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OBSERVATIONS

R34D1NG W0RD5 W1TH NUMB3R5

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Letter identities and number identities are usually thought to imply different cortical mechanisms. Specifically, the left fusiform gyrus responds more to letters than to digits (T. A. Polk et al., 2002). However, a widely circulated statement on the internet illustrates that it is possible to use numbers (leet digits) as parts of words, 4ND TH3 R35ULT1NG S3NT3NC3 C4N B3 R34D W1TH0UT GR34T 3FF0RT. Two masked priming lexical decision experiments were conducted to determine whether leet digits produce (automatic) lexical activation. Results showed that words are identified substantially faster when they are preceded by a masked leet word (M4T3R14L–MATERIAL) than when they are preceded by a control condition with other letters or digits. In addition, there was only a negligible advantage of the identity condition over the related leet condition. This leet-priming effect is not specific to numbers: A prime in which leet digits are replaced by letter-like symbols (MΔT€R!ΔL–MATERIAL) facilitates word processing to the same degree as an identity prime. Therefore, the cognitive system regularizes the shape of the leet digits and letter-like symbols embedded in words with very little cost.

Keywords: masked priming, word recognition, letter processing

Words in alphabetic languages are not read as a whole but are processed via their constituents: the letters (Pelli, Farell, & Moore, 2003; Perea & Rosa, 2002) or larger units, such as syllables (Carreiras & Perea, 2002). In recent years, there has been a growing interest in how letter identity and letter position are processed during visual word recognition. Curiously, attention to this topic has increased due to a widely circulated e-mail pointing out that letter position in words is not essential to successful reading (see Grainger & Whitney, 2004; Rayner, White, Johnson, & Liversedge, 2006, for discussion). More recently, another widely circulated message on the internet (included in e-mail messages and forums) illustrates another fundamental mechanism involved in reading (referring to letter identity): NUMB3R5 C4N B3 U53D 4S L3TT3R5 1N 4 S3N73NC3, 4ND TH3 R35ULT1NG S3NT3NC3 C4N B3 R34D W1TH0UT GR34T 3FF0RT. Although the readability of the previous sentence can be influenced by contextual, top-down factors, a significant part of this R34D1NG-W0RD5 effect may be due to the way in which the brain encodes the identities of digits embedded in printed words. Interestingly, there is empirical evidence that shows that characters encountered in normal reading (e.g., %, *, ∼) seem to engage letter-shape-detection processes but not abstract letter-identification processes (Finkbeiner, Almeida, & Caramazza, 2006; see also Gauthier, Wong, Hayward, & Cheung, 2006).

The question under scrutiny in the present article is whether or not digits can (automatically) activate lexical information. Clearly, the coding of digits as letters presents an important challenge for cognitive neuropsychologists: letter identities and number identities are usually thought to imply different cortical mechanisms. Specifically, the left fusiform gyrus responds more to letters than to digits (Polk & Farah, 1998; Polk et al., 2002; see also James, James, Jobard, Wong, & Gauthier, 2005). This distinction is consistent with neuropsychological evidence: there are patients that recognize all the digits but cannot identify a single letter (e.g., see Cohen & Dehaene, 1998).

The use of numbers as parts of words is not new. It is called leet (or 1337) and its origins can be traced to the early 1980s. The major developments of leet came out of filter evasions (e.g., strings like l0tt3ry cannot be easily detected), securing passwords, gaming, or computer hacking. The rationale of using leet is that it employs a visual encryption code that allegedly can be easily read by any human reader (e.g., the digit 3 may look like the letter E) but would foil most search engines. There are varying styles of leet, ranging from the basic and easier to read to the incredibly complex (see http://en.wikipedia.org/wiki/Leet, for a discussion of this issue); and it has been identified as a broad cultural phenomenon– even appearing in the names of TV series (e.g., NUMB3RS).

