particular level of representation, contrary to the Marr and Nishihara proposal.

Closer to Marr's notion of levels is the proposal by Caramazza and Hillis (1990, henceforth C&H). They assumed that in word recognition the three stages involved are: (1) A stage at which the relevant discontinuities of the image are computed directly from the spectrum of light intensities; the representation at this level consists of a retino-centric description of the edges of the image (the *feature map*). (2) A stage at which the spatial relationships between segments within each letter and among the letters of a string are computed from the set of the extracted features; the representation at this level consists of a veridical representation of spatial arrangement of line segments in relation not to their absolute position in the visual field but to the stimulus itself. This representation is also dependent on the observer's point of view (the *letter-shape map*). (3) A stage at which the letter shapes are translated into a sequence of graphemes—abstract units that do not retain information on case, font, and orientation of the input letter string. The representation at this level consists of a word-centred description of the graphemes and their relative position within the string (the *graphemic map*).

Empirical support for C&H's proposal comes from the reading performance of a brain-damaged patient, NG, affected by a right visual neglect. On a number of experimental tasks, this patient exhibited deficits in correctly reporting the final part of the words. Most interestingly, her performance was unaffected by the spatial orientation of the string. Errors always involved the end of the word, irrespective of the word's orientation (whether strings were horizontally oriented, vertically oriented, or mirror-reversed). This fits with the proposal that the visual system, through successive elaboration, produces a graphemic representation in which the string is normalized in a horizontal left-to-right canonical format, and in which the spatial position of component graphemes is specified. This same representation is constructed irrespective of the initial orientation of the string. The performance of other brain-damaged patients has been analysed in terms of this framework in order to isolate different deficits at various processing stages (Hillis & Caramazza, 1991; Rapp & Caramazza, 1991) (see later on).

Some empirical evidence reported in the literature—although not discussed with reference to this particular model—can be shown to be consistent with it.

The idea of a first stage in object recognition in which stimulus features are extracted is proposed in studies on feature-integration processes. Processes operating at this stage are assumed to be independent of the nature of the stimulus and computed in a fast, efficient, parallel fashion. Empirical support for such assumptions comes from the fact that, within certain boundary conditions, a target stimulus defined by a difference in a simple feature relative to other stimuli in the field is detected efficiently and independently from the number of neighbouring distractors (Donnelly, Humphreys, & Riddoch, 1991; Treisman, 1985; Treisman, 1991). Based on such results, it appears that simple features such as colour, orientation, closure, and symmetry are coded at this stage (Duncan & Humphreys, 1989; Treisman & Gelade, 1980). Furthermore, the speed of the target detection has been shown to be dependent on distractor homogeneity, thus suggesting that this level of representation is sensitive to low-level organization principles such as similarity (Duncan & Humphreys, 1989). Concerning letter strings, Krueger and Shapiro (1979) collected evidence in favour of a representation stage *common* to all types of letter sequences, in which letter features are specified. In their study, the well-known word superiority effect was found when subjects had to detect a target letter within words and non-words, but not when subjects had to decide whether or not the target letter was mutilated, the mutilation consisting in the deletion of one or more letter segments.

A second line of evidence relevant to the model proposed by C&H is provided by orthographic priming. Several studies have shown that when two letter strings are presented in rapid succession for a very short time, priming effects can be obtained (Columbo, 1986; Humphreys, Evett, Quinlan, & Besner, 1987; but see Forster, 1987, for some constraints on the effect). Priming effects increase as a function of both the number and the position of the letters shared by primes and targets (Peressotti & Grainger, in press). Furthermore, the effects seem to depend crucially on experimental procedures that make prime and target not perceived as two separate events, and, as they occur with letter-string primes and are independent of the effects of word frequency, they appear to reflect prelexical stages of word processing (Humphreys et al., 1987). Three main conclusions from these studies are of interest here: (1) Word recognition is not based on the simple description of the component letter representations (presumably used for single-letter identification), but it requires an orthographic description of the entire string (Humphreys, Evett, & Quinlan, 1990). (2) The orthographic description is computed through several stages (Humphreys et al., 1987). (3) The orthographic description consists of a sequence of graphemes in which the abstract letter identities (Coltheart, 1981) and the relative positions of the letters (Humphreys et al., 1990) are specified. This latter argument is also supported by position-preserving migration errors in tachistoscopic identification (Allport, 1977). By and large, then, this empirical evidence supports the notion of a level of representation at which the information specified concerns an abstract sequence of graphemes constituting the input for lexical access. This corresponds closely to the third stage, the graphemic map, of the C&H model. Empirical evidence from normal subjects for the second level of the model is scarce. However, some neuropsychological data have been reported which bear on this issue. Hillis and Caramazza (1991) described the reading and spelling performance of patient RW, who had left hemispatial neglect. She made errors to the left halves of words, which increased with word length and with extra spacing between the letters. The errors she made were always confined to the left part of the stimulus, irrespective of the spatial arrangement of the string: she neglected the beginnings of normally arranged words but the final letters of mirror-reversed words. The authors argue that the functional locus of the impairment concerns a visually based level of representation at which spatial relationships are computed—that is, the letter-shape map.

The experiments reported in the present paper were designed to evaluate the idea of a multi-stage word recognition process. In the C&H model, several factors are assumed to play a role at the different levels of representation. In particular, lexical factors such as word frequency are thought to affect the set of processes that allow lexical access—that is, the processes that take the third level of representation as input—to take place. Spatial information, on the other hand, is assumed to affect all three stages, the specific type of information varying with respect to the coordinate system and the primitives involved. At the first stage, the absolute position of each letter segment in the visual field is relevant; at the second stage, the spatial relationships between letter segments become relevant; at the third stage, the relationship among graphemes becomes relevant. We manipulated several factors assumed to affect different levels of processing in word recognition and used tasks aimed at tapping into these different levels. The factors varied were chosen to affect coding : (a) at feature level (i.e. the differential thickness of a letter segment); (b) at a spatial letter-shape level (i.e. the elevation of a letter with respect to the others, the reversing of a letter, and the spacing between letters); (c) at a word-centred, graphemic level (i.e. the lexical status of the letter strings, word versus non-word; the orthographic regularity of non-words, legal versus illegal strings; and the frequency of words, high- versus low-frequency words). The tasks performed by subjects were designed to detect the influence, or lack of it, of these factors at the various postulated stages of word processing.

The paper is organized in such a way as to show first effects of lexicality, non-word orthographic regularity, and word frequency, using a task requiring lexical access. We then go on to show that in a task requiring information about letter identities, lexicality and frequency no longer play a role, although the orthographic structure of the stimuli still does. Subsequently we show that, in a task in which the spatial relationships between letters must be computed, the effect of orthographic structure disappears whereas spatial factors come into play. Finally, in a task in which a primitive feature must be detected, none of the factors manipulated had an effect. The logic used is thus similar to that used previously by Schvaneveldt and McDonald (1981) who also used different tasks in an attempt to tap different levels of representation in word processing, although both the reference model and the experimental paradigms are quite different. In fact, they used a priming paradigm and employed lexical decision, detection of a rotated letter in a word, or detection of a gap in one letter of a word as experimental tasks, with the aim of measuring contextual effects on subjects' performance.

