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The Mental Representation of Parity and Number Magnitude

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Nine experiments of timed odd–even judgments examined how parity and number magnitude are accessed from Arabic and verbal numerals. With Arabic numerals, Ss used the rightmost digit to access a store of semantic number knowledge. Verbal numerals went through an additional stage of transcoding to base 10. Magnitude information was automatically accessed from Arabic numerals. Large numbers preferentially elicited a rightward response, and small numbers a leftward response. The Spatial–Numerical Association of Response Codes (SNARC) effect depended only on relative number magnitude and was weaker or absent with letters or verbal numerals. Direction did not vary with handedness or hemispheric dominance but was linked to the direction of writing, as it faded or even reversed in right-to-left writing Iranian Ss. The results supported a modular architecture for number processing, with distinct but interconnected Arabic, verbal, and magnitude representations.

How are numbers mentally represented and manipulated? Despite recent advances in the cognitive psychology and neuropsychology of numerical abilities, theories of the basic architecture of number representations have remained highly controversial. Both modular and interactive views have been proposed to account for the same set of data. On the modular side, McCloskey, Caramazza, and Basili (1985; see also McCloskey, 1992; McCloskey & Caramazza, 1987; McCloskey, Sokol, & Goodman, 1986) have postulated a central amodal and abstract representation of numbers, which would constitute a bottleneck entry to calculation routines and to stored number knowledge and that would be interfaced by notation-specific comprehension and production modules. On the opposite, interactive side, Campbell and Clark (1988; see also Clark & Campbell, 1991) have denied the existence of a central abstract representation and suggested that "visuospatial, verbal, and other modality-specific number codes are associatively connected as an encoding complex" (p. 204) and activate each other during retrieval and calculation. Somewhat intermediate models have been proposed by Dehaene (1992) and by Noël and Seron (in press). Dehaene's (1992) triple-code model postulates three cardinal representations of number—verbal, Arabic, and magnitude—each of which supports specific procedures such as number comparison or mental multiplication. Noël and Seron (in press), on the other hand, have hypothesized a unique preferred entry code, which would be used to access number knowledge and calculation routines but which may be either verbal or Arabic depending on the subject's idiosyncrasies.

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This article aims at separating these conflicting models of mental number processing by focusing on a limited domain of adult numerical competence: the representation of the concepts of parity and of magnitude. We study the predictive ability of the models in the context of a very simple task of parity judgment in which subjects are asked to decide whether a given number is odd or even. By examining the numbers for which odd–even classification is fast and those for which it is slow, we hope to identify the nature of the computations underlying parity judgment. By using different numerical notations for the input stimuli—for instance, one- and two-digit Arabic numerals versus French number words—we probe the existence of modality-specific number-processing systems and examine how the mental representations associated with each input notation connect with each other. We also study the intrusion of numerical magnitude, an a priori irrelevant parameter, into the parity judgment task. Finally, by testing subjects from several linguistic communities and with differing mathematical backgrounds, we estimate the degree of individual variability in the mental architecture for number processing.

Access to Parity and Magnitude Knowledge During Number Processing

Parity and, to a lesser extent, number magnitude are relatively abstract mathematical properties. Before investigating their mental representations, it is therefore necessary to show that even in mathematically unsophisticated subjects these parameters are easily conceptualized and extracted. In fact, several studies have demonstrated that subjects readily access and use parity and magnitude information during mental calculation. When verifying an arithmetic operation (e.g., 2 + 3 = 7), subjects rapidly evaluate the plausibility of the proposed result by checking whether its magnitude is compatible with that of the operands. Grossly false results are rejected in about 900 ms (split effect; Ashcraft & Battaglia, 1978; Ashcraft & Stazyk, 1981; Dehaene & Cohen, 1991; Krueger & Hallford, 1984; Stazyk, Ashcraft, & Hamann, 1982; Zbrodoff & Logan, 1990). A similar check is also performed with parity. In addition verification, subjects apply the rule, If one and only one of the two addends is odd, then the correct sum must be odd; or, it must be even (Krueger & Hallford, 1984, p. 171). In multiplication verification, subjects likewise use the rule "If any multiplier is even, then the correct product must be even; otherwise it must be odd" (Krueger, 1986). Violations of these rules are detected within 1,100–1,500 ms.

Shepard, Kilpatrick, and Cunningham (1975) used a multidimensional scaling analysis to probe the adult internal representation of numbers. Subjects rated the conceptual similarities of all pairs of the numbers 0–9. Magnitude and parity were the two principal parameters that characterized the subjective similarity matrix. With the same technique, Miller and Gelman (1983) have studied the development of number-similarity judgments. Parity had no influence until the sixth grade. By contrast, even kindergartners showed an early structuring of their mental number representations by number magnitude. Thus, kindergartners judged 2 to be more similar to 3 than to 7, but unlike adults they did not find 2 more similar to 6 than to 5.

These studies underline the psychological significance of parity and number magnitude and the developmental precedence of magnitude over parity in the early structuring of mental number representations. Few studies, however, are relevant to the question of how these parameters are mentally represented and computed. In an off-line rating task, Armstrong, Gleitman, and Gleitman (1983) demonstrated that subjects readily classify some numbers as more even than others. For instance, 10 was rated as more even than 34. Yet, the precise rules governing the degree of prototypicality of each number within the odd–even categories were not investigated.

An online parity judgment task was used by Hines (1990), who found that the *even* response was systematically faster than the *odd* response. He attributed this difference to the linguistic markedness of the odd concept. Sudevan and Taylor (1987) compared the availability of parity information with that of magnitude information. On randomly intermixed trials, the same target digits had to be classified either as *odd versus even* or as *smaller than 6 versus larger than 5*. The larger–smaller comparison task was consistently faster than the parity judgment task (see also Boles, 1986). Furthermore, on parity judgment trials, the larger–smaller status of the target digit interfered with the odd–even classification, suggesting an irrepressible activation of numerical comparison. This finding again suggests that numerical magnitude is more readily available than parity.

Neuropsychological evidence also supports the same conclusion. Dehaene and Cohen (1991) have described a severely aphasic and acalculic patient, NAU, who could not read, memorize, or calculate with numbers in any exact way but remained able to compare and approximate numerical quantities. NAU was at chance level in parity judgment. This loss of parity information contrasted sharply with his perfect performance in larger–smaller comparison, indicating an intact magnitude representation.[1] Parity and magnitude information may thus have distinct neurobiological substrates. Because the converse dissociation has not been reported yet, it is also possible parity judgment is simply a more demanding task than magnitude comparison.

Processing Architectures for Parity Judgment

Given that normal subjects readily use parity and magnitude information in various numerical tasks, we may now examine the available models of number processing and how they envisage the mental organization of numerical information. The processing architectures of the various models are shown in Figure 1.

McCloskey's Model

According to McCloskey's (1992) model, any input numeral must be converted to an abstract internal representation. This initial conversion is performed by a dedicated Arabic comprehension module if the target is in Arabic notation (e.g., 13) or by a dedicated verbal comprehension module if the target is in verbal notation (e.g., thirteen). Following this conversion, the target is processed in the same way, regardless of its original format. The abstract representation in which it is encoded is essentially a magnitude code with base-ten structure, which specifies the quantity associated with each power of ten. The number 13, for instance, would be represented as {3} 10EXP0, {1} 10EXP1: quantity {3} in the units slot and quantity {1} in the tens slot. The abstract representation is assumed to represent an obligatory bottleneck to further numerical processing. McCloskey's model therefore implies that, regardless of input notation, parity information is always calculated from an abstract, amodal representation of the target (see Figure 1).

Noël and Seron's Preferred Entry-Code Hypothesis

Contrary to McCloskey and his colleagues, Noël and Seron (in press) deny that the code from which abstract knowledge and calculation procedures are accessed is an abstract semantic representation of numbers. They postulate instead that each individual has a preferred concrete entry code to which all numerals are initially transcoded. For instance, Noël and Seron's (in press) patient NR was thought to convert all input numerals, including those in Arabic format, to a verbal representation before accessing mental calculation procedures and a representation of quantity. Other subjects might use Arabic notation as their preferred entry code. The critical point is that, before accessing parity or magnitude information about the target numeral, there is a bottleneck in information flow at the level of a concrete representation of number, either Arabic or verbal (see Figure 1).

Campbell and Clark's Encoding-Complex Model

In a radically different proposal called the *encoding-complex model*, Campbell and Clark (1988; see also Clark &

[1] NAU even showed an intact Spatial–Numerical Association of Response Codes (SNARC) effect (see Experiments 1–7): Even though he classified numbers randomly with respect to their odd–even status, he tended to press the right-hand key more often in response to a large number and the left-hand key in response to a small number.

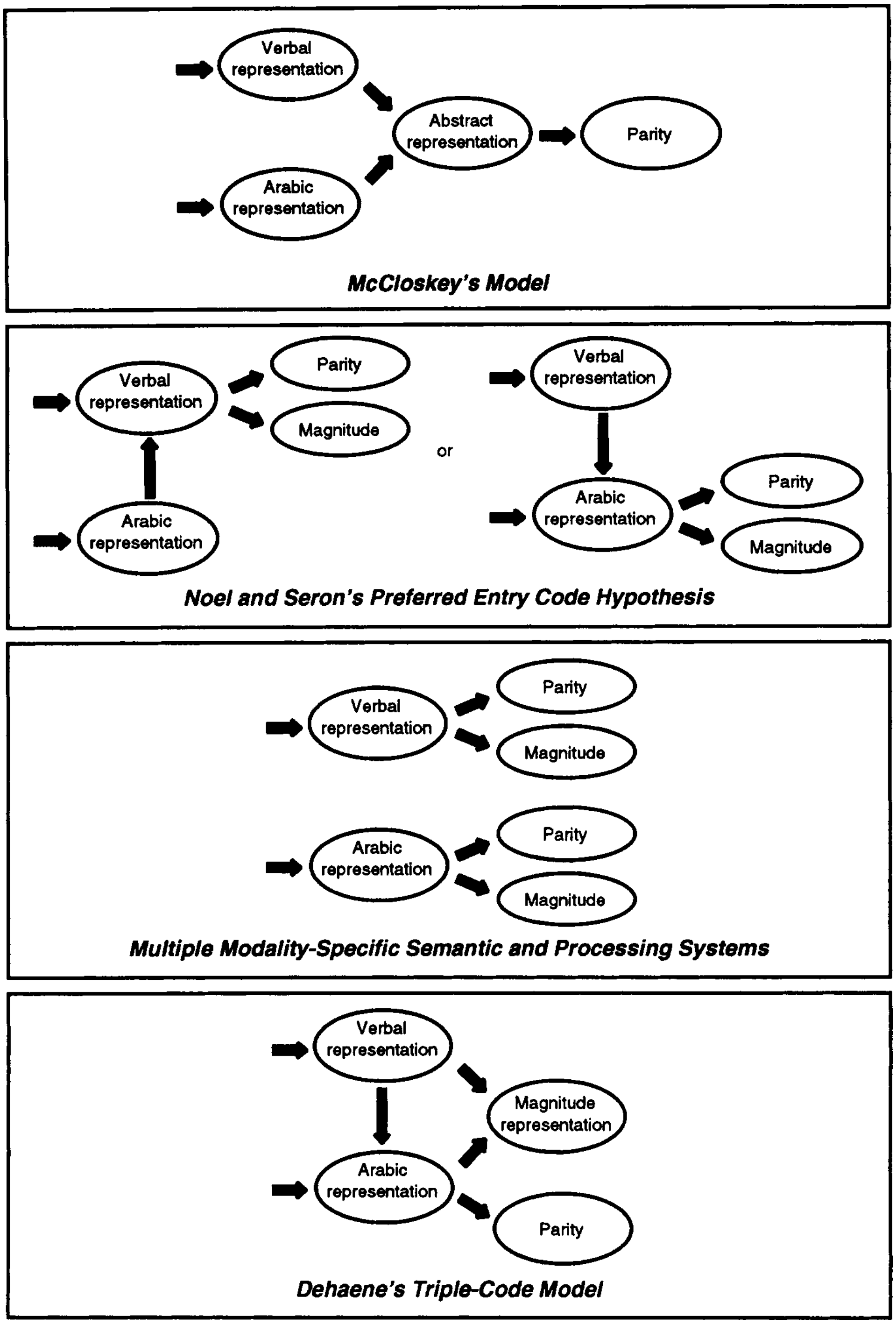

Figure 1. Four alternative models of mental number processing applied to parity judgments of Arabic and verbal numerals.

Campbell, in press) have suggested that numbers evoke "an integrated network of format-specific number codes and processes that collectively mediate number comprehension, calculation and production, without the assumption of central abstract representation" (p. 204). In support of this notion, they cite data that suggest that arithmetic operations of addition or number comparison are performed qualitatively differently depending on the numerical notation used for input (e.g., Besner & Coltheart, 1979; Gonzalez & Kolers, 1982, 1987; Takahashi & Green, 1983; but see McCloskey, 1992, for discussion). Because Campbell and Clark take an interactive rather than a modular stance and because they have not specified in any detail the different number representations and the manner in which they interact, it is difficult to derive from their model any specific predictions concerning the parity judgment task. As Campbell and Clark themselves have noted, the encoding-complex view is sufficiently flexible and underspecified as to mimic the behavior of any modular model (Sokol, Goodman-Schulman, & McCloskey, 1989). For instance, Clark and Campbell (1991) suggested that "different stimulus codes may all be translated into a dominant number–word or visual–digit format (i.e., common but specific code)" (p. 213), an assumption essentially equivalent to Noël and Seron's (in press) preferred entry-code hypothesis. In this article, we consider two restricted versions of Campbell and Clark's model. Although we are well aware that they might not recognize themselves in any of these two versions, we feel that their general propositions cannot be distinguished from modular theories with the present experimental techniques.

The first concrete implementation that we consider is a model with multiple modality-specific semantic and processing systems (see Figure 1). Such a model assumes that the semantic databases and procedures that are accessed vary with the format of the input numeral. This is in line with Clark and Campbell's (1991) suggestion that "odd–even judgments are based on multiple, format-specific codes that may be differently lateralised, rather than a single abstract code" and that "processing of odd–even status differs as a function of format" (p. 211). Contrary to McCloskey's or Noël and Seron's models, the multiple semantic systems hypothesis predicts that, in the parity judgment task, quite different patterns of results should be found depending on whether the target numeral is presented in Arabic or verbal format.

Dehaene's triple-code model may be considered as an alternative implementation of Campbell and Clark's views. Dehaene (1992) suggested that there are three cardinal mental representations of number: (a) an auditory verbal word frame in which numbers are represented in verbal notation, (b) a visual Arabic number form in which numbers are represented in Arabic notation, and (c) an analogical magnitude representation in which "numerical quantities are represented as inherently variable distributions of activation over an oriented analogical number line" (p. 30). In the course of number processing, numbers may be transcoded several times from one internal representation to the other. However, the model remains modular in that each numerical procedure is supposed to be tied to a unique input–output code. The retrieval of parity information, for instance, is assumed to proceed only from the Arabic representation. If the parity of verbal numerals needs to be determined, these numerals will first have to be internally transcoded to the Arabic representation (see Figure 1).

As should be clear from this short review, the available models of number processing differ mostly in their predictions regarding the influence of input number notation. Some models predict that number processing should be little affected by variations in number notation (McCloskey, 1992; Noël & Seron, in press), whereas other models allow for some differential effects of input format (Campbell & Clark, 1988; Dehaene, 1992). In Experiment 8 and 9, variations in the surface notation of target numerals are used as a systematic tool for separating models of number processing.

How Parity Is Extracted

Quite independently of which information-processing pathways are used for parity judgment, the models must also specify how parity information is extracted. Only one model has been somewhat specific in that respect. According to Clark and Campbell (1991, p. 210), a mental division by 2 is performed during parity judgment: "Odd and even are in fact defined and presumably determined by numerical calculations (e.g., multiple or non-multiple of 2)." In this view, parity judgment relies on simple procedures of mental calculation. It might therefore be expected, for instance, that if the time to compute $2 \times 4 = 8$ is slow, then the time to determine that 8 is even will also be slow.

Although odd and even integers are mathematically defined in terms of their divisibility by 2, this does not necessarily imply that the concept of parity is mentally represented as such. It is relatively easy to find alternatives to Clark and Campbell's mental calculation strategy. Parity information may be simply stored in memory, perhaps along with some other memorized characteristics of numbers. Alternatively, subjects might use the rule that the numbers ending in 0, 2, 4, 6, or 8 are even, and all others are odd. These possibilities shall be put to a test in Experiments 1 and 2. Note, however, that even though the mental calculation strategy has been introduced by Clark and Campbell (1991) in the context of their nonmodular, encoding-complex model of number processing, the two issues are actually quite independent. For instance, the mental calculation strategy could be implemented equally well in McCloskey's modular model. Conversely, its rejection does not necessarily entail rejection of the broader encoding-complex framework.

