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Does the brain regularize digits and letters to the same extent?

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Abstract

The cognitive system does not just act as a mirror from the sensory input; instead, it tends to normalize this information. Given that letter processing seems to be much more specialized than digit processing in the cortex, we examined whether the regularization process occurs differently from digits to letters than from letters to digits: We employed a masked priming same/different experiment (e.g., probe: VESZED, prime, V35Z3D, and target VESZED). When embedded in letter strings, digits that resemble letters (e.g., 3 and 5 in V35Z3D-VESZED) tend to be encoded in a letter-like manner, whereas when embedded in digit strings, letters that resemble digits (e.g., E and S in 9ES7E2-935732) tend not to be encoded in a digit-like manner.

Key words: word recognition, priming, letter processing

Letters, words and numbers are cultural inventions of our society which have become an integral part of our daily cognitive operations. Even though our brain efficiently processes letters and digits in similar contexts (e.g., in the expression April 24, 1905), it does not seem to be the case that they are being processed in the same way. Recently, Dehaene, Cohen, Sigman, and Vinckier (2005) proposed a neuronal model according to which the brain decodes letters/words (but not digits) through a hierarchy of local *combination detectors* in the occipito-infero-temporal pathway. They tentatively proposed detectors for letter shapes in V4, abstract letters in V8 (i.e., irrespective of CaSe, size, and **font**), and for letter strings in the left fusiform gyrus. Indeed, a number of fMRI studies have shown that words and letter strings produce a larger activation in the left fusiform gyrus than digit strings (Baker et al., 2007; James, James, Jobard, Wong, & Gauthier, 2005; Polk et al., 2002). In contrast, there is no unambiguous empirical evidence supporting greater activation in any particular area in the cortex for visually processing digits relative to visually processing letters or words (Polk et al., 2002). (footnote 1) Furthermore, the letter/digit distinction is consistent with neuropsychological evidence (see Cohen & Dehaene, 1998, for evidence of pure alexia).

How does the brain normalize the information from the sensory input? Readers are constantly exposed to various font types and to handwriting, and hence they do have experience with the mapping of shapes (with varying ranges of physical similarity) onto a particular letter/digit representation. Indeed, readers compute a representation of visually presented stimuli that generalizes over physical differences (Bowers, 2000, for review). For instance, access to stored 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). But the question we examine in the present experiment is how robust the letter and the digit processing systems are to distortion. We do so by employing a visual encryption code which has become relatively popular –in particular on the internet and in gaming: the so-called *leet* code. The term *leet* describes a form of symbolic writing used widely on the internet internet (see http://en.wikipedia.org/wiki/Leet). The basic strategy is to use symbols that closely resemble the letters for which they stand (e.g., the digit 3 may look somewhat like the letter E, as in L0TT3RY, and this would foil most search engines for the purposes of filter evasions).

The *leet* code employs characters that can be easily read by any human reader (e.g., L0TT3RY). But is there a cost associated with reading the *leet* stimulus M4T3R14L as MATERIAL? This issue was recently examined in a series of experiments by Perea, Duñabeitia, and Carreiras (2008; see also Carreiras, Duñabeitia, & Perea, 2007) with readers with no prior knowledge of *leet*. They used a masked priming paradigm in a lexical decision task (i.e., "Is the target stimulus a word or not?"; see Forster, 1998, for a review) to investigate whether words with numbers activate their base words. The results were clear-cut: Response times to words preceded by a briefly presented (50 ms) masked *leet* prime (M4T3R14L-MATERIAL) were close to the response times to words preceded by an identity prime (MATERIAL-MATERIAL). Furthermore, the responses to target words preceded by a masked *leet* prime (M4T3R14L-MATERIAL) were substantially faster than the responses to target words preceded by appropriate control primes (e.g., the letter control prime was MOTURUOL-MATERIAL and the digit control prime was M6T8R86L-MATERIAL). In a subsequent study, Duñabeitia, Perea, and Carreiras (in press) tested whether there is a reading cost associated with the replacement of letters with symbols or numbers which have form resemblance in an online sentence reading experiment that included words with leet characters (e.g.,

YESTERDAY I SAW THE SECRE74RY WORKING VERY HARD). Participants' eye movements showed that when reading for comprehension, and when the manipulations are consciously perceived by the participants, the leet-to-letter normalization process involves some cost, especially when the non-letter was a number.