Clearly, the hierarchical model of C&H assumes that the different tasks tap different stages of word recognition rather than being performed on the basis of "ad hoc" representations. So, independently of the task, we would expect the same type of representation (i.e. the same coordinate system and the same primitives) to be computed to extract specific information at any given level of the process and, conversely, that information required to execute the different tasks would be available at different levels of representation. We do not mean that, for each task, the processing of information stops at the level at which the information required by the task is available, thus blocking any further processing. Rather, we claim that even though the processing may sometimes be exhaustive, in the sense that all the permissible and relevant levels of processing are computed, the decision required from subjects is made as soon as the relevant information is available at a particular level of representation.

The logic behind this study is to show that a factor affecting a later stage in word processing (e.g. the graphemic level) does not play a role at a lower level (e.g. at the level of the feature map). Of course, this does not mean that in general a factor may have only one locus of effect, or that there may not be carry-over effects from earlier to later levels of processing. Rather, we assume that because of the strict paring of processing stages and variables in our experimental conditions we are in a position to detect selective effects at each level of representation.

GENERAL METHOD

Apparatus and Display Conditions. The experiment was controlled by a Macintosh Classic computer. The stimuli were displayed on a screen, placed approximately 65 cm from the eyes of the subject. The fixation point was an asterisk appearing in the centre of the screen for 500 msec; 500 msec after its offset, the stimulus followed at the same location. The stimulus consisted of a string of either five or seven letters. When displayed, a letter on the screen subtended a visual angle of 0.54° vertically and 0.45° horizontally. The space between letters was varied between conditions. In the "normal-space" condition the inter-letter space subtended approximately 0.17°; in a second extra-space condition it was 0.55°. Therefore, the string of five letters subtended approximately 2.93° and 4.5° in the normal and extra-space conditions, respectively;

the seven-letter string subtended approximately 4.17° and 6.48°. All the stimuli were displayed for 200 msec in a dark-on-light format and were followed by a pattern mask, which covered the same spatial region as the stimuli. The mask was generated from randomly orienting letter segments and was presented for 200 msec. These exposure durations were "nominal" rather than exact, because display changes in reality occurred within the standard 16.66-msec scan rate of the Macintosh Classic monitor. This means that all actual durations varied in a random manner with a uniform probability between exposure time and exposure time plus 16.66 msec.

The bottom row rightmost key (KeyPad) and the bottom row leftmost key (Control) of the keyboard were selected as response buttons. The keyboard was placed in front of the subject.

The experiment took place in a sound-attenuated, dimly illuminated cubicle.

Stimuli. A total of 288 letter strings was used, 168 seven-letter strings and 120 five-letter strings.[1] The strings were either words or non-words and were classified into four categories: high-frequency words, low-frequency words, legal non-words, and illegal non-words. The list of seven-letter strings contained 42 items in each class; that for five-letter strings contained 30 items in each class. For word frequencies the Bortolini, Tagliavini, and Zampolli (1977) corpus was used (high-frequency class, mean frequency = 106.01; low-frequency class, mean frequency = 1.80). Legal non-words were created by changing one or two letters of real words, without violating the phonotactic rules. Illegal non-words consisted of consonant sequences that are unpronounceable in Italian. All strings were displayed in upper case (font: MicroBoston 24).

Apart from Experiment 1 (see Experiment 1, Method section), half of the stimuli were experimental items and half were fillers (the former are listed in the Appendix). For the experimental items, one of the letters of the string was the target letter. It could occupy any position in the string, with the constraint that there were 12 items per position equally distributed between the types of string (i.e. 3 items for each type of string). Target letter identity and position were constant between the four types of strings. The target letters were always *M*, *T*, *R*, or *A*. Given these stimuli, it was possible to test the same letters at all serial positions in each of the four context conditions. Accordingly, any difference in the context conditions could not be due to testing different letters or different positions. In the filler items there was no manipulation of the target letters.

The 288 letter strings were always presented twice, once with normal spacing between letters and once with an extra space between letters.

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[1] The experiments were done in Italian, so Italian words were used, and the orthographic regularity of the non-words concerns Italian rules.

Experimental Design. There was a repeated-measure design with three within-subject factors: (a) *spacing*, with normal spacing and extra-spacing as two blocked levels; (b) *number of letters*, with five-letter strings and seven-letter strings as two blocked levels; and (c) *type of string*, with high-frequency words, low-frequency words, legal non-words, and illegal non-words as four non-blocked levels. The significance level for statistical analyses was set at $p < 0.05$.

Procedure. Each subject was presented with four blocks of strings: (a) the list of five-letter strings with normal spacing between the letters; (b) the list of five-letter strings with extra-spacing between the letters; (c) the list of seven-letter strings with normal spacing between the letters; (d) the list of seven-letter strings with extra-spacing between the letters.

The order of presentation was balanced within subjects. Items within each block were randomized before presentation.

The task varied depending on the experiment. A period of 1000 msec was allowed for the response. If the subject did not respond within that time, a deadline sound announced the following trial. Both response times and accuracy were recorded.

At the beginning of the session two training lists, each containing 40 items, were presented to the subject. The items in the first list had normal spacing between their letters and in the second list there was extra spacing between the letters.

After each block of stimuli the subject had a rest period of approximately 4 min. The overall session took 45 min.

Subjects. A total of 64 subjects—undergraduate students at the University of Padova—participated in the study in order to fulfil a course requirement. Separate groups of 16 subjects were used in each experiment. Each subject was tested in a single experimental session. Ages ranged between 20 and 30 years. All participants had Italian as their first language, and had either normal or corrected-to-normal vision.

EXPERIMENT 1

Subjects performed a lexical decision task. As this task requires word-level information, significant effects of the lexical status of the string (word vs. non-word), frequency (high-frequency word vs. low-frequency word), and orthographic regularity (legal non-words vs. illegal non-words) were expected (for empirical evidence of these effects see reviews by Forster, 1976; Garman, 1990; Taft, 1991). Note that the term "orthographic regularity" refers to the orthographic structure of the non-words, as Italian has practically no orthographically irregular words. The orthographic irregular (i.e. illegal) strings used here were unpronounceable sequences of consonants, which were compared to regular (and therefore pronounceable) non-words derived by changing one letter of a word.

Introducing an extra space between letters might have multiple effects. On the one hand, increasing the spacing between letters reduces the amount of lateral masking between letters and so may enhance letter visibility. On the other hand, increasing eccentricity may lower letter visibility. Furthermore, extra spacing between letters could affect the word-shape information or the computation of sub-lexical units. The empirical evidence on this issue is somewhat equivocal (Mewhort, Marchetti, and Campbell, 1982; for contrasting results see Terry, Samuels, & LaBerge, 1976). According to the C&H model, spacing and linguistic variables affect different processing stages, and so no interaction of spacing with either word frequency or orthographic regularity should be expected.

Method

Subjects had to decide whether or not each string was a word and then reply by pressing either one of two selected response buttons. Half of the subjects had to press the right key with the right hand if they were presented with a word and the left key with the left hand if they were presented with a non-word. For the other half of the subjects the pairing was reversed.

Results

The mean latencies for correct responses were calculated separately across subjects and items, and each data set was submitted to an analysis of variance (ANOVA).[2] Error rates were not submitted to statistical analysis, being less than 7%.

Figure 1 shows response times and error percentages for "word" and "non-word" responses averaged over subjects in the different conditions.

