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Primed Numbers: Exploring the Modularity of Numerical Representations With Masked and Unmasked Semantic Priming

Etienne Koechlin
Unité 483, Institut National de la Santé
et de la Recherche Médicale

Lionel Naccache, Eliza Block, and
Stanislas Dehaene
Laboratoire de Sciences Cognitives et Psycholinguistique,
Centre National de la Recherche Scientifique

In Experiment 1, participants classified a 1st number (*prime*) as smaller or larger than 5 and then performed the same task again on a 2nd number (*target*). In Experiment 2, participants classified a target number as smaller or larger than 5, while unknown to them a masked number was displayed for 66 ms prior to the target. Primes and targets appeared in Arabic notation, in verbal notation, or as random dot patterns. Two forms of priming were analyzed: quantity priming (a decrease in response times with the numerical distance between prime and target) and response priming (faster responses when the prime and target were on the same side of 5 than when they were not). Response priming transferred across notations, whereas quantity priming generally did not. Under conditions of speeded processing, the internal representation of numerical quantities seems to dissociate into multiple notation-specific subsystems.

A large amount of experimental work has explored the way human adults mentally represent and process numbers (for a review, see Dehaene, 1992). Neuropsychological studies of brain-lesioned patients have revealed highly specific dissociations between various aspects of number processing, such as identification of Arabic numerals versus number words. Such data have been interpreted as suggesting a modular organization of number processing in the human brain, with distinct systems for processing numbers in various notations and for performing distinct operations with them (for a review, see Dehaene & Cohen, 1995; McCloskey, 1992). Yet this modular stance has been subjected to criticism (e.g., Campbell & Clark, 1988), and several alternative models of the architecture of number processing have been proposed.

McCloskey and his colleagues (McCloskey, Caramazza, & Basili, 1985; McCloskey, Macaruso, & Whetstone, 1992) have proposed an integrated view based on a modular model that assumes the existence of a central amodal representation of numbers. Such an amodal representation receives inputs from notation-specific comprehension modules and sends outputs to notation-specific production modules. A key feature of McCloskey's model is that the numerical knowledge and calculation procedures involve only the amodal number representation. For instance, whether a multiplication problem is presented as 3 × 6 or as "three times six" and whether the result is produced orally as "eighteen" or in writing as 18 should not affect the way in which the multiplication itself is mentally computed.

In contrast, Campbell and Clark (1988, 1992) have proposed a model based on "an integrated network of format-specific number codes and processes that collectively mediate number comprehension, calculation and production, without the assumption of a central abstract representation" (Campbell & Clark, 1988, p. 204). They suggested that calculation procedures may be performed qualitatively differently according to the input notation of the operands. This model assumes that numerical processing may be potentially mediated in parallel by an interactive network that consists of many representations, including phonological, graphemic, and analogue internal codes.

Dehaene (1992) has proposed a third model, called the *triple-code model*, which can be viewed as a compromise between the two preceding ones. Like Campbell and Clark's model, the triple-code model does not assume the existence of a single central number representation. Rather, it relies on the assumption that numbers are represented mentally in three different codes: a verbal word frame, an Arabic number form, and an analogue magnitude code. These codes are related to three distinct functional modules that communicate with each other through specific translation procedures that convert numbers from one code to another, as in McCloskey's model. An important feature of the triple-code model is that each specific numerical ability is posited to rely on a fixed number representation. For example, the comparison of two numbers is thought to engage the magnitude code regardless of the input notation of the operands. Likewise, judging whether a number is odd or even is assumed to engage the Arabic number code, and retrieving arithmetic

Etienne Koechlin, Unité 483, Institut National de la Santé et de la Recherche Médicale (INSERM), Paris, France; Lionel Naccache, Eliza Block, and Stanislas Dehaene, Laboratoire de Sciences Cognitives et Psycholinguistique, Centre National de la Recherche Scientifique, Paris, France.

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Correspondence concerning this article should be addressed to Stanislas Dehaene, who is now at INSERM Unité 334, Service Hospitalier Frédéric Joliot, Commissariat à l'Energie Atomique, 4 Place du Général Leclerc, 91401 Orsay, Cedex, France. Electronic mail may be sent to dehaene@shfj.cea.fr.

facts such as addition or multiplication tables is thought to involve the verbal word code.

The controversy over these models hinges on the issue of whether the mental representation of the quantity associated with a given number, which is usually called its *semantic representation,* varies with the input or output notation and sensory modality in which the number appears. In McCloskey's model as well as in Dehaene's model, the semantic representation of numbers is a common internal quantity code independent of number notation and modality. In Campbell and Clark's model, by contrast, the semantic representation varies depending on the strength of connections between basic elements in each code or between different codes and may therefore be differentially instantiated for numbers presented in various notations or modalities.

In normal adults, the issue of the modularity of semantic representations of numbers has been addressed by comparing the performance of participants in a given numerical task across different notations or modalities. In most such experiments, the profiles of responses remained essentially the same when the input notation was changed. For instance, in the number comparison task, the time to compare two numbers is an inverse function of the numerical distance between them (semantic distance effect; Dehaene, Dupoux, & Mehler, 1990; Moyer & Landauer, 1967), and this function is virtually identical whether the numbers are presented as Arabic digits, spelled-out number words, or even random sets of dots (Buckley & Gillman, 1974; Foltz, Poltrock, & Potts, 1984; Tzeng & Wang, 1983). Furthermore, event-related potentials have suggested a similar bilateral inferior parietal source for the distance effect with Arabic digits and number words (Dehaene, 1996). Similar findings of parallel performance across notations have been reported in other tasks, including same–different judgments (Dehaene & Akhavein, 1995), parity judgments (Dehaene, Bossini, & Giraux, 1993), and simple arithmetic operations (Vorberg & Blankenberger, 1993). When differences were found, they were generally ascribable to differences in encoding time rather than in task-specific processing (Noël & Seron, 1992). A possible exception is the multiplication task, in which Campbell (1994) has reported a small but systematic variation of performance with input notation, suggesting that the verbal code plays a special role in our memory for multiplication facts (for a discussion, see Brysbaert, Fias, & Noël, 1998; Campbell, 1998; Noël, Fias, & Brysbaert, 1997; Noël, Robert, & Brysbaert, 1998).

Although the bulk of the data points to a common semantic representation independent of notation, the interpretation of all such experiments remains affected by a logical difficulty. The finding of parallel performance across variable notations is certainly most economically accounted for by postulating a single common representation underlying task performance. However, on purely logical grounds it cannot be excluded that the similarity in performance results from multiple notation-specific semantic representations with similar functional properties. For instance, the finding of a similar distance effect in number comparison of Arabic digits and number words (Foltz et al., 1984) could possibly be due to two distinct Arabic and verbal representations governed by a similar distance metric. This is all the more plausible that a distance effect is found in all sorts of comparison tasks, including perceptual comparisons of physical parameters, such as weight, length, or light intensity, as well as symbolic comparisons, for instance of letters in the alphabet (see, e.g., Moyer, 1973; Parkman, 1971; Potts et al., 1978). It seems unlikely that there is a single common mental representation underlying all such dimensions. Rather, the distance effect seems to be a widespread functional property of the way quantitative variables are compared in the human brain (see, e.g., Link, 1990; Poltrock & Schwartz, 1984). If this is the case, then the similarity of the distance effect across stimuli in Arabic, verbal, or dot notations cannot be used to argue that a single common representation of number quantity underlies them.

In this article, we address this problem by studying priming across notations in a numerical comparison task. We first study whether comparing a first number (*prime*) to a fixed standard of 5 has an influence on performing the same task on a second number (*target*) that appears immediately after (a double-comparison experiment; Experiment 1). We examine whether the amount of priming depends on the numerical relations between the prime and target numbers, as well as on their notations. Previous experiments using naming or covert reading tasks have shown that the amount of priming varies as a continuous function of the numerical distance between two digits presented in the same notation in successive trials (Brysbaert, 1995; den Heyer & Briand, 1986; Marcel & Forrin, 1974). For instance, having just named digit 7 yields facilitation in naming digit 6 on the next trial, relative to a situation in which 6 is preceded by a more distant digit such as 9. Because this effect depends on the numerical relation of proximity between prime and target, it is a form of semantic priming that must occur at the level of a quantitative or an ordinal representation of numbers.

Here, we study whether this semantic-priming effect generalizes to the number comparison task. For instance, does having just decided that 7 is larger than 5 yield any savings on the subsequent decision that 6 is larger than 5? Most critically, we examine whether similar facilitation is observed when one or both of the numbers is presented as a spelled-out number word (Experiment 1A) or as a set of dots (Experiment 1B). If there is a single semantic representation for numbers presented in Arabic, verbal, and dot formats, then the amount of semantic priming should not be affected by the notation used for the prime and target. If, however, there are multiple notation-specific semantic representations, then semantic priming is expected only when the prime and target numbers are presented in the same input format but not when they appear in different input format.

However, in the word-reading literature, priming tasks, although they have been widely used, have also been criticized as being potentially subject to strategic influences (Neely, 1991). It has been suggested that participants can willfully monitor the semantic relations between the prime and target, and that upon seeing the prime they can develop expectancies as to what the target might be. Priming effects might then reflect the violation of this expectancy (Neely, 1977), the process of trying to match the prime to the target (de Groot, 1984), or both.

To circumvent these difficulties, we also study numerical priming within and across notations in a masked-priming experiment to investigate the early stages of semantic processing in a situation in which participants cannot use controlled processing (Neely, 1991). In the masked-priming experiment (Experiment 2), participants decided as in the double comparison experiment whether a target number was larger or smaller than 5, and each target number was preceded by another prime number. In the new situation, however, the prime was presented for a very short duration (66 ms) and was preceded and followed by masks of the same duration consisting of random strings of symbols. Thus, the prime–target stimulus onset asynchrony was now only 113 ms, a duration hardly compatible with the strategical development of expectancies. In addition, the presence of the prime was not mentioned to the participants, and indeed most of them later reported not being aware of the prime during the experiment. Hence, the situation was optimized to prevent the possibility of controlled processing of prime–target relations. In such masked-priming conditions, the question was, would semantic priming still be observed within and across notation?

In both experiments, double comparison and masked priming, we analyzed two effects in that respect. First, *response priming* was monitored. Response priming refers to the fact that reaction times are faster when both prime and target yield the same response than when they yield different responses (e.g., when both prime and target are larger than 5, relative to the situation when one is larger and the other is smaller than 5). The observation of response priming would imply that the prime, even when it was masked, had been categorized as being larger or smaller than 5. Second, within the cases where the prime and target were on the same side of 5, *quantity priming* was monitored. As mentioned above, this is the effect on reaction times of the numerical distance between the prime and target. Shorter reaction times for prime–target pairs that are numerically close than for pairs that are numerically farther apart would indicate that the prime was able to activate a representation of the corresponding quantity. In the following, the term *numerical relation* is used to refer to the absolute numerical difference between primes and targets, whereas the term *distance* refers to the absolute numerical difference between 5 and prime or target numbers. This terminology is used for clarity only and is not supposed to reflect any theoretical distinction.

Response priming and quantity priming were systematically measured for primes and targets presented in various notations: arabic digits versus verbal numerals and Arabic digits versus dot patterns. Models that postulate a single common representation of quantity predict that priming effects should be independent of the notations used for the prime and target.

Experiment 1A: Double Comparison With Arabic and Verbal Notations

In Experiment 1A, we studied whether having just performed a number comparison task on a given Arabic digit or verbal numeral would prime the subsequent comparison of nearby numbers. Participants decided whether numbers were larger or smaller than 5. To maximize priming effects, the second number (target) was presented immediately after the participant had responded to the first number (prime). For instance, a participant might first respond to the digit 3 and then immediately respond to the word FOUR. We examined whether the response to FOUR would then be faster than if it had been preceded by the digit 1. By using either Arabic or verbal notation for both primes and targets, we also examined whether such quantity priming held across notations.

Method

Participants. Sixteen right-handed male French students, ages 20–29 years ($M = 24$), were tested individually.