The presence of a *leet* priming effect for words strongly suggests that access to word forms can be achieved somewhat independently of physical form, probably on the basis of some top-down feedback that regularizes the visual input. As indicated by Dehaene and Cohen (2007) in the context of their neuronal model, "the letter detectors, which are thought of as the front end of invariant word recognition, tolerate some shape distortion, thus enabling the letter detector for 'A' to react to 'Δ' or '4'" (p. 456). Following this letter stage, processing would continue at bigram, morpheme and word levels with only a minor reduction in the amount of bottom-up information" (p. 456). Note that, in the Dehaene et al. model, this regularization process purportedly takes place at the level of domain-specific neurons involved in letter-word identification at the level of the left fusiform gyrus. Indeed, the findings from Perea et al. (2008) are consistent with a top-down feedback mechanism (see also Jordan et al., 1999). But would a similar *leet* priming effect occur for digit strings? Bear in mind that the letter processing area in the cortex seems to activate a more restricted area than digit processing (see Polk et al., 2002.). If *leet* digits and letters share a sufficient set of features (see Grainger, Rey, & Dufau, 2008), the *leet* priming could be due to mere perceptual overlap, and thereby occur to the same degree in *leet* digit-to-letter regularization processes (e.g., V35Z3D-VESZED) and in *leet* letter-to-digit regularization processes (e.g., 9ES7E2-935732). This is precisely what Dehaene and Cohen (2007) suggested regarding *leet* priming: "visual similarity alone can explain the results" (p. 456). In contrast, if letter perception is based on a higher degree of tolerance to shape variation as compared to number recognition, there would be greater *leet* priming for digit-to-letter regularizations than for letter-to-digit regularizations.

Thus, the question under scrutiny in the present paper is whether the same *leet* priming effect occurs going from digits to letters as from letters to digits. More specifically, does the *leet* string 9ES7E2 activate the digit string 935732 to the same extent that the *leet* string V35Z3D activates the letter string VESZED? We tested this by using a same-different task – a task which taps low level, pre-lexical, processing and that (unlike lexical decision) can be used for digit strings. (Note that the manipulated *leet* characters are equally similar to their target characters when going from letters to digits and from digits to letters, thereby controlling for visual similarity; e.g., as in the strings V35Z3D-VESZED and 9ES7E2-935732.) Furthermore, the same-different task has a long history (Norris & Kinoshita, 2008, for a review). In the context of a masked priming paradigm, participants in the same-different task are required to press the "same" button if the probe and target are the 'same', and to press the "different" button if the probe and target are 'different' (see Norris & Kinoshita, 2008). Norris and Kinoshita adapted the task for masked priming by putting a masked prime before the target; they showed that when the probe and target were the same (e.g., probe: faith, target: FAITH), a related masked prime (e.g., fiath) produced an advantage in response time relative to a control prime (fouth). Furthermore, Norris and Kinoshita demonstrated that this effect was due to the activation of abstract (letter) representations. It is important to note that all priming effects in this task occur with "same" responses: the reason is that for "different" responses both the related and unrelated primes provide information that is different from the probe (Norris & Kinoshita, 2008).

The procedure in the present experiment is straightforward: On each trial, a *probe* (e.g., the letter string VESZED or the digit string 734238) is presented above a *forward mask* consisting of six hash marks (######) for 1000 ms. The probe then disappears and the forward mask is replaced by a *prime* in lowercase presented for 50 ms, which in turn is replaced by the *target* stimulus. A target string of letters (e.g., VESZED) was preceded either by: a) an identity prime (VESZED), b) a *leet* prime (V35Z3D; with 3 *leet* characters), c) a control letter prime (VYNZYD) or, d) a control digit prime (V87Z8D). Given that part of the *leet* effect for letter strings might be due to feedback from the word-level, none of the letter strings looked like real words (e.g., the letter string VESZED). Similarly, a target string of digits (e.g., 935732) was preceded either by: a) an identity prime (935732), b) a *leet* prime (9ES7E2; with 3 *leet* characters), c) a control letter prime (9UN7U2) or, d) a control digit prime (987782). The participants' task was to decide whether the probe and the target were the same or different. To minimize physical continuity between primes and targets, primes were presented in 11-pt font and targets were presented in 12-pt font.