Sketch of Experiments 1–9

The following nine experiments were systematically designed to separate these models of the architecture of number processing. All of the experiments used the same task of odd versus even classification of target numbers. Experiments 1 and 2 addressed the question of how parity information is extracted: Is it retrieved from memory or is it calculated on-line by using general mental calculation routines? Experiments 3–7 examined the relation between parity and magnitude information. A novel finding called the Spatial–Numerical Association of Response Codes (SNARC) effect was used to demonstrate that magnitude information is automatically activated during parity judgment and to show how this fact further constrains theoretical models of number processing. Finally, Experiments 8 and 9 studied how parity judgment times vary with the input notation of the target number. Again, the models make distinctive predictions regarding the similarity and relative speed of parity judgment times when numbers are presented in either Arabic or verbal notation.

Experiment 1: One-Digit Arabic Numerals

In Experiment 1, subjects were presented with Arabic digits in the range 0–9. They had to press one response key if the target was even and another response key if the target was odd. The assignment of the odd and even responses to the right and left keys was systematically varied, as was the degree of mathematical training of the subjects.

Comparison of parity judgment times to different digits, as well as examination of the effect of mathematical training, should permit testing of Clark and Campbell's (1991) mental calculation hypothesis. If subjects used simple mental calculation procedures to examine whether the target number can be decomposed into "2 times another number," then parity judgment times should be well predicted by the time to access the corresponding facts in the multiplication table. For instance, the time to decide that 6 is even should be related to the time to retrieve the fact that $2 \times 3 = 6$. It is well known that arithmetic facts take longer to retrieve the larger the size of the operands (e.g., Ashcraft, 1992; Parkman, 1972). Therefore, parity judgment times should generally increase with number magnitude. The targets 4 and 9 should constitute exceptions, because the "tie" multiplication facts, such as $2 \times 2 = 4$ and $3 \times 3 = 9$, are easy to access (Miller, Perlmutter, & Keating, 1984; Parkman, 1972). Responses to the targets 0, 1, and 2 should also be fast because of the easy applicability of the rules $0 \times 2 = 0$, $1 \times 1 = 1$, and $1 \times 2 = 2$ (e.g., McCloskey, Aliminosa, & Sokol, 1991).[2] In brief, the mental calculation strategy predicts relatively fast responses to 0, 1, 2, 3, 4, and 9 and relatively slow responses to 5, 6, 7, and 8. In addition, because this ordering is based on multiplication facts presumably shared by every normal subject, it should not be affected much by mathematical expertise.

Method

Subjects. Twenty right-handed French students, aged between 20 and 27 years (average = 21.7 years), were tested individually. Ten of them, aged between 20 and 27 years (average = 22.3 years), were following literary studies at the Ecole Normale Supérieure in Paris, France. We refer to them as the L group. The other 10 students, the S group, were studying scientific disciplines (mathematics, physics, or biology) at the same place and were aged between 20 and 23 years (average = 21.0 years).

Instructions. The subjects were told that they would see numbers between 0 and 9. They were to decide whether each number was odd or even by pressing one of two response keys. The instructions emphasized both speed and accuracy. In both the L and S groups, half of the subjects had to answer in a first block with the odd response assigned to the right-hand key and the even response assigned to the left-hand key. They then went through a second experimental block with the reverse assignment of responses to keys. For the other half of the subjects, the reverse order of the two experimental blocks was imposed.

Procedure. For each block, a random list of the numbers 0–9 was built so that every number followed every other once and only once. Consecutive presentations of the same number were not allowed. Each number was therefore presented exactly nine times. The experimental list was preceded by a training list of 12 numbers for a total of 102 target numbers per block.

The experiment was controlled by a PC-compatible portable Toshiba T-2100 computer with orange plasma screen. Bimanual responses were recorded by way of two large Morse keys 26 cm apart. In each trial, an empty rectangular frame (22 mm × 32 mm) first appeared centered on the screen for 300 ms. Then the target number (10 mm × 17 mm) appeared, and the subject's response was recorded with a 1-ms precision over a period of 1,300 ms. The frame and the number were then erased and the screen remained blank for 1,500 ms before the next trial. Each block of 102 trials lasted around 5 min. Including a short resting period in between the two blocks, the entire experiment lasted approximately 15 min.

Results

Error rate averaged over the two blocks did not exceed 8.3% per subject (average = 2.7%). There was no speed–accuracy trade-off, as indicated by a positive correlation of reaction times (RTs) and errors over the 20 cells of the design, $r(18) = +.52$, $p = .019$. Median RTs for correct answers were computed for each target, each side of response, and each subject. These data were analyzed in a 2 (order of blocks) × 2 (group: L vs. S) × 2 (parity: odd or even target) × 5 (target magnitude: 0–1, 2–3, 4–5, 6–7, 8–9) × 2 (side of response: right key vs. left key) analysis of variance (ANOVA) with order and group as between-subjects variables.

First, the effect of order of blocks was not significant, nor did order enter in any significant interactions. The main effect of parity was not significant, either, $F(1, 16) = 1.14$, failing to replicate Hines's (1990) finding of slower RTs to odd targets. Magnitude, however, had a significant effect, $F(4, 64) = 3.35$, $p < .025$, reflecting systematic differences in the speed of classification of different numbers (see Figure 2). For even numbers, the responses to 0 and 6 appeared slow relative to the responses to 2, 4, or 8. Pairwise comparisons that used the Newman-Keuls method ($\alpha = .05$) revealed the following significant pairwise differences: $2 < 0$, $4 < 0$, and $8 < 0$ (6 stood in between and was not significantly different from either 0 or 2, 4, and 8). Although no similar pairwise differences were found for the odd numbers, there was a significant quadratic trend, $F(1, 16) = 6.43$, $p < .025$, for RTs across the range 1–9, meaning that the responses to 1 and 9 were slow relative to the responses to 3, 5, and 7.

Side of response had a significant effect, too, $F(1, 16) = 4.56$, $p < .05$: Subjects responded 35 ms faster with the right hand than with the left hand (450 ms vs. 485 ms), which is consistent with their right-handedness. Surprisingly, side of response also interacted very significantly with magnitude, $F(4, 64) = 5.92$, $p < .001$. The source of this effect is clearly visible in Figure 3 in which we plotted, for each target, the difference between the median RT when pressing the right key and the median RT when pressing the left key. Large numbers were answered about 30 ms faster to the right than to the left, and the converse was true for small numbers. This was confirmed by a significant interaction of side of response and a linear contrast for magnitude, $F(1, 16) = 10.07$, $p < .005$.

These effects were qualified by a Group × Parity interaction, $F(1, 16) = 7.18$, $p < .025$. The Group × Magnitude interaction was also close to significance, $F(4, 64) = 2.47$, $.05 < p < .10$. To clarify the effect of group, two separate

[2] In the case of zero, the data are slightly ambiguous. Multiplications involving zero are processed faster than nonzero multiplications when subjects have to compute the result and name it (Miller, Perlmutter, & Keating, 1984), but they are processed slower when subjects have to verify a proposed result (e.g., $2 \times 0 = 0$; Parkman, 1972; Stazyk, Ashcraft, & Hamann, 1982).

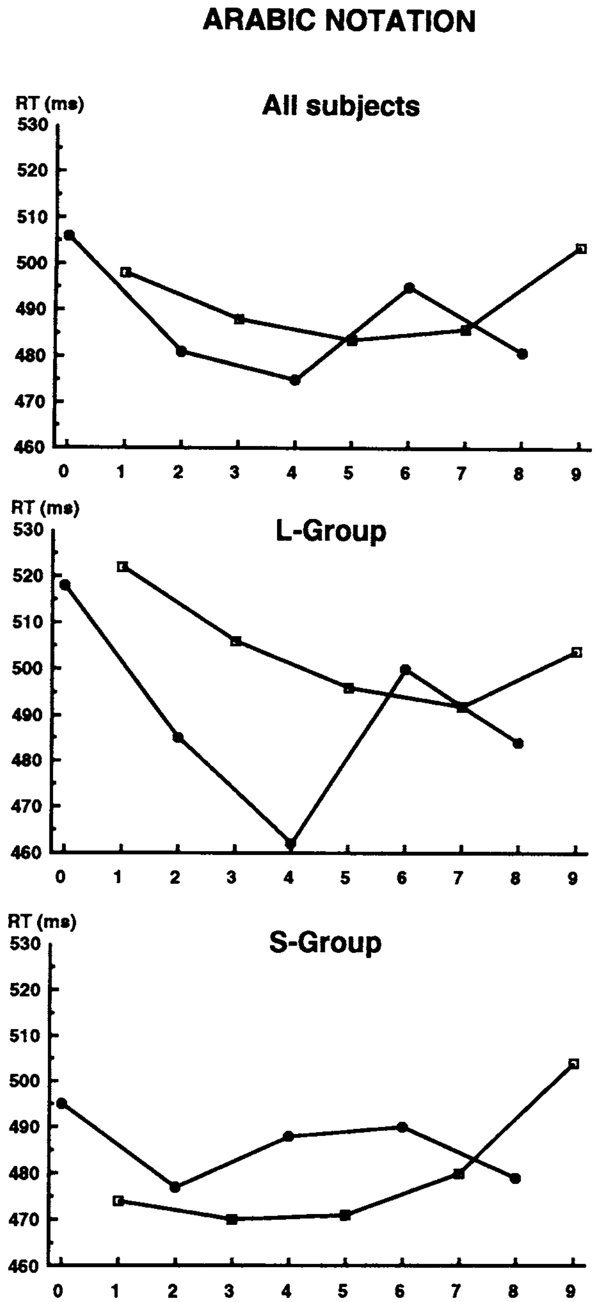

Figure 2. Mean reaction time (RT) for parity judgment of Arabic digits 0–9 in French right-handers as a function of dominant training. (In this figure and all subsequent figures, the two curves on each graph separate odd vs. even targets. L = literary; S = scientific.)

ANOVAs were performed on the median RTs from the L and S groups with the same variables noted earlier. For the S group, no significant differences emerged between specific numbers, and the RT curves were much flatter than those when all subjects were mixed (see Figure 2). However, the effect of side of response was still significant, $F(1, 8) = 12.85$, $p < .01$, with a higher speed for the right key than for the left key. The interaction between the side of response and the linear contrast for magnitude persisted, too, $F(1, 8) = 6.35$, $p < .05$. Again, the larger the target, the faster the response with the right-hand key relative to the response with the left-hand key (see Figure 3).

Finally, for the L group, all the effects uncovered by the global ANOVA were reproduced, except the main effect of side of response, $F(1, 8) = .12$. In addition, responses were globally faster for even numbers than for odd numbers, $F(1, 8) = 5.38$, $p < .05$ (see Figure 2; Hines, 1990). The RT differences between target numbers were also amplified, although only the $0 < 4$ comparison reached significance at $p < .05$ by using the Newman-Keuls method.

Discussion

In Experiment 1, reproducible differences were found in the speed of classification of odd and even numbers. These differences often ran against several predictions of the mental calculation strategy outlined by Clark and Campbell (1991). As shown in Figure 2, parity judgment times did not generally increase as a function of the target number, contrary to what the problem size effect predicted. The RTs to the targets 0 and 1 were relatively slow, whereas they should have been fast if the simple rules $0 \times 2 = 0$ and $1 \times 1 = 1$ had been applied. Finally, the RT to the target 9 was also slow, although it corresponds to an easy multiplication tie 3×3. (The other such tie, $4 = 2 \times 2$, was responded to fast.)

Semantic characteristics of the targets apparently had more influence on parity judgment times than mental calculation speed. Within the even category, the powers of 2 (2, 4, and 8) were classified faster than the other even numbers (0 and 6). This result meshes well with Shepard et al.'s (1975) finding that the powers of 2 form a salient mental category. Within the odd category, we found a U-shaped curve, with 3, 5, and 7 classified faster than 1 and 9. We have only tentative explanations for this finding. The numbers 3, 5, and 7 are prime numbers, whereas 1 and 9 are not. Prime numbers may evoke a fast odd response, because only one prime number (2) is even. In addition, 9 may be slow to classify as odd because it equals 3^2; hence, it may evoke a sense of twoness. Mathematically trained students were perhaps more sensitive to this effect, as suggested by relatively slower RTs to 9 in the S group.

One of the strongest effects concerned the slow responses to 0 and 1. This effect might arise because the series of even numbers, as taught at school, starts with 2. In some intuitive sense, the notion of parity is familiar only for numbers larger than 2. Indeed, before the experiment, some L subjects were unsure whether 0 was odd or even and had to be reminded of the mathematical definition.

The evidence, in brief, suggests that instead of being calculated on the fly by using a criterion of divisibility by 2, parity information is retrieved from memory together with a number of other semantic properties (e.g., if the number is a power of 2, a prime, a member of the series 2, 4, 6, 8, . . .). We postulate that a cluster of semantic properties contribute to the concept of parity and that numbers that share many of these properties are classified faster as odd or even than less prototypical numbers. For instance, Armstrong et al. (1983) showed that numbers whose digits were all even (e.g., 46 and 682) were rated as subjectively more even than other num-

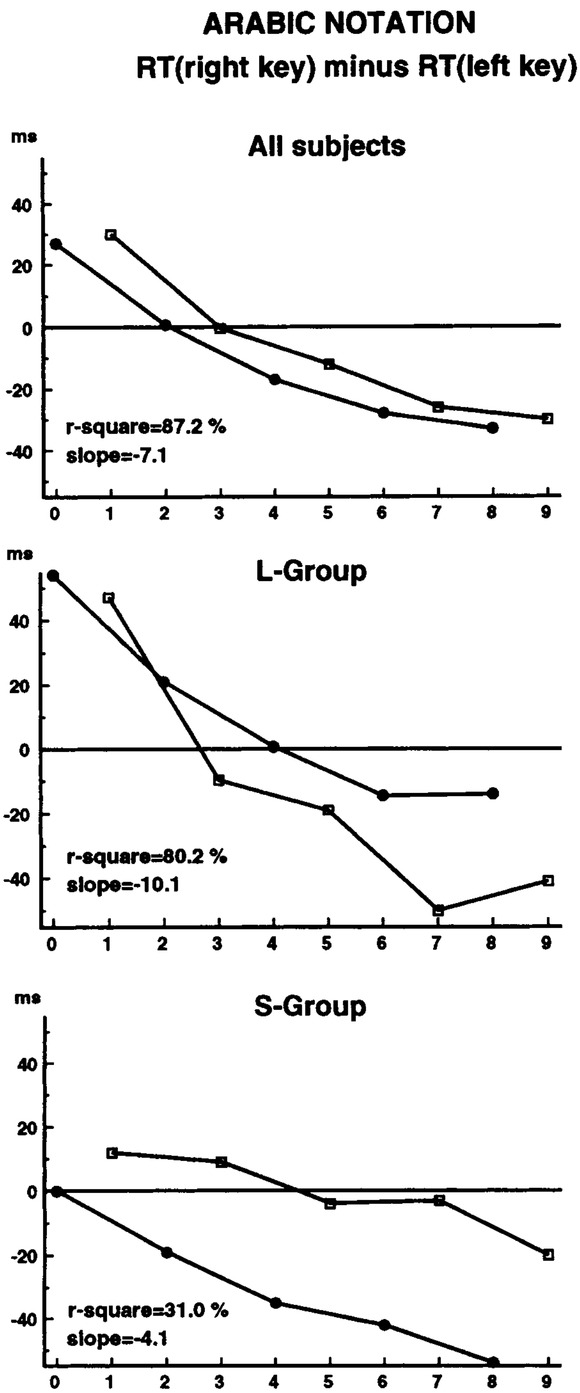

Figure 3. The Spatial–Numerical Association of Response Codes effect for Arabic digits 0–9 in French right-handers. (Regardless of mathematical training, small numbers elicit a faster left response, whereas large numbers elicit a faster right response. RT = reaction time; L = literary; S = scientific.)

bers (e.g., 56 and 792). Likewise, numbers that are powers of 2 might promote an even response, and prime numbers might elicit an odd response.

This memory retrieval hypothesis may also account for the effects of mathematical training. If a semantic memory is accessed in parity judgments, then interindividual differences should be found depending on the familiarity of the subjects with number concepts. Indeed, we found that for students with a scientific background, the differences between the numbers were flattened relative to students with a literary background. This may be accounted for by a larger familiarity with the numbers 0–9. In particular, for the S group, 0 was hardly slowed relative to the other numbers; the zero effect was essentially found in the L group.

Also consistent with an account based on differential training is the finding that even numbers are classified globally faster than odd numbers but only by the L group. Hines (1990) attributed this effect to linguistic markedness. Classification would be faster when using a nonmarked adjective such as *even* rather than a marked adjective such as *odd.* Our results would then suggest that the effect of markedness varies with experience in mathematics. As the subjects would become more familiar with the mathematical meaning of odd and even, the linguistic features of these words might become less salient.