Instructions. Participants were told that they would see numbers between 1 and 9, excluding 5, written either in Arabic notation or in verbal notation. They had to decide whether each number was larger or smaller than 5 by pressing one of two response keys. Eight participants responded "larger" by using the right hand and "smaller" by using the left hand (larger–right group). The other 8 participants received the converse assignment (larger–left group). In the following, the terms larger–right and larger–left are used to refer to key assignments. Instructions emphasized both speed and accuracy.

Procedure. Consecutive stimuli were grouped in pairs. The first element of the pair (the prime) was a number ranging from 1 to 9, excluding 5. The second element (the target) was either 1, 4, 6, or 9. Both elements could be presented in Arabic notation or in verbal notation (capitalized letters). The combination of these variables defined $8 \times 4 \times 2 \times 2 = 128$ pairs of numbers, each of which was presented three times in random order. The full list, comprising 384 experimental trials, was divided into three blocks separated by pauses. Fifteen additional pairs were presented initially for training.

The experiment was controlled by a PC-compatible portable Toshiba T-5100 computer with plasma screen running the Expe5 software package (Pallier, Dupoux, & Jeannin, 1997). Bimanual responses were recorded with millisecond precision by way of two large Morse keys. Stimuli were flashed for 200 ms, synchronized with the refresh cycle of the screen. They were centered and appeared orange on a black background. Characters were presented in a Triplex font, 10 mm high. Digits were 5–7 mm wide, and words were 18–45 mm wide. The viewing distance was about 0.5 m.

The first element of the pair was flashed first. As soon as the participant's response was recorded, the computer waited for 200 ms and then flashed the second number of the pair, again for 200 ms. The participant's second response was recorded, and approximately 2 s elapsed before the next pair was presented. The entire experiment lasted about 30 min.

Results

Quantity priming. The main goal of this experiment was to analyze the influence of the prime number on the response to the second, target number. To this end, we selected trials fulfilling the following conditions: (a) the prime and target were either both larger or both smaller than 5, (b) the responses to the prime and target were correct, and (c) response time to both numbers fell between 150 ms and 1,000 ms, in order to remove outliers (i.e., either anticipatory or delayed responses; 1.5% of trials). We then performed a 2 × 2 × 2 × 4 analysis of variance (ANOVA) on mean response time with four orthogonal factors. *Notation* was the notation of the target number (Arabic or verbal). *Notation change* indicated whether the prime and target appeared in the same notation or not. *Distance* indicated whether the target was close to 5 (targets 4 and 6) or far from 5 (targets 1 and 9). *Relation,* finally, was a four-level factor measuring the numerical separation between the prime and the target. Relation ranged from 0 (repetition of the same number, possibly in different notations) to 3. Note that by restricting the analysis to trials on which the prime and the target fell on the same side of 5, the relation factor was orthogonal to the numerical distance separating either the prime or the target from 5, a factor that is known to have an important influence on number comparison times. The design did not permit us to study the relation effect when the prime and the target fell on different sides of 5, because on such trials the relation factor was confounded with the distance separating the prime from 5.

All main effects were significant. Most importantly, a main effect of relation was found, $F(3, 45) = 48.7$, $p < .0001$, $MSE = 1{,}952$. Response time increased as a function of the relation between prime and target (see Figure 1). There was also a distance effect, $F(1, 15) = 64.7$, $p < .0001$, $MSE = 4{,}700$; an effect of notation, $F(1, 15) = 80.1$, $p < .0001$, $MSE = 1{,}877$; and an effect of notation change, $F(1, 15) = 32.5$, $p < .0001$, $MSE = 3{,}000$. Responses were 49 ms faster for targets far from 5 than for targets close to 5, they were 34 ms faster for targets in Arabic notation than for targets in verbal notation, and finally they were 28 ms faster when the prime and target notations matched than when the prime and target notations did not match.

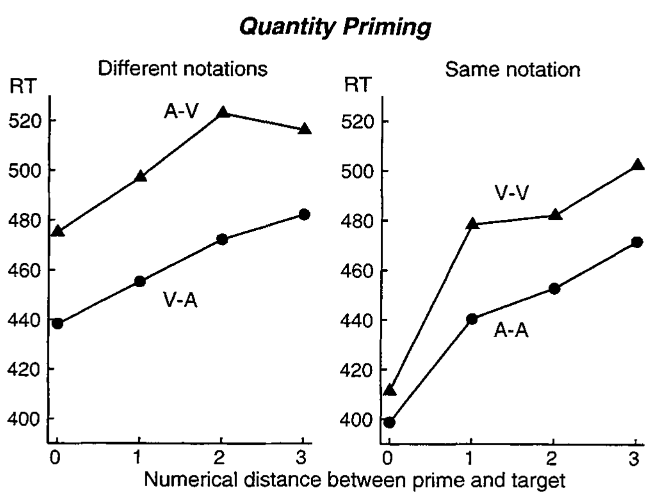

Figure 1. Quantity-priming effect with prime and target numbers in Arabic (A) or verbal (V) notation in Experiment 1A. Each curve shows the response time (RT) to the target number as a function of its numerical relation with the preceding prime number (absolute value of the difference between prime and target) and for a particular condition of notation (e.g., A–V = Arabic prime, verbal target).

The main effect of relation was qualified by interactions with distance, $F(3, 45) = 5.86$, $p = .0018$, $MSE = 1{,}835$; with notation change, $F(3, 45) = 6.97$, $p = .0006$, $MSE = 1{,}446$; and by a Relation × Distance × Notation Change interaction, $F(3, 45) = 3.07$, $p = .037$, $MSE = 980$. These interactions reflected the fact that response times were particularly fast in one category of trials, namely those in which the same number was repeated twice in the same notation (see Figure 1). This effect was particularly pronounced for target numbers that fell close to the standard of 5, indicating a reduction of the distance effect on repeated trials. To confirm this, two post hoc ANOVAs were performed to analyze separately the number repetition effect and the genuine effect of the semantic relationship between prime and target. In the first ANOVA, the relation factor was replaced by the numerical identity factor, which contrasted trials in which the same number was repeated twice (e.g., prime 1 or ONE, target 1 or ONE) and trials in which the prime and target numbers were adjacent (such as prime TWO and target 1 or prime 2 and target ONE). In the second ANOVA, the relation factor was replaced by the number proximity factor, which contrasted trials in which the absolute difference between the prime and target was either 1, 2, or 3 (excluding trials when the same number was repeated twice).

The main effect of numerical identity was significant, $F(1, 15) = 99.7$, $p < .0001$, $MSE = 878$. Globally, repeated trials were 37 ms faster than nonrepeated trials. However, this depended heavily on notation change, $F(1, 15) = 11.5$, $p = .004$, $MSE = 1{,}703$. Post hoc analyses of this interaction showed that when the prime and target both appeared in the same notation, responses were 55 ms faster for repeated than for nonrepeated trials, $F(1, 15) = 95.8$, $p < .0001$, $MSE = 992$, whereas they were only 20 ms faster when the notation changed between the prime and target, $F(1, 15) = 7.63$, $p = .015$, $MSE = 1{,}589$. Hence, the participants' responses were much accelerated when the prime and target were physically identical.

There was also a Numerical Identity × Distance interaction, $F(1, 15) = 6.69$, $p = .021$, $MSE = 1{,}873$: The distance effect dropped from 51 ms on nonrepeated trials to 23 ms on repeated trials. This effect was also qualified by an Identity × Distance × Notation Change interaction, $F(1, 15) = 11.0$, $p = .0048$, $MSE = 275$. When the prime and target were in the same notation, this reduction in the distance effect was greater (from 64 to 22 ms) than when they were in different notations (from 37 to 23 ms). Hence, the distance effect was minimal, though still significant, when the prime and target were physically identical, $F(1, 15) = 9.76$, $p = .007$, $MSE = 1{,}602$.

Moving now to trials where the prime number and the target number differed, there was a main effect of number proximity, $F(1, 15) = 11.4$, $p = .0002$, $MSE = 1{,}820$. When the prime was 1, 2, or 3 units from the target, reaction times increased from 468 ms to 483 ms and to 493 ms, respectively. This effect was independent of interactions with other variables such as notation ($F < 1$), notation change, $F(2, 30) = 2.66$, $p > .086$, $MSE = 1{,}040$, or distance ($F < 1$). Nevertheless, there was a small unexplained triple interaction with notation change and distance, $F(2, 30) = 3.35$, $p = .049$, $MSE = 1{,}157$, resulting from particularly slow responses to the target numbers 4 and 6, when preceded by the primes 2 and 8 with no notation change, and from particularly fast responses in the same conditions but when notation changed. Finally, a post hoc analysis revealed that the effect of number proximity was significant both when the prime and the target appeared in the same notation, $F(2, 30) = 9.81$, $p = .0005$, $MSE = 1{,}316$, and when they appeared in different notations, $F(2, 30) = 6.90$, $p = .0034$, $MSE = 1{,}544$. The difference between Relation 1 and Relation 3, which provided a measure of proximity priming, was 27 ms on same-notation trials and 24 ms on different-notation trials, suggesting virtually complete transfer of priming across different notations.

An identical ANOVA on error rates revealed essentially identical effects. Most importantly, there was again a main effect of relation, $F(3, 45) = 8.77$, $p = .0001$, $MSE = 117$. As the numerical relation between the prime and the target rose from 0 to 3, errors rates went from 1.6% to 5.2%, 7.8%, and 7.4%, respectively. (A complete printout of the results is available from Stanislas Dehaene.)

Response priming. Although the main focus of this experiment was on quantity priming, we also analyzed the results for the presence of response priming (see Figure 2). To this end, a second ANOVA was performed on response times to the target numbers, contrasting trials in which the prime and the target were either both smaller or both larger than 5 and trials in which they fell on different sides of 5 (response change variable). The factors of distance, notation, and notation change were also included in this ANOVA to study their possible interactions with response change.

The main effect of response change fell short of significance, $F(1, 15) = 4.31$, $p = .055$, $MSE = 3{,}328$. When the same response was repeated twice, it tended to be 15 ms faster than when a different response had to be performed. Response change interacted with distance, $F(1, 15) = 6.55$, $p = .022$, $MSE = 780$. Post hoc analyses indicated that response priming was found only for targets far from 5, effect size = 24 ms, $F(1, 15) = 11.96$, $p = .0035$, $MSE = 1{,}530$, but not for targets close to 5 (effect size = 6 ms, $F < 1$). Response change also interacted with notation change, $F(1, 15) = 23.4$, $p = .0002$, $MSE = 642$. On average, participants were 15 ms faster when they made the same response to consecutive numbers appearing in the same notation, or when they made different responses to consecutive numbers appearing in different notations, than in the converse situations.

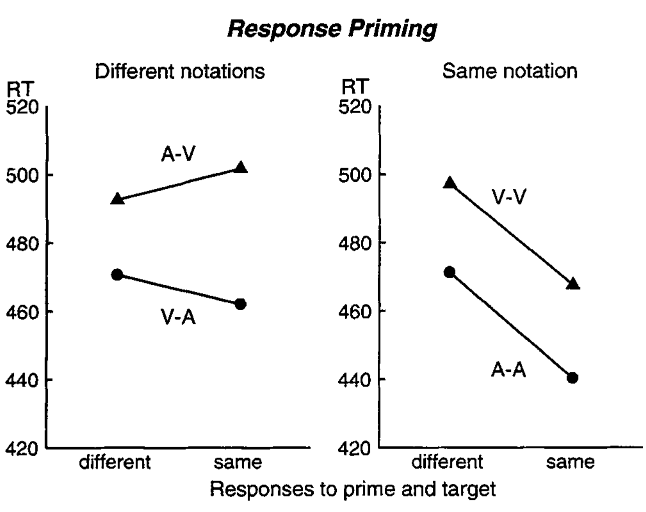

Figure 2. Response-priming effect with prime and target numbers in Arabic (A) or verbal (V) notation in Experiment 1A. Response times (RTs) to the target number are plotted separately for trials in which the prime and target numbers fell on different sides of 5, and hence called for different responses, and for trials in which they fell on the same side of 5, and hence called for the same response.