How can leet digits be encoded in a letter-like manner? Presumably, this may be carried out by means of digit-to-letter regularization or by virtue of their physical similarity. That is, it may well be the case that their numeric value is never accessed, and that this particular item property is irrelevant. If so, other visual shapes without any numeric value that are similar to letters will be just as

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effective. That is, one could argue that a triangle (Δ) may effectively take the place of the letter A, and a dollar sign ($) may take the place of the letter S without much cost. Indeed, because most readers have been exposed to different font types and to handwriting, they do have experience with the mapping of a range of physically similar shapes onto a particular letter representation (see Manso de Zuniga, Humphreys, & Evett, 1991). That is, cursory information of digits (or symbols) that resemble letters, together with letter information from critical positions, may help to generate sufficient lexical activation.

For the present article, we conducted two experiments to examine the extent to which leet words can activate their base words for readers with no previous knowledge of leet and in the absence of context. To avoid any conscious, top-down effects that may occur when the visible words contain leet digits (e.g., when reading a sentence), we employed a masked priming paradigm (Forster & Davis, 1984) at a 50 ms stimulus-onset asynchrony. Under these conditions, the masked prime is largely unavailable for conscious report. The participants' task was to decide whether the target was a word or not (lexical decision task). Furthermore, to examine whether the leet priming effect has anything to do with numbers (and, therefore, can be used to inform theories about commonalities and differences in letter and number processing) or whether it is just a visual similarity effect (e.g., via some form of self-organizing attractor dynamics, see Rueckl, 2002), we also examined the processing of pseudoletters (letter-like symbols) embedded in words (e.g., MΔT€R!ΔL).

In Experiment 1, target words and nonwords had at least three leet digits (e.g., M4T3R14L instead of MATERIAL). The leet numbers employed were A = 4, E = 3, I = 1, and S = 5 (i.e., leet digits that looked like their corresponding letters). The prime-target conditions were the following: (a) an identity condition (MATERIAL–MATERIAL), (b) a related leet condition (M4T3R14L–MATERIAL), (c) a priming condition in which the leet digits were replaced by visually similar pseudoletters (related symbol condition; MΔT€R!ΔL–MATERIAL), and (d) a control letter condition (MOTURUOL–MATERIAL). To avoid physical continuity between primes and targets, primes were presented in 10-point font and targets were presented in 12-point font.

Experiment 1

Method

Participants. Twenty-eight students from the University of La Laguna took part in the experiment. All of them either had normal or corrected-to-normal vision and were native speakers of Spanish. None of the participants had previous knowledge of leet.

Materials. We selected 240 Spanish words of six to eight letters (mean word length: 7.2 letters). The mean word frequency per one million words in the Spanish database was 73 (range: 20–864; Davis & Perea, 2005). The targets were presented in uppercase and were preceded by primes that were (a) the same as the target (identity condition, e.g., MATERIAL–MATERIAL); (b) the same as the target except for a replacement of leet numbers instead of their corresponding letters (related leet condition, e.g., M4T3R14L–MATERIAL; the leet numbers employed were A = 4, E = 3, I = 1, and S = 5); (c) the same as the target except that we replaced the leet letters with letter-like symbols, as in MΔT€R!ΔL–MATERIAL (related symbol condition; the symbols were A = Δ, E = €, I = !, and S = $); and (d) the same as the related leet/symbol condition except for the replacement of leet digits (or symbols) with other letters (control letter condition; e.g., MOTURUOL–MATERIAL). An additional set of 240 orthographically legal nonwords of six to eight letters was included for the purposes of the lexical decision task. The manipulation of the nonword trials was the same as that for the word trials. Four lists of materials were constructed so that each target appeared once in each list, but each time in a different priming condition. Different groups of participants were used for each list.