A plausible alternative, however, is differential training: The series of even digits 2, 4, 6, 8, . . . is better known than the series 1, 3, 5, 7, 9, . . . because it is practiced more often, for instance, when counting by twos. Indeed, recitation of the even series is sometimes preserved in brain-lesioned aphasic patients who fail to recite the odd series (e.g., Dehaene & Cohen, 1991). Only after extensive training in scientific domains, as in our S group, would this facilitation for even numbers disappear.

Experiment 2: Two-Digit Arabic Numerals

Experiment 1 did not provide support for Clark and Campbell's (1991) suggestion that the odd–even status is determined by numerical calculations. Subjects apparently did not revert to the mathematical definition of parity (i.e., divisibility by 2). The data were more compatible with a memory retrieval model according to which odd–even status would be stored in memory together with additional semantic numerical information.

Experiment 2 examines whether memory retrieval is also used for parity judgments of two-digit Arabic numerals. Two theoretical hypotheses may be opposed. First, two-digit Arabic numerals might access their own entries in semantic memory. For instance, the target 16 might access an entry specifying that it is even, a power of 2, the base of the hexadecimal system, and so on. This memory retrieval model predicts little or no relationship between the parity judgment times to a two-digit number (e.g., 16) and to its isolated component digits (i.e., 1 and 6). However it predicts the intrusion of global mathematical properties of the numbers. Specifically, on the basis of the results of Experiment 1, one may predict parity judgment to be faster for prime numbers, powers of 2, numbers that have a high exponent for 2 in their decomposition into prime factors (e.g., $40 = 2 \times 2 \times 2 \times 5$), and multiples of 10. As in Experiment 1, the effect of these variables should vary as a function of mathematical training.

Alternatively, the subjects may attempt to focus their attention only on the units digits and then judge of its parity as if it were presented in isolation. This decomposition model predicts no influence of global properties. In principle, the RT to a two-digit target should be strictly equal to the RT to its units digit, as measured in Experiment 1. For instance, the RTs to targets 6, 16, 26, 36, and so on, should be identical. However, completely ignoring the decades digit may not be feasible. In analogy with the Stroop effect, one may then expect response facilitation when the decades and units digits are both odd or both even. This would mesh well with Armstrong et al.'s (1983) observation that numbers whose digits have congruent parities (e.g., 24 and 57) look more even or more odd than similar but incongruous numbers (e.g., 54 and 27).

To separate the memory retrieval model from its decomposition alternative, Experiment 2 focused on whether the time to determine the parity of a two-digit Arabic numeral could be predicted by the RT to its component digits.

Method

Twenty right-handed French students, aged between 17 and 23 years (average = 20.7 years), were tested individually. As in Experiment 1, 10 were L students (ages ranging from 17 to 22 years; average = 20.5 years), and 10 were S students (ages ranging from 19 to 23 years; average = 20.8 years). In each group, half of the subjects had to answer with the even response assigned to the right-hand key (even-right task), whereas the other half had to answer with the even response assigned to the left-hand key (even-left task). For each subject, a random list of the numbers 10–99 was built so that each number appeared exactly three times, and the same number never appeared twice in a row. The experimental list of 270 items was preceded by a training list of 11 random numbers in the range 10–99. Stimulus presentation was identical to Experiment 1. The experiment lasted about 15 min.

Results

Individual error rates did not exceed 5.6% (average = 2.5%), and there was no speed-accuracy trade-off, $r(18) = +.56$, $p = .009$. Correct RTs were successively analyzed for the following effects: (a) the presence of a congruity effect between the parities of the decades and units digits, (b) the effect of the units digits on RT, (c) the influence of mathematical properties such as primality or powers of 2, and (d) any effect of the hand or side of response.

To assess the presence of a congruity effect, median RTs were computed for each subject and for each value of the units digit, separately for numbers whose two digits had congruent parities (e.g., 24 and 57) and for numbers whose two digits had incongruous parities (e.g., 54 and 27). These data were analyzed in a 2 (group: L vs. S) × 2 (task: even-right vs. even-left) × 2 (congruity) × 2 (parity of the units digit) × 5 (magnitude of the units digit) ANOVA, with group and task as between-subjects variables. The effect of congruity was highly significant, $F(1, 16) = 32.1$, $p < .0001$. Congruity did not interact with any other variables, except for an obscure triple interaction with task and magnitude, $F(4, 64) = 5.11$, $p < .002$. The average RT was 487 ms for congruent numbers and 505 ms for incongruous numbers. Thus, the data indicated that parity judgments were impeded when the parity of the decades digit conflicted with the parity of the units digit.

The same ANOVA uncovered an effect of the units digits, $F(9, 144) = 2.61$, $p = .008$. This reflected systematic differences in the speed of classification of numbers with differing units digits (see Figure 4). Pairwise comparison that used the Newman-Keuls method showed that among even numbers, those ending with 6 were significantly slower than all other numbers and that among odd numbers, those ending with 7 were faster than those ending with 3, 5, or 9. Contrary to Hines (1990), no global difference was found in the speed of odd and even responses, $F(1, 16) < 1$. Responses were similar in the L and S groups, as indicated by the lack of significance of interactions involving the group variable. The pattern of RTs was also similar to the one found in Experiment 1 with the numbers 0–9 (e.g., the slow RTs to numbers ending with 6 and 9; see Figure 4). However, a major difference was the fast responses to numbers ending with 0 or 1: These digits were slow to classify when presented in isolation. Finally, the Task × Parity × Magnitude interaction was not significant, $F(4, 64) < 1$: Contrary to Experiment 1, large-units digits were not responded to faster with the right hand and small-units digits were not responded to faster with the left hand.

Another ANOVA was used to assess possible differences in RTs due only to the decades digits. Median RTs were computed for each subject for numbers with the same decades digit, separately for left-hand and right-hand responses. For instance, for subjects in the even-right task, the numbers 40, 42, 44, 46, and 48 were grouped into one category (right-hand responses, decades 4), and the numbers 41, 43, 45, 47, and 49 were grouped into another category (left-hand responses, decades 4). Median RTs were then analyzed in a 2 (group: L vs. S) × 9 (decades digit 1–9) × 2 (side of response: right key vs. left key) ANOVA, with group as the only between-subjects variable. The interaction of side of response with a linear contrast for magnitude fell short of significance, $F(1, 18) = 3.65$, $p = .072$. Its direction, nevertheless, suggested that numbers with larger decades digits (i.e., in the 80s or 90s) tended to be responded to faster with

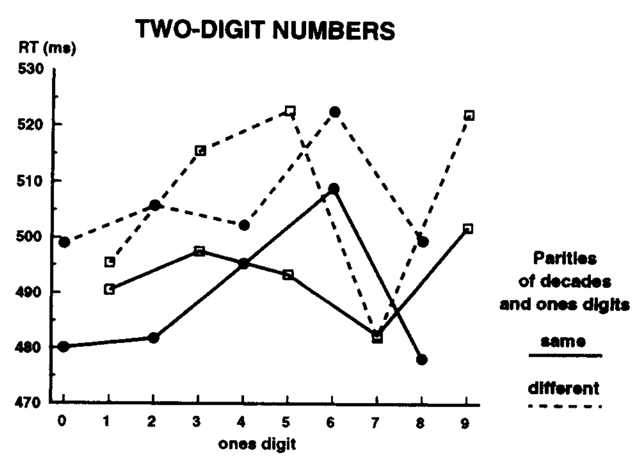

Figure 4. Mean reaction time (RT) for parity judgment of two-digit Arabic numerals as a function of the value of the ones digit. (Parity judgments were impeded when the parity of the decades digit conflicted with the parity of the ones digit [dashed line]. This congruity effect was additive with the effect of the ones digit.)

the right hand, whereas numbers with smaller decades digits (e.g., the teens) tended to be responded to faster with the left hand. No other effects or interactions were significant.

Finally, to examine the possible influence of global mathematical properties, median RTs to each two-digit numeral were submitted to a stepwise multiple regression analysis. Five variables were entered that coded for mathematical properties of the two-digit numbers that might have been represented in semantic memory: (a) parity (0 for even numbers and 1 for odd numbers), (b) prime (1 if the number is prime and 0 otherwise), (c) zero (1 if the number ends with digit 0 and 0 otherwise), (d) power2 (1 if the number is a power of 2 and 0 otherwise), and (e) exp2 (the exponent of 2 in the decomposition into prime factors; e.g., exp2[16] = 4 and exp2[17] = 0). Three other nonmathematical variables were introduced: (a) congruity (1 if the two digits have the same parity and 0 otherwise), (b) RTunits (the mean RT to the units digit alone, as measured in Experiment 1), and (c) RTdecades (the mean RT to the decades digit alone, as measured in Experiment 1).

Parity judgment times were well predicted by the following equation:

$$RT = -14.5 - 14.1\ \text{congruity} - 39.1\ \text{zero} + 1.09\ \text{RTunits} - 17.4\ \text{parity}.$$

In this equation the variables were listed in order of entering into the stepwise regression. All but the constant were significant at $p < .005$ ($r^2 = 34.1\%$). The lack of significance of the constant term, as well as the coefficient close to 1 for variable RTunits, showed that the RT to a two-digit Arabic target was well predicted by the RT to its units digit. The additional influence of congruity demonstrated interference from the decades digit. The effect of parity suggested that two-digit odd numbers were classified faster than predicted on the basis of Experiment 1. Finally, the effect of variable zero indicated that numbers ending with 0 were rapidly classified as even, whereas in Experiment 1 parity judgments of the digit 0 in isolation were very slow. Remarkably, mathematical properties that were specific to the two-digit number as a whole had no measurable influence on parity judgment times. Primes or powers of 2 were not classified significantly faster than other target numbers. Analyzing separately the data from the L and S groups lead to similar regression results.

Discussion

The results of Experiment 2 were clear-cut in favor of the decomposition model and were against the semantic retrieval hypothesis. There was no evidence that the two-digit stimulus as a whole contacted a lexicon specifying the semantic properties of numbers. In particular, no facilitation was observed for prime numbers or for powers of 2, even in a subgroup of mathematically sophisticated subjects. Experiment 2 does not preclude the existence of a semantic lexicon for two-digit numbers, but it shows that such a lexicon is not used in the parity judgment task.

Two-digit number parity judgment times were well predicted by the RT to the isolated units digit, as measured previously in Experiment 1. This result is compatible with a decomposition model and with a strategy of selective processing of the units digit. In addition, there were indications that the subjects failed to focus completely on the units digit and that the decades digit was partially processed. The effect of congruity showed that the parity of the decades digit was extracted and interfered with the main parity judgment performed on the units. Responses to numbers ending with 0 or 1 were also quite fast, whereas in previous experiments the isolated digits 0 and 1 took much longer to classify. We have suggested earlier that, to some subjects, applying the notion of parity to numbers smaller than 2 seemed peculiar. Evidently, their reluctance vanished with numbers from the range 10–99.

Conclusion for Experiments 1 and 2

Together, Experiments 1 and 2 provide a good working hypothesis for how parity information is extracted from numbers in Arabic notation. First, if the target is a multidigit number, only its rightmost digit is selected for further processing. Other digits are filtered out, although the congruity effect demonstrates that they occasionally interfere with the main task. Second, the rightmost digit is used to access a semantic memory, which stores miscellaneous numerical information about numbers, including their parity. Finally, the odd or even status of the target is retrieved and reported.

The model that we have just outlined is silent about the modularity and organization of the processing architecture in which the parity retrieval algorithm is embedded. Parity information might be retrieved from a modality-specific representation of the target (Dehaene, 1992; Noël & Seron, in press) or from an encoding complex (Campbell & Clark, 1988), or it could be accessed only from an abstract internal representation of numbers (McCloskey, 1992). To separate these models, Experiments 3–7 assess the status of magnitude information in the course of parity judgment. According to McCloskey's model, an abstract internal representation is necessarily accessed during any form of number processing. Because this representation is essentially a magnitude code with base-ten structure, the model predicts a compulsory access to magnitude information during parity judgment. Likewise, Dehaene's triple-code model suggests that an analogue magnitude code is central to number representation, although it need not be automatically activated in all tasks. The two other models, Noël and Seron's preferred entry code and Campbell and Clark's encoding complex, do not assign a critical role to magnitude information in the structuring of number representation.

In Experiment 1, an effect was found that seems relevant to the relationships between parity and magnitude information. It appeared as a Side of Response × Number Magnitude interaction: the larger the target number, the faster the response on the right-hand side relative to the response on the left-hand side. A fully continuous crossover effect was obtained: Left-hand responses were faster than right-hand responses for small numbers, and the converse was true for large numbers (see Figure 3). This result may be described as a double association or preference: Large is associated with right and small with left. We refer to this association as the SNARC effect.

The extreme regularity of the spatial–numerical association is intriguing (see Figure 3). Numerical magnitude is mathematically irrelevant when judging the parity of a number. It is therefore unexpected that magnitude should have such a sizable effect on RTs. The SNARC effect might be taken as evidence for an automatic activation of a magnitude representation from Arabic notation, thereby providing further cues to the mental organization of number representations. However, the effect was weaker, if not absent, in Experiment 2 with two-digits numerals. Experiments 3–7 further explore the replicability of the SNARC effect and its relevance to mental number representations.

Experiment 3: Two Numerical Intervals

Before accepting the SNARC effect as an index of automatic access to number magnitude, nonnumerical alternatives should be considered. The frequency of numerals and number words is highly correlated with number magnitude (Dehaene & Mehler, 1992). In many languages, the word *one* is more frequent than the word *two*, *two* is itself more frequent than *three*, and so forth. This decrease in frequency extends to Arabic notation. Could the SNARC effect depend on frequency rather than on numerical magnitude?

The frequency explanation runs into difficulties when the responses to 0 are considered. As an Arabic numeral or as a number word, *zero* is less frequent than *one*, or even than *nine*, in many different languages (Dehaene & Mehler, 1992). Yet, in Experiment 1, digit 0 elicited responses that were 27 ms faster with the left hand than with the right hand. Despite its low frequency, 0 showed a SNARC effect in the same direction as the high-frequency stimuli 1 and 2, suggesting that magnitude, not frequency, was responsible for the SNARC effect.

Experiment 3 aimed at strengthening this conclusion in a more direct fashion. We examined whether the SNARC effect depends on any absolute characteristics of the numbers (frequency, visual appearance, etc.) or whether it depends on the relative magnitude of each stimulus number with respect to some prespecified interval. Subjects participated in two experiments of parity judgment, one with numbers in the interval 0–5 and one with numbers in the interval 4–9. The same numbers 4 and 5 were in one case the largest numbers tested and in the other case the smallest numbers tested. If the SNARC effect is governed by relative numerical magnitude, then these numbers should be preferentially associated in one case with the right-hand key and in the other case with the left-hand key. Alternatively, if the SNARC effect is governed by some absolute characteristics of the stimuli, then the numbers 4 and 5 should show the same amount of facilitation for one or the other key, regardless of numerical context.

Method

Twelve French students, aged between 19 and 31 years (average = 23.8 years) with no particular training in mathematics, were tested individually (2 other subjects were rejected for failing to comply with the instructions). All subjects went through two consecutive blocks of two tests. In one block the numbers ranged from 0 to 5, and in the other block the numbers ranged from 4 to 9. Order of the two blocks was counterbalanced across subjects. Within each block, the subjects took part in the parity judgment task twice, once with the odd response assigned to the right-hand key and once in the converse condition, in counterbalanced order. In each condition, there was an initial training list of 12 items, and then each target number was presented 15 times (3 times preceded by each of the 5 other targets) for a total of 102 items.

Results

Error rate averaged over the four tests did not exceed 9.2% per subject (average = 3.7%), and there was no speed–accuracy trade-off, $r(22) = +.66$, $p < .001$. Median RTs for correct answers were analyzed in a 2 (order of blocks) × 2 (order within blocks) × 2 (interval: 0–5 vs. 4–9) × 2 (parity: odd or even target) × 3 (target magnitude: small, medium, or large in the interval tested) × 2 (side of response: right key vs. left key) ANOVA. As shown in Figure 5, the speed of parity judgment differed systematically for different numbers, coarsely replicating the results of Experiment 1 and in particular the slow RTs to the numbers 0 and 1. Two interactions involving the ordering factors were also found, revealing a shortening of RTs in the course of the experiment, which is not analyzed further.

Most relevant to the purpose of this experiment, side of response interacted significantly with number magnitude, $F(2, 16) = 13.1$, $p < .001$, thus showing a significant SNARC effect. The interaction remained significant within each interval of numbers tested, $F(2, 16) = 8.55$, $p < .003$, for interval 0–5, and $F(2, 16) = 7.02$, $p < .007$, for interval 4–9. The lack of a Side of Response × Magnitude × Interval interaction, $F(2, 16) = 1.79$, $p > .10$, showed that the SNARC effect was not governed by absolute characteristics of the numbers but only by their relative magnitude within the interval tested. Thus, relatively small numbers (0–1 in the interval 0–5 and 4–5 in the interval 4–9) were responded to faster with the left hand than with the right hand, and relatively large numbers (4–5 in the interval 0–5 and 8–9 in the interval 4–9) were responded to faster with the right hand. This resulted in a complete reversal of the relative speeds of the right and left responses to the numbers 4 and 5, depending on the intervals in which they were presented, $F(1, 8) = 14.4$, $p < .005$ (see Figure 5).