Distance effect. Experiment 1A also afforded an analysis of the shape of the distance effect as a function of the notation in which the numbers were presented. An ANOVA was performed on mean correct response times to the primes with factors of distance from 5 (now a four-level factor, because the primes varied from 1 to 9), notation (Arabic or verbal), and response (larger or smaller than 5). Group (larger–right vs. larger–left as key assignment, see the *Method* section) was also entered as a between-subjects factor.

The main effect of distance, $F(3, 42) = 61.0$, $p < .0001$, $MSE = 591$, was qualified only by an interaction with response, $F(3, 42) = 3.80$, $p = .017$, $MSE = 682$. As shown in Figure 3, the distance effect was steeper when the numbers were smaller than 5 than when they were larger than 5 (see Dehaene et al., 1990). Importantly, the distance effect was independent of notation, $F(3, 42) = 1.39$, $p = .26$, $MSE = 520$, and group ($F < 1$). There was a main effect of notation, $F(1, 14) = 47.9$, $p < .0001$, $MSE = 438$, participants being 18 ms faster with Arabic digits than with words. Notation also interacted with response, $F(1, 14) = 9.46$, $p = .0082$, $MSE = 865$. When participants responded "smaller" to digits or "larger" to words, they were 11 ms faster on average than in the converse conditions. We discuss this effect below as a potential effect of interference from physical size, because the words indeed appeared physically larger than the digits on the screen. Finally, the Response × Distance × Notation interaction was not significant, $F(3, 42) = 1.42$, $p = .25$.

The only effect involving the group factor was a Group × Response interaction, $F(1, 14) = 11.7$, $p = .0041$, $MSE = 2{,}182$, indicating that the fastest response times were observed when participants in the larger–right group responded "larger" or when participants in the larger–left group responded "smaller." Hence, this interaction simply reflected faster responses with the right hand than with the left, a finding congruent with the participants' right-handedness. A similar analysis of error rates disclosed only a main effect of distance, $F(3, 42) = 5.55$, $p = .0027$, $MSE = 29$, with no significant interactions.

Discussion

In Experiment 1A, we found two effects that depended exclusively on the quantitative relations between numbers

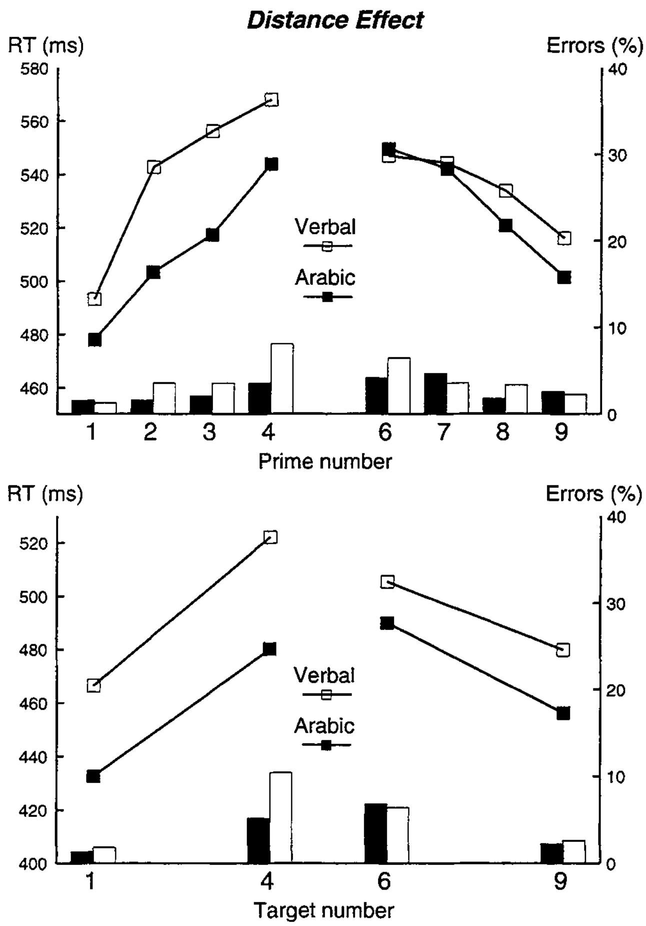

Figure 3. Distance effect with prime and target numbers in Arabic or verbal notation in Experiment 1A. Top panel: response times (RTs; curves) and error rates (bars) to the primes, which ranged from 1 to 9 (excluding 5). Bottom panel: RTs and error rates to the targets, which were always 1, 4, 6, or 9. Note the different scales for RTs in the top and bottom graphs.

and not on the notation used to present them. First, we replicated the semantic distance effect (Moyer & Landauer, 1967): Responses were increasingly faster as the numerical distance between the numbers to be compared increased, and the shape of this distance effect was highly similar whether numbers were presented in verbal or in Arabic notation. Second, we observed an effect of semantic priming on the basis of number proximity. When participants had just responded to a prime number, they responded even faster to a second target number when the numerical relation between the prime and target was small. Again, this effect was mainly independent of input number format. In particular, it was unchanged when the prime number appeared in a different notation than the target number (note, however, that the change of input number format modulates slightly the number proximity effect in different ways depending on specific prime–target combinations, as indicated by a small unexplained Number Proximity × Distance × Notation Change interaction).

These findings are largely consistent with the existence of a common semantic representation of numbers, accessible by both verbal and Arabic inputs, as postulated by the models proposed by McCloskey and his colleagues (McCloskey et al., 1985, 1992) and by Dehaene (1992). According to Dehaene's triple-code model, during number comparison numerical quantities are represented mentally as local distributions of activation over an oriented analogical number line. In this model, both the distance effect and the semantic-priming effect can be explained as resulting from the variable overlap between the distributions associated with different numbers. As two numbers become increasingly closer, their distributions show greater overlap, and it becomes increasingly difficult to distinguish which is the larger (distance effect). Thus, when two numbers are simultaneously represented on the number line and must be compared, the overlap is detrimental to performance. Conversely, when two numbers are presented in close temporal succession, as in the present double-comparison task, the overlap may be beneficial to performance. The second number may benefit from the distribution of activation left over by the first number (semantic-priming effect). Because these effects are thought to occur at the level of a semantic, notation-independent quantity representation, this interpretation predicts that they should be similar whether the numbers are presented in Arabic or in verbal notation. This is exactly the pattern of results we found.

Number notation did have some effects on performance, but they seemed to occur only at a nonsemantic level of processing. First, comparing an Arabic digit was faster than comparing a number word (notation effect). This effect, which has been repeatedly observed (e.g., Dehaene, 1996), is compatible with a slower process of visual identification for words than for digits (McCloskey et al., 1992). Second, responses were faster when the prime and the target appeared in the same notation than when they did not (notation change effect). This situation indicates that there was a cost in switching from one notation to the other, an effect that is again compatible with the existence of distinct visual identification processes for both notations. Third, notation change interacted with response change. Participants were biased to repeat the same response twice when the prime and the target appeared in the same notation. This effect suggests that participants were monitoring whether the prime and the target appeared in the same notation and that they were erroneously using the result of this comparison to decide whether or not to repeat the same response twice.

Fourth, notation interacted with response: Participants were consistently faster to respond "larger" to a verbal numeral and to respond "smaller" to an Arabic numeral than in the converse situations. This effect is potentially important because it might be taken to provide support for Campbell and Clark's (1988) encoding complex model by suggesting that the code on which number comparison is based varies with input notation. We think that this is unlikely, however, for several reasons. In the encoding complex model, Arabic and verbal numerals are assumed to activate partially distinct internal codes when specific numerical tasks are performed. Therefore, this model does not specifically predict our observation that, within a given response (e.g., numbers smaller than 5), the distance curves are parallel to one another (see Figure 3). The encoding complex model also does not explain why this notation effect should differentially affect, as a whole, numbers larger than 5 versus numbers smaller than 5 without affecting the shape of the distance effect within each category of numbers. The model is sufficiently flexible to accomodate such effects a posteriori, but it did not specifically predict them. Finally, it would seem extremely surprising, even within the encoding complex model, that comparison of verbal numerals should become as fast as comparison of Arabic numerals, as is the case here for numbers larger than 5. Given that identification of verbal numerals is slower than identification of Arabic numerals, the putative format-specific code for verbal numerals would have to be more accurate for numbers larger than 5 to compensate for that effect, an assumption that appears gratuitous.

The very fact that the Notation × Response interaction affects, as a whole, numbers above 5 distinctly from numbers below 5 suggests that it occurs at a level of processing posterior to number comparison, where numbers have already been categorized as larger or smaller. It can receive a simple explanation in terms of size interference. In our experiment, the physical size of the stimuli varied considerably: Arabic numerals subtended only one character, whereas verbal numerals subtended 2–6 characters. Physical size has been shown to interfere with numerical size comparisons (Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992). Hence, the fact that participants preferentially responded "smaller" to Arabic stimuli and "larger" to verbal stimuli may simply reflect the well-known intrusion of size judgments in numerical judgments. When physical and numerical size were incongruent, as is the case for Arabic numerals larger than 5 and for verbal numerals smaller than 5, responses were slower, resulting in a Notation × Response interaction. We believe that physical–numerical interference effects provide a more economical explanation of that interaction than an appeal to putative differences in internal semantic representations for Arabic and verbal numerals.

Finally, another effect of notation was that responses were considerably accelerated when the prime and target numbers were physically identical (same notation and same quantity). A similar effect was observed by Dehaene (1996), who suggested that on such repeated trials the participants detect that the stimulus is repeated and reproduce their earlier response. Indeed, on such trials, there was a considerable reduction in the size of the distance effect, suggesting that participants had short-circuited the comparison stage.

In summary, our findings to date provide no evidence for the existence of separate notation-specific semantic representations of numbers, as initially suggested by Campbell and Clark (1988, 1992). These findings show at least that, if there are any distinct semantic representations for numbers in Arabic and in verbal notation, their activation must be short-lived. By about 600 ms, which was the approximate interval between the prime and the target in Experiment 1A, the internal representation of quantity appears to be independent of input number notation, because the target number receives identical amounts of semantic priming whether or not its notation matches that of the prime number. Nevertheless, marginal effects of notation change on quantity priming were found and may support the assumption that distinct, short-lived semantic activations for numbers in Arabic and verbal notation might be observed (see Experiment 2). In Experiment 1B, we explored whether this result can be generalized to a nonsymbolic input format for numbers, such as the numerosity of a set of dots.

Experiment 1B: Double Comparison With Arabic Digits and Dot Patterns

An internal representation of the numerosity of sets of objects seems to play a key role in the acquisition of the meaning of numerals. Human infants and even newborns have been shown to perceive changes in the numerosity of sets of dots, at least for small numbers, independently of other physical parameters (Antell & Keating, 1983; Starkey & Cooper, 1980; Starkey, Spelke, & Gelman, 1983, 1990; Strauss & Curtis, 1981; Treiber & Wilcox, 1984). Human infants and newborns have also been shown to infer the numerosity of small sets of hidden objects when objects are successively added or removed from behind a screen (Koechlin, Dehaene, & Mehler, 1997; Simon, Hespos, & Rochat, 1995; Wynn, 1992a). Many species of animals (including rats, pigeons, dolphins, monkeys, and chimpanzees) have also been found to possess impressive abilities for the perception and internal manipulation of numerosity (e.g., Boysen & Capaldi, 1993; Hauser, MacNeilage, & Ware, 1996). Thus, human infants and various animals appear to possess a mental representation of numerosity, independent of any symbolic notation system for numbers.