Procedure. Participants were tested individually in a quiet room. Presentation of the stimuli and recording of response times were controlled by PC compatible computers. The experiment was run using DMDX (Forster & Forster, 2003). Reaction times were measured from target onset to the participant's response. On each trial, a forward mask consisting of a row of hash marks (#'s) in 12-point Courier was presented for 500 ms in the center of the screen. Next, the prime was presented in 10-point Courier. It stayed on the screen for 50 ms (three cycles; each cycle corresponding to 16.6 ms on the CRT monitor). The prime was followed immediately by the presentation of the target stimulus in uppercase (12-point Courier). Both prime and target were presented in the same screen location as the forward mask. The target remained on the screen until the participants responded. Participants were instructed to press one of two buttons on the keyboard to indicate whether the uppercase letter string was a legitimate word or not. Participants were instructed to make this decision as quickly and as accurately as possible. They were not informed of the presence of lowercase items, and none of them reported (after the experiment) conscious knowledge of the existence of any prime. Each participant received a different order of trials. Each participant received a total of 24 practice trials (with the same manipulation as in the experimental trials) prior to the 480 experimental trials. The whole session lasted approximately 14 min.

Results and Discussion

Incorrect responses (3.9% of the data for word targets) and reaction times shorter than 250 ms or longer than 1,500 ms (less than 1.2% of the data for word targets) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 1. Planned comparisons were conducted to assess the differences between the related leet condition and the identity and control conditions and to assess the differences between the related symbol condition and the identity and control conditions. In all statistical analyses, the factor list was included as a dummy variable to extract the variance due to the error associated with the lists (Pollatsek & Well, 1995). All significant effects had p values less than the .05 level.

Word data. On average, response times were 13 ms faster in the related leet condition than in the control condition, $F1(1, 24) = 11.17$, $\eta^2 = .32$; $F2(1, 236) = 11.94$, $\eta^2 = .05$, whereas the 4 ms advantage of the identity over the related leet condition did not approach significance, both Fs < 1. With respect to the symbol primes, on average, response times were 19 ms faster in the related symbol condition than in the control condition, $F1(1, 24) = 10.39$, $\eta^2 = .30$; $F2(1, 236) = 23.69$, $\eta^2 = .09$, whereas the 2 ms difference between the related symbol condition and the identity

Table 1
Mean Lexical Decision Times (in ms) and Percentage of Errors (in Parentheses) for Word and Nonword Targets in Experiments 1 and 2

	Type of prime					
Target	Identity	Related leet	Related symbol	Control letter	Control leet	Control symbol
Experiment 1						
Words	651 (3.9)	655 (3.5)	649 (4.7)	668 (3.5)		
Nonwords	765 (3.9)	759 (4.2)	760 (4.7)	766 (3.9)		
Experiment 2						
Words	558 (2.9)	563 (3.5)	556 (2.7)	607 (6.9)	599 (6.5)	581 (4.3)
Nonwords	669 (7.2)	669 (8.0)	679 (8.6)	662 (5.8)	678 (7.1)	679 (6.8)

condition did not approach significance, both Fs < 1. The statistical analyses on the error data did not show any significant effects.

Nonword data. The statistical analyses on the latency and error data did not reveal any significant effects (all ps$>$.15).

The results are clear-cut: Response times to words preceded by a prime composed of (at least) three leet digits (M4T3R14L–MATERIAL) or three pseudoletters (MΔT€R!ΔL–MATERIAL) were very similar to the response times to words preceded by an identity prime identity condition (MATERIAL–MATERIAL). In addition, there was an advantage of these related priming conditions relative to a control letter condition (MOTURUOL–MATERIAL). Thus, it is visual similarity rather than the status of the leet digits as numbers that seems to be responsible for the leet priming effect.