The ANOVA by subjects was performed with number of letters (7 vs. 5 letters), spacing (normal spacing and extra spacing), and type of string (high-frequency words, low-frequency words, legal non-words, illegal non-words) as within-subjects factors.

A significant effect of type of string was obtained, $F1(3, 45) = 110.13$, $MS_e = 4470.95$, showing effects of both frequency and orthographic regularity. Illegal strings (347 msec) were rejected more rapidly than were the other types of strings, high-frequency words were accepted more rapidly than were low-frequency words (378 vs. 420 msec), and legal non-words were rejected more slowly than were the other types of strings (547 msec). Comparing the means

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[2] Throughout the text the ANOVA by subjects will be labelled *F*1 and the ANOVA by items will be labelled *F*2.

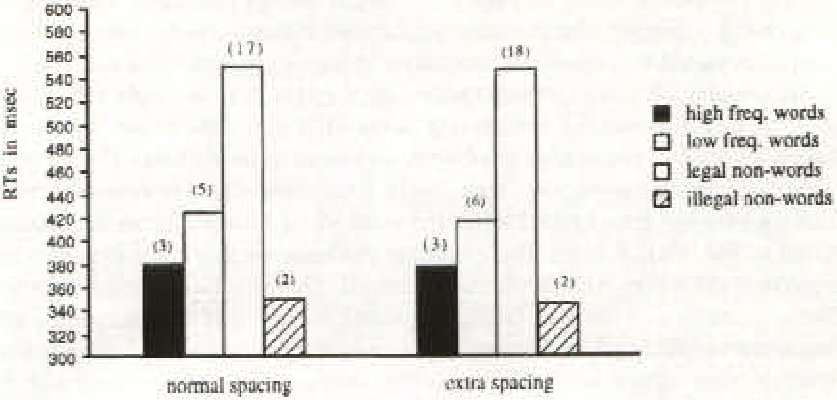

FIG. 1. Response times and error percentages (in parentheses) obtained in the experimental conditions of Experiment 1.

using the Newman-Keuls test, all these differences were significant, $p < 0.01$. Furthermore, an effect of the number of letters emerged, $F1(1, 15) = 120.73$, $MS_e = 1098.74$. Strings with seven letters were responded to more slowly than were five-letter strings (432 vs. 413 msec, respectively). No other effect or interaction reached significance.

The ANOVA by items was performed with number of letters and type of string as between-item factors and spacing as a within-item factor. There were significant effects of type of string, $F2(3, 280) = 592.09$, $MS_e = 1795.86$, and of number of letters, $F2(1, 280) = 19.69$, $MS_e = 1795.86$. Furthermore, the Type of String × Number of Letters interacrtion reached significance $F2(3, 280) = 4.78$, $MS_e = 1795.86$. The Newman-Keuls test, $p < 0.01$, showed that the difference between five- and seven-letter strings was significant only for the legal non-words. Spacing had a small but significant effect, $F2(1, 280) = 5.58$, $MS_e = 633.51$, strings with extra-spacing being responded to more rapidly than normally spaced strings (419 vs. 424 msec).

Discussion

As expected, the variables of word frequency and orthographic regularity affected lexical decision times. Frequency effects presumably reflect the relative speed of lexical access, with lexical information for high-frequency words being accessed faster than that for low-frequency words. The effects of orthographic regularity were apparent in the fast rejection of orthographically illegal strings relative to orthographically legal strings. This is congruent with the results of previous studies (e.g. James, 1975). Furthermore, in the analysis by items a significant effect of spacing emerged; strings with extra-spacing were responded to faster than were those with normal spacing. This result suggests that increasing the spacing between letters speeded up lexical access, probably by reducing lateral masking between the letters (cf. Bouma, 1970). However, the difference between widely spaced and normal-spaced strings, although statistically significant, was very small in size (5 msec); hence, we should not attach too much importance to it. Consistent with our predictions, the interaction between spacing and type of string was not significant. This reinforces the conclusion that spatial information is coded independently from the lexical status of the string.

In Experiment 2 we used a task aimed at tapping a stage of processing not affected by either the lexical status of the string (word vs. non-word) or word frequency. On the same materials as used in Experiment 1, subjects were required to detect the presence of a letter turned upside-down. Our assumption here was that the recognition of a rotated letter occurs when computing the abstract identities of graphemes from the corresponding letter shapes. Thus, this task is assumed to be based on information available during the process of grapheme identification, which terminates in an abstract representation of the graphemes and of their relative position within the string, independent of other properties, such as orientation, case, and font.

EXPERIMENT 2

According to C&H's multi-stage model of word recognition, lexical access takes place after computing a representation in which the abstract identities of the graphemes are specified (see also Coltheart, 1981; Evett & Humphreys, 1981; Friedman, 1980). Thus, the process of grapheme identification should be independent from the fact that the string is either a word or a non-word. However, this process could be affected by other variables, such as orthographic regularity; several studies have shown that, over and above effects of bigram frequency, sub-lexical orthographic units—such as syllables—can affect word processing at an early perceptual stage (Carr, Posner, Pollatsek, & Snyder, 1979; Prinzmetal, Hoffman, & Vest, 1991; Rapp, 1992; Seidenberg & McClelland, 1989).

As anticipated, in order to recognize a rotated letter, the visual system needs to analyse the presented letter shapes and to match them with a memory representation.[3] This task is quite different from lexical decision, because it necessitates that subjects identify a target element within the string without necessarily taking into account the entire string as such. Effects of orthographic regularity may emerge if the search process is facilitated by the presence of regular sub-lexical orthographic units (e.g. Aderman & Smith, 1971).

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[3] Recognizing that a letter is rotated does not a priori mean that the letter is identified. However, some cursory processing at least at shape level (and not necessarily at name level) should be carried out.

Increasing the spaces between letters should not affect the processes of grapheme identification, as (we assume) spatial information is not coded at this level but must have been coded previously. Thus, as in Experiment 1, no interaction between spacing and type of string is expected.

Method

The same strings as those used in Experiment 1 were divided into two groups: half were experimental items and half fillers (see the General Method section). The experimental items consisted of letter strings in which one of the component letters was turned upside-down[4] (see examples in Table 1a). The fillers did not contain any rotated letter.

The subjects were requested to press the left key ("Yes" response) if one of the letters of the string was rotated and the right key ("No" response) if the string did not contain a rotated letter.

Results

Figure 2 shows correct response times (RTs) for the detection of the rotated letter ("Yes" responses) and error rates averaged over subjects. The mean latencies for correct "Yes" responses were calculated separately across subjects and items, and each data set was submitted to statistical analysis (ANOVA), as in Experiment 1.

The ANOVA by subjects showed a significant effect of type of string, $F1(3, 45) = 13.87$, $MS_e = 2601.09$. Pairwise comparisons using the Newman-Keuls test, $p < 0.01$, revealed that the rotated letter was detected equally fast in high-frequency words, low-frequency words, and legal non-words, but consistently longer RTs were obtained when the rotated letter was contained in an illegal non-word. Also, the first-order Type of String × Number of Letter interaction reached significance, $F1(3, 45) = 3.18$, $MS_e = 990.56$. The Newman-Keuls test, $p < 0.01$, revealed that the disadvantage for illegal strings was more

TABLE 1
Examples of the Stimuli Used in Experiment 2 (a), in Experiment 3 (b), and in Experiment 4 (c)

a	*b*		*c*
	Experimental	*Control*	
NEONAꞱO	NEONATO	NEONATO	NEONATO
C∀VALLO	CAVALLO	CAVALLO	CAVALLO

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[4] In Italian the rotated M is not potentially ambiguous, as it is in other languages, because W is not part of the Italian alphabet.