If the letter-detector system readily normalizes the signal from the *leet* prime, as deduced from the lexical decision experiments reported by Perea et al. (2008), then one would predict an advantage of the *leet* condition V35Z3D-VESZED over the control conditions VYNZYD-VESZED and V87Z8D–VESZED; in addition, the advantage of the identity condition (VESZED-VESZED) over the *leet* condition (V35Z3D-VESZED), if any, should be relatively small. But the key question here is whether the *leet* priming effect also occurs with digit strings. If the left fusiform gyrus tends to process letter-like stimuli, the characters in the *leet* primes (e.g., E in the sequence 9ES7E2) may not initially be processed as digits but as letters, and hence the resulting percept may not benefit as much from the visual similarity of the *leet* characters. If so, the advantage of the identity condition (935732-935732) over the *leet* condition (9ES7E2-935732) should be smaller than the analogous comparison with letter strings. Furthermore, the advantage of the *leet* condition (9ES7E2-935732) over the control digit condition (987782-935732) should be relatively small. That is, tolerance to letter variation may be higher than tolerance to number variation, and therefore greater digit-to-letter effects would be expected. Nonetheless, in a recent study, Tydgat and Grainger (in press) claimed – on the basis of a series of behavioral two-alternative forced choice experiments – that "numbers are processed using the same mechanism as letter strings (in which case the term 'alphanumeric array' would be more appropriate)". If the Tydgat and Grainger hypothesis is correct, one would expect a similar *leet* priming effect for letters and for digits; indeed, from this perspective, one might expect even a greater effect going from letters to digits as there are only ten digits to be discriminated among.

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 expertise in *leet.*

Materials. There were two sets of targets: (a) two-hundred orthographically legal six-letter pseudowords (e.g., VESZED, KEIREF, JESCER, CASKAG, DASPAB, CIADIZ, etc.), and (b) two-hundred six-digit numbers (e.g., 734238, 214717, 931837, 635632). (The number strings did not include the digit 0.) The pseudoword targets were presented in uppercase and were preceded by primes that were: i) the same as the target (*identity condition*, e.g., VESZED-VESZED; 935732-935732), ii) the same as the target except for a replacement of *leet* characters for the corresponding letters in the 2nd, 3rd, and 5th positions (*leet condition*, e.g., V35Z3D- VESZED, 9ES7E2-935732;

as in the Perea et al. (2008) experiments, the *leet* characters were A=4, E=3, I=1, and S=5), iii) the same as the *leet* condition except that the *leet* characters were replaced with other letters, as in VYNZYD-VESZED or 9UN7U2-935732 (*letter control condition*) and iv) the same as the *leet* condition except that the *leet* characters were replaced with other digits (*digit control condition*; e.g., V87Z8D–VESZED or 987782-935732). On half of the trials, the probe and the target were the same and on the other half of trials, the probe and the targets were different (e.g., for the probe BESFEN, the primes could be the prime CIADIZ, C14D1Z, CYUDUZ or C87D8Z and the target would be CIADIZ; for the probe 236439, the primes could be 814616, 8IA6I6, 869666, 8UO6U6 and the target would be 814616). The probe and target were always either both pseudowords or both numbers. Four lists of materials were constructed so that each target appeared once in each list (25 items/condition), but each time in a different priming condition. Different groups of participants were used for each list.

Procedure. Participants were tested individually. The stimuli were presented using PCs running the DMDX software for Windows (Forster & Forster, 2003) on a CRT monitor with a 16.6 ms refresh rate. Reaction times were measured from target onset until the participant's response. On each trial, a 12-pt probe was presented above a forward mask consisting of six hash marks (######) for 1000 ms. Next, the probe disappeared, and the forward mask was replaced by an 11-pt prime presented for 50 ms, which was replaced by a 12-pt target. The target stimulus remained on the screen until the response. Participants were told that they would see strings of letters or a string of digits, and that they were to press the button marked “SÍ” [YES] (with their right index finger) if they thought the probe and target were the same stimulus, and they were to press the button marked “NO” (with their left index finger) if they thought the probe and target was a different stimulus. Participants were instructed to make this decision as quickly and as accurately as possible. Participants were not informed of the presence of prime stimuli. Each participant received a different, randomized order of trials. There were 20 practice trials. The experiment lasted less than 20 minutes.