Discussion

The SNARC effect was replicated in Experiment 3, and it did not appear to depend on any intrinsic characteristics of the target numbers, such as frequency, visual appearance, or absolute numerical magnitude. The numbers 4 and 5 were preferentially associated with a right-hand response when they were the largest in a list comprising the numbers 0–5. Conversely, the same numbers, 4 and 5, were preferentially associated with a left-hand response when they were the smallest in a list comprising the numbers 4–9. Thus, the SNARC effect depended only on the relative magnitude of the target numbers within the tested interval.

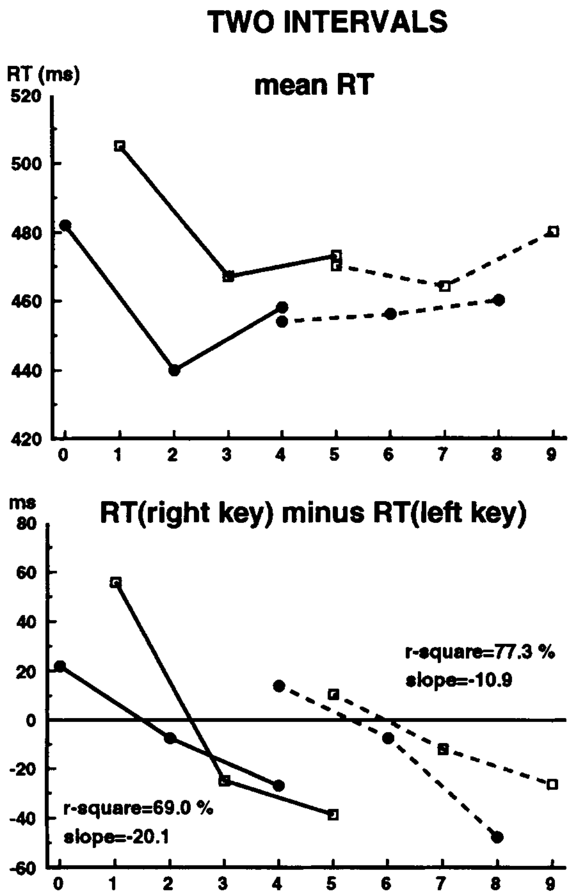

Figure 5. Mean reaction time (RT; top panel) and the Spatial–Numerical Association of Response Codes effect (bottom panel) as a function of the numerical interval tested. (Continuous line represents RTs to numerals 0–5; dashed line represents RTs to numerals 4–9.)

It is, however, still possible that the effect is not numerical in nature but rather depends on the overlearned sequential structure of the stimuli. A spatial gradient of preference for the right or left hand might emerge whenever the stimuli obey a fixed sequential order. The effect would therefore depend on the ordinal, and not the cardinal, aspects of number representations. This possibility is examined in Experiment 4 by using letters instead of numbers. If the SNARC effect arises only from a representation of number magnitude, rather than from a representation of sequential order, then it should not show up with letter stimuli.

Experiment 4: Letters

Experiment 4 was designed to be as similar as possible to Experiments 1 and 3, but with letters instead of numbers. Because there is no direct analogue to parity in the letter domain, two tasks were used that were both similar to parity judgment in different respects. The first task, referred to as ACE–BDF classification, was isomorphic to the parity judgment of digits 0–5 (see Experiment 3). Subjects had to press one key when presented with the letters A, C, or E and another key when presented with the letters B, D, or F. Although this task preserved the sequential structure of Experiment 3, it also put a heavier burden on memory because the stimulus classes ACE versus BDF seemed arbitrary. Consonant–vowel classification was therefore used as a second, more natural task. Only the letters A, C, E, G, I, L, O, R, U, and X were used, so that vowels alternated with consonants in the stimulus set. The sequential structure of the letter stimuli was therefore quite similar to Experiment 1 with Arabic digits 0–9.

If the SNARC effect was governed by the sequential structure of stimuli, it should show up in both the ACE–BDF and consonant–vowel classification tasks: Letters closer to the beginning of the alphabet should be responded to faster with the left hand than with the right hand, and the converse should be true for letters closer to the end of the alphabet. Conversely, the absence of any SNARC effect in both tasks would be strong evidence that the effect is specific to a representation of number magnitude.

Method

Twenty French subjects, aged between 18 and 53 years (average = 30.3 years), with no particular training in mathematics, were tested individually. Ten of them were tested in the ACE–BDF classification task. The method was identical to the 0–5 block of Experiment 2, except that the letters A–F were substituted for the digits 0–5. The other 10 subjects were tested in the consonant–vowel classification task, which was identical to Experiment 1, except for the substitution of the letters A, C, E, G, I, L, O, R, U, and X for the digits 0–9.

Results

ACE–BDF classification. Error rate did not exceed 3.9% per subject (average = 1.7%), and there was no speed–accuracy trade-off, $r(10) = +.10$, *ns*. Median RTs for correct answers were submitted to a 2 (order of blocks) × 2 (letter set: ACE vs. BDF) × 3 (alphabetical position within group: AB, CD, or EF) × 2 (side of response: right key vs. left key) ANOVA. The Side of Response × Alphabetical Position interaction was not significant, $F(2, 16) < 1$, indicating the absence of a SNARC effect. This was not due to a general lack of statistical power in the experimental design, because significant effects were found for letter set, $F(1, 8) = 7.49$, $p = .026$, alphabetical position, $F(2, 16) = 24.9$, $p < .0001$, and their interaction, $F(2, 16) = 22.1$, $p < .0001$. We note in passing that the results were compatible with a serial, self-terminating search through the ACE set, because RT increased with alphabetical position for letters A, C, and E and was constant for letters B, D, and F (see Figure 6).

Consonant–vowel classification. Error rate did not exceed 4.4% per subject (average = 1.4%), and there was no speed–accuracy trade-off, $r(18) = +.28$, *ns*. Median RTs for correct answers were submitted to a 2 (order of blocks) × 2 (consonant vs. vowel) × 5 (alphabetical position: AC, EG, IL, OR, UX) × 2 (side of response: right key vs. left key) ANOVA. Again, no SNARC effect was found, as attested by the lack of a Side of Response × Alphabetical Position interaction, $F(4, 32) = 1.98$, $p > .10$. This was not due to a

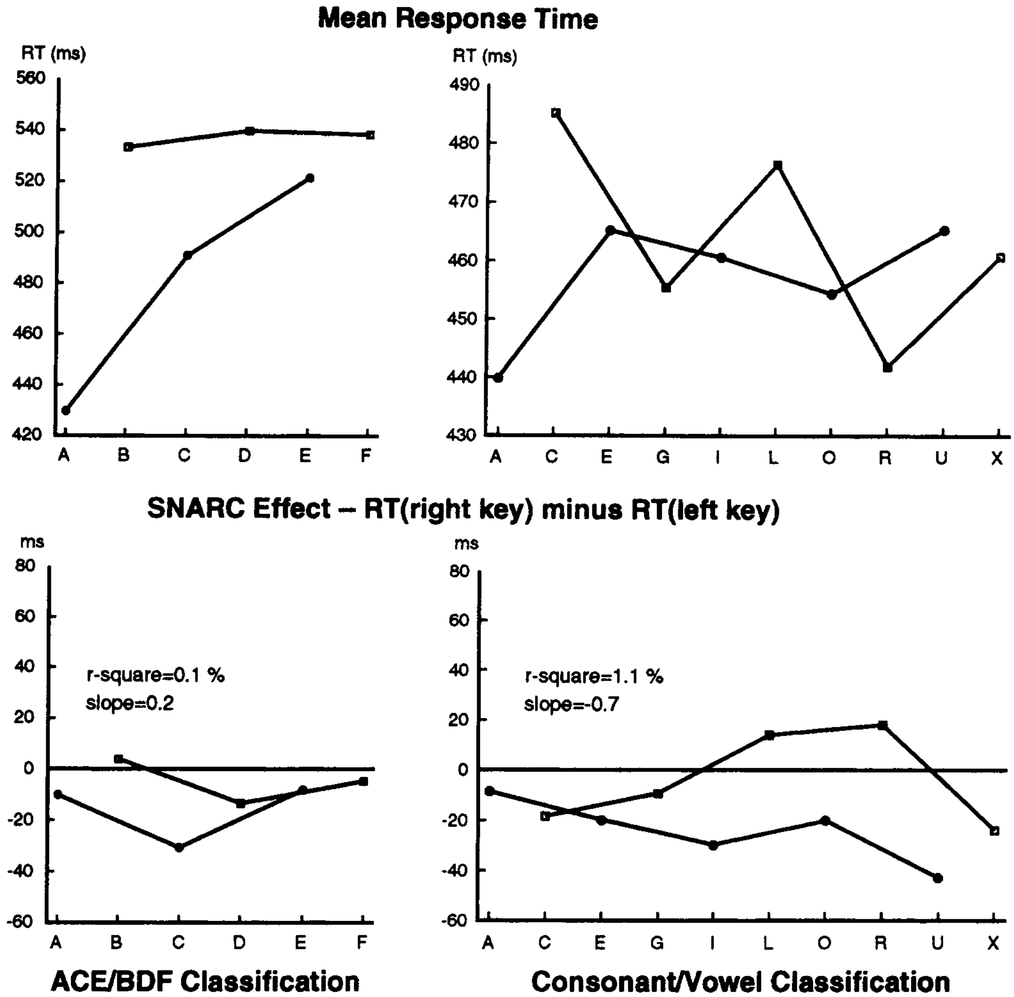

Figure 6. Mean reaction time (RT) and absence of the Spatial–Numerical Association of Response Codes (SNARC) effect when letters were used instead of numbers in Experiment 4.

lack of statistical power, because significant differences emerged between left and right responses, $F(1, 8) = 9.03$, $p = .017$, and between the 10 target letters, $F(9, 72) = .0013$. In terms of absolute speed, the results were also quite comparable with parity judgment (mean RT = 461 ms; see Figure 6).

Discussion

No preference for the right or left hand was found when letters were used instead of numbers. Thus, the SNARC effect observed in Experiments 1 and 3 appears to be specific to numerical stimuli. The conclusion that the SNARC effect is of numerical origin is strengthened by the observation of a similar effect in at least one numerical task other than parity judgment. In Dehaene, Dupoux, and Mehler's (1990) Experiment 2, subjects compared two-digit target numbers to a fixed standard number, 65. For one group of subjects, the larger response was assigned to the right-hand key and the smaller response to the left-hand key (larger right group); the reverse assignment was used for the larger left group. The results indicated that the larger right group responded faster on average than the larger left group. This effect was later replicated in a within-subjects design. The present parity experiments extend this finding to one-digit numbers.

Having demonstrated the genuine numerical origin of the SNARC effect, we now examine its spatial characteristics. The association of large numbers with the right conforms with an introspection commonly found at least in Western countries and shared by subjects who claim to possess a rich visuospatial representation of numbers (Seron, Pesenti, Noël, Deloche, & Cornet, 1992). Yet, its nature and origins are unclear and are examined in Experiments 5–7. At least three left–right asymmetries were present in Experiments 1 and 2 and might have contributed to the SNARC effect. First, all subjects were right-handed. The influence of handedness on the direction of the SNARC effect is assessed in Experiment 5. Second, most subjects probably had a normal pattern of hemispheric dominance. The role of hemispheric asymmetry is explored in Experiment 6. Third, all subjects lived in a literate culture in which writing goes from left to right. The effect of the direction of writing is tested in Experiment 7.

Experiment 5: Left-Handers

Experiment 5 assessed the effect of handedness on the direction of the SNARC effect. Ten left-handed subjects were tested in the same conditions as the 20 right-handed subjects of Experiment 1.

Method

Ten left-handed French subjects, with no particular mathematical training, were tested individually. They were aged between 19 and 44 years (M = 31 years). Coefficients of left-handedness, as determined from a 10-item questionnaire, ranged from −.37 to −1.00 (average = −.81), where a coefficient of +1.00 means right-handedness for all 10 items, and a coefficient of −1.00 means complete left-handedness. The procedure and instructions were identical to those in Experiment 1.

Results

Error rate averaged over the two blocks did not exceed 6.7% per subject (average = 3.2%), and there was no speed–accuracy trade-off, $r(18) = +.40$, *ns*. Median RTs were analyzed in an ANOVA similar to the ANOVA used in Experiment 1. Subjects responded 31 ms faster with the left hand than with the right hand, a difference that fell short of statistical significance, $F(1, 8) = 4.75, p = .06$, but is consistent with their left-handedness. Side of response also interacted with number magnitude, $F(4, 32) = 4.94$, $p < .005$. As shown in Figure 7, large numbers were again responded to faster with the right hand than with the left hand, and the converse was true for the small numbers. Number magnitude also had a significant effect by itself, $F(4, 32) = 8.62, p < .001$. As in Experiment 1, there were significant overall differences in response time to the 10 digits, $F(9, 72) = 5.15$, $p < .001$. Pairwise comparison that used the Newman-Keuls method revealed the following ordering of even and odd RTs: 2 = 4 = 8 = 6 < 0 and 3 = 7 = 9 = 5 < 1.

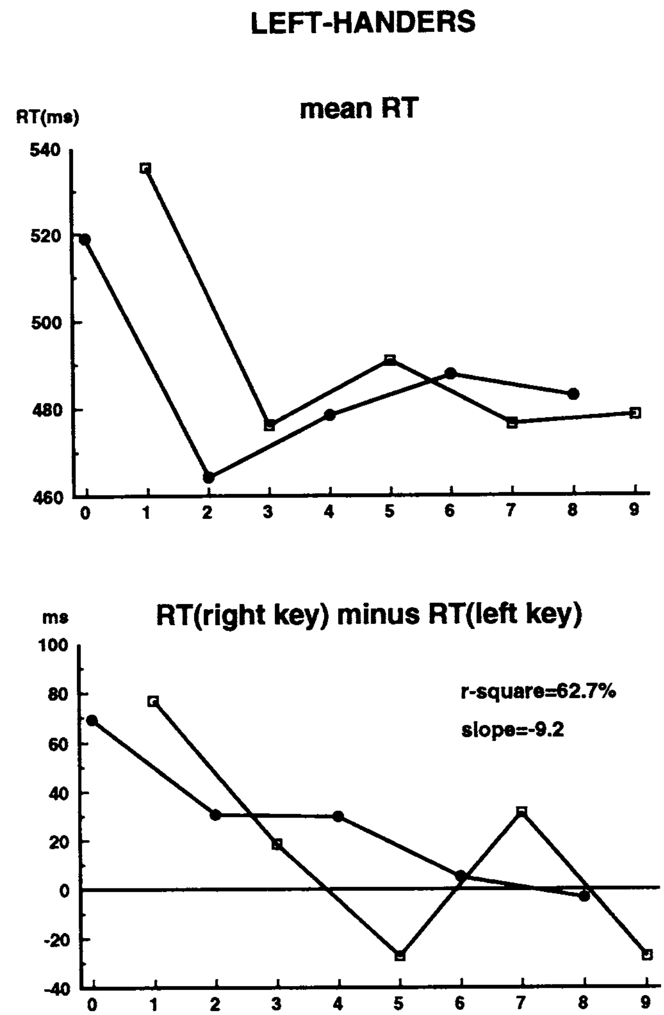

Figure 7. Mean reaction time (RT; top panel) and the Spatial–Numerical Association of Response Codes effect (bottom panel) for 10 French left-handers.

Discussion

No major differences emerged between right-handers and left-handers concerning parity judgments. In particular, the SNARC effect was replicated with left-handers: Large numbers were again associated with the right-hand key and small numbers with the left-hand key. Handedness is therefore not responsible for the direction of this association.

Most left-handers, however, share with right-handers a left-hemisphere specialization for linguistic material. Several, often conflicting, hypotheses have been proposed concerning the hemispheric specialization for number processing. Number transcoding and calculation deficits are mostly observed following left-hemisphere damage (e.g., Hécaen, Angelergues, & Houillier, 1961). However, the similarity of Arabic notation to ideographic writing like Japanese kanji may indicate a right-hemisphere basis (Coltheart, 1980). The experimental literature that uses hemifield presentation is inconclusive (Holender & Peereman, 1987). In an experiment similar to those reported here, Klein and McInnes (1988) found a 14-ms right-hemisphere advantage in parity judgments of digits 1–6. It is therefore not inconceivable, although admittedly farfetched, that perhaps relatively small numbers are processed by way of the right hemisphere and relatively large numbers by way of the left hemisphere. This would predict left- and right-hand advantages in conformity with the SNARC effect. The possible influence of hemispheric dominance on the SNARC effect is evaluated in Experiment 6.