The current view of early numerical development, therefore, is that even before the acquisition of language, children already have at their disposal an abstract representation of numbers similar to the adult number line. This concept would help them acquire the meaning of numerals by learning to map numerals onto this previously available nonverbal representation (Dehaene & Changeux, 1993; Gallistel & Gelman, 1992; Simon et al., 1995; Wynn, 1992b). In this view, the internal representation of quantity used by adults to retrieve the quantitative meaning of a symbol, such as 2 or TWO, would be the same one that is activated when perceiving the numerosity of a set and that is available to humans since infancy (Dehaene, 1992; Dehaene et al., 1990; Gallistel & Gelman, 1992). Indeed, both Dehaene's (1992) triple-code model and McCloskey's (1992) model of number processing postulate that the numerosity of sets of dots is internally represented in the same common quantitative format that is accessed by Arabic and verbal numerals (see Macaruso, McCloskey, & Aliminosa, 1993).

The prediction of these models is straightforward: Semantic priming should be obtained as easily between numbers presented in Arabic notation and as sets of dots than between the Arabic and verbal numerals used in Experiment 1A. Experiment 1B was thus identical to Experiment 1A, except that numbers were presented either as Arabic digits or as sets of 1–9 dots. Participants decided whether the numbers were larger or smaller than 5. We again studied whether having just compared the numerosity of a set of dots to 5 would prime the subsequent comparison of nearby numbers on the number line, and vice versa. If numerosity is represented in the same common format as Arabic and verbal numerals, as predicted by developmental models, then the amount of quantity priming should be the same regardless of the notation used for the prime and target.

Method

Participants. Sixteen right-handed male French students, ages 22–35 years (M = 25), were tested individually.

Procedure. The instructions and procedures were similar to those used in Experiment 1A, except that number words were replaced by random sets of dots. Participants were asked not to count the dots but only to estimate whether the numerosity was smaller or larger than 5. As in Experiment 1A, participants were randomly assigned to larger–right or larger–left groups. Arabic digits, 20 mm wide and 30 mm high, appeared at the center of a visible square frame subtending 110 mm × 110 mm. Sets of dots comprised from 1 to 9 small, filled squares appearing at variable locations within the same frame, with a minimal interitem distance of 5 mm. The dot size was constant in each trial but was varied across trials from 4 to 8 mm. On each trial, both the size and the location of dots were uniformly randomized by the computer so that all locations within the frame could be potentially occupied. The viewing distance was about 0.5 m.

Results

Quantity priming. To analyze the influence of the prime number on the response to the second (target) number, we selected trials fulfilling the same conditions as in Experiment 1A: (a) The prime and target were either both larger or both smaller than 5, (b) the responses to the prime and target were correct, and (c) response time to both numbers fell between 150 ms and 1,000 ms in order to remove outliers (i.e., either anticipatory or delayed responses; 1.7% of trials). We then performed a 2 × 2 × 2 × 4 ANOVA on mean response time with the same factors as in Experiment 1A: notation (Arabic or dots), notation change (same or different notation), distance (close or far from 5), and relation (a four-level factor measuring the numerical separation between the prime and the target).

As in Experiment 1A, all main effects were significant. A main effect of relation was found, $F(3, 45) = 13.61$, $p < .0001$, MSE = 1,202. Response time increased monotonically as a function of the relation between prime and target (see Figure 4). There was also a distance effect, $F(1, 15) = 312.1$, $p < .0001$, MSE = 1,374; an effect of notation, $F(1, 15) = 103.2$, $p < .0001$, MSE = 1,644; and an effect of notation change, $F(1, 15) = 40.4$, $p < .0001$, MSE = 4,975. Responses were 58 ms faster for targets far from 5 than for targets close to 5, they were 36 ms faster for targets in Arabic digits than for sets of dots, and finally they were 40 ms faster when the target number was presented in the same input format as the prime than when it was not.

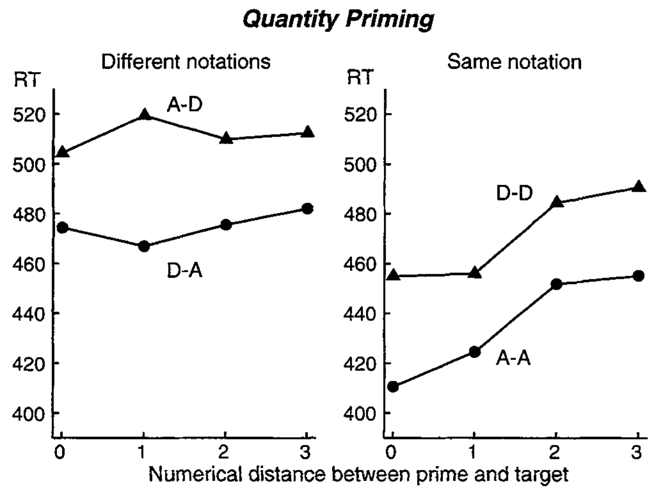

Figure 4. Quantity-priming effect with prime and target numbers presented as Arabic (A) digits or as dot (D) patterns in Experiment 1B. Each curve shows the response time (RT) to the target number as a function of its numerical relation with the preceding prime number (absolute value of the difference between prime and target) and for a particular condition of notation (e.g., A–D = Arabic prime, dot target).

The main effect of relation was qualified by an interaction with notation change, $F(3, 45) = 7.31$, $p = .0004$, MSE = 1,352. The relation effect was present only when the prime and the target were presented in the same notation. In this condition, reaction times increased from 433 ms to 440 ms, to 468 ms, and to 473 ms when the numerical relation between the prime and the target went from 0 to 3, respectively, $F(3, 45) = 20.73$, $p < .0001$, MSE = 1,232. In contrast, when the input format of the prime and the target differed, reaction times went from 489 ms to 493 ms, to 493 ms, and to 497 ms, which is a nonsignificant increase, $F(3, 45) = 0.52$.

The relation factor was broken down into a numerical identity factor and a number proximity factor (see Experiment 1A). Contrary to Experiment 1A, no significant effect of numerical identity was found, $F(1, 15) = 1.26$, $p > .27$, MSE = 1,623, nor was there any interaction of numerical identity with the other factors. This absence of a numerical identity effect may be attributed to the randomization of the dot patterns, which implied that in Experiment 1B most of the stimuli were never physically repeated. Note that there was a 14-ms trend for a numerical identity effect when both the prime and the target appeared in Arabic notation, the only condition of actual physical repetition; yet this effect failed to reach significance, $F(1, 15) = 2.27$, $p = .15$, MSE = 1,361.

However, a main effect of number proximity was again observed, $F(2, 30) = 9.13$, $p = .0008$, MSE = 1,283, and it interacted with notation change, $F(2, 30) = 5.33$, $p = .01$, MSE = 1,634. Again, the effect of number proximity was present only when the prime and target were in the same notation, $F(2, 30) = 13.66$, $p < .0001$, MSE = 1,464, but not when the notations differed, $F(2, 30) = 0.29$. No other factor was found to interact with the number identity, number proximity, and relation factors.

The only other significant effect was an interaction of distance with notation, $F(1, 15) = 28.35, p = .0001, MSE = 2{,}357$, indicating that the distance effect was stronger with dots than with Arabic digits (we analyze this further below).

An identical ANOVA on error rates confirmed the results on response times. In particular, there was a main effect of relation, $F(3, 45) = 3.38, p = .0002, MSE = 59$, interacting with notation change, $F(3, 45) = 13.78, p < .027, MSE = 87$: The relation effect was again present when the prime and target notations were identical, $F(3, 45) = 13.78, p < .0001, MSE = 55$, but not when they differed, $F(3, 45) = 0.27$. As the relation between prime and target rose from 0 to 3, error rates increased from 0.5% to 2.5%, 6.8%, and 7.8% in the absence of a notation change, whereas error rates went from 7.6% to 6.9%, 8.1%, and 8.2% when notation changed. (A complete printout of the results is available from Stanislas Dehaene.)

Response priming. To analyze the presence of response priming as in Experiment 1A, a second ANOVA was performed on response times to the target numbers with factors of response change (whether the prime and target fell on the same side of 5, and therefore called for the same response, or not), distance, notation, and notation change.

No main effect of response change was found, but the notation change factor yielded a highly significant 20-ms effect, $F(1, 15) = 32.3, p < .0001, MSE = 797$. As in Experiment 1A, both factors interacted strongly, $F(1, 15) = 26.80, p < .0001, MSE = 1{,}020$ (see Figure 5). Participants were faster by 21 ms when a change in notation was accompanied by a change in response than when it was not. A marginal effect of response priming was found when notation did not change. In that case, participants' responses tended to be accelerated by 16 ms when both the prime and the target fell on the same side of 5, $F(1, 15) = 4.05, p = .062, MSE = 2{,}051$.

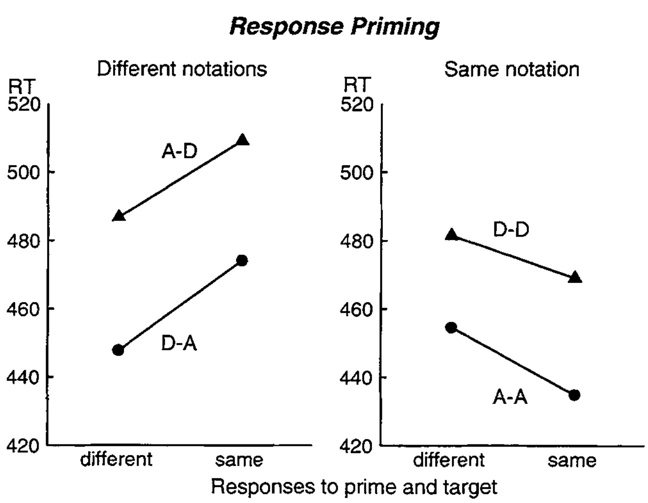

Figure 5. Response-priming effect with prime and target numbers presented as Arabic (A) digits or as dot (D) patterns in Experiment 1B. Response times (RTs) to the target number are plotted separately for trials in which the prime and target numbers fell on different sides of 5, and hence called for different responses, and for trials in which they fell on the same side of 5, and hence called for the same response.

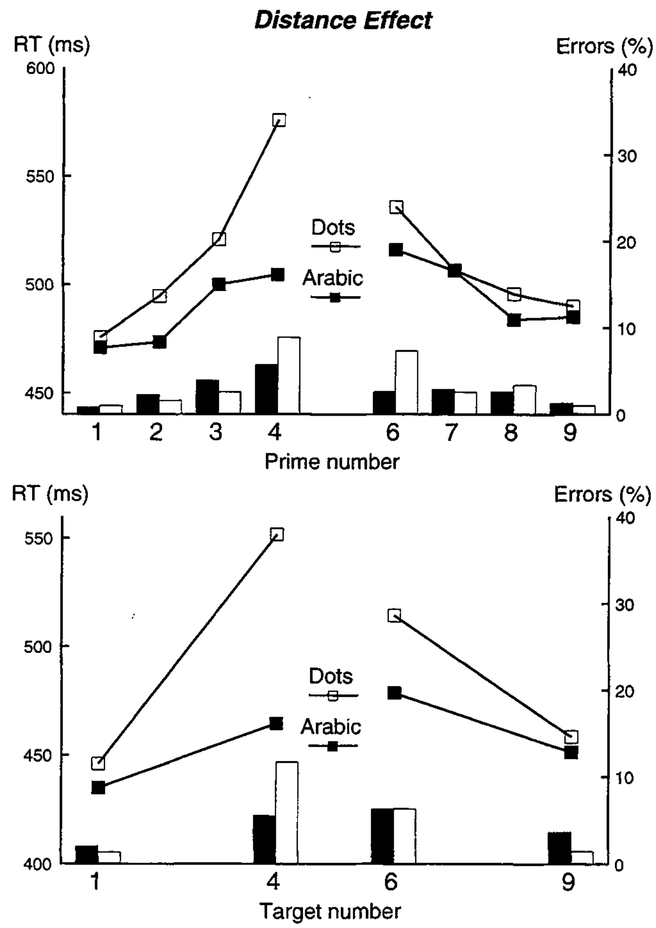

Figure 6. Distance effect with prime and target numbers presented as Arabic (A) digits or as dot (D) patterns in Experiment 1B. Top panel: response times (RTs; curves) and error rates (bars) to the primes, which ranged from 1 to 9 (excluding 5). Bottom panel: RTs and error rates to the targets, which were always 1, 4, 6, or 9. Note the different scales for RTs in the top and bottom graphs.