Results

Incorrect responses (5.8% of the data) and reaction times less than 250 ms or greater than 1500 ms (less than 0.5% of the data) were excluded from the latency analysis. The mean latencies for correct responses and error rates are presented in Table 1. Participant and item ANOVAs for the "same" response latencies and percentages of error were conducted based on a 2 (Type of string: letter string, number string) x 4 (Type of prime: identity, *leet*, control letter, control digit) x 4 (List: list 1, list 2, list 3, list 4). In all statistical analyses, the factor List was included as a dummy variable to extract the error variance due to counterbalancing (Pollatsek & Well, 1995).

On average, response times for "same" responses were 35 ms faster for letter strings than for number strings, $F1(1,24)=31.81$, $MSE=1857$, $p<.001$; $F2(1,192)=64.16$, $MSE=3344$, $p<.001$. The effect of prime type was also significant, $F1(3,72)=88.32$, $MSE=479$, $p<.001$; $F2(3,576)=54.87$, $MSE=2760$, $p<.001$. More important, there was a significant interaction between the two factors, $F1(3,72)=3.72$, $MSE=860$, $p<.02$; $F2(3,576)=4.80$, $MSE=2760$, $p<.003$, which reflected a different pattern of priming effects for letter strings and for number strings. On the one hand, for letter strings, responses in the identity condition were 23 ms faster than those in the *leet* condition, $F1(1,24)=15.85$, $MSE=458$, $p<.001$; $F2(1,96)=9.51$, $MSE=3040$, $p<.003$. In addition, responses in the *leet* condition (v35z3d-VESZED) were 31 ms faster than in the digit control condition (v87z8d–VESZED), $F1(1,24)=15.05$, $MSE=907$, $p<.003$; $F2(1,96)=14.34$, $MSE=3270$, $p<.003$, and 40 ms faster than the responses in the letter control condition (vynzyd-VESZED), $F1(1,24)=72.93$, $MSE=312$, $p<.003$;

F2(1,96)=28.22, MSE=2716, p<.003, while there was no significant difference between the two control conditions (both ps>.20). On the other hand, for digit strings, although responses in the identity condition were 47 ms faster than the responses in the *leet* condition, F1(1,24)=27.74, MSE=686, p<.003; F2(1,96)=29.98, MSE=2797, p<.003, responses in the *leet* condition (9ES7E2-935732) were virtually the same as the responses in the control digit condition (987782-935732) (576 vs. 571 ms, respectively, both ps>.25). In addition, responses in the letter control condition were 58 ms slower than in the digit control condition, F1(1,24)=27.42, MSE=508, p<.003; F2(1,96)=14.21, MSE=2755, p<.003.

The error data only showed an effect of prime type, F1(3,576)=3.57, MSE=86.4, p<.02; F2(3,72)=4.63, MSE=32.9, p<.01, which reflected a higher accuracy for the identity condition than for the other three conditions (see Table 1).

Finally, as expected, there were no signs of a priming effect for “different” responses. The only significant effect on the latency data was that responses to letter strings were 24 ms faster than the responses to digit strings, F1(1,24)=12.38, MSE=2089, p<.02; F2(1,192)=21.94, MSE=5004, p<.001. The only significant effect in the error data was that participants made more errors to digit strings than to letter strings, F1(1,24)=10.0, MSE=15.1, p<.005, F2(1,192)=3.82, MSE=141.2, p=.052 – note that there were no speed/accuracy trade-offs.

Discussion

The results of the present masked priming experiment are clear-cut. The way the cognitive system processes letters embedded in digit strings appears to be different from the way the cognitive system processes digits embedded in letter strings. When embedded in letter strings, *leet* characters (e.g., 3 and 5 in V35Z3D-VESZED) in the appropriate context tend to be encoded in a letter-like manner, whereas when embedded in digit strings, *leet* characters (e.g., E and S in 9ES7E2-935732) tend not to be encoded in a digit-like manner. First, the advantage of the identity condition over the *leet* condition was twice as big for the digit strings (47 ms) than for the letter strings (23 ms). (Note that the magnitude of masked priming effects, including that of the *leet* priming effect, seems to be greater in the same/different task than in the lexical decision task; see Norris & Kinoshita, 2008.) Perhaps, what is even more diagnostic is that we found a robust *leet* priming effect (around 35 ms) for letter strings relative to both control conditions with other letters or digits, whereas there was virtually no *leet* priming effect (5 ms) for digit strings relative to its corresponding control digit condition (9ES7E2-935732 vs. 987782-935732). Finally, for letter strings, we found no difference between the two control conditions whereas, for digit strings, responses were much faster for the control digit condition (987782-935732) than for the control letter condition (9UN7U2-935732).