Experiment 6: Hands Crossed

In Experiment 4, subjects performed a parity judgment task with their hands crossed. For instance, responses to the right-hand key were made by using the subject's left hand. A reversal of the direction of the SNARC effect would indicate a strict dependency of the effect on the hand performing the response, thereby suggesting a hemispheric dominance effect. The absence of a reversal may indicate that the SNARC effect operates at a more abstract level of representation of the left and right sides of response.

Method

Eight right-handed French subjects, aged between 19 and 33 years (average = 25.5 years), with no particular mathematical training, were tested individually (1 additional subject was eliminated because 25% of his RTs exceeded 1 s). The procedure was identical to that in Experiment 1, except that throughout the testing session the subjects were asked to place their left hand on the right-hand key and their right hand on the left-hand key.

Results

Error rate averaged over the two blocks did not exceed 3.9% (average = 2.6%), and there was no speed–accuracy trade-off, $r(18) = +.39$, *ns*. Median RTs were analyzed in the same ANOVA as in Experiment 1, with side of response computed according to the key of response (left key vs. right key), which is now inversely related to the hand of response. Number magnitude again interacted with side of response, $F(4, 24) = 6.89, p < .001$. Figure 8 shows that large numbers were again responded to faster with the right-hand key (now the left hand) than with the left-hand key (now pressed by using the right hand), and the converse was true for small numbers. The slope of this SNARC effect was in fact larger than in Experiment 1 (9.9 ms/number vs. 7.1 ms/number) and in the same direction.

Number magnitude also had a significant effect by itself, $F(4, 24) = 3.98$, $p < .025$. Again, significant overall differences were observed in the RTs to the 10 stimuli, $F(9, 54) = 4.08$, $p < .001$. Pairwise comparisons that used the Newman-Keuls methods revealed the following ordering of even RTs: 2 = 8 = 4 = 0 < 6. For odd responses, the only significant difference was 7 < 1.

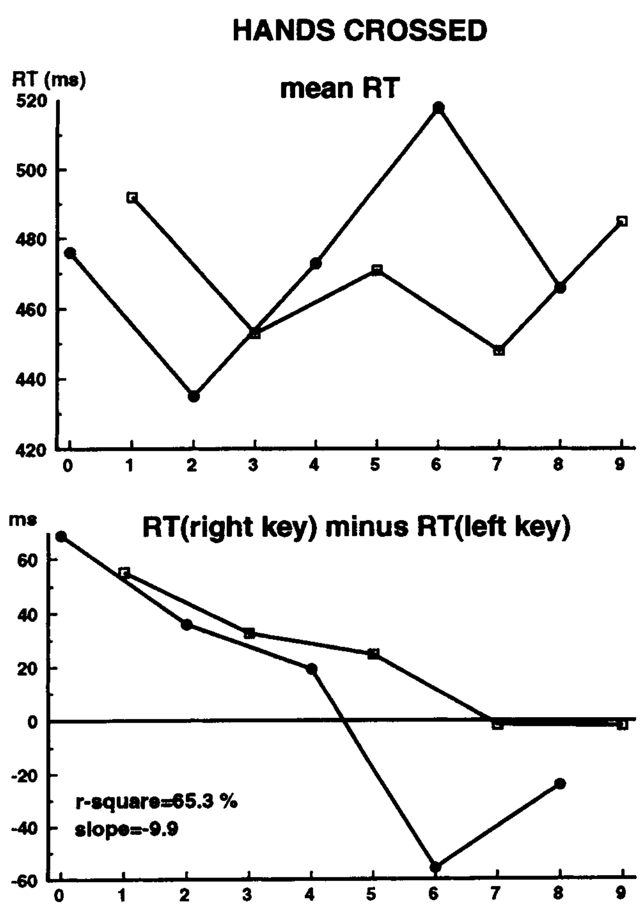

Figure 8. Mean reaction time (RT; top panel) and the Spatial–Numerical Association of Response Codes effect (bottom panel) for French right-handers crossing their hands during Experiment 6.

Discussion

When the subjects responded with their hands crossed, the SNARC effect was accentuated rather than diminished or reversed. Large numbers were again classified faster by using the right-hand key, even though this key was now pressed with the left hand. Conversely, small numbers were again classified faster by using the left-hand key, even though this key was now pressed with the right hand. The data therefore indicate that large or small numerical magnitudes are not associated with a particular hand of response. Rather, large numerical magnitudes are associated with the right-hand side of extracorporal space, and small magnitudes are associated with the left-hand side of extracorporal space. These associations hold regardless of the particular hand that is making the response in that part of space.

Experiment 6 rules out any simple hemispheric interpretation of the SNARC effect that would postulate a differential representation of small and large numbers within the hemispheres commanding respectively the left and right hands. The evidence suggests that the interaction between number magnitude and the left–right coordinates intervenes at the level of a more abstract representation of the left–right axis. Of course, the left and right extracorporal hemispaces are themselves, to some degree, represented cortically in the contralateral hemispheres (e.g., Bisiach & Luzzatti, 1978). Therefore, the theoretical possibility of a differential hemispheric representation for small and large numbers is not totally undermined by Experiment 6. Experiment 7 provides a more satisfying refutation.

Experiment 7: Iranian Subjects

Experiment 7 assessed the influence of the direction of writing on the SNARC effect. Iranian subjects, who write from right to left in their native language, were tested in the conditions of Experiment 1. A reversal of the direction of the SNARC effect would indicate an influence of the writing system on the conceptualization of number magnitude. Because Iranian and French subjects presumably have the same pattern of hemispheric dominance, it would also dismiss hemispheric lateralization as a variable relevant to the SNARC effect.

The testing of Iranian subjects also enabled us to probe effects of the surface notation of numbers (see Experiments 8 and 9). In addition to the standard Arabic notation, another positional number notation called east Arabic numerals is also in use in Iran. According to Menninger (1969), this notation is used "by all Arabic-writing peoples of the Orient (Egyptians, Syrians, Turks, Persians)," (p. 413) and it derives directly from the ancient Indian numeration system. It is a base-ten positional system, but with the 10 east Arabic digits 0–9 differing from the usual Arabic digits (see Figure 9). East Arabic numerals are used within sentences written from right to left, but they are nevertheless written from left to right. For instance, when writing the east Arabic numeral 51, the decades digit 5 is written first and appears to the left of the units digit 1.

The east Arabic notation was generally taught to our subjects simultaneously with or slightly before the Arabic notation. Arithmetic procedures were generally acquired first in the east Arabic notation. In Experiment 7, we took advantage of the numerical bilingualism of our subjects and studied their parity judgment with both notations. Because east Arabic and Arabic numerals are used respectively in the context of right-to-left and left-to-right writing, we wondered whether the direction of the SNARC effect would vary with number notation.

Method

Twenty right-handed Iranian subjects, aged between 18 and 29 years (average = 22.0 years) were tested individually. Most were medical students in Parisian universities and had received moderate training in mathematics. All were born in Iran from Iranian parents and had initially studied there before leaving for France between 1.5 and 12 years ago (average = 6.7 years). All subjects first participated in a parity judgment test consisting of two blocks of trials similar to Experiment 1 but with east Arabic digits 0–9 (maximum size 20 mm × 30 mm, surrounded by a frame 37 mm × 43 mm; see Figure 9). They then participated in a second test identical to Experiment 1 with Arabic digits 0–9. Across the four blocks of trials, the assignment of the odd response to the right- or left-hand key was varied in a ABBA sequence. Because of an error of the experimenter, 8 subjects started with the odd response assigned to the left-hand key and 12 subjects started with the odd response assigned to the right-hand key.

Results

Error rate averaged over the four blocks of trials did not exceed 8.1% (average = 2.7%), and there was no speed–accuracy trade-off, $r(38) = +.12$, *ns*. Median RTs were analyzed in a 2 (notation: east Arabic vs. Arabic) × 2 (parity: odd or even target) × 5 (target magnitude: 0–1, 2–3, 4–5, 6–7, or 8–9) × 2 (side of response: right key vs. left key) ANOVA, where all variables were within-subjects. There was a main effect of notation, $F(1, 19) = 9.18$, $p < .007$, where east Arabic digits were classified on average 32 ms slower than Arabic digits (525 ms vs. 493 ms).

Arabic	East Arabic	French Numerals		Mirror Image
0	۰	ZERO	DIX	OЯƎZ
1	۱	UN	ONZE	ИU
2	۲	DEUX	DOUZE	XUƎᗡ
3	۳	TROIS	TREIZE	ƧIOЯT
4	۴	QUATRE	QUATORZE	ƎЯTAUϘ
5	۵	CINQ	QUINZE	ϘИIϽ
6	۶	SIX	SEIZE	XIƧ
7	۷	SEPT	DIX-SEPT	TꟼƎƧ
8	۸	HUIT	DIX-HUIT	TIUH
9	۹	NEUF	DIX-NEUF	ꟻUƎИ

Figure 9. Input number notations used for parity judgment.

For both east Arabic and Arabic notation, significant overall differences were found in RTs to the 10 stimuli, respectively, $F(9, 171) = 6.23$, and $F(9, 171) = 4.58$, both $ps < .001$. For Arabic notation, classification times were similar to those of Experiment 1 with native French subjects: The slow responses to the numbers 0, 1, 6, and 9 were replicated (see Figure 10), and the following differences were found significant by using the Newman-Keuls method: $2 = 4 = 8 < 6 = 0$ for even numbers and $3 < 9$, $3 < 1$, $7 < 9$, and $7 < 1$ for odd numbers. However, a significantly different pattern was observed with east Arabic notation, $F(9, 171) = 3.23$, $p < .002$. The slow responses to 0 and 1 were present, as were the fast responses to 2, 3, and 4. However, the zero effect tended to be larger, perhaps because of the small size of the east Arabic symbol (i.e., a dot). The responses to 7 and 8 were also unusually slow, suggesting that perhaps the subjects tended to confound these two mirror-symmetric symbols (see Figure 9). The following differences were found significant by using the Newman-Keuls method: $4 < 8$, $2 < 0$, $4 < 0$, $6 < 0$, and $8 < 0$ for even numbers and $3 < 7$ and $3 < 1$ for odd numbers.

More critically, no SNARC effect was found in either east Arabic or Arabic notation, $F(4, 76) = 2.41$, $p > .05$, and $F(4, 76) = 1.40$, $p > .20$, respectively. When both data sets were pooled, the Side of Response × Number Magnitude interaction reached significance, $F(4, 76) = 2.67$, $p = .038$. However, the effect was small and nonlinear, as attested by the lack of an interaction of side of response with a linear contrast on magnitude, $F(1, 19) = 2.52$, $p > .10$. In Arabic notation, the slope of the SNARC effect for Iranian subjects was significantly flatter than the slope observed in Experiment 1 with French subjects (−1.87 ms/item vs. −7.08 ms/item; one-tailed $p = .05$).

Thus, whereas the SNARC effect was significantly different for Iranian versus French subjects, these group analyses gave no evidence of a complete reversal of the spatial–numerical association as a function of the direction of writing. This might have been due to interindividual differences in the direction of the SNARC effect, with some Iranians having the effect in the same direction as French subjects and other Iranians having the effect in the opposite direction. Individual analyses were designed to assess this possibility. For each subject, median RT was computed for each number and each side of response in both east Arabic and Arabic notations. The difference between RTs to the right and to the left was then entered into a regression with number magnitude as an independent variable. The slope of this regression was taken as a measure of the direction and magnitude of the SNARC effect. A negative slope indicated a SNARC effect in the direction of French subjects (i.e., large numbers associated with the right-hand side), whereas a

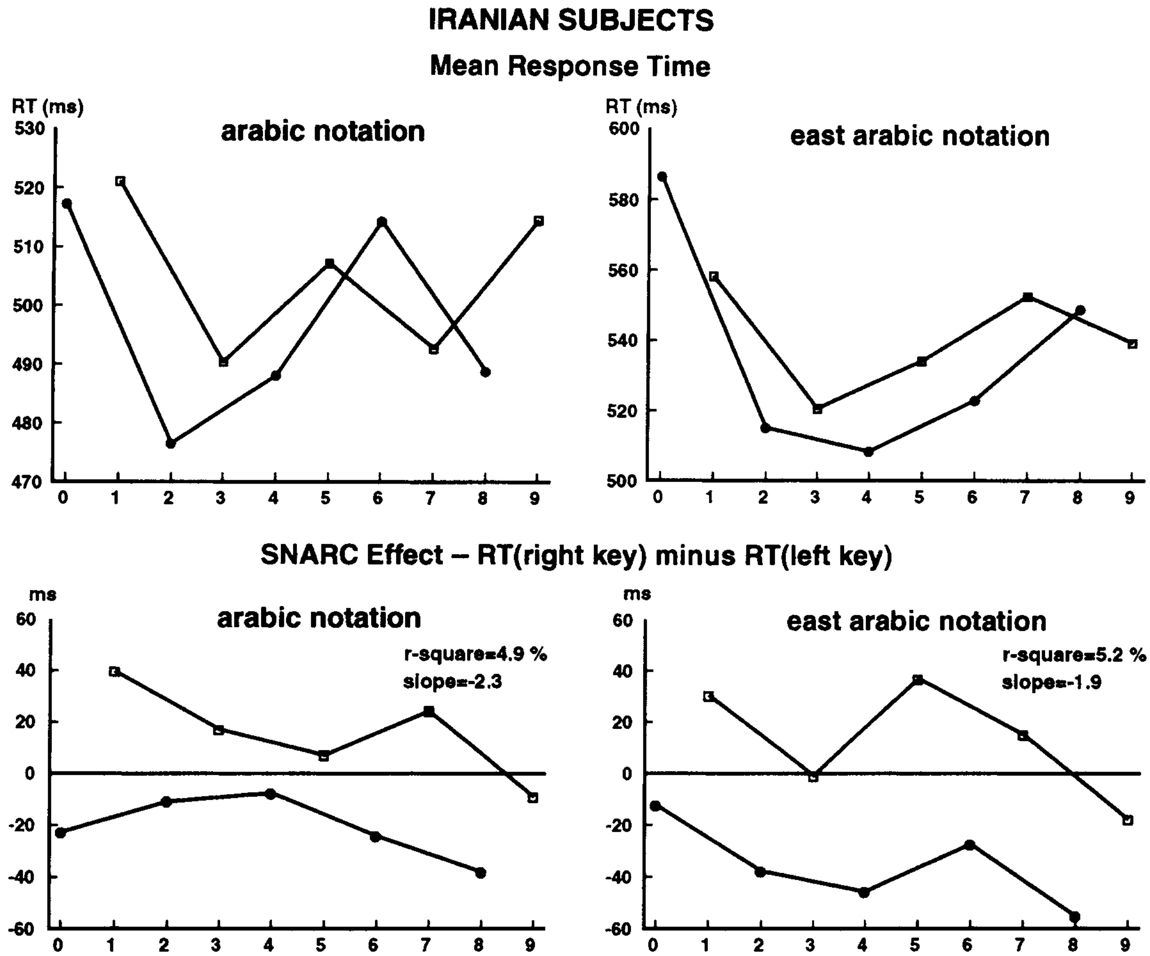

Figure 10. Mean reaction time (RT; top panels) and absence of the Spatial–Numerical Association of Response Codes (SNARC) effect (bottom panels) for parity judgments of Arabic versus east Arabic digits by a group of 20 Iranian right-handers.

positive slope indicated the converse association (i.e., large numbers associated with the left-hand side).

Individual subjects' slopes of the SNARC effect were then entered into stepwise regression analyses, separately for east Arabic and Arabic notations, with the following variables characterizing each subject: age at the time of testing; ages of acquisition of east Arabic numerals, Arabic numerals, and the second language (French or English); years elapsed since arrival in France; and the subject's self-rated frequencies for speaking, writing, and reading in their native Persian language.

For east Arabic notation, the only significant effect was that of the number of years elapsed since arrival in France (referred to as the variable *arrival*). The slope of the SNARC effect was more negative, and therefore more similar to that of French subjects, for subjects who had spent longer time away from Iran. A scatterplot of this regression appears in Figure 11. The regression equation was as follows: slope = 19.0 – 3.19 arrival ($r^2[18] = 36.3\%, p < .005$). The constant coefficient 19.0 was significantly positive ($p < .015$), indicating that when the data were extrapolated to Iranian subjects who have not emigrated (arrival = 0), a SNARC effect was predicted in a direction opposite to that of French subjects.

With Arabic notation, the same stepwise regression on the slopes of the SNARC effect isolated a single significant variable: age of acquisition of a second language (referred to as the variable *acqui*). The slope of the SNARC effect was more negative, and therefore more similar to that of French subjects, for subjects who had learned a second language earlier in life (see Figure 11). The regression equation was as follows: slope(Arabic notation) = –12.7 + 1.25 *acqui* (r^2 [18] = 21.2%, $p = .041$).