The aim of Experiment 2 was twofold. Firstly, it is important to reexamine the null effect of the identity condition versus the related leet and symbol conditions, keeping in mind that arguing that the null hypothesis is true is always difficult, though in certain cases it may be appropriate. Secondly, Experiment 1 lacked the appropriate orthographic controls for the leet and symbol conditions. For that reason, Experiment 2 included these two conditions: a control leet condition, and a control symbol condition. More specifically, we examined whether other digits (i.e., digits that are dissimilar to the corresponding letters of the base word; e.g., M6T2R76L–MATERIAL) or other symbols (i.e., symbols that are dissimilar to the corresponding letter of the base word; M□T%R?□L–MATERIAL) are more effective as primes than mismatching other letters (e.g., MOTURUOL–MATERIAL). The rationale here is to investigate whether the digit-to-letter (or symbol-to-letter) regularization takes place only when there is considerable physical similarity between the physical representation of the word and the leet/symbol priming stimulus (i.e., the leet digits in the control prime M6T2R76L may not activate any letter identities). If this is so, responses to words in the control letter condition will be slower, because of partial activation of competing candidates, than responses to words in the control leet or control symbol conditions (e.g., see Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Hinton, Liversedge, & Underwood, 1998; Lee, Rayner, & Pollatsek, 2001).

Experiment 2

Method

Participants. Twenty-four students from the University of Valencia took part in the experiment. All of them had normal or corrected-to-normal vision and were native speakers of Spanish. None of the participants had previous knowledge of leet.

Materials. These were the same as in Experiment 1, except that we added two new control conditions. In addition to the four prime-target conditions from Experiment 1, we added two priming conditions: (e) the prime was the same as the related leet condition except for the replacement of leet letters with other numbers (control leet condition; e.g., M6T2R76L–MATERIAL) and (f) the prime was the same as the related symbol condition except for the replacement of letter-like symbols with other symbols (control symbol condition; e.g., M□T%R?□L–MATERIAL).

Procedure. This was the same as in Experiment 1.

Results and Discussion

Incorrect responses (4.5% of the data for word targets) and reaction times shorter than 250 ms or longer than 1,500 ms (less than 0.5% of the data for word targets) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 1. Planned comparisons were conducted to assess the differences between the three related conditions (identity, related leet, and related symbol) and to assess the differences between the three control conditions (control letter, control leet, and control symbol).

Word data. On average, response times were very similar for the identity, related leet, and related pseudoletter conditions (558, 563, and 556 ms, respectively); and, therefore, none of the pairwise differences approached significance, all Fs < 1. With respect to the control conditions, response times to words were 8 ms faster in the control leet condition than in the control letter condition, $F1(1, 18) = 3.20$, $p = .09$, $\eta^2 = .15$, $F2(1, 234) = 3.37$, $p = .06$, $\eta^2 = .02$, and response times to words were 18 ms faster for the control symbol condition than for the control leet condition, $F1(1, 18) = 11.80$, $\eta^2 = .40$, $F2(1, 234) = 8.34$, $\eta^2 = .04$. (Not surprisingly, there was a robust advantage of the related leet and related symbol conditions over their corresponding control conditions; all ps$<$.001.)

The statistical analyses on the error data only revealed that participants committed fewer errors to the control pseudoletter condition than to the control leet condition, $F1(1, 18) = 5.78$, $\eta^2 = .24$; $F2(1, 234) = 4.93$, $\eta^2 = .02$, and the control letter condition, $F1(1, 18) = 3.93$, $\eta^2 = .18$, $p = .06$; $F2(1, 234) = 5.34$, $\eta^2 = .02$. (As in the response time data, there was an advantage of the related leet and related symbol conditions over their corresponding control conditions; all ps$<$.03.).

Nonword data. The statistical analyses on the latency and error data did not reveal any significant effects (all $ps > .15$).

As in Experiment 1, the response times to words preceded by primes composed of (at least) three pseudoletters (MΔT€R!ΔL–MATERIAL) or three leet digits (M4T3R14L–MATERIAL) were very similar to the response times to words preceded by an identity prime (MATERIAL–MATERIAL). With respect to the control conditions, the control letter condition (MOTURUOL–MATERIAL) produced longer response times than the control leet or control symbol conditions (M6T2R76L–MATERIAL; M□T%R?□L–MATERIAL). Furthermore, there were some differences in the control priming conditions, depending on the type of mismatching letters/symbols (see the *General Discussion* section).