Distance effect. As in Experiment 1A, an analysis of the shape of the distance effect as a function of notation was also performed. An ANOVA was performed on the mean correct response times to the primes, with factors of distance from 5 (now a four-level factor, because the primes varied from 1 to 9), notation (Arabic or dots), and response (larger or smaller than 5). Group (larger–right vs. larger–left) was also entered as a between-subjects factor.

The main effect of distance, $F(3, 69) = 57.8, p < .0001, MSE = 627$, was qualified by an interaction with response, $F(3, 42) = 4.14, p = .012, MSE = 589$. As in Experiment 1A, the distance effect was steeper when the numbers were smaller than 5 than when they were larger than 5 (see Dehaene et al., 1990). In addition, the distance effect interacted with notation, $F(3, 42) = 13.0, p < .0001, MSE = 404$, but was independent of group ($F < 1$). As shown in Figure 6, the distance effect was steeper for dots than for Arabic digits. There was also a main effect of notation, $F(1, 14) = 22.3, p < .0001, MSE = 1{,}079$, participants being 19 ms faster with Arabic digits than with dots. Notation also interacted with response, $F(1, 14) = 6.15, p = .026, MSE =$ 1,082: Participants were faster to respond "smaller" to digits and "larger" to dots than the converse. This effect was qualified by a Notation × Response × Distance interaction, $F(3, 42) = 6.14, p = .0015, MSE = 329$, an effect that was attributable to particularly slow responses to sets of four dots (see Figure 6).

As in Experiment 1A, the only effect involving the group factor was a Group × Response interaction, $F(1, 14) = 5.41$, $p = .036, MSE = 2{,}024$, indicating that the fastest response times were observed when participants in the larger–right group responded "larger" or when participants in the larger–left group responded "smaller." Hence, this interaction simply reflected faster responses with the right hand than with the left, a finding that is congruent with the participants' right-handedness. A similar analysis of error rates disclosed only a main effect of distance, $F(3, 42) =$ 21.7, $p < .0001, MSE = 14$, with a significant interaction with notation, $F(3, 42) = 5.01, p = .0046, MSE = 14$.

Comparison of distance effects in Experiments 1A and 1B. Incidentally, Experiments 1A and 1B made it possible to compare response times to the same Arabic digits in the context of surrounding trials with either number words (Experiment 1A) or dot patterns (Experiment 1B). In an ANOVA on mean response times to the prime, with the same factors as above and an additional between-group factor of experiment (Experiment 1A or 1B), the only effect involving the experiment factor was a Distance × Experiment interaction, $F(3, 90) = 3.21, p = .027, MSE = 612$, indicating a significantly smaller distance effect in dot context than in verbal context (cf. Figures 3 and 6). However, participants were also faster by 27 ms in Experiment 1B than in Experiment 1A, though this trend did not reach significance, $F(1, 30) = 1.38, p = .25, MSE = 34{,}122$. A within-subject design would probably have to be used to conclusively decide whether the comparison of Arabic digits is significantly influenced by context.

Discussion

In contrast to Experiment 1A, which found similar semantic effects for Arabic and verbal numerals, the results of Experiment 1B reveal a dissociation between the comparison of Arabic digits and the numerosity of dot patterns. First, although there was a strong distance effect in both notations, which replicated Buckley and Gillman's (1974) results, it was steeper for dots than for Arabic numerals. By itself, this result may still be consistent with a single representation of quantities common to both notations. It might simply be the case that the Arabic digits, which are digital symbols, yield a sharper and more precise distribution of activation on the number line than the dot patterns do. This greater sharpness would make it easier to compare digits 4 or 6 with 5 than to make the same judgment with sets of 4 or 6 dots.

A second finding, however, rules out this interpretation. Quantity priming was found only when the input format remained the same between the target and the prime. No quantity priming occurred when the input format changed from random dots to digits and vice versa. For instance, after having responded to digit 2, there was a reduction in reaction time to a subsequent digit 1 but not to a dot pattern of numerosity 1. Thus, it cannot be the case that a common notation-independent representation is responsible for quantity priming with digits and dots because, if such were the case, it should have shown similar quantity-priming effects across notations and within notations.

Two alternative interpretations of the lack of cross-notation priming can be rejected. First, responses to the targets were slower when the prime and target notations differed than when they were identical (notation change effect). Hence, it might be suggested that, in cross-notation trials, the activation left over by the prime had decayed, thus explaining the lack of priming. However, note that in Experiment 1A, there was a similar notation change effect for Arabic and verbal notations, and yet highly significant cross-notation priming was found.

A second possibility that must be discussed is that with dot patterns, some low-level physical parameter of the stimuli might have been highly correlated with numerosity and might have enabled participants to perform the comparison task with dot patterns by using a lower level representation than that used with Arabic digits. Although we made several efforts to control all the nonnumerical parameters of the dot patterns, there might have remained a systematic low-level physical difference between patterns with 1–4 dots and patterns with 6–9 dots. In a post hoc test, we examined this possibility by assessing how well participants could have performed the task if they had based their responses on one of three physical parameters: luminance, dispersion, and surface. Total luminance was computed by summing the number of active pixels, dispersion of the dots was assessed by their two-dimensional standard deviation, and occupied surface was measured by computing the convex hull of the polygon formed by the dots. In each case, we calculated the predicted error rates assuming that participants used an optimal classification criterion based on maximum likelihood. For luminance and dispersion, the predicted error rates averaged over all targets were 18% and 15%, respectively, and they peaked at 50% or higher for numerosities 4 and 6. This is clearly inconsistent with the observed error rates and indicates that participants could not have based their responses on only these parameters. For surface, the predicted error rate averaged only 3.5%, a value that matches the observed average error rates. However, errors were predicted only for numerosities of 4 and 6, in which case the predicted error rates (15% and 12%, respectively) were still almost twice as high as those observed in our data (8.9% and 7.3%, respectively). Thus, the predicted values again seemed too elevated compared with the observed ones, especially given that the model does not take into account additional errors that can occur in perception or motor stages in real participants.

Thus, this post hoc test shows that none of the above parameters accounts for the performance of participants with dot patterns. Clearly, this finding cannot rule out that other untested physical parameters, alone or in combination with others, may suffice to classify our dot patterns with high accuracy, especially in such a binary decision task. Further experiments using multiple-choice tasks, such as number naming, would be necessary to exclude such hypotheses. Nevertheless, the current evidence suggests that the representation that our participants used to compare dot patterns was organized according to numerical quantity. Furthermore, reaction times to dot patterns were subject to distance and priming effects similar to those found with Arabic or verbal stimuli. This finding suggests that the internal representation reached for dot patterns was organized according to similar principles as that activated by Arabic and verbal numerals. In fact, the quantity-priming effect was essentially identical for dot–dot trials and for Arabic–Arabic trials (see Figure 4). This similarity suggests that comparing Arabic digits and comparing dot patterns involves similarly structured representations, both organized according to numerical distance—but the lack of cross-notation quantity priming indicates that it cannot be one and the same representation.

The results lead us to qualify a commonly held view of numerical development, according to which the acquisition of number words proceeds by mapping them onto a preverbal representation of numerosity (Dehaene, 1992; Gallistel & Gelman, 1992). The abilities for numerosity perception and manipulation that can be observed in preverbal infants (Antell & Keating, 1983; Koechlin et al., 1997; Starkey et al., 1980, 1983, 1990; Strauss & Curtis, 1981; Treiber & Wilcox, 1984; Wynn, 1992a) probably play an important role in numerical development. The preverbal numerosity representation is likely to be deeply involved in setting forth and in shaping the quantity representation associated with Arabic and verbal numerals. Indeed, our observations confirm that both representations obey highly similar distance and priming effects. However, they also suggest that in adults, the quantity representation associated with symbolic numerals is not strictly identical to the one associated with dot numerosity. Thus, numerical development may be accompanied by the dissociation of the initial magnitude representation into two specific representations, one specialized for numerical symbols and the other for perceptual analogs of numbers such as dot patterns.

Experiment 2: Masked Priming

In Experiment 1, we found experimental evidence for at least two similar representations of numerical quantity, one devoted to symbolic input formats (Arabic digits and spelled-out number words) and one devoted to a nonsymbolic format (dot patterns). No cross-notation quantity priming was found when we contrasted Arabic digits and dot patterns, suggesting that the comparison of the numerosity of dot patterns is based on a representation distinct from that used for Arabic and verbal numerals. Although participants, when given enough time, can obviously relate dot numerosity with Arabic or verbal numerals, in a speeded comparison task the quantity representation appears to dissociate into multiple format-specific components. By contrast, when Arabic digits and number words were mixed in the same experiment, quantity priming was as strong between numbers presented in different notations than between numbers presented in the same notation, suggesting that the comparison could occur at a level independent of input format.

However, one must be cautious before drawing the conclusion that there are no separate quantity representations for Arabic digits and number words. First, although quantity priming was found both within and across arabic and verbal notations, Experiment 1A also revealed a marginal interaction between quantity priming and notation change, $F(2, 30) = 2.66, p = .086, MSE = 1{,}040$, indicating that the amount of quantity priming was marginally larger within the same notation than across notations. This may reveal the presence of additional, distinct quantity representations for each notation, because a unique quantity representation for both notations would have predicted the same amount of quantity priming within and across notations. Second, because of the speed with which humans process information, it can be extremely difficult to prove or disprove issues about the modularity of information processing in the human brain by using data from normal participants. Two processing systems may well have distinct "encapsulated" inputs and formats of internal representation, thus functioning as separable cognitive "modules" (Fodor, 1975). Yet, if these systems exchange their outputs rapidly, then given enough time they may seem to function as a single integrated whole. Likewise, it is possible that there are distinct notation-specific representations of the quantity associated with an Arabic digit and with a word (Campbell & Clark, 1992) but that these representations interact so rapidly as to seem to form a single, common, notation-independent representation.

In Experiment 2, we further investigate this issue by asking whether, under even more stringent temporal constraints, the quantity representations for Arabic digits and for verbal numerals might also dissociate. Here we study within- and across-notation priming effects in a masked-priming comparison task. Participants were asked to classify a target number as being smaller or larger than 5, whereas unknown to them a masked number was displayed for 66 ms prior to the target.

Experiment 2A: Masked Priming Across Arabic and Verbal Notations

Method

Participants. Twenty-five right-handed male French students, ages 21–32 years ($M = 25$), were tested individually.

Instructions. Instructions were identical to those used in Experiment 1A, with one exception: Participants were told that a neutral signal appeared before each number and was helpful in getting ready to respond. Twelve participants responded "larger" by using the right hand and "smaller" by using the left hand (larger–right group). The other 13 participants received the converse assignment (larger–left group).

Procedure. Unknown to the participants, the signal was composed of three consecutive images, each appearing for 66 ms synchronized with the refresh cycle of the screen. The first and the third images consisted of a string of random nonalphanumerical ASCII characters that served as forward and backward masks. The second image consisted of a number (the prime) ranging from 1 to 9 and written either in Arabic notation or in verbal notation. The numbers to which participants were told to respond appeared just after the offset of the third image and disappeared as soon as a response was recorded. As in Experiment 1, only the trials with the visible numbers 1, 4, 6, or 9 were included in the analyses of response- and quantity-priming effects. In this way, the numerical relation factor between the prime and these target numbers was orthogonal to the numerical distance factor separating either the prime or these targets from 5 (provided that both the prime and target were either smaller or larger than 5; see the *Results* section). In the following sections, we refer to the numbers 1, 4, 6, and 9 as *targets* and to the numbers 2, 3, 7, and 8 as *distractors* (although the numbers were not described as such to the participants). Primes, targets, and distractors could be presented in Arabic notation or in verbal notation. The combination of all these factors defined $9 \times 4 \times 2 \times 2 = 144$ prime–target pairs, each of which was presented three times in random order, and $9 \times 4 \times 2 \times 2 = 144$ prime–distractor pairs, each of which was presented once in random order. The full list, comprising 576 experimental trials, was divided into three blocks separated by pauses. Fifteen additional trials were presented initially for training. Once the participant's response in a trial was recorded, approximately 2 s elapsed before the next trial began. The entire experiment lasted about 30 min.