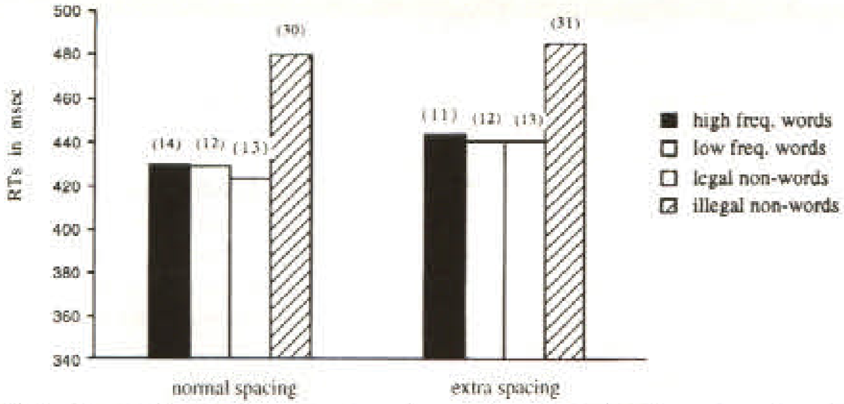

FIG. 2. Response times and error percentages (in parentheses) obtained in the experimental conditions of Experiment 2.

marked when the strings were seven letters long ($437 = 438 = 435 < 498$) than when the strings were five letters long ($435 = 430 = 428 < 465$). No other factor or interaction reached significance.

The ANOVA by items showed a significant effect of type of string, $F2(3, 133) = 8.58$, $MS_e = 3182.95$, and of spacing, $F2(1, 133) = 11.18$, $MS_e = 1670.92$. The latter was due to the fact that strings with extra spacing were responded to more slowly than were normally spaced strings (453 vs. 438 msec).

As can be seen from Figure 2, error rates paralleled response times. An ANOVA using arcsin transformations of the percentage errors was also performed, with spacing, number of letters, and type of string as three within-subjects factors. Significant effects of both number of letters, $F1(1, 15) = 53.55$, $MS_e = 0.075$, and type of string, $F1(3, 45) = 19.46$, $MS_e = 0.206$ emerged. Subjects failed to detect the rotated letter in a seven-letter string on 21% of trials and in a five-letter string on 13% of trials. Furthermore, the Newman-Keuls test, $p < 0.01$, showed that more misses were made when the rotated letter was contained in an illegal non-word than if it was either in a legal non-word or in a high- or low-frequency word ($31\% > 13\% = 13\% = 11\%$, respectively).

Discussion

Globally, the results show an effect of orthographic regularity. All the analyses performed revealed a significant effect of the type of string factor, with a disadvantage for the illegal strings relative to the other types of string. This is consistent with the hypothesis that the process of grapheme identification from letter shapes is facilitated by orthographic regularity. Furthermore, the fact that no effects of both wordness and frequency were found makes us more confident about our assumption that a representation of the abstract identities of the graphemes is constructed before lexical access.

As for the effects of inter-letter spacing, there was at best only a trend for slower RTs to extra-spaced strings, but this was statistically significant only in the analysis over items. Also, the interaction between spacing and type of string failed to reach significance. This suggests that spacing affects all types of string equally, independently of both orthographic and lexical factors.

From the comparison between Experiment 1 and 2, however, a puzzling inconsistency emerges. Extra spacing between letters speeds up lexical decision slightly, but it retards the detection of rotated letters. Neither low-level lateral masking nor eccentricity can account for this asymmetry, because the same letter sequences and the same visual conditions were used in the two experiments. It would be tempting to interpret these opposite results as confirming that the two tasks are based on different representations. However, we do not attach too much importance to the 5-msec difference obtained in Experiment 1, because (a) it is very small, (b) it is reliable only in the analysis by item, and (c) it is probably due to extra-spaced strings benefiting more than normally spaced strings when presented as the second block.

Experiment 3 aimed at showing that, in a task in which spatial information is relevant for the response, there are no effects of either orthography, wordness, or frequency. On the same set of strings used in the previous experiments, subjects had to detect the presence of a letter that was elevated above the horizontal plan with respect to the others. Here we assume that this task taps into a level in which spatial relationships between elements are computed.

EXPERIMENT 3

In line with models of object perception (Marr, 1982), C&H's model postulates a second stage of analysis after visual feature extraction, in which the primitive features are combined into the correct spatial combinations. At this level the relevant information is the spatial position of each element with respect to the other elements, coded independently from their absolute position on the retina, but in relation to the observer point of view. Postulating such a stage for word recognition may be unwarranted, as in reading the relevant spatial information is the relative position of each letter in a word and the relative position of each word in a sentence. So, from an ecological point of view, a stage at which spatial information about unidentified letter shapes is computed in relation to the observer point of view might be unnecessary. Furthermore, spatial information could be computed in parallel with feature extraction: there is no motivating reason to distinguish between two serial processing stages, one in which features are extracted and the other in which spatial relationships are computed (Sanoky, 1991). We discuss this issue more fully in the General Discussion. For the moment, let us simply assume that spatial information is coded at a stage of processing prior to the construction of an abstract representation of the letter identities, and so independently from the lexical status of the string, as suggested by the lack of interaction between letter spacing and type of string in Experiments 1 and 2. The task we selected to examine spatial representations in word processing—judging the alignment of letters—may appear to have little to do with word recognition. However, to decide that a letter is elevated with respect to the other letters in the string requires the computation of the spatial relationships among the letter shapes: letter segments have to be grouped into spatially segmented shapes functional to word recognition, and the relationships among these shapes have to be analysed.

Method

The experimental items contained a letter that lay two pixels above the horizontal plan with respect to the other letters. The fillers contained letters placed on the same horizontal plan, but one of them was two pixels taller than the others in such a way that it protruded from the top edge of the string, as did the elevated letter (see Table 1). Thus, detecting the elevated letter should depend on the detection of differential spatial relationships between letter shapes, and could not simply be based on the spatial extent of the area occupied by the stimulus in a retinally projected image. Subjects were requested to press the left key ("Yes" response) if one of the letters of the string was elevated and the right key ("No" response) if the string did not contain an elevated letter.

Results

Figure 3 shows correct RTs for the detection of the elevated letter ("Yes" responses) and error rates (missing) averaged over subjects.

In the ANOVA by subjects only the Spacing × Number of Letters interaction reached significance, $F1(1, 15) = 4.96$, $MS_e = 2090.97$. Pairwise comparisons using the Newman-Keuls test showed that, in the normal spacing condition, subjects could detect an elevated letter contained in a seven-letter or five-letter string equally quickly (435 and 438 msec, respectively). On the other hand, in the extra-spacing condition, RTs to seven-letter strings were consistently longer than RTs to five-letter strings (471 and 449 msec, respectively, $p < 0.05$). No other effect or interaction reached significance.