Discussion

Taken as a group, Iranian subjects showed little signs of a SNARC effect. However, individual analyses disclosed the presence of different types of subjects in our sample. Those subjects who had long been in France, who had learned a second (i.e., Western) language early in life, or both, presented results similar to French subjects: They showed an association of large numbers with the right-hand side (see Figure 12). Conversely, subjects who had left Iran only re-

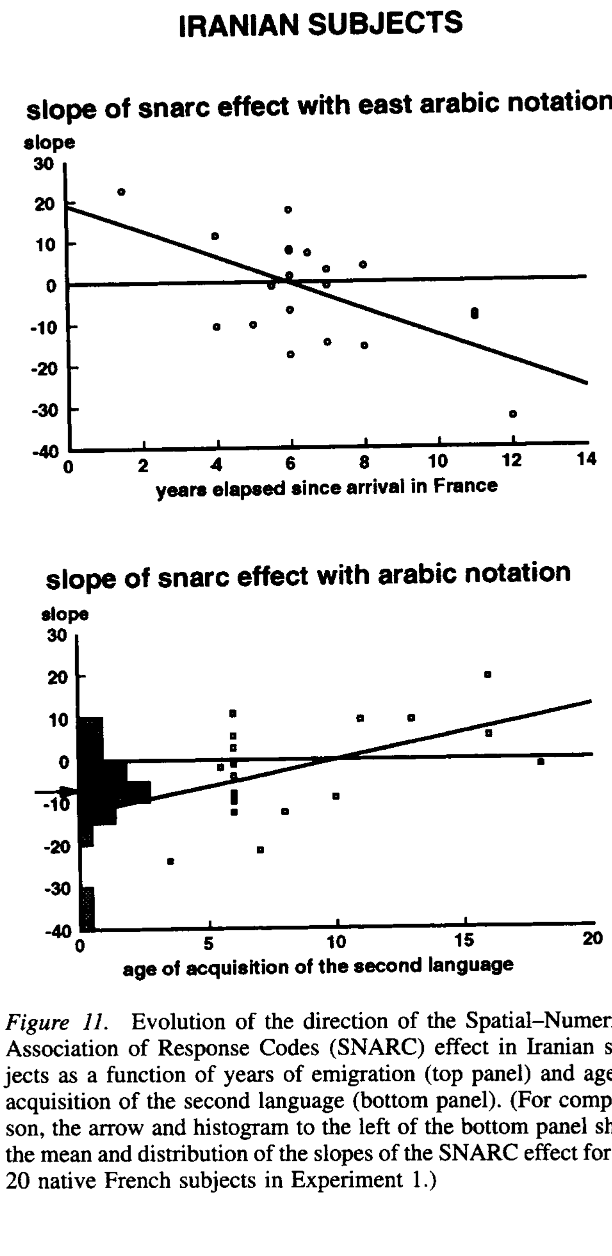

Figure 11. Evolution of the direction of the Spatial–Numerical Association of Response Codes (SNARC) effect in Iranian subjects as a function of years of emigration (top panel) and age of acquisition of the second language (bottom panel). (For comparison, the arrow and histogram to the left of the bottom panel show the mean and distribution of the slopes of the SNARC effect for the 20 native French subjects in Experiment 1.)

cently, who had learned a second language late in life, or both, presented a weaker or reversed association. Experiment 7 therefore demonstrated an effect of the direction of writing on the direction of the SNARC effect. Subjects who were more familiar with a right-to-left writing system tended to associate large numbers with the left-hand side, whereas subjects who were more familiar with a left-to-right writing system tended to associate large numbers with the right-hand side.

A minute of reflection shows that indeed the organization of Western writing system has pervasive consequences on the everyday use of numbers. Whenever a series of numbers is written down, small numbers appear first in the sequence; hence, they are located to the left of larger numbers. In this manner a left-to-right organization is imposed on numbers on rulers, calendars, mathematical diagrams, library bookshelves, floor signals above elevator doors, typewriter or computer keyboards, and so on. How does immersion in this left-to-right-oriented environment shape spatial conceptualization of numbers? American children tend to explore sets of objects from left to right, whereas the converse is true of Israeli children (see Tversky, Kugelmass, & Winter, 1991, and the references therein). This is likely to become the order in which they normally count a set, even if they may adapt to other less familiar ways of counting (e.g., Gelman, Meck, & Merkin, 1986). This regular association of the beginning and ending points of counting with differents directions of space may then become internalized as an integral characteristic of the mental representation of numbers.

A peculiar aspect of our data is that different variables, *arrival* and *acqui*, predicted the direction and amplitude of the SNARC effect in east Arabic and Arabic notation, respectively. This might suggest interesting developments for the study of second-language acquisition and acculturation. Our data might indicate that subjects immersed into a new language and culture forget the characteristics of their native culture in proportion to how long they have been abroad, whereas their eventual proficiency with the new, nonnative language or culture depends more on the age at which they started to acquire it (see Johnson & Newport, 1989).

The present data do not firmly warrant such a conclusion, however, because there was a correlation between the two critical variables *acqui* and *arrival* in our limited sample of subjects: Subjects that had learned a second language earlier in life also tended to emigrate earlier, $r(18) = -.324$, one-tailed $p = .081$. Across subjects, the slopes of the SNARC effect were also positively correlated between east Arabic and Arabic notation, $r(18) = .48, p = .032$). Figure 12 shows the shape of the SNARC effect separately for the 5 Iranian subjects who arrived in France the most recently (average = 4 years; range = 1.5–5.5 years) and the 5 Iranian subjects who arrived in France the least recently (average = 10 years; range = 8–12 years). Clearly, in the two groups the direction of the effect was identical in east Arabic versus Arabic notation. We do not know whether the direction of the SNARC effect would vary with notation in a larger sample of subjects in which the two variables *acqui* and *arrival* would be decorrelated. On the basis of the present study, it can be firmly asserted only that left-to-right versus right-to-left writing had a significant effect on the direction of the spatial–numerical association.

Conclusion for Experiments 3–7

Mathematically speaking, number magnitude is irrelevant to the parity judgment task. Nevertheless, Experiments 1, 3, 5, 6, and 7 have repeatedly demonstrated that unbeknownst to the subjects, the magnitude of the target numbers has a strong effect on their RTs by facilitating responses to one side of space relative to the other side. This SNARC effect bears some similarity to the classical Stroop and Simon effects (Simon & Rudell, 1967; Stroop, 1935). The Stroop effect shows that color naming is impeded by automatic access to the meaning of color words. The Simon effect indicates that bimanual classification of the words *left* and *right* is influenced by irrelevant variations in the left–right position of the stimuli. Similarly, the SNARC effect demonstrates the in-

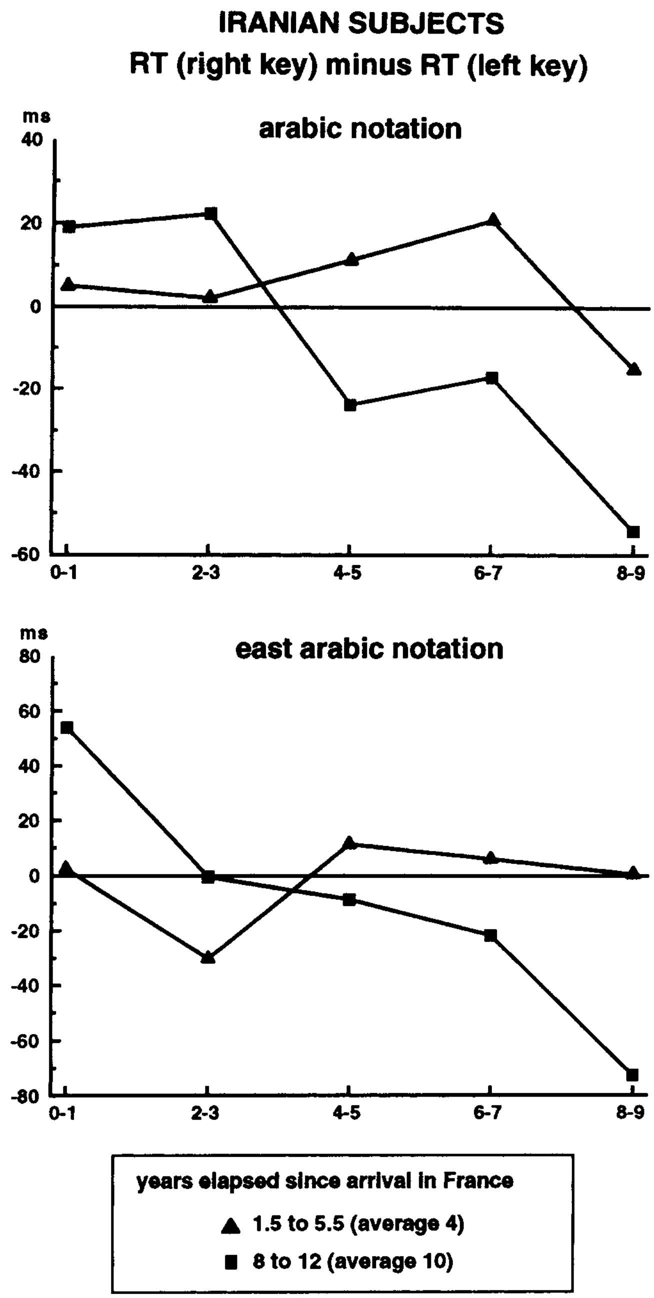

Figure 12. The Spatial–Numerical Association of Response Codes effect in Arabic and east Arabic notation for 5 Iranians who arrived in France 1.5–5.5 years ago and for 5 Iranians who arrived in France 8–12 years ago. (RT = reaction time.)

fluence of an irrelevant stimulus parameter—relative numerical magnitude—when another less salient parameter—number parity—must be processed. The analogy suggests that the magnitude of each numeral, relative to other previous targets, is automatically activated from the presentation of Arabic numerals in a parity judgment task. A similar influence of number magnitude on parity judgment times had been previously reported by Sudevan and Taylor (1987). However, because in their experiments the parity judgment trials were intermixed with number comparison trials, number magnitude was not totally irrelevant, and the demonstration of automaticity was therefore less convincing.

The automatic activation of number magnitude when accessing parity information brings new constraints to bear on models of number processing. McCloskey's (1992) model is the only model that actually predicted a compulsory access to a magnitude code prior to the retrieval of parity information (see Figure 1). Indeed, because the abstract internal representation of magnitude is postulated to be a compulsory bottleneck to any further number processing, McCloskey's model predicts that a SNARC effect should be found in any experiment of number processing with bimanual responses. Note, however, that the model did not predict the exact form of the effect, that is, the fact that number magnitude would interact with the left–right spatial coordinates. McCloskey's (1992) abstract representation would therefore have to be modified to allow for internal magnitudes to be encoded in a spatially extended representation, for instance, a left-to-right-oriented number line (Restle, 1970).

Such a representation has been hypothesized in Dehaene's (1992) triple-code model of number processing. The triple-code model emphasizes the central role of a magnitude representation in mental number processing (Dehaene, 1989; Dehaene & Cohen, 1991; Dehaene et al., 1990; Dehaene & Mehler, 1992). Following the original work of Moyer and Landauer (1967) and Restle (1970), this representation is thought to take the form of an analogical number line oriented from left to right. Its quasi-spatial characteristics can therefore explain why number and space interact as shown by the SNARC effect. On the other hand, contrary to McCloskey's model, the triple-code model does not necessarily predict an automatic activation of the magnitude representation in a parity judgment task. The model would therefore have to be modified to allow for automatic Arabic-to-magnitude transcoding.

The other two models, Campbell and Clark's (1988) encoding complex and Noël and Seron's (in press) preferred entry code, have not specified the role of a magnitude representation in number processing and therefore have provided no basis for expecting a SNARC effect in parity judgments. Both models would therefore have to be modified on an ad hoc basis to accommodate the present results. It might be postulated, for instance, that parity and magnitude information are actually retrieved from the same code or semantic memory store and hence that parity information cannot be accessed without simultaneously retrieving magnitude information.

In summary, the SNARC effect fits more naturally with models of number processing that attribute a central role to a magnitude representation (Dehaene, 1992; McCloskey, 1992). With the help of a few additional hypotheses, however, the effect could also be accommodated within Campbell and Clark's (1988) or Noël and Seron's (in press) models. To separate these models, a more stringent test of the mental architecture of number processing must therefore be used. In the last two experiments, variations in the surface notation of target numbers are used as a systematic tool for the study of mental number processing.

A first issue concerns whether parity information is accessible from a unique mental representation of numbers, as

McCloskey's (1992) model, Noël and Seron's (in press) preferred entry-code hypothesis, and Dehaene's (1992) triple-code model would predict, or whether parity information is distributed within multiple modality-specific semantic systems (see Figure 1). In Experiments 8 and 9, evidence for parallelism in parity judgment times to Arabic and verbal targets is used to suggest that parity information is accessed from a unique mental representation, regardless of input notation. A second issue concerns the nature of this pivotal representation: Is it abstract (McCloskey, 1992), or is it more similar to Arabic notation (Cohen & Dehaene, 1991; Dehaene, 1992) or to verbal notation (Noël & Seron, in press)? This issue is examined in Experiment 9.

Experiment 8: Normal and Mirror-Image Verbal Numerals

In Experiment 8, subjects judged the parity of numbers 0–9 written in French verbal number notation (*zéro*, *un*, *deux*, . . .). By comparing the results obtained in verbal notation with those of Experiment 1 with Arabic notation, we should be able to probe the mental encoding of parity information. If there is a bottleneck in numerical information processing, and if parity information is eventually accessed from a unique mental representation (Dehaene, 1992; McCloskey, 1992; Noël & Seron, in press), then the variations of RT with target number should be parallel in verbal notation and in Arabic notation. For instance, the slow RTs to 0, 1, 6, and 9 should be replicated with verbal notation. If, on the other hand, parity information is handled by multiple modality-specific semantic and processing systems, each specialized for a given input notation, then "processing of odd/even status [should] differ as a function of format" (Clark & Campbell, 1991, p. 211). There should be no reason to expect identical effects with different input number notations (see Figure 1).

A secondary goal of Experiment 8 was to further study the link between the orientation of the SNARC effect and the direction of writing. Experiment 7 with Iranian subjects suggested that it took several years of immersion into another culture before the SNARC effect reversed. To confirm this finding, we asked whether French subjects engaged in right-to-left reading would show a reversal of the SNARC effect. We compared parity judgment of normal and of mirror-image number words (see Figure 9). If the SNARC effect results from a prolonged cultural impregnation with a given direction of writing, it should not be affected by a change in surface notation.

Method

Twenty-four right-handed French students, aged between 21 and 33 years (average = 23.3 years), with no particular training in mathematics, were tested individually. Blocks of trials were similar to those in Experiment 1, but the stimuli were capitalized French number words, 11 mm high, centered on the screen, and surrounded by a 84 mm × 23 mm frame. Mirror-image stimuli were obtained by a vertical axial symmetry of the normal words (see Figure 9). Each subject participated in four blocks of trials, two blocks with normal (N) verbal number notation and two blocks with mirror-image (M) verbal number notation. In both M and N notations, each subject participated in the parity judgment task twice, once with the odd response assigned to the right-hand key (R assignment) and once in the converse condition (L assignment). The order of the four blocks (NR, NL, MR, and ML) was counterbalanced by assigning 3 subjects to each of the following eight task orderings: NR/NL/MR/ML, NL/NR/ML/MR, MR/ML/NR/NL, ML/MR/NL/NR, NR/MR/NL/ML, NL/ML/NR/MR, MR/NR/ML/NL, and ML/NL/MR/NR.

Results

Error rate averaged over the four blocks of trials did not exceed 9.2% per subject (average = 3.0%), and there was no speed–accuracy trade-off, $r(38) = +.36, p = .022$). Median RTs were analyzed in a 2 (notation: N vs. M) × 2 (side of response: right key vs. left key) × 2 (parity: odd vs. even target) × 5 (target magnitude: 0–1, 2–3, 4–5, 6–7, 8–9) ANOVA, where all variables were within-subjects. Consistent with their right-handedness, the subjects were globally faster with the right hand than with the left hand, $F(1, 23) = 8.83, p = .007$. Notation had a significant effect on RTs $F(1, 23) = 29.91, p < .0001$: RTs were shorter with N notation than with M notation (505 ms vs. 550 ms).

For both notations, significant overall differences were found in the RT to the 10 stimuli, $F(9, 207) = 10.1, p < .0001$, for N, and notation, $F(9, 207) = 10.95, p < .0001$, for M notation. For N notation, RT differences between numbers were similar to those obtained in Experiment 1 with Arabic notation (see Figure 13). Pairwise comparison that used the Newman-Keuls method revealed the following significant differences: $4 = 2 < 8 = 6 < 0$ for even numbers and $3 < 1, 5 < 1, 7 < 1$, and $7 < 9$ for odd numbers. Thus, the slow responses to the numbers 0, 1, 6, and 9 were replicated as well as the fast responses to the numbers 2 and 4.