Stimuli presentation and response recording were as in Experiment 1A. In an effort to reduce low-level visual priming, verbal primes were presented in lowercase and verbal targets in uppercase (8 mm tall, 15–36 mm wide in both cases). Likewise, Arabic primes subtended 8 mm × 5 mm, whereas Arabic targets were 25% larger (10 mm × 6 mm). Masks consisted of six juxtaposed lowercase random characters of the same size as the verbal primes (36 mm wide). The viewing distance was about 0.5 m.

Results

Quantity priming. As in Experiment 1, we examined the quantity-priming effect by selecting trials fulfilling the following conditions: (a) the prime and target were either both larger or both smaller than 5, (b) the response was correct, and (c) response time fell between 150 ms and 1,000 ms in order to remove anticipatory or delayed responses (1.4% of trials). Trials with distractors were not included in the statistical analysis. We then performed a $2 \times 2 \times 2 \times 4$ ANOVA on mean response time with factors of target notation (Arabic or verbal), notation change (whether the prime and target appeared in the same notation or not), distance (target close to 5 or far from 5), and relation (a four-level factor, ranging from 0 to 3, measuring the numerical separation between the prime and the target).

A main effect of relation was found, $F(3, 72) = 6.11, p < .0009$, $MSE = 1{,}357$. Response time increased monotonically as a function of the relation between the masked prime and the target (500, 504, 506, and 515 ms; see Figure 7). There was also a distance effect, $F(1, 24) = 81.7, p < .0001$, $MSE = 4{,}716$: Responses were 44 ms faster for targets far from 5 than for targets close to 5. The effect of notation was also significant, $F(1, 24) = 70.53, p < .0001, MSE = 2{,}674$: Responses were 31 ms faster for targets in Arabic notation than for targets in verbal notation. However, no significant main effect of notation change was found ($p = .11$; see Figure 7).

No main factor was found to interact with the effect of relation. In particular, the Relation × Notation Change

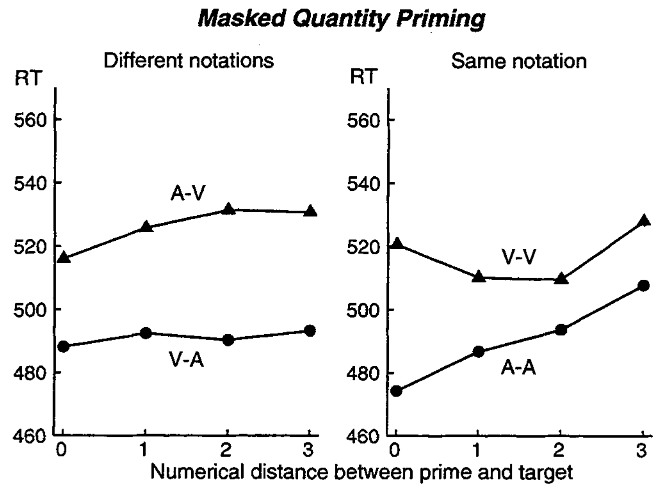

Figure 7. Quantity-priming effect with prime and target numbers in Arabic (A) or verbal (V) notation in Experiment 2A. Each curve shows the response time (RT) to the target number as a function of its numerical relation with the preceding prime number (absolute value of the difference between prime and target) and for a particular condition of notation (e.g., A–V = Arabic prime, verbal target).

interaction was not significant, $F(3, 72) = 2.16, p = .10$, $MSE = 1{,}299$. However, the Relation × Notation × Notation Change interaction approached significance, $F(3, 72) = 2.72, p = .051, MSE = 1{,}652$, and the inspection of the mean response times (see Figure 7) suggested different curves for the relation effect in the different conditions. We therefore examined the relation effect in each of the notation conditions. There was no significant relation effect on trials in which the notations of the prime and targets differed—overall: $F(3, 72) = 1.19, p = .32, MSE = 1{,}641$; verbal–Arabic trials: $F < 1$; Arabic–verbal trials: $F(3, 72) = 1.55$, $p = .21$, $MSE = 1{,}612$. There was however a significant relation effect on same-notation trials—overall: $F(3, 72) = 9.0, p < .0001, MSE = 1{,}015$—which was mostly due to Arabic–Arabic trials—Arabic–Arabic: $F(3, 72) = 9.52, p < .0001$, $MSE = 1{,}031$; verbal–verbal: $F(3, 72) = 2.40$, $p = .075, MSE = 1{,}636$. As seen in Figure 7, the shape of the relation effect differed on verbal–verbal and on Arabic–Arabic trials, $F(3, 72) = 2.79, p = .047, MSE = 1{,}652$.

This peculiar effect seemed mostly due to particularly slow response times on verbal–verbal trials in which the same numeral was repeated twice (relation = 0; see Figure 7). To distinguish trials in which the same number was repeated twice, and which could therefore involve specific repetition effects (e.g., Humphreys, Besner, & Quilan, 1988), from those in which the prime and target numbers were distinct, the relation factor was broken down as in Experiment 1 into a numerical identity factor and a number proximity factor. There was no main effect of numerical identity ($p = .30$), nor did this factor enter into any interaction with the other factors. By contrast, there was a main effect of number proximity, $F(2, 48) = 4.24, p = .021$, $MSE = 1{,}646$. As the prime fell one, two, or three units away from the target, reaction times increased from 504 ms to 506 ms and to 515 ms. This effect did not interact with target notation ($F < 1$) or with distance ($p = .10$), but it did interact weakly with notation change, $F(2, 48) = 3.10$, $p = .054$, $MSE = 1{,}358$. Because this interaction was critical to models of number processing, post hoc analyses were performed. No main effect of number proximity was found when the prime and target notations differed ($F < 1$ overall, for verbal–Arabic trials only and for Arabic–verbal trials only), whereas a strong effect of number proximity was found when the prime and target notations remained the same, $F(2, 48) = 9.71$, $p = .0003$, $MSE = 1{,}129$. When the analysis was restricted to same-notation trials, no interaction was found between number proximity and notation ($F < 1$). Post hoc tests indeed showed a highly significant proximity effect for Arabic–Arabic trials, $F(2, 48) = 5.69$, $p = .0061$, $MSE = 1{,}025$, as well as a marginally significant effect for verbal–verbal trials, $F(2, 48) = 3.14$, $p = .052$, $MSE = 1{,}751$.

An identical ANOVA on error rates revealed only main effects of distance, $F(1, 24) = 33.3$, $p < .0001$, $MSE = 44$; notation, $F(1, 24) = 4.80$, $p = .039$, $MSE = 38$; and proximity priming, $F(2, 48) = 3.52$, $p = .037$, $MSE = 44$, with no significant interactions. As the relation between prime and target rose from 1 to 3, error rates went from 1.8% to 2.1% and 3.4%, thus indicating that proximity priming was not affected by a speed–accuracy trade-off.

After the experiment, 7 of the 25 participants reported occasionally seeing the prime on a small fraction of trials.[1] The above ANOVA was rerun using only the data from the remaining 18 participants who were unaware of the presence of the prime. The results were essentially identical to those reported above. In particular, there was again a significant main effect of relation, $F(3, 51) = 4.95$, $p = .0043$, $MSE = 1{,}240$, with a significant proximity-priming effect on same-notation trials, $F(2, 34) = 5.49$, $p = .0086$, $MSE = 1{,}168$, but not on different-notation trials ($F < 1$).

Response priming. To study response priming, we performed a second ANOVA on response times to all correct trials with factors of response change (whether or not the prime fell on the same side of 5 as the target, and hence favored the production of the same response), distance, notation, and notation change. A strong main effect of response change was found, $F(1, 24) = 58.8$, $p < .0001$, $MSE = 597$. When the prime and the target fell on the same side of 5, participants were 19 ms faster than when they fell on different sides of 5 (see Figure 8). Response change interacted with distance, $F(1, 24) = 4.55$, $p = .043$, $MSE = 261$. Response priming was larger for targets far from 5 (22 ms) than for targets close to 5 (15 ms), although it remained significant in both cases ($p < .0001$). Response change did not interact with notation change ($F < 1$); notation, $F(1, 24) = 2.89$, $p = .10$, $MSE = 262$; or both, $F(1, 24) = 2.22$, $p = .15$, $MSE = 354$. Post hoc analyses indicated that response priming was significant in all four combinations of prime and target notations (all ps $< .003$).

Again, the same ANOVA was run excluding participants who reported having seen the prime on some trials, with very similar results. Crucially, the response-priming effect

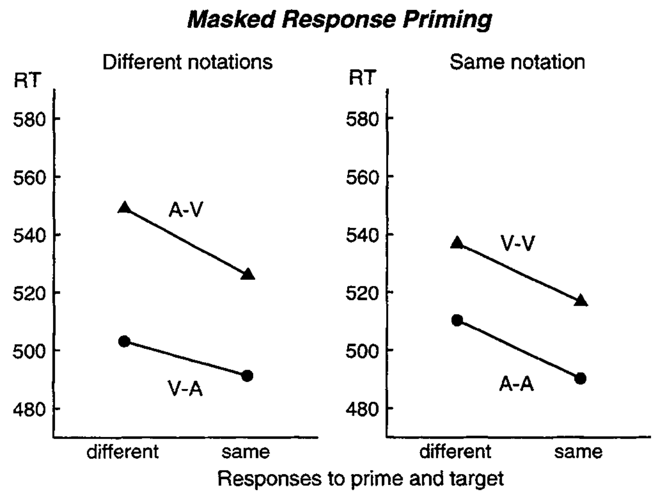

Figure 8. Response-priming effect with prime and target numbers in Arabic (A) or verbal (V) notation in Experiment 2A. Response times (RTs) to the target number are plotted separately for trials in which the prime and target numbers fell on different sides of 5, and hence called for different responses, and for trials in which they fell on the same side of 5, and hence called for the same response.

remained highly significant, $F(1, 17) = 35.2$, $p < .0001$, $MSE = 604$, and did not interact with any other variable.

This experiment also provided the opportunity to analyze whether the response-priming effect was facilitatory, inhibitory, or both, because a neutral prime (number 5) was used on some trials. When the prime and target fell on the same side of 5, response times were not significantly faster than when the target was preceded by the neutral prime, indicating no facilitation effect, $F(1, 22) = 1.45$, $p > .24$, $MSE = 1{,}825$. On the contrary, when the prime and target fell on different sides of 5, response times were significantly slower than in the neutral case, $F(1, 22) = 8.65$, $p = .0071$, $MSE = 1{,}903$. Hence, response priming was essentially due to an inhibition effect on incongruent trials.

A similar ANOVA on error rates disclosed a marginal effect of response priming, $F(1, 24) = 3.68$, $p = .067$, $MSE = 15$, and a significant interaction with distance, $F(1, 24) = 4.41$, $p = .047$, $MSE = 11$. When the target was close to 5, response-change trials yielded significantly more errors than no-change trials (5.3% vs. 3.8% errors), $F(1, 24) = 5.76$, $p = .025$, $MSE = 18$, whereas there was no such effect when the target was far from 5 (respectively, 1.2% and 1.1% errors). Most importantly, as in the response time analysis, no interactions involving the response-change and the notation-change factors were found.

Distance effect. The distance effect was also analyzed as a function of the notation in which the numbers 1–9 were presented. An ANOVA was performed on mean correct

[1]Because of an experimenter error, the data from an unknown number of additional participants who reported seeing the prime were discarded without analysis. Hence, the proportion of participants aware of the prime is unknown and must have been greater than 7/25, or 28%.

response times to the targets and distractors with factors of distance from 5 (now a four-level factor), notation (Arabic or verbal), and response (larger or smaller than 5). Group (larger–right vs. larger–left) was also entered as a between-subjects factor.