The ANOVA by items showed a significant main effect of spacing, $F2(1, 136) = 35.21$, $MS_e = 1338.02$, and, consistent with the ANOVA by subjects, there was a significant first-order Spacing × Number of Letters interaction, $F2(1, 136) = 9.27$, $MS_e = 1338.02$. Strings with extra spacing were responded to more slowly than were normally spaced strings (472 vs. 446 msec). This difference, however, was almost totally due to the seven-letter strings. In fact, mean latencies in the extra space and the normal space conditions were 486 and 447 for seven-letter strings, and 458 and 446 for five-letter strings, respectively.

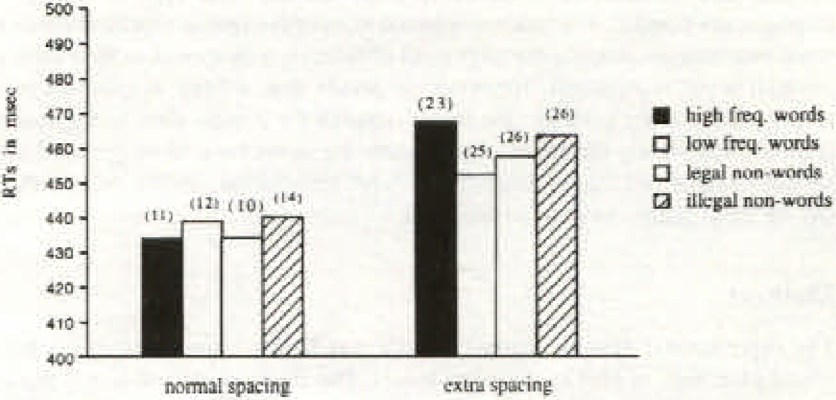

FIG. 3. Response times and error percentages (in parentheses) obtained in the experimental conditions of Experiment 3.

An ANOVA was also performed on arcsin-transformed error percentages with spacing, number of letters, and type of string as within-subject factors. There were significant main effects of spacing, $F1(1, 15) = 62.65$, $MS_e = 0.17$, and number of letters, $F1(1, 15) = 91.20$, $MS_e = 0.050$. More errors were made to seven-letter strings than to five-letter strings (21% vs. 14%), and more errors were made to extra-spaced strings than to normally spaced strings (24% vs. 11%). However, there was no hint of a significant interaction, $F < 1$.

Experiment 1 vs. 2 vs. 3

Globally considered, the results of Experiment 3 show no effects of orthography, lexicality, and frequency. However, given the weakness of a conclusion based on a null effect, a statistical analysis comparing the three experiments was performed in order to clarify whether the different types of string are indeed treated differently by the visual system in the first two tasks (i.e. lexical decision, and detection of a rotated letter), but in the same way in this task (i.e. detection of an elevated letter). The mean latencies obtained in the different conditions were entered in a four-way ANOVA with the experiment factor varying between subjects and the factors spacing, number of letters, and type of string varying within subjects. Main effects of the factor number of letters, $F(1, 45) = 8.89$, $MS_e = 3887.13$ and type of string, $F(3, 135) = 42.27$, $MS_e = 2656.97$, were obtained. Seven-letter strings were responded to more slowly than five-letter strings (445 vs. 432 msec, respectively). The main effect of type of string is qualified by the Type of String × Experiment interaction, $F(6, 135) = 78.44$, $MS_e = 2656.97$. Mean latencies obtained in the three experiments are represented in Table 2.

TABLE 2
Mean Response Times for Words and Non-words Obtained in Experiments 1, 2, and 3

Experiment	*Words*		*Non-words*	
	High-freq.	*Low-freq.*	*Legal*	*Illegal*
1	378	420	547	347
2	436	434	431	481
3	450	446	446	452

Planned comparisons between the means showed that for Experiment 1, all the differences between the four types of strings were significant; for Experiment 2, only illegal non-words differed from the other types of string; for Experiment 3, the four types of string did not differ from each other. Furthermore, the three-level Experiment × Number of Letters × Type of String interaction was significant, $F(6, 135) = 2.66$, $MS_e = 876.56$. This interaction occurred because there was a larger difference between seven- and five-letter strings within legal non-words in Experiment 1 and within illegal non-words in Experiment 2 than in the other conditions. Given that the RTs of Experiment 3 do not differ from those of Experiments 1 and 2, it is unlikely that the lack of effect of frequency or orthographic regularity was due to Experiment 3 being more difficult or easier to perform.

Discussion

The analysis across experiments confirms that the elevated letter was detected independently of the lexical status of the string. Indeed, within this task, only factors strictly related to the spatial arrangements of the stimulus affected performance: the efficiency of detecting an elevated letter depends both on the spacing between the letters and the number of letters. While this pattern shows an effect of spatial factors, it does not allow us to decide whether the spatial relationships between letters are computed in parallel with feature extraction or, as suggested by Marr's object recognition model (1982) and/or Treisman's pattern recognition model (1985), they are computed at a separate, subsequent stage. To this end, the next experiment was devised. Using the same set of strings of the previous experiments, subjects were required to detect the presence of a bold segment contained in one of the letters, with the assumption that this task would tap into feature extraction processes. If feature detection is a process not affected by spatial relations between letters, we should not expect effects deriving from either the number or the spatial arrangement of letters.

EXPERIMENT 4

Feature extraction is assumed to be a bottom-up process that depends strictly on both the physical characteristics of the stimulus and the receptor system involved. It is assumed to be independent, however, of the abstract properties of the stimulus. According to Treisman's theory (1985, 1986), during early stages of visual analysis the visual system decomposes the physical array of light along separate dimensions in which the "basic elements" or "unique features" are defined. This process is assumed to be spatially parallel and the area or visual angle of the display should have little effect, provided that acuity limits are not exceeded. Only at a later stage would the basic elements be re-combined into coherent combinations of features through focused attention, and this operation can be performed only serially. Several factors affect the type of processing and the type of unit involved at this stage (cf. Donnelly et al., 1991; Treisman, 1991), as well as the specific mechanisms assumed to be responsible for coding parts into objects (see, e.g., Duncan & Humphreys, 1992; Treisman, 1992).

If spatial relationships between letters are computed independently from feature identification, and if this latter process is performed in parallel, at least under certain boundary conditions, we should expect that detecting a simple feature will be independent from both the number and the spatial arrangement of the elements in an array.

Method

The experimental items consisted of letter strings in which a segment of one of the component letters was typed in bold (see examples in Table 1c). The subjects were requested to press the left key ("Yes" response) if one of the letters of the string contained a bold segment and the right key if the string did not contain any bold segments ("No" response).

Results and Discussion

Figure 4 shows the correct response times for the detection of the bold segment and error rates (missing) averaged over subjects.

None of the ANOVAs, either by subjects or by items, showed significant effects of any of the factors. Furthermore, no interactions reached significance. This same pattern of results was obtained in the analysis on the error data, performed as in the previous experiments. A bold segment was detected independently of the number of letters of the string, all Fs < 1; independently of the spacing between letters, all $F1$s < 1 in the analysis of RTs and errors by subjects, $F2(1, 135) = 3.2$ in the error analysis by items; and independently of the lexical status of the string, $F1(3, 45) = 1.3$, $F1 < 1$ in the analysis of RTs and errors by subjects, respectively, $F2 < 1$ in the analysis by items.