The take-home message is straightforward: the cognitive system readily normalizes *leet* digits (e.g., 3) to letters (E, as in SOCI3TY), but not *leet* letters (E) to digits (3, as in 9ES7E2). The cognitive system – presumably the left fusiform gyrus in terms of the neuronal model of Dehaene and colleagues – regularizes the shape of the *leet* characters embedded in words or pseudowords with little cost. 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) rather than an 'alphanumeric array' (Tydgat & Grainger, in press). This might imply some perceptual preference of the human visual system, whereby it tends to treat a string of letter-like symbols as a string of readable letters, rather than as a meaningless string of letters and digits. Such preference might partially reflect a top-down, strategic regulation of bottom-up computations. Another possibility is that that letters appear in such varied forms (especially in handwriting) that the cognitive system allows much more slop than for digits, where there is little variation in their form (e.g., compare the shapes of a, a, a. vs. 4, 4, 4 in Times New Roman, Comic Sans, and Brush script fonts, respectively). Finally, we must take into account that letter strings are different from the digit strings in that there is a more unitary code for them (i.e., the pronunciation of the pseudoword) and also some resonance with real words. In contrast, the digit strings are just random sequences of digits. What we should also note here is that the fact that letter strings in this experiment formed pronounceable Spanish pseudowords cannot be taken as direct evidence for a top-down advantage (e.g., because of a potential similarity of the pseudowords to real words) that might have contributed to the observed asymmetry. In order to quantify the similarity of the pseudowords to Spanish real words, two measures were computed. First, the number of orthographic neighbors (N) of these strings was obtained. The mean N value for the items was 0.03 (±0.17), and only 3 of the pseudowords had real words as neighbors (N=1 in the three cases). Thus, this explanation does not seem suitable for accounting for the obtained asymmetry. Second, in a new attempt to explore this issue, we computed the Orthographic Levenshtein Distance 20 (OLD20; see Yarkoni, Balota, & Yap, 2008), which is a composite measure which also takes into account embedded words and other types of orthographic neighboring representations. The mean OLD20 value for the pseudowords was 2.97 (±0.31; range: 2.0-3.8). We conducted correlation analyses between the OLD20 values and the reaction times in each condition, as well as between the OLD20 and the priming effects. None of the correlation coefficients between the OLD20 values and the reaction times were close to significant (Identity: r=.02, p=.85; Leet: r=.14, p=.17; Control Letter: r=.05, p=.65; Control Digit: r= -.06, p=.53). The correlations between OLD20 values and net priming effects were also non-significant (Identity effect: r=.02, p=.83;

Leet effect: $r=-.13$, $p=.20$). Hence, the potential similarity of the letter strings to real words does not seem responsible for the observed priming asymmetry.

To summarize, the *leet* priming phenomenon suggests that access to stored entries in the brain can be achieved somewhat independently of physical form, presumably on the basis of some top-down feedback that regularizes the visual input. This is consistent with the model of visual-word recognition proposed by Dehaene et al. (2005; Dehaene & Cohen, 2007), when they claim that feedback and lateral connections are numerous in the visual system, and probably contribute to shaping the neurons. Importantly, this normalization process is particularly strong for letter strings, thus suggesting that the letter processing area in the brain is highly specialized.

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Table 1

Mean response times (in ms) and percentage of errors (in parentheses) for targets in the experiment

	Type of Prime			
	Identity	*Leet*	Control_digit	Control_letter
“Same” responses				
Letter string	506 (5.0)	529 (6.1)	560 (9.3)	569 (9.9)
Digit string	529 (4.7)	576 (6.6)	571 (6.9)	629 (7.0)
“Different” responses				
Letter string	552 (4.3)	564 (3.9)	543 (3.1)	543 (4.6)
Digit string	576 (6.6)	574 (5.4)	572 (5.1)	575 (5.3)

Footnotes

Footnote 1. Although the inferior parietal cortex plays a key role in the sense of quantity (see Piazza, Izard, Pinel, LeBihan, & Dehaene, 2004), this may have little to do with the early stages of digit form processing.

Authors' notes

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