The main effect of distance, $F(3, 69) = 59.2, p < .0001$, $MSE = 457$, was qualified by an interaction with response, $F(3, 69) = 4.06, p = .01, MSE = 497$. As shown in Figure 9, the distance effect was steeper when the numbers were smaller than 5 than when they were larger (see Dehaene et al., 1990). The distance effect was also found to interact with notation, $F(3, 69) = 4.11$, $p = .0096$, $MSE = 329$, and group, $F(3, 69) = 3.40, p = .022, MSE = 457$. The distance effect was steeper for number words than for Arabic digits. It was also steeper for participants who responded larger with the right hand than for participants who responded larger with the left hand. As expected, there was also a main effect of notation, $F(1, 23) = 155$, $p < .0001$, $MSE = 666$, participants being 32 ms faster with Arabic digits than with words. Notation also interacted with response, $F(1, 23) = 16.8$, $p = .0004$, $MSE = 303$, an effect that may be due to interference from physical size. As in Experiment 1, responses were 7 ms faster when participants responded "smaller" to digits and "larger" to words, than in the converse situations.

A similar analysis of error rates disclosed a main effect of distance, $F(3, 69) = 20.4, p < .0001, MSE = 10$, with the same significant interactions as above except the interaction with the group factor. This last factor was found to interact with response, $F(1, 23) = 8.12$, $p = .0091$, $MSE = 14$, indicating that participants made 3.3% errors when responding with their left hand, versus only 2.2% with their right hand, consistent with their right-handedness.

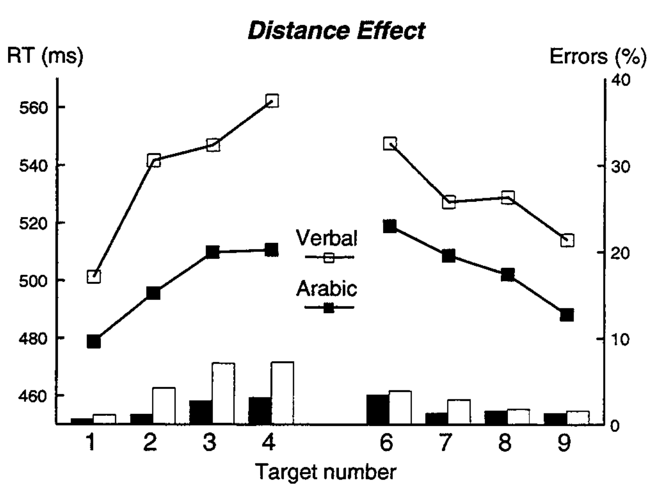

Figure 9. Distance effect with target numbers in Arabic or verbal notation in Experiment 2A. The graph shows the response times (RTs; curves) and error rates (bars) to the target numbers 1, 4, 6, and 9 (making up 75% of trials) as well as to the distractor numbers 2, 3, 7, and 8 (25% of trials).

Discussion

Experiment 2A disclosed two different forms of masked priming with Arabic and verbal numerals, with strikingly different properties. On the one hand, quantity priming—a continuous speed-up of responses as the prime number fell increasingly closer to the target number—was found within each notation, but not across notations. On the other hand, response priming—a slowing down of responses when the prime and target numbers fell on different sides of 5, and hence favored the production of different responses—was found both within and across notations.

The finding of a response-priming effect indicates that all primes were processed up to a high level despite their short presentation (66 ms) and the presence of forward and backward masks. To affect response selection, the primes must have been identified and categorized as larger or smaller than 5. The results also indicate that this categorization did not simply result in an automatic activation of spatial–numerical associations. Independently of the task, large numbers are known to facilitate a response to the right, whereas small numbers automatically evoke a response to the left (Dehaene et al., 1990, 1993; Fias et al., 1996; Huha, Berch, & Krikorian, 1995). Such a spatial–numerical association of response codes (SNARC effect; Dehaene et al., 1993) cannot account for the present response-priming effect. Here, two groups of participants were run, one group responding "larger" with the right hand and "smaller" with the left hand (larger–right group) and another group responding following the converse instructions (larger–left group). If the sole effect of the prime was to promote a left or right response independently of the instructions, then these two groups should have shown opposite response-priming effects. If primes larger than 5 always facilitated a right-hand response, participants in the larger–right group would have shown facilitation for a subsequent "larger" response, whereas participants in the larger–left group would have shown facilitation for a subsequent "smaller" response. On average, then, there should have been no response-priming effect, but response priming should have interacted with group. The results clearly contradicted this prediction. First, the response-priming effect was highly significant in an analysis averaging across the two groups ($p < .0001$). Second, a reanalysis of response priming with group introduced as an additional between-subjects factor showed no interaction of this factor with response change, $F(1, 23) = 1.72$, *ns*. In fact, response priming was significant in both the larger–right group, 15-ms effect, $F(1, 11) = 18.8, p = .0012$, $MSE = 609$, and the larger–left group, 22-ms effect, $F(1, 12) = 44.6, p < .0001, MSE = 553$.

In summary, in the larger–right group, large primes facilitated a rightward response, whereas in the larger–left group, the same primes facilitated a leftward response. These results therefore imply that the prime number was processed according to the exact instructions given to each group of participants. Thus, the number comparison task was performed on the prime number before being performed on the target number. Further evidence for this hypothesis came from an analysis of distance effect. The speed of numerical comparison is known to be affected by the numerical distance between the two numbers to be compared (Dehaene et al., 1990; Moyer & Landauer, 1967). Here, just as there was a numerical distance effect on target numbers, the distance of the prime to 5 also had an influence on the size of the response-priming effect. Primes far from 5 yielded a greater response-priming effect than primes close to 5, as expected if the comparison of the prime with 5 yielded a faster and more salient response for far primes than for close primes.

Our conclusion so far is that all prime and target numbers were identified, compared according to the instructions, and eventually categorized as larger or smaller than 5. Nevertheless, it cannot be concluded that all primes and targets went through a single comparison process regardless of their notation. Notation had a strong impact on the quantity-priming effect. Whenever the prime and the target were in the same notation, either both Arabic or both verbal, quantity priming was observed. By contrast, whenever the prime and target were in different notations, no quantity priming was present.

The exact pattern of results was complex, because even for same-notation trials, the exact curve for the relation effect varied in an unexplained way with target notation (see Figure 7), apparently because of exceptionally slow response times on repeated trials with verbal numerals. Our attempts to eliminate repetition priming observed in Experiment 1A by using different fonts and sizes for primes and targets were apparently successful, but repeated trials with verbal numerals were affected in a different manner. This effect may be due to the perceptual phenomenon known as *repetition blindness* (Kanwisher, 1987). Repetition blindness was found to occur when two perceived items were presented in close succession and was related to a decrease of participant's performances when the two presented items were identical (e.g., Humphreys et al., 1988; Luo & Caramazza, 1995). Humphreys et al. found repetition priming when the two occurrences of a same word were separated by a large temporal gap and repetition blindness when the two occurrences were in immediate succession. Luo and Caramazza showed that repetition blindness is modulated by the presentation duration of masked primes. Accordingly, a possible explanation of the exceptionally slow response times to repeated verbal numerals in our experiments would be that the repetition-priming effect observed in Experiment 1A reversed to a repetition-blindness effect under the conditions of Experiment 2A.

To distinguish quantity priming from such repetition effects, nonrepeated trials were analyzed separately. When only nonrepeated trials were analyzed, the results were straightforward: There was proximity priming on only same-notation trials but none on different-notation trials. In apparent contradiction with current modular models of number processing, the finding of a significant influence of notation on the relation effect suggests that there is a stage in the comparison process that differs for numbers in Arabic and in verbal notation and where the numbers are nevertheless represented internally as quantities. In McCloskey's (1992) model, as well as in Dehaene's (1992) triple-code model, the quantity representation is considered to be format independent and common to numbers presented in all input–output notations. If that were the case, however, we should have observed a similar effect of quantity priming within and between notations. Both a verbal prime such as TWO or an Arabic prime such as 2 should have internally activated the same internal representation of quantity 2, and this should have yielded identical decreases in response time to a subsequent Arabic target 1. This prediction was not supported by the data. The results showed that when a prime such as 2 is presented, it does yield a decrease in response time to target numbers that are in the same quantity range, but only for targets that appear in the same notation. We therefore reach the seemingly inescapable conclusion that there must be notation-specific representations of numbers that contain quantity information. We examine the nature of these representations in the General Discussion.

At this point, however, given the surprising outcome of Experiment 2A, we introduce a replication of the masked-priming findings with another pair of number notations, namely Arabic notation versus random dot patterns. By using a double-comparison task in Experiment 1, we had found that these two notations yielded notation-specific quantity priming, suggesting that they were supported by two distinct representations of numerical quantity. Hence, the results in the present masked-priming situation should be even clearer than with Arabic and verbal notations. We predict quantity priming when the prime and target appear in the same notation, but not otherwise. When both the prime and target appear in Arabic notation, the results should replicate those of the Arabic–Arabic trials in Experiment 2A. Finally, given the evidence for notation-specific processes for Arabic and dot notations, we were particularly interested in examining whether the notation-independent effect of response priming observed in Experiment 2A could be replicated.

Experiment 2B: Masked Priming Between Arabic Digits and Dot Patterns

Method

Twenty-four right-handed male French students, ages 24–34 ($M = 28$), were tested individually (12 were assigned to the larger–right group and 12 to the larger–left group). Two additional participants were rejected, 1 for making over 10% errors and another for having over 10% of his response times greater than 1 s. The procedure and instructions were similar to those in Experiment 2A, with the following differences. First, dot patterns were used instead of number words. The dot patterns were generated randomly on each trial according to the procedure described in Experiment 1B. Second, the masking patterns were redesigned to efficiently suppress the perception of both Arabic and dot primes. As a forward mask, prior to prime presentation, a 3×3 array of random letters, each 20 mm high, was flashed. The array covered the whole area in which dots could appear. Furthermore, the letters were in the same size and font as the Arabic primes, and the middle letter of the array fell at the same location used for Arabic primes. As a backward mask, immediately following prime presentation, the same letter array was supplemented with four additional letters, each 30 mm high, appearing at locations intermingled with those of the original 3 × 3 array. Primes as well as forward and backward masks were exposed for 66 ms, and the subsequent target remained on screen until a response was recorded. In an effort to reduce low-level visual matching, Arabic targets were 50% larger than Arabic primes (30 mm vs. 20 mm high), and the random dot patterns used as primes and targets were independently generated. The viewing distance was 0.5 m.

Results

Quantity priming. The same statistical analyses as in Experiment 2A were performed to study the influence of the prime number on responses to the target number. Trials fulfilling the same conditions as in Experiment 2A (primes and targets both smaller or both larger than 5; correct response; and response time between 150 and 1,000 ms, thus excluding 0.8% of anticipatory or delayed responses) were selected, and we performed a 2 × 2 × 2 × 4 ANOVA on mean response time with the same factors of notation (Arabic or dot pattern), notation change, distance, and relation. There was a main effect of distance, $F(1, 23) = 214$, $p < .0001$, $MSE = 4006$; an effect of notation, $F(1, 23) = 156$, $p < .0001$, $MSE = 3,193$; and an effect of notation change, $F(1, 23) = 63.0, p < .0001, MSE = 1,446$. Responses were 67 ms faster for targets far from 5 than for targets close to 5; they were 51 ms faster for Arabic digits than for dot patterns; and finally they were 22 ms faster when the target number was presented in the same notation as the prime than when it was not. Distance also interacted with notation, $F(1, 23) = 36.4$, $p < .0001$, $MSE = 3,034$, indicating that the distance effect was more pronounced with dots than with Arabic digits (see below).

Most importantly, the main effect of relation was not significant, $F(3, 69) = 1.46$, $p = .23$, $MSE = 1,547$, but there were trends toward an interaction of relation with notation, $F(3, 69) = 2.62, p = .058, MSE = 1,269$, and of relation with notation change, $F(3, 69) = 2.38$, $p = .077$, $MSE = 1,369$. There were also significant triple interactions of relation, notation, and distance, $F(3, 69) = 4.30$, $p = .0078$, $MSE = 1,231$; and of notation, notation change, and distance, $F(1, 23) = 6.56$, $p = .017$, $MSE = 1,607$. To understand these effects, separate analyses were run on Arabic targets and on dot targets.