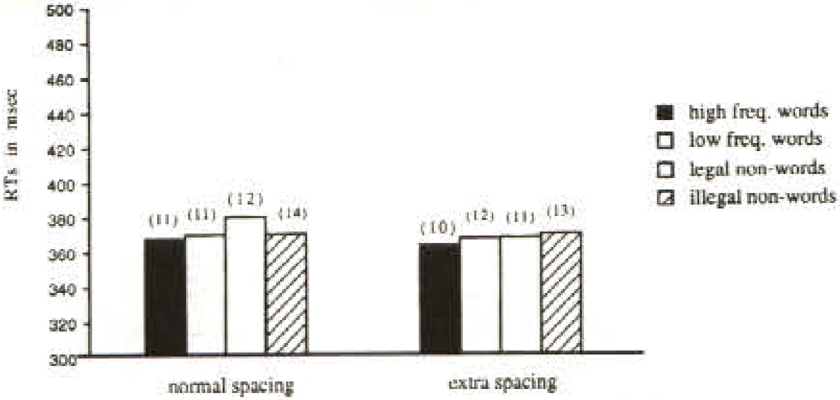

FIG. 4. Response times and error percentages (in parentheses) obtained in the experimental conditions of Experiment 4.

Discussion

We have assumed that recognizing a bold segment involves solely a process of feature extraction. The results obtained suggest that at this early stage visual analyses are conducted independently of both spatial and linguistic variables. The data suggest that spatial variables (i.e. the spacing between the letters in a letter string) have an effect when detecting an elevated letter, but have no effects when detecting a bold segment, indicating that spatial information and feature extraction are computed at separate levels of processing.

In order to show that there is a substantial difference in processing spatial information in the two tasks, a further statistical analysis was run, comparing the data of Experiment 3 and Experiment 4. The means obtained for normally spaced and extra-spaced five- and seven-letter strings in the two experiments are presented in Table 3. The means were entered in a three-way ANOVA with experiment as a between-subjects factor and spacing and number of letters as within-subject factors.

If spatial information is processed when detecting an elevated letter but not when detecting a bold segment, we would expect to obtain a significant interaction between experiment and spacing. The analysis showed a significant main effect of Experiment, $F(1, 30) = 14.51$, $MS_e = 15{,}401.74$. Independently of the other factors, it takes less time to detect a bold segment than it does to detect an elevated letter (370 vs. 456 msec, respectively). More interestingly, the crucial Spacing × Experiment interaction reached significance, $F(1, 30) = 4.48$, $MS_e = 1790.20$. As expected, planned comparisons between the means showed that while spacing affects the detection of the elevated letter, it has no effect in the detection of the bold segment.

TABLE 3
Mean Response Times for Extra and Normal Spacing Obtained in Experiments 3 and 4

Experiment	*Spacing*	
	Normal	*Extra*
3	440	467
4	372	368

Finally, we should note that the lack of an effect of the current variables on the feature detection task in Experiment 4 was not simply because the task was too easy to observe any effect; RTs for high-frequency words and for illegal non-words in Experiment 4 differed little from latencies for the same stimuli in Experiment 1 (the lexical decision task), where effects of frequency and orthographic regularity were apparent. This also suggests that the failure to find any effect of spacing here (though spacing affected performance in the other experiments) was not because detecting the bold segment was less affected by the constraints of acuity, as decreasing acuity ought also to affect lexical decision. This argument is also supported by the analysis of the distribution of errors within the string, on the assumption that the initial and the final positions should be more prone to errors than the central position as a function of acuity. The relevant comparison, in this case, is between Experiment 4 (detection of a bold segment) and Experiment 2 (detection of a rotated letter), where subjects may fail to report the target element. We compare accuracy to targets in the central position with respect to targets either in the final or the initial positions. Comparing the central versus the final position, in both experiments there is an equivalent slight increase in error rates for the final position. Comparing the central versus the initial position, somewhat more errors are made to the initial position in Experiment 4, and to the central position in Experiment 2. This pattern clearly shows that acuity affects the two tasks in a similar manner and, if anything, affects the initial position of the strings more in Experiment 4 than in Experiment 2.

GENERAL DISCUSSION

Main Findings

Four different tasks were performed on the same set of five- and seven-letter strings, which varied as to both their lexical status and orthographic regularity (i.e. high-frequency words, low-frequency words, legal non-words, and illegal non-words) and the spatial relationship between the component letters (i.e. there was either normal or extra-spacing between the letters). Each task required specific computations in order to make the information for the response available. In a lexical decision task (Experiment 1) a representation of the letter string specifying the graphemes' identity has to be constructed and matched with the memory descriptions of the words. In order to detect a rotated letter (Experiment 2), letter forms have to be computed and matched with the abstract representations of graphemes stored in memory. In order to judge whether letters fall on the same horizontal line, and thus to detect an elevated letter (Experiment 3), the spatial relationships among the strings' letter forms have to be computed. Finally, in order to detect a bold segment (Experiment 4), the letters' component features have to be computed.

In Experiment 1, effects of both frequency and orthographic regularity emerged. High-frequency words were responded to faster than low-frequency words. Non-words with an orthographically regular structure (legal non-words) were responded to more slowly than non-words with an irregular orthographic structure (illegal non-words). This same pattern of results was obtained with both normally and widely spaced letters. In Experiment 2, an effect of orthographic structure emerged, with longer response times to the rotated letter when it occurred in an illegal non-word relative to when it occurred in orthographically regular strings (words and legal non-words). Again, spacing did not interact with these effects. In Experiment 3, no effects of either word frequency or orthographic regularity were observed, but a spatial effect was detected: responses to extra-spaced seven-letter strings were slower than to the other strings. Finally, in Experiment 4, performance was affected neither by lexical nor by spatial variables.

Issues

The four tasks employed are differentially affected by the factors manipulated. This suggests that they are mediated by separate sets of codes and/or visual representations, which are constructed at different rates, depending on the experimental manipulation and task. So, when the task is to search for a bold segment, the representation constructed is sensitive neither to spatial nor to orthographic nor to lexical factors. When the task is to search for an elevated letter, the representation constructed is sensitive to spatial factors but not to orthographic and lexical factors. When the task is to search for a rotated letter, the representation constructed is sensitive to orthographic factors, but it is independent of lexicality and frequency. Finally, when performing a lexical decision task, the representation constructed is affected by orthography, lexicality, and frequency. According to this general observation, we may argue that the set of experiments here isolates several independent visual representations (and/or processes), these representations (and/or processes) being selectively affected by different factors.

Let us first discuss the effect of orthographic structure on subjects' responses. In the first two experiments—the only two in which such a variable plays a role—the strings' orthographic structure has an opposite effect: in Experiment 1, responses to illegal strings are faster than to any other type of string; in Experiment 2, responses to illegal strings are slower than to any other type of string. The main difference between the two experiments is that, in the first, subjects are required to judge the entire string, whereas in the second subjects are required to analyse a single letter. The fact that RTs to illegal strings are so fast in Experiment 1 suggests that one representation used to make a lexical decision is an orthographic description of the word: if the orthographic description characterizing a string is not compatible with language-specific constraints (i.e. is illegal with respect the orthographic rules of a language), no further processing is carried out, and a negative response can be executed rapidly (Jacobs & Grainger, 1992; Seymour, 1987). On the other hand, the slow responses to illegal strings in Experiment 2 suggest that these strings do undergo a search process for the target letter just like all other strings, but such a process is slowed down by the lack of orthographic structure. Further on we present some reasons as to why the lack of orthographic structure may produce such an effect. Here, we would like to compare this result with those obtained by McClelland (1976), with different tasks aimed at tapping into letter identification in words and non-words. Subjects had to either report the letters present in a string or choose the correct letter between a target and a distractor. For words and legal non-words, performance was worse with case-alternated strings than with single-case strings, whereas for illegal non-words no effect of case alternation was observed, performance being quite low in both cases. Such a pattern is readily explainable if we assume that case alternation interferes with the exploitation of orthographic structure by preventing the use of multi-letter orthographic units. When no orthographic structure is present, strings are processed in a letter-by-letter fashion. Data compatible with this view stem from the interaction obtained in Experiment 2 between type of string and number of letters—seven-letter illegal strings were slower than five-letter illegal strings—an outcome predicted by a letter-by-letter strategy.

The explanation for the pattern obtained with illegal strings rests crucially on the notion that these stimuli lack orthographic structure: the difficulty in processing them is thus due to their being difficult to analyse into specific sub-lexical structures. Several candidate sub-lexical units are suggested by the literature: syllables (Prinzmetal et al., 1991; Rapp, 1992), vocalic centre groups (Sphoer & Smith, 1974), letter trigrams (Mozer, 1987), consonant and vowel clusters (Seymour, 1987), a code such as BOSS (Taft, 1979), or units based on bigram frequency (Seidenberg, 1987). Alternatively, the disadvantage for the illegal strings could be brought about by these items being unable to activate a phonological code, contrary to what may happen for words and legal strings (van Orden, 1987). Our data do not allow us to determine which of these possibilities is the correct one, but they do point to the fact that, at a level of computation in which letter identity is recovered, the orthographic structure plays a major role. Furthermore, they suggest that this orthographic effect is independent of both lexicality, as no difference was found between words and legal non-words, and frequency, as no difference was found between high- and low-frequency words.

The fact that none of the linguistic variables had an effect in Experiments 3 and 4 suggests that the processing stages in which spatial and visual analyses are carried on are affected neither by lexicality nor by orthographic regularity, thus providing evidence for some common early coding processes for both words and non-words. This result is consistent with the claim that the locus of word (and/or pseudoword) superiority is verbal rather than spatial-visual, as suggested by Krueger and Shapiro (1979). These authors have constrained the generality of the word superiority effect by showing that it disappears both when items are presented at so fast a rate that performance is near chance, and when subjects' task requires to detect the mutilation of a letter, thus leading to the conclusion that early feature extraction processes are independent of the lexical status of the string.

A second issue to consider is the effect of the spatial manipulation on subjects' responses. Our predictions were that spacing should affect the tasks tapping the level at which letter shape is computed. Therefore, the earlier (i.e. feature-map) level should not be affected by spacing. Furthermore, this factor should not have effects—apart from generic carry-over effects—on the later (i.e. grapheme description) levels of representation. In particular, it should not interact with word frequency and orthographic regularity, as these variables affect later levels of processing. We should then expect spacing to have analogous effects on all types of letter strings. To reiterate, we expected spacing to affect the detection of the elevated letter (Experiment 3) but not the detection of the bold segment (Experiment 4), as only in the former case are the spatial relationships among letters relevant and does extra spacing make computations more difficult. Such a prediction was borne out, accuracy being affected for both five- and seven-letter strings and reaction times only for seven-letter strings in Experiment 3. No effect was detected in Experiment 4. This pattern is consistent with our predictions, but it could be due to the fact that the experimental manipulation of this variable was not able to bring about relevant effects. However, another study (Peressotti & Job, 1993), in which letter strings were irregularly spaced (i.e. the letters of a string could be separated by a mix of no extra-space, one extra space, and two extra spaces) produced a similar pattern of results: the detection of an elevated letter proved again to be heavily affected by spacing conditions, whereas the detection of a bold segment did not. So, the fact that no effects are obtained in Experiment 4 suggests that, to detect a bold segment in a letter string, the search process was carried out in parallel independently of the number of letters (as no difference was detected between five- and seven-letter strings) and letter spatial arrangement (as no difference was detected between normal and extra-spacing). In Experiment 3, on the other hand, the task of detecting an elevated letter requires subjects to take into account the spatial relationships between elements.

Also, for Experiment 1 and 2 predictions were met, with an exception for Experiment 1, which is to be discussed shortly. In fact, spacing did not interact with type of string in either experiment, and in Experiment 2 extra-spaced strings were slower than were normally spaced strings. In Experiment 1, however, extra-spaced strings were faster than were normally spaced strings. The 5-msec advantage was reliable only in the item analysis. This result is not particularly troublesome for the model, because it is quite small and it has not been replicated using a stronger manipulation of the spacing variable. In a study (Peressotti, 1995) in which strings were irregularly spaced, there was a significant 15-msec advantage for normally spaced strings—a pattern congruent with the predicted carry-over effects. It may be worth noting that in that study no interaction between spacing and type of string emerged either.

Another study in which spacing between letters was manipulated was reported by Mewhort et al. (1982). These authors used two tasks: a bar-probe task, in which subjects had to report a cued letter, and a free recall task, in which subjects had to report all the letters of the string. The stimuli were non-words with different degrees of approximation to English words (a factor they call familiarity). Congruent with our results (Experiment 2), they did not find an interaction between spacing and familiarity in the bar probe task. However, in the free recall task spacing had a decremental effect on more familiar letter strings, but not on less familiar strings. This result may be seen as inconsistent with the results of our Experiment 1, as it may be argued that the free recall task requires taking into account the entire string, just as the lexical decision task does. However, the comparison between the two studies may not be appropriate. In the free-recall task episodic memory is heavily involved (subjects had to code the letter sequence—presented for 100 msec—and then recall the component letters). The results obtained, therefore, could be due to the coding processes as well as to recall strategies. The coding processes are certainly affected by inter-letter spacing, and therefore a disadvantage may be expected for spaced strings with respect to non-spaced strings. However, we suggest that this difference should be obtained independently of the familiarity of the string, and so we would expect to find a disadvantage for spaced strings also when the letter sequence is very unfamiliar. The lack of this disadvantage in the Mewhort et al. study could be due to a floor effect: the subjects reported only about 3 to 3.5 letters (out of 8) of unfamiliar strings. This is quite a low performance when compared to the number of letters reported in the classical iconic memory studies (Sperling, 1960). Thus, the interaction between familiarity and spacing obtained by Mewhort et al. may reflect limitations in recalling letters from *both* spaced and unspaced unfamiliar strings from iconic memory.

Up to this point we have discussed the present results assuming that each of the experimental tasks is based on a certain visual representation sensitive to certain factors. A more constraining explanation would posit that these representations are not only different but also hierarchically organized. In this sense, the low-level visual representation that allows subjects to detect a bold segment would be necessary in order to construct a topographic representation in which spatial relationships among features are available and letter shapes are computed (i.e. in which an elevated letter is recognized). In turn, the task of recovering graphemic identities (and so to recognize a letter as rotated) depends on the availability of letter shapes. Finally, a graphemic description is necessary in order to access the mental lexicon and make a lexical decision. Of course, this hierarchical interpretation of the results rests crucially on the assumption—outlined in the Introduction—that a representation underlying a certain process (e.g. feature extraction) does not vary according to the task the subject is required to perform.