A significant Notation × Target Number interactions, $F(9, 207) = 3.75, p = .0002$, indicated that the variations of RT across target numbers were not strictly identical in N versus M notation. This discrepancy could be attributed to a strategy of letter-by-letter reading of the mirror-image stimuli. The difference of RTs in N notation and in M notation, computed for each target number, was well predicted by the stimulus length in letters ($r^2 = 42.6\%, p = .041$): Each additional letter added a 9.6-ms increment to RT in the mirror-image condition relative to the normal condition. Mirror-image RTs corrected for this effect of word length were extremely similar to the RTs obtained with Arabic stimuli in Experiment 1, with slow RTs to 0, 1, 6, and 9 (cf. Figures 2 and 13). After correction for stimulus length, the following comparisons were found significant by using the Newman-Keuls method: $2 < 0, 4 < 0, 6 < 0, 8 < 0, 2 < 6, 4 < 6$, and $4 < 8$ for even numbers and $3 < 1, 5 < 1, 7 < 1, 9 < 1, 5 < 9$, and $7 < 9$ for odd numbers.

Concerning the SNARC effect, the Magnitude × Side of Response interaction was significant, $F(4, 92) = 3.12, p = .019$, as was the interaction of side of response with a linear contrast for magnitude, $F(1, 23) = 6.28, p < .020$. There were no signs of a triple interaction of these variables with notation, $F(4, 92) = 0.31, p = .87$, and $F(1, 23) = 0.54, p = .54$, respectively. As shown in Figure 14, the SNARC effect was oriented in the same direction for both N and M notations. In both cases, large numbers were preferentially

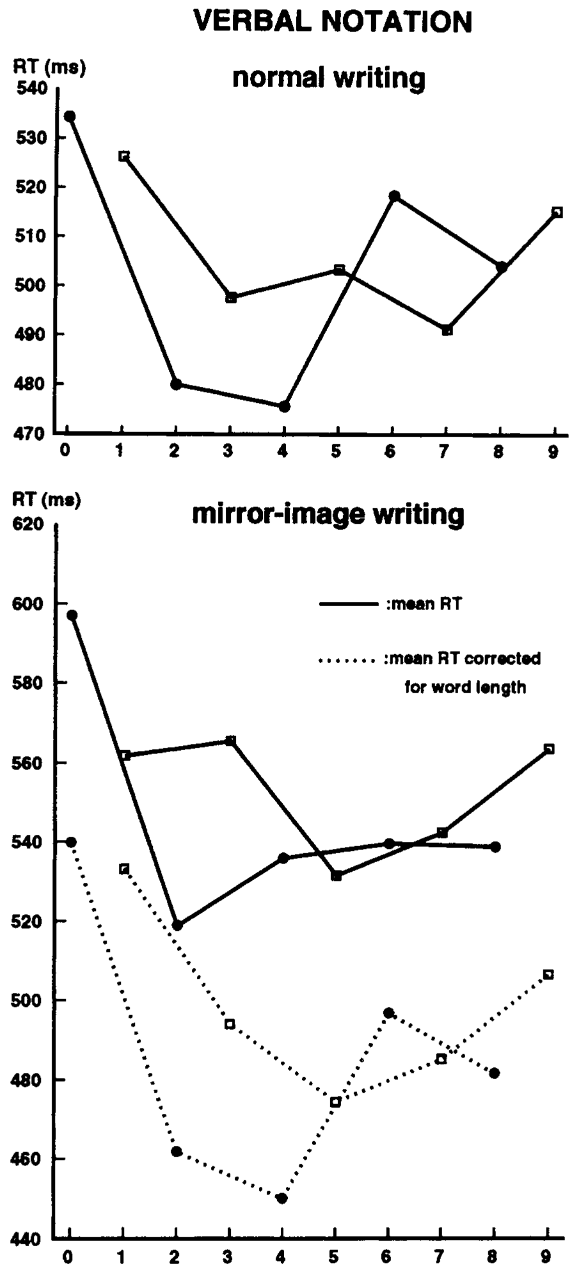

Figure 13. Mean reaction time (RT) for parity judgment of normal versus mirror-image verbal numerals in French right-handers. (The dotted curve is the residual RT after correction for word length.)

responded to with the right-hand key and small numbers with the left-hand key. However, the slopes of −2.3 ms/item and −3.8 ms/item indicated that the SNARC effect was significantly less pronounced with verbal stimuli than with the Arabic stimuli used in Experiment 1, in which the slope was −7.1 ms/item (p = .005 and p = .043, respectively).

Discussion

The main goal of Experiment 8 was to assess the influence of input number notation on parity judgment times. If identical results were found with stimuli in Arabic and in verbal notation, then this would be strong evidence for the use of a single number representation in parity retrieval and against the notion of multiple modality-specific semantic systems. The results, however, were mixed.

On the one hand, RT profiles over the range 0–9 were virtually identical for Arabic notation and for verbal notation (cf. Figures 2 and 13). Even with the unusual mirror-image verbal stimuli, the slow RTs to the targets 0, 1, 6, and 9 were replicated when a correction was applied for an additional initial stage of letter-by-letter reading. The evidence, therefore, runs against Clark and Campbell's (1991) postulate that parity judgment times vary as a function of input notation. Rather, our data suggest that following an initial comprehension stage (which appears to take 45 ms longer with verbal numerals as compared with Arabic numerals), the two types of stimuli are encoded and processed in the same fashion for parity retrieval. Experiment 8 does not allow us to determine if the common code is an abstract code (McCloskey, 1992), Arabic notation (Dehaene, 1992), or verbal notation (Noël & Seron, in press). This issue will be addressed in Experiment 9.

The SNARC effect, on the other hand, did vary with input notation. Experiment 8 revealed a significant SNARC effect with verbal stimuli, both in normal and in mirror-image presentation. The absence of a reversal of the SNARC effect with mirror-image presentation was consistent with the hypothesis, derived from Experiment 7 with Iranian subjects, that the association of large numbers with the right-hand side is due to a slow process of impregnation with the direction of writing in the subjects' culture. However, overall the SNARC effect was significantly weaker with verbal numerals than with Arabic numerals. Note that both McCloskey's model and Noël and Seron's preferred entry-code model should have predicted identical SNARC effects in both notations, because both models assume that the input numerals are converted to a common format before either parity or magnitude information is retrieved (see Figure 1). Neither of these models can explain the simultaneous occurrence in Experiment 8 of an effect of input notation on the SNARC effect, but without any effect of input notation on parity judgment times averaged across the two sides of response.

Only Dehaene's (1992) triple-code model seems to be able to account for this dissociation. The model postulates that parity information is accessed only from the Arabic notation. Verbal input numerals must therefore be converted to Arabic notation before their parity can be assessed, and this can explain both the parallelism of parity judgment times with Arabic and verbal notation and the additional 45-ms delay with verbal numerals as compared with Arabic numerals. Furthermore, the triple-code model postulates that the magnitude representation—the oriented number line assumed to be responsible for the SNARC effect—can be activated independently from the Arabic representation and from the verbal representation (see Figure 1). Assuming that the Arabic-to-magnitude transformation is faster or more automatic than the corresponding verbal-to-magnitude transformation, the model can therefore accommodate a weaker SNARC effect with verbal stimuli as compared with Arabic stimuli.

Experiment 9: Arabic and Verbal Numerals 0–19

Given that the results of Experiment 8 have considerable implications for models of number processing, Experiment 9 was mainly designed as a replication in a within-subjects design. The same subjects performed the parity judgment task with Arabic stimuli and with verbal stimuli in two consecutive blocks. Our main goal was to examine if, as in Experiment 8, parity judgment times would be parallel in both notations, whereas the SNARC effect would be weaker in verbal notation as compared with Arabic notation.

To maximize the chances of observing a differential effect of input notation on parity judgment times, as predicted by Clark and Campbell (1991), the numbers 0–19 were presented for odd–even classification. For verbal teens targets (e.g., twelve), the hypothesis of an internal transcoding toward an Arabic representation (Dehaene, 1992) leads to specific and easily falsifiable predictions. Suppose that the stimulus *twelve* is first transcoded internally to *12* and that its right-hand digit *2* is then used to retrieve its odd–even status. Two predictions should follow. First, the parity judgment times to the targets twelve, two, 12, and 2 should all be similar (except for a delay for verbal targets as compared with Arabic targets). Second, a congruity effect should occur (see Experiment 2): The even response to the target twelve should be delayed by the presence of the odd decades digit 1 in the internal Arabic representation. With verbal teens, the presence of a decades digit 1 in the postulated intermediate Arabic representation should bias subjects toward the odd response. These predictions of the triple-code model are examined below.

Method

Twenty-four right-handed French students, aged between 21 and 28 years (average = 23 years), with no particular mathematical training, were tested individually. The stimuli were the numbers 0–19 in Arabic or French verbal notation, printed in the same fonts as in Experiments 2 and 8. Number words were surrounded by a 90 mm × 23 mm frame. All subjects went through two consecutive blocks of two tests: one block with verbal notation and the other block with Arabic notation. The order of these two blocks was counterbalanced across subjects. Within each block, the subjects took part in the parity judgment task twice, once with the odd response assigned to the right-hand key and once in the converse condition, in counterbalanced order. In each condition, there was an initial training list of 12 items, and then each target number 0–19 was presented four times for a total of 92 items. Consecutive presentations of the same number were not allowed.

Results

Error rates averaged over the four blocks did not exceed 7.2% per subject (average = 3.2%), and there was no speed–accuracy trade-off, $r(78) = +.36$, $p = .001$. Median RTs for correct answers were computed for each target, each side of response, each notation, and each subject. These data were analyzed in a 2 (parity of the target) × 2 (decade of the target: 0–9 vs. 10–19) × 5 (magnitude of the ones digit: 0–1, 2–3, 4–5, 6–7, 8–9) × 2 (side of response: right key vs. left key) × 2 (notation: Arabic vs. verbal) ANOVA. This analysis is described in the following order. First, we examine the effect of number notation on the range of the target numbers 0–9. Second, we analyze RTs to the target numbers 10–19 and compare them with those for the range 0–9. In particular, we assess the existence of a congruity effect in Arabic and in verbal notation. Third, we examine the presence of a SNARC effect in the data.

First, significant differences were found in the speed of classification of the numbers 0–9, $F(9, 207) = 10.14$, $p < .0001$, and in Arabic notation as well as in verbal notation, $F(9, 207) = 5.43$, $p < .0001$, and $F(9, 207) = 6.94$, $p < .0001$, respectively (see Figure 15). In both notations, even numbers were classified globally faster than odd numbers (Arabic notation: 474 ms vs. 491 ms, $F(1, 23) = 10.75$, $p = .003$; verbal notation: 537 ms vs. 554 ms, $F(1, 23) = 5.69$, $p = .026$). Follow-up comparisons replicated most of the differences between numbers observed respectively in Experiments 1 and 8, especially the slow RTs to the targets 0, 1, and 9 and the fast RTs to the targets 2, 4, and 8. These differences were present in both Arabic and verbal notation (see Figure 15). The Newman-Keuls method revealed the following ordering of RTs: $8 = 4 = 2 = 6 < 0$ and $7 = 3 = 5 = 9 < 1$ for Arabic stimuli and $8 = 2 = 4 = 6 < 0$ and $3 = 7 = 5 = 9 < 1$ for verbal stimuli.

On average, Arabic targets were answered 63 ms faster

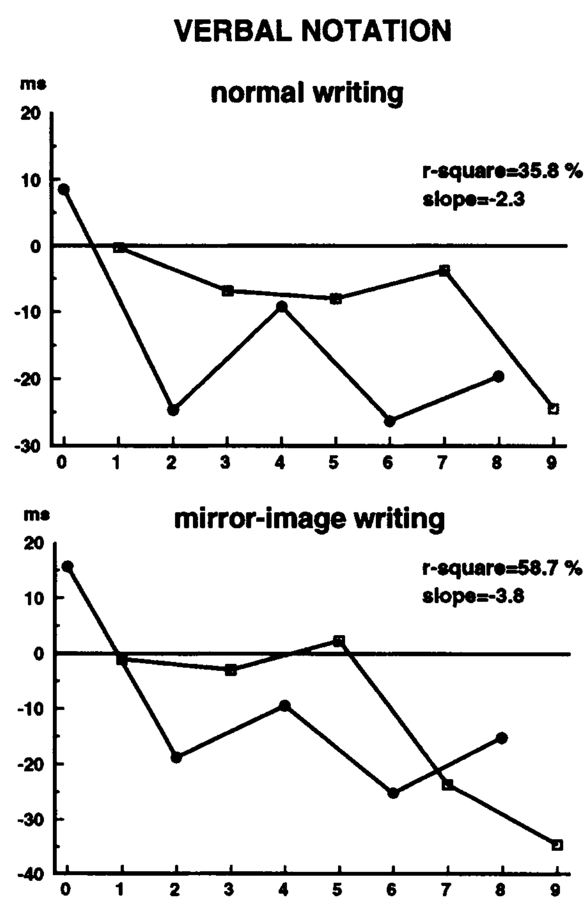

Figure 14. The Spatial–Numerical Association of Response Codes effect for normal versus mirror-image verbal numerals in French right-handers.

than verbal targets (482 ms vs. 545 ms), as indicated by a significant main effect of notation, $F(1, 23) = 74.54$, $p < .0001$. However, over the range 0–9 there were no Notation × Parity interactions, $F(1, 23) < 1$, Notation × Magnitude interactions, $F(4, 92) < 1$, or Notation × Target Number interactions $F(9, 207) < 1$. As in Experiment 8, the only effect of notation was a global delay of 63 ms with verbal inputs.

Significant overall differences were also found in the speed of classification of the numbers 10–19, $F(9, 207) = 4.09$, $p = .0001$ (see Figure 15). This effect was significant in verbal notation, $F(9, 207) = 4.15$, $p = .0001$, but not in Arabic notation, $F(9, 207) = 1.13$, $p = .22$. However, the interaction with notation was not significant, $F(9, 207) = 1.54$, $p = .14$, and in both notations RTs increased linearly over the range 10–19, as revealed by a significant linear contrast for magnitude, $F(1, 23) = 8.00$, $p = .009$, for Arabic notation, and $F(1, 23) = 27.87$, $p < .0001$, for verbal notation. A significant interaction of this linear contrast with notation indicated that the increase in RTs was slightly steeper for verbal notation than for Arabic notation, $F(1, 23) = 6.46$, $p = .018$.

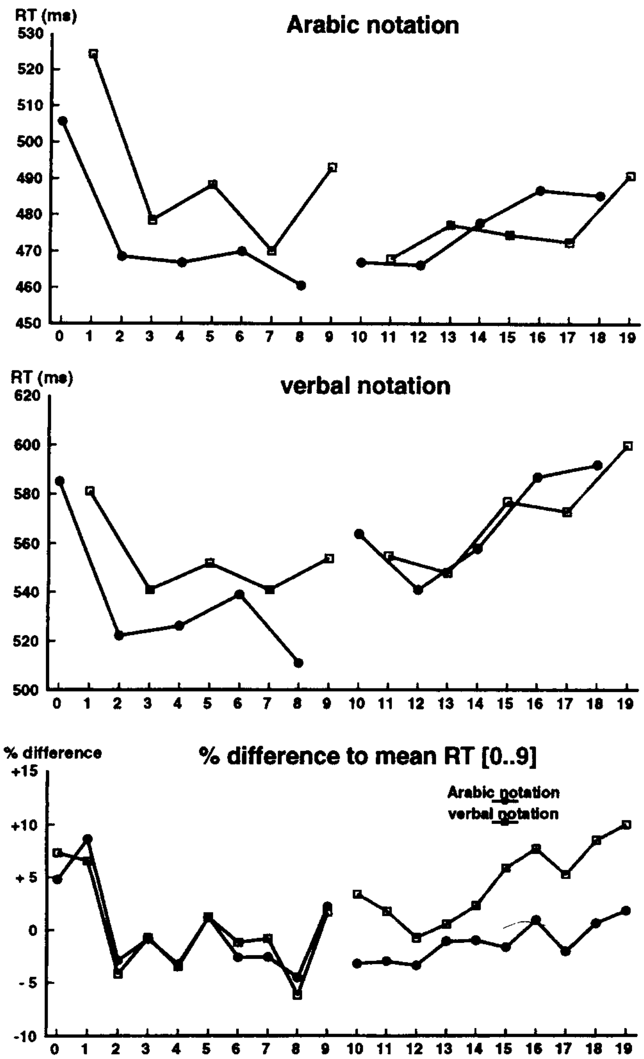

Figure 15. Mean reaction time (RT) for parity judgment of Arabic versus verbal numerals 0–19. (The bottom panel is a comparison of the two number notations after normalization for differences in RT over the range 0–9.)