For Arabic targets, there was a main effect of relation, $F(3, 69) = 4.08, p = .01, MSE = 1,102$, that was additive with the effect of distance, $F(3, 69) = 1.55, p = .21, MSE = 954$, but that interacted with notation change, $F(3, 69) = 2.90, p = .041, MSE = 1,165$. Follow-up analyses indicated that the relation effect was only present when both the prime and target were in Arabic notation, $F(3, 69) = 6.59$, $p = .0006$, $MSE = 1,175$, but not when the prime was a dot pattern and the target was an Arabic digit ($F < 1$; see Figure 10).

For dot targets, there was no main effect of relation ($F < 1$ overall, for dot–dot trials and for Arabic–dot trials). The only significant effect was a Relation × Distance interaction, $F(3, 69) = 4.50, p = .0061, MSE = 1,290$. This interaction could be reinterpreted as a residual effect of the distance between the prime and 5: As the distance between the prime and 5 increased from 1 to 4, response times to dot targets were successively 550, 547, 548, and 536 ms.

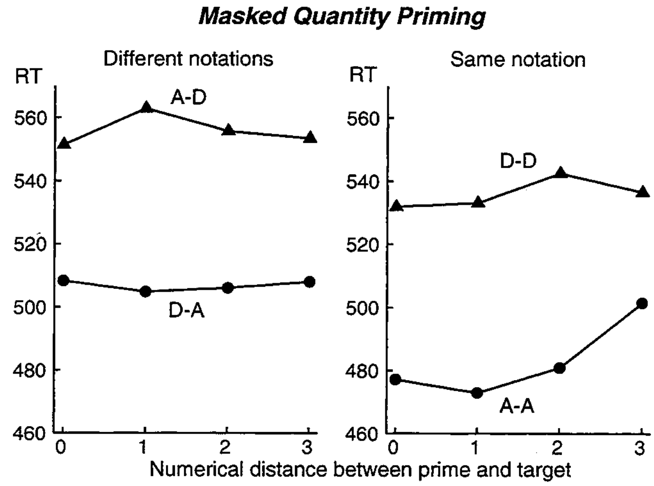

Figure 10. Quantity-priming effect with prime and target numbers presented as Arabic (A) digits or as dot (D) patterns in Experiment 2B. Each curve shows the response time (RT) to the target number as a function of its numerical relation with the preceding prime number (absolute value of the difference between prime and target) and for a particular condition of notation (e.g., A–D = Arabic prime, dot target).

As in Experiment 2A, the relation factor was again broken down into identity and proximity factors. Numerical identity did not have a significant main effect, nor did it enter into significant interactions with other factors. The main effect of numerical proximity was also nonsignificant, $F(2, 46) = 1.1$, but proximity interacted with notation, $F(2, 46) = 4.06$, $p = .024$, $MSE = 1,194$, and with distance and notation, $F(2, 46) = 6.83, p = .0025, MSE = 1,056$. As in the above analysis, the effect of number proximity was present only for digit targets, $F(2, 46) = 5.89, p = .0053, MSE = 1,091$, but not for dot targets ($F < 1$). For digit targets, response times increased from 489 ms to 494 ms and to 505 ms when the numerical separation between the prime and the target increased from 1 to 2 and 3. For dot targets, the corresponding response times were 548, 549, and 545 ms. Moreover, even within digit targets, the numerical proximity factor was found to interact with notation change, $F(2, 46) = 3.69, p = .033, MSE = 1,132$. The effect of numerical proximity was again limited to the case when both the prime and the target were digits, $F(2, 46) = 9.49$, $p = .0004$, $MSE = 1,104$, and was not found when the prime was a dot pattern and the target an Arabic digit ($F < 1$; see Figure 10).

An identical ANOVA on error rates revealed a main effect of distance, $F(1, 23) = 29.7, p < .0001, MSE = 74$, and of notation, $F(1, 23) = 21.4$, $p = .0001$, $MSE = 46$. As in previous experiments, these two factors interacted, $F(1, 23) = 6.09, p = .021, MSE = 69$. The distance factor was also found to interact with notation change, $F(1, 23) = 6.48$, $p = .018, MSE = 69$, indicating that the distance effect was slightly stronger when notation did not change between the prime and target than when it did change. No other effects and interactions were found.

At the end of the experiment, 14 of 24 participants reported occasionally seeing the prime on a small proportion of trials. Thus, the same ANOVA was run on the remaining 10 participants. The results remained very similar, although their significance was reduced because of the small sample size. In particular, there was again a trend toward an effect of numerical proximity when both primes and targets were in Arabic notation, though it now fell short of significance, $F(2, 18) = 3.48$, $p = .053$, $MSE = 987$. On such Arabic–Arabic trials, response times increased from 491 ms to 503 ms and to 517 ms as the prime–target relation increased from 1 to 3. Highly significant effects of notation change, $F(1, 9) = 20.3$, $p = .0015$, $MSE = 2{,}771$, and of the Notation Change × Relation interaction, $F(3, 27) = 5.11$, $p = .006$, $MSE = 980$, were also found, and there was no trace of an effect of relation in notation-change trials.

Response priming. As in Experiment 2A, a second ANOVA was performed to analyze the presence of response priming. This ANOVA was again performed on correct response times to all target numbers with factors of response change, distance, notation, and notation change.

A main effect of response change was found, $F(1, 23) = 26.2$, $p < .0001$, $MSE = 1{,}606$. When the prime and the target fell on the same side of 5, participants were 22 ms faster than when they fell on different sides of 5. Response change interacted with distance, $F(1, 23) = 20.0$, $p < .0002$, $MSE = 412$. Response priming was larger for targets far from 5 (30 ms) than for targets close to 5 (12 ms), although the effect remained significant in both cases ($p < .0001$ and $p = .05$, respectively). Response change also interacted with notation, $F(1, 23) = 7.90$, $p = .01$, $MSE = 380$: Response priming was larger for digits (26 ms) than for dots (16 ms), although the effect again remained significant in both notations ($p < .0001$ and $p = .002$, respectively). Finally a Response Change × Notation × Notation Change interaction was found, $F(1, 23) = 8.03$, $p = .009$, $MSE = 574$. As shown in Figure 11, this triple interaction was due to a larger effect of response priming when both primes and targets were digits. Subsequent analyses found significant response priming in all but one combination of prime and target notations (digits followed by dots: 19-ms effect, $p = .0026$; digits followed by digits: 37-ms effect, $p < .0001$; dots followed by digits: 17-ms effect, $p = .0014$; dots followed by dots: 11-ms effect, $p = .06$).

As in Experiment 2A, an ANOVA on response times including trials with the neutral prime 5 revealed that response priming was entirely due to an inhibition effect on incongruent trials, $F(1, 23) = 8.81$, $p = .0069$, $MSE = 2{,}474$, with no facilitation effect on congruent trials, $F(1, 23) = 1.11$, $p = .30$, $MSE = 1{,}722$. Furthermore, a reanalysis of the data with group as an additional factor showed that response priming was found both in the larger–right group: 24-ms effect, $F(1, 11) = 18.0$, $p = .0014$, $MSE = 1{,}551$; and in the larger–left group: 18-ms effect, $F(1, 11) = 8.81$, $p = .013$, $MSE = 1{,}718$. This finding suggests that response priming cannot be reduced to an automatic SNARC effect (Dehaene et al., 1993; see above discussion).

The same ANOVAs were run on the 10 participants who did not report having seen the prime at any time during the

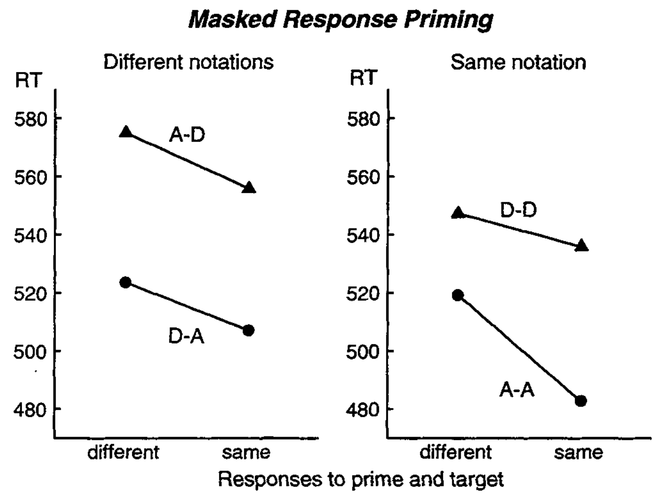

Figure 11. Response-priming effect with prime and target numbers presented as Arabic (A) digits or as dot (D) patterns in Experiment 2B. Response times (RTs) to the target number are plotted separately for trials in which the prime and target numbers fell on different sides of 5, and hence called for different responses, and for trials in which they fell on the same side of 5, and hence called for the same response.

experiment. Very similar results were found, including a significant main effect of response priming, $F(1, 9) = 6.13$, $p = .035$, $MSE = 1{,}684$. A positive effect was found in all conditions of notation (digits followed by dots: 11 ms; dots followed by dots: 17 ms; dots followed by digits: 6 ms; digits followed by digits: 31 ms), though it tended to be weaker than in the main analysis and now reached significance in only the Arabic–Arabic condition, $F(1, 9) = 8.94$, $p = .015$, $MSE = 1{,}077$.

Finally, the initial ANOVA was run on error rates. The main effect of response change was not significant, $F(1, 23) = 1.66$, $p = .21$, $MSE = 30$. However, as in the response time analysis, response change interacted with notation, $F(1, 23) = 17.8$, $p = .0003$, $MSE = 4$. Post hoc tests showed a significant difference between response-change and no-change trials only when the target was in Arabic notation (respectively, 3.2% and 1.6% errors), $F(1, 23) = 5.93$, $p = .023$, $MSE = 19$, but not when the target was a dot pattern (respectively, 3.8% and 3.9% errors, $F < 1$).

Distance effect. As in Experiment 2A, a finer grained analysis of the distance effect was performed by means of the same ANOVA on mean correct response times to the targets and distractors with factors of distance from 5 (a four-level factor), notation, and response (larger or smaller than 5). Group (larger–right vs. larger–left) was also entered as a between-subjects factor.

The main effect of distance, $F(3, 66) = 154$, $p < .0001$, $MSE = 415$, was qualified by an interaction with response, $F(3, 66) = 5.19$, $p = .0028$, $MSE = 335$. As expected, the distance effect was steeper when the numbers were smaller than 5 than when they were larger than 5 (Dehaene et al., 1990). The distance effect also interacted with notation, F(3,

66) = 34.7, $p < .0001$, $MSE = 442$. The distance effect was steeper for dot patterns than for Arabic digits (see Figure 12). There was also a Distance × Notation × Response interaction, $F(3, 66) = 3.19$, $p = .029$, $MSE = 230$, because of particularly slow responses for dot patterns comprising 3, 4, or 6 dots (see Figure 12). The main effect of notation, $F(1, 22) = 77.5$, $p < .0001$, $MSE = 1{,}235$, was also qualified by an interaction with response, $F(1, 22) = 7.89$, $p = .01$, $MSE = 374$. As in previous experiments, with digit targets, "smaller" responses were faster than "larger" responses, whereas the converse held for dot targets, an effect that can be interpreted as an interference of physical size on the main judgment of numerical size (dot patterns having a greater extension than single digits). No effects or interactions were found involving the group factor.

A similar analysis of error rates disclosed effects of distance, $F(3, 66) = 15.3$, $p < .0001$, $MSE = 12$; notation, $F(1, 22) = 7.96$, $p = .01$, $MSE = 12$; and their interaction, $F(3, 66) = 3.77$, $p = .015$, $MSE = 11$. There was also a main effect of group, $F(1, 22) = 9.65