Furthermore, this interpretation rests on the fact that the different variables affect processing in a constrained way. It would be falsified if a certain variable affects processes at an early and at a later stage but not at an intermediate stage. Of course, there could be carry-over effects at later stages, especially when visual conditions are limited. However, these effects should follow the hierarchical structure of the model. Finally, factors affecting different processes would be expected to have additive effects and not to interact. So, for example, if spatial information is processed before grapheme identity is computed and spacing affects the former process while orthographic regularity affects the latter, these two variables can eventually summate but not interact (Sternberg, 1969). Note that we are not proposing that grapheme processing would start only when processing of spatial information has already finished: these processes may be brought about in cascade (see McClelland, 1979).

The Model

Let us now develop this hypothesis of a hierarchical model and discuss the pattern of results with reference to C&H's multi-stage model of word recognition outlined in the introduction to the paper.

In C&H's model, a first stage is assumed in which the relevant discontinuities of the image are computed directly from the spectrum of light intensities. The representation at this level consists of a retino-centric description of the edges of the image (i.e. a *feature map*), which is constructed in parallel, independently of the meaningfulness of the stimulus. The results of the bold segment detection task support the existence of such a level of representation as well as the nature of the hypothesized computations. As no effects of the location and the number of letters are observed, the identification of the bold segment must be performed in a parallel fashion. Furthermore, as there are no effects of type of string, the representation underlying such processing must be insensitive to both the lexicality and the frequency of the target strings. The fact that such conclusions are based on the acceptance of the null hypothesis is less troublesome than it may appear, given that the pattern is that exactly predicted by the model.

Furthermore, as already noticed, this pattern is congruent with data reported by Krueger and Shapiro (1979, Experiment 5) and also with data obtained by Schvaneveldt and McDonald (1981). These latter authors found no effects of the semantic context in their semantic priming paradigm when subjects had to detect a gap in one letter of a word.

The second stage postulated in C&H's model concerns the spatial relationships between segments within each letter and among the letters of a string. These spatial relationships are computed from the set of extracted features, and this process scans different portions of the array at different times. The representation at this level consists of a veridical representation of the spatial arrangement of line segments in relation to the stimulus itself and to the observer's point of view (i.e. a *letter-shape map*). The results of the elevated letter-detection task support the existence of this level by showing that this task is sensitive to the spatial relations among letter shapes, but it is insensitive to lexical factors. The fact that in this task an effect of string length is obtained also supports a (limited) serial processing of the string, in the sense that different portions are analysed sequentially (although this pattern is also consistent with a parallel limited-capacity processing).

Finally, a third stage is postulated by C&H's model in which a sequence of graphemes is recovered from the shape properties. The end result is a sequence of graphemes that are independent of case, font, and orientation (i.e. that do not retain the "physical" features of the stimulus string). The results of the rotated-letter detection task clearly demonstrate that such a process is influenced by orthographic structure, thus revealing that the graphemic map contains information relative to the orthographic characteristics of the string (see also Humphreys et al., 1990). No lexical effects are observed here, and this finding is congruent with the data reported by Schvaneveldt and McDonald (1981), who also used stimuli with a rotated letter in their semantic priming paradigm. The subjects' task was to decide whether the target stimulus was a regularly written word or whether it contained a rotated letter. They found that, although regular word stimuli did show effects of semantic context, altered word stimuli did not. This is exactly what would be predicted by the model, as information about rotation would be available at a level of processing not affected by lexicality and semantics. The representation at this third level specifies a word-centred description of the graphemes and their relative position within the string and serves as input to the stage of lexical access. Lexical factors are assumed to have an effect at this stage.

The empirical data here reported are far from exhaustive, of course, but our aim was not to test for all the aspects of the model. Rather, our aim was to show that specific predictions derived from the hierarchical model were *congruent* with a set of data collected, taking into account the assumptions underlying the model. In this vein, our study offers a working hypothesis that needs further empirical evidence from both normal subjects and neurological patients.

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APPENDIX

Experimental items (the italic letter was the target letter).

High-freq. Words	*Low-freq. Words*	*Legal Non-words*	*Illegal Non-words*
Seven-letter strings			
*M*ILIONE	*M*ALARIA	*M*ASTOLO	*M*SDFGRT
*R*AGAZZO	*R*ETTORE	*R*ISTOLO	*R*LPRZZS
*R*ICORDO	*R*AFFICA	*R*ONTOLO	*R*LPTRSZ
B*A*MBINO	V*A*LVOLA	B*A*NDIMO	L*A*TTRNB
B*R*ACCIO	A*R*MADIO	C*R*ACCIA	P*R*DFLPZ
C*A*VALLO	T*A*LENTO	C*A*VANNA	C*A*FFLPD
MO*M*ENTO	FU*M*ETTO	LU*M*ETTA	LD*M*SSDT
NO*T*IZIA	IN*T*UITO	IN*T*RUGO	GP*T*SZNC
MA*T*ERIA	AR*T*ERIA	AR*T*OSTA	FQ*T*DFPB
ESE*M*PIO	FOR*M*ICA	STE*M*PIO	NVC*M*ZPR
ANI*M*ALE	STO*M*ACO	ARI*M*ATO	VQN*M*TPL
PAD*R*ONE	SPI*R*ALE	AND*R*OLE	LFS*R*CBP
ALBE*R*GO	REPA*R*TO	IMPE*R*TO	GFSB*R*GN
SOLD*A*TO	ASSE*T*TO	COVE*T*TA	GSLP*T*VC
OGGE*T*TO	POLL*A*IO	REESP*A*IO	CVQS*A*TR
SISTE*M*A	LEGNA*M*E	SURIS*M*O	MLPDC*M*F
MERCA*T*O	NEONA*T*O	METRI*T*O	CDQMP*T*G
EFFET*T*O	PULPI*T*O	SALPI*T*O	GFDQP*T*B
SIGNOR*A*	SILLAB*A*	ARRINZ*A*	FGDTSB*A*
GUARDI*A*	TRECCI*A*	GROCCI*A*	PLMNGR*A*
LETTER*A*	PUPILL*A*	AMPILL*A*	CSZZLP*A*
Five-letter strings			
*M*ONDO	*M*ERCE	*M*OSTE	*M*SDFL
*M*ORTE	*M*ITRA	*M*ERTA	*M*RQCP
*T*ESTA	*T*ASTO	*T*IRLO	*T*SZPG
T*R*ENO	B*R*ACE	C*R*ANO	C*R*LPF
G*A*MBA	F*A*LCE	F*A*NCO	G*A*NMC
S*T*ATO	S*T*UFA	S*T*OVA	L*T*MDR
CA*M*PO	LE*M*BO	LE*M*PO	DC*M*RE
ME*T*RO	RI*T*MO	VA*T*RO	LP*T*MC
FO*R*ZA	CO*R*VO	PA*R*ZO	NB*R*QC
CAR*T*A	CUL*T*O	NUS*T*O	MDS*T*B
LIB*R*O	TIG*R*E	SIG*R*A	PTZ*R*A
FOR*M*A	GER*M*E	VAR*M*E	VRF*M*S
COLP*A*	TORT*A*	MOLP*A*	LPFR*A*
VOLT*A*	PANC*A*	COLD*A*	NCDV*A*
FEST*A*	DIET*A*	CIST*A*	MQRT*A*