Aside from this slope difference, there was a clear similarity between the RT curves for the two notations over the range 10–19 (see Figure 15). Again, verbal targets were processed slower than Arabic targets (571 ms vs. 477 ms, $F(1, 23) = 114$, $p < .0001$. This difference was larger over the range 10–19 than over the range 0–9 (95 ms vs. 63 ms), as revealed by a Notation × Decade interaction, $F(1, 23) = 57.6$, $p < .0001$.

There was a global effect of parity over the range 0–9: Even responses were 17 ms faster than odd responses. However, over the range 10–19 the effect of parity was far from significance, $F(1, 23) < 1$, for both notations. The Parity × Decade interaction fell short of significance, $F(1, 23) = 3.62$, $p = .070$ (Arabic notation: $F(1, 23) = 2.45$, $p = .13$; verbal notation: $F(1, 23) = 2.36$, $p = .14$). In the case of Arabic notation, this interaction replicates the congruity effect described in Experiment 2. The presence of the odd decades digit 1 facilitates the odd response and slows down the even response to the numbers 10–19 relative to the numbers 0–9. Critically, this congruity effect also seemed to be present in verbal notation.

In the surface form of French verbal teens, there is no component word that serves a role analogous to the decades digit 1 in Arabic notation and that could induce a bias toward the odd response. On the contrary, in the numerals *dix-sept* (seventeen), *dix-huit* (eighteen), and *dix-neuf* (nineteen), the presence of the component word *dix* (ten) might be expected to induce a bias toward the even response. In that case, the congruity effect would reverse for the numbers 17–19 in verbal notation relative to Arabic notation. To assess this hypothesis, we computed for each subject and each notation the difference between RT to the target 8 and the mean RT to the targets 7 and 9 (d0) as well as the difference between RT to the target 18 and the mean RT to the targets 17 and 19 (d1). For Arabic notation, d0 and d1 differed significantly and in the direction predicted by the congruity effect, $F(1, 23) = 4.24$, one-tailed $p = .025$. There was a slowing down of the response to 18 relative to the responses to 17 and 19 because of the nonmatching parities of the digits composing the Arabic numeral 18. For verbal notation, the difference between d0 and d1 was again significant, $F(1, 23) = 9.15$, $p = .006$, and in the same direction as for Arabic notation. It was not the case that the matching parities of the words *dix* and *huit* facilitated the even response to the target *dix-huit*. Rather, responses to *dix-huit* were slowed relative to the targets *dix-sept* and *dix-neuf*, just like when these targets were presented in Arabic notation.

Finally, the presence of a SNARC effect was assessed. A significant interaction of side of response and a linear contrast on number magnitude indicated a significant SNARC effect over the range 0–9, $F(1, 23) = 5.49$, $p = .028$ (see Figure 16). The triple interaction with notation was in the direction expected from the results of Experiment 8, $F(1, 23) = 3.37$, one-tailed $p = .039$, indicating that a SNARC effect was present in Arabic notation, $F(1, 23) = 8.70$, $p = .007$, but not in verbal notation, $F(1, 23) < 1$. Similar analyses showed no significant SNARC effect over the range 10–19

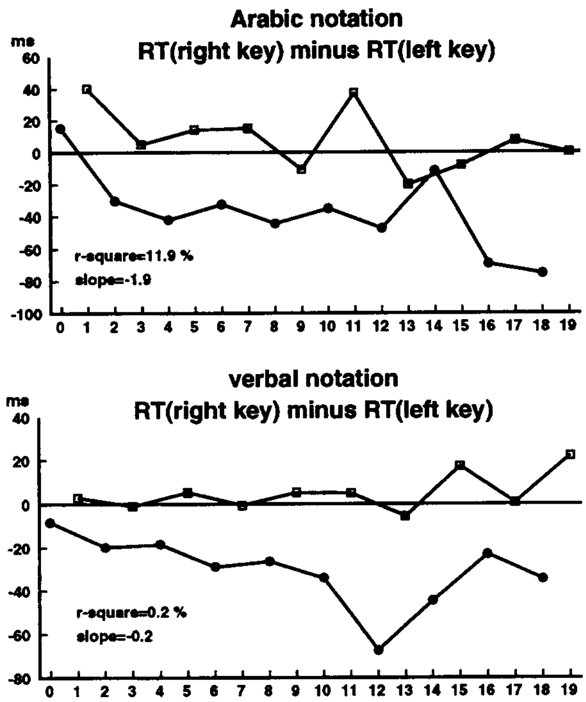

Figure 16. The Spatial–Numerical Association of Response Codes effect for Arabic versus verbal numerals 0–19. (RT = reaction time.)

in both notations. However, over the entire range 0–19, the Side of Response × Decade interaction was in the predicted direction, $F(1, 23) = 3.48$, one-tailed $p = .038$: The targets 0–9 were preferentially responded to with the left-hand key and the targets 10–19 with the right-hand key. This effect fell short of significance in Arabic notation, $F(1, 23) = 4.16$, $p = .053$, but was far from significance in verbal notation, $F(1, 23) = 1.02$.

Discussion

Experiment 9 replicated and extended the critical findings of Experiment 8. First, parity judgment times were largely independent of the particular number notation used for input. Second, a SNARC effect was found in Arabic notation but not in verbal notation.

Experiment 9 provided further evidence that there is only one mental representation of numbers from which parity information is retrieved. As in Experiment 2, we found that the RT to a two-digit Arabic numeral was predictable from the RT to its rightmost digit alone. In Experiment 9, this finding was extended to verbal notation. Figure 17 shows the difference between RT to a number in the interval 10–19 and RT to the corresponding one-digit number in the interval 0–9 (e.g., RT[13] − RT[3]). A lawful relation is evident between RTs over the interval 10–19 and RTs over the interval 0–9. In the case of Arabic notation, this suggests that the subject is not attending to the entire two-digit number but only to its rightmost digit. However, no such explanation is available for verbal notation. There is little surface similarity between the numerals *onze* and *un*, *douze* and *deux*, and so on. If the parity of verbal numerals was accessed from a lexicon with distinct entries for ones and for teens, no particular relationship would be expected between RTs to these two sets of targets. We suggest instead that verbal targets are first internally transcoded into a base-ten representation and are thereafter classified as odd or even, just like Arabic targets, depending on the parity of the units digit.

The finding of a congruity effect with both Arabic and verbal notations provides further support for this model. As in Experiment 2, we found that for Arabic targets, the parity of the leftmost digit impeded parity judgments. Over the range 10–19, even responses were slowed and odd responses were accelerated by the presence of the odd leftmost digit 1. However, Experiment 9 extended this finding to verbal notation. This is particularly counterintuitive for the numerals *dix-sept*, *dix-huit*, and *dix-neut*. Although their surface form contains the word *dix* (ten), the odd response is facilitated, not the even one. Understanding of this finding requires the postulation of an internal transcoding to a representation with base-ten structure, such as McCloskey's (1992) abstract representation or Dehaene's (1992) visual Arabic number form.

Finally, differences in parity judgment times to verbal stimuli and to Arabic stimuli can be ascribed to characteristics of either the comprehension process or the postulated verbal-to-Arabic transcoding stage. Parity judgments were 78 ms slower on average with verbal notation as compared with Arabic notation, a delay that may correspond to transcoding, to faster comprehension of one- and two-digit stimuli, as compared with longer letter strings, or to both. For the numbers 0–9, this delay was fixed at 63 ms. For the teens 10–19, the delay averaged 95 ms and tended to increase for larger magnitudes. Presumably, processing of teens took longer because (a) teens are less frequent numerals (Dehaene & Mehler, 1992), (b) they are often longer in letters and in words, or (c) the result comprises two Arabic digits instead of one Arabic digit. For mirror-image verbal numerals (see Experiment 8), an additional delay proportional to the number of letters in the stimulus can be similarly explained by letter-by-letter reading preceding lexical access.

General Discussion

The purpose of this article was to study how parity and number magnitude are mentally represented and how they are extracted from numerals written in either Arabic or verbal notation. The nine experiments that have been described can be summarized under three major headings.

First, Experiments 1 and 2 studied how parity is extracted. To this end, we measured the parity judgment times to all one- and two-digit Arabic numerals. The results permitted rejection of the hypothesis that odd–even status is computed on each trial by using a mental division by 2. For single digits, RTs were fast for powers of 2 and for odd primes, suggesting the direct retrieval of parity information from a semantic store of simple arithmetical properties. For two-digit numerals, the evidence suggested selective extraction of the units digit, with some interference from the odd–even status of the decades digit.

The second set of experiments (Experiments 3–7) fo-

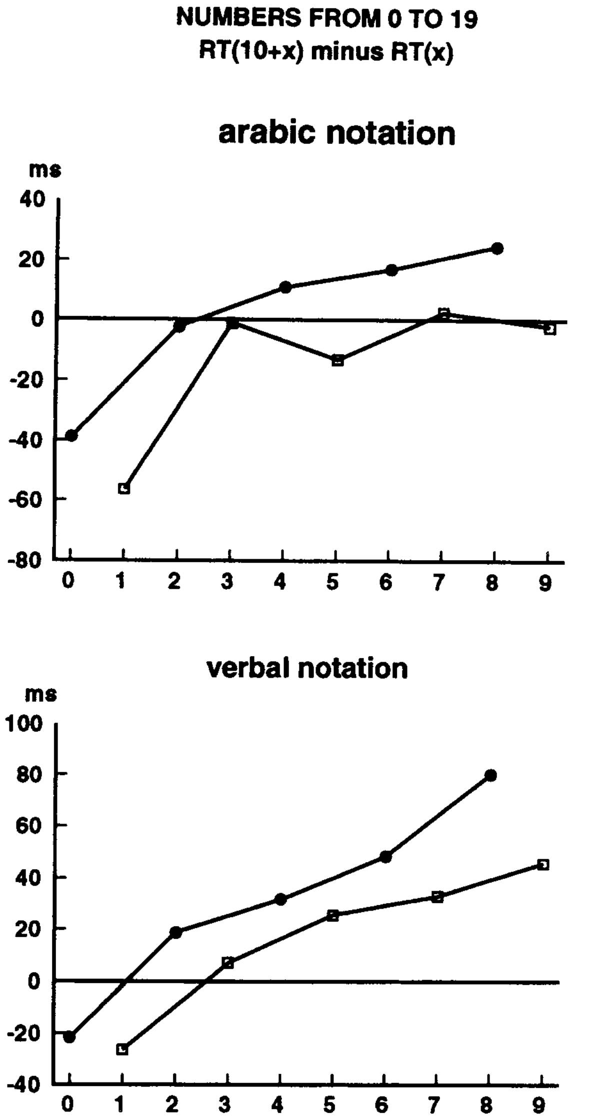

Figure 17. Difference between reaction times (RTs) to numerals 10–19 and RTs to numerals 0–9 for Arabic versus verbal numerals.

cused on whether and how a representation of number magnitude is accessed during parity judgment. A SNARC effect was found in Experiment 1: Large numbers were responded to faster with the right-hand key, whereas small numbers were responded to faster with the left-hand key. Experiments 3 and 4 demonstrated the genuinely numerical origin of this effect by proving that the SNARC effect depends on the relative magnitude of the target numbers within the interval tested and that no similar effect is found when letters are used instead to numbers. The spatial characteristics of this effect were then explored. It was successively shown that the direction of the spatial–numerical association does not reverse in left-handed subjects, in right-handed subjects crossing their hands, or in French subjects reading mirror-image verbal numerals. However, the SNARC effect tended to reverse in immigrant Iranian subjects who were raised in a right-to-left writing culture. Taken together, these results indicate that a representation of number magnitude is automatically accessed during parity judgment of Arabic digits. This representation may be likened to a mental number line (Restle, 1970), because it bears a natural and seemingly irrepressible correspondence with the left–right coordinates of external space. The particular direction of the spatial–numerical association seems to be determined by the direction of writing.

Third, given that parity and magnitude representations had been found active in the parity judgment task, Experiments 8 and 9 examined whether the same representations were also accessed when verbal numerals were used instead of Arabic numerals. Here a dissociation was found between parity and magnitude information. Parity information appeared to be extracted in a similar way, regardless of input notation, at least over the range of the numbers 0–19. Parity judgment times were always very similar with verbal stimuli as compared with Arabic stimuli, albeit with a small additional delay. This suggests that input numerals are first converted to a common base-ten representation before parity extraction. By contrast, the SNARC effect differed across notations. The spatial–numerical association was always stronger with Arabic numerals than with verbal numerals, and it tended to weaken or disappear with numbers larger than 10 (see Experiments 2 and 9). This suggests that the representation of number magnitude or number line is automatically activated only by Arabic numerals of relatively small magnitude.

What do these results tell us about the wider issue of the mental architecture for number processing? First, an extreme version of Campbell and Clark's (1988) encoding-complex model, which we have termed the *multiple modality-specific semantic and processing systems*, can be rejected. This model holds that radically different mental representations are activated depending on the input notation of the target numbers and that number processing therefore varies qualitatively as a function of format (e.g., Besner & Coltheart, 1979; Gonzalez & Kolers, 1982, 1987; Takahashi & Green, 1983). The present experiments demonstrate that processing of odd–even status does not vary much as a function of input notation—in fact, it varies so little that the RT to verbal teens such as fifteen is quite similar to the RT to Arabic digits such as 5 (see Figures 15 and 17). McCloskey (1992), Sokol, McCloskey, Cohen, and Aliminosa (1991), and Macaruso, McCloskey, and Aliminosa (in press) have also presented detailed empirical evidence against the notion that arithmetic facts and calculation routines vary as a function of the input number notation.

Our results also create difficulties for McCloskey's (1992) model of number processing. That parity judgments times do not vary with notation is of course quite consistent with McCloskey's postulate of a central abstract representation, which would constitute a common bottleneck to all further numerical processing. However, because this abstract representation encodes the magnitude associated with each power of 10 in the target number, the model predicts that the same magnitude representation should be activated to a similar extent by both Arabic and verbal numerals in any task requiring number transcoding or calculation. Assuming, as suggested by Experiments 3 and 4, that the SNARC effect arises from this representation of number magnitude, then a SNARC effect should be predicted with both Arabic and verbal numerals in all kinds of numerical tasks. In fact, Experiments 8 and 9 found a significantly weaker SNARC effect with verbal numerals as compared with Arabic numerals. Likewise, Experiment 2 found no SNARC effect on the rightmost digit of a two-digit Arabic numeral, although this rightmost digit was clearly extracted and used for accessing parity information. Finally, Experiment 2 and 9 also suggested that for larger numbers the amplitude of the SNARC effect might be weaker.

These findings are not damaging only to McCloskey's (1992) model. Indeed, they argue against any model that postulates that the input numerals must be converted to a common format, concrete or abstract, before further numerical processing can take place (Noël & Seron, in press). To reiterate, if all numerals were processed in the same way, regardless of their input format, then the SNARC effect should be identical in verbal notation and in Arabic notation.

All contradictions may be lifted, however, if a central assumption of Campbell and Clark's (1988) encoding-complex model is retained: that there are multiple codes or mental representations of numbers and that there may be privileged connections between some of these representations. Dehaene's (1992) triple-code model implements this hypothesis by postulating three concrete representations for number: a visual Arabic number form, an auditory verbal word frame, and an analogue magnitude representation (see Figure 1). Each of these representations is a gateway to specific calculation and knowledge-retrieval procedures. In agreement with Experiments 3–7, the SNARC effect may be postulated to originate from the left-to-right spatial organization of an analogical representation of number magnitude or number line. The observation of a strong SNARC effect with Arabic numerals can be explained by supposing that Arabic-to-analogue transcoding is an automatic process. The observed weakening of the SNARC effect with verbal numerals, on the other hand, suggests a less automatic (or altogether absent) verbal-to-analogue pathway.

Conclusion

The current controversy over the mental architecture for number processing rests mainly on an argument about the fate of different input number notations. Are Arabic and verbal numerals processed in radically different ways? Or do both rapidly converge to a common processing pathway immediately after an initial notation-specific comprehension stage? The present data indicate that neither alternative of this dichotomy gives an accurate description of number processing in the parity judgment task. On the one hand, all input numerals seem to be transcoded to a common base-ten representation before parity information is retrieved. On the other hand, only the small Arabic stimuli seem to automatically activate a representation of number magnitude.

According to the proposed triple-code model, which transcoding pathways get used depends on the task at hand. Thus, the model holds that, in the present experiments, all the numbers had to be transcoded to a base-ten representation because this representation was the only gateway to a semantic store holding memorized parity information. If the task had been numerical comparison, for instance, then the model would predict all input numerals to be transcoded first to the magnitude representation. If the task had been reading aloud or arithmetic fact retrieval, then all input numerals might have been mentally transcoded into verbal notation (Dehaene, 1992). The systematic comparison of RTs with stimuli in different notations, as used in this article, seems to provide an adequate general methodology for testing these predictions.

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