General Discussion

The results of the present experiments are clear-cut: When embedded in words, leet digits are encoded in a letter-like manner. Words are identified substantially faster when they are preceded by a masked leet word (M4T3R14L–MATERIAL) than when they are preceded by a control condition with other letters, digits, or symbols (MOTURUOL–MATERIAL, M6T2R76L–MATERIAL, M□T%R?□L–MATERIAL). Thus, the take-home message is that words can be readily accessed in their leet form for readers with no prior knowledge of leet.[1] Nonetheless, this phenomenon is not specific to letter-like numbers (e.g., E = 3): Primes composed of letter-like symbols (e.g., MΔT€R!ΔL–MATERIAL) are as effective as leet digits (e.g., M4T3R14L–MATERIAL). This finding rules out the special status of numbers per se as responsible for leet priming.

In sum, despite the fact that digits and letters may have different cortical mechanisms when they are presented together with other digits or letters (Polk et al., 2002), the cognitive system regularizes the shape of the leet digits (and letter-like symbols) embedded in words with very little cost. In this sense, there is some empirical evidence that shows that, in the initial stages of word processing, brain activity generated to strings of pseudoletters created with false fonts is to some degree similar to that generated by words (e.g., see Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999, for MEG evidence; see also Grossi & Coch, 2005, for ERP evidence). This suggests the presence of a visual analysis system that acts as a complex filter between the visual and language domains (see Pammer et al., 2004). That is, it may be the case that the numeric value of the leet digits was never accessed and that this particular item property was irrelevant (i.e., the leet digits may have been normalized early in the process of word recognition).[2]

Interestingly, there are differences across the control conditions: Words preceded by control primes composed of nonleet-like digits (e.g., M6T2R76L–MATERIAL) and, especially, nonletter-like symbols (e.g., M□T%R?□L–MATERIAL) were responded to faster than words preceded by control primes composed of letters (MOTURUOL–MATERIAL). That is, when there is little physical similarity between the digit (or pseudoletter) and its letter equivalent, as was the case in the control primes, primes composed of mismatching letters produce longer response times than primes composed of mismatching symbols/digits. This finding suggests that the digit-to-letter (or symbol-to-letter) regularization process takes place only when there is considerable physical similarity between the physical stimulus and the orthographic representation of the stimulus. This is consistent with the empirical evidence that shows that including unrelated letters in the prime (as occurs in the control letter condition) hinders word processing compared with a partial prime (e.g., as in *blcn–BALCONY*; or *b_lc_ny–BALCONY*; see Peressotti & Grainger, 1999; also see Carreiras, Gillon-Dowens, Vergara, & Perea, 2007; Hinton et al., 1998).

To summarize, the leet priming phenomenon suggests that access to lexical entries can be achieved somewhat independently of physical form, presumably on the basis of some top-down feedback that normalizes the visual input (see Jordan, Thomas, & Scott-Brown, 1999, for an effect of illusory letters in word identification). These processing dynamics can be readily captured—via top-down normalization—in an adaptive resonance model (Grossberg & Stone, 1986). That is, the pattern-matching process between the visual stimulus and the long-term representation achieves stability (i.e., a stable percept) quite rapidly for M4T3R14L–MATERIAL and MATERIAL–MATERIAL pairs. Because of the top-down dynamics in an attractor network, recognition of a target word preceded by a prime composed of leet digits would only be slightly hindered (around 4–5 ms) relative to an identity priming condition. As Jordan et al. (1999) indicated, "word recognition can be achieved on the basis of something other than precise visual form" (p. 1416).

[1] Likewise, words can be readily accessed without recourse to the full letter-position-order (e.g., *CHOLOCATE* activates *CHOCOLATE* to a great extent; see Perea & Lupker, 2004; Rayner et al., 2006; see also Johnson, Perea, & Rayner, 2007),

[2] Perhaps, the effectiveness of leet digits could be substantially reduced if their numeric property was transparent (e.g., if the prime consisted *only* of leet digits or if the prime contains several leet digits in a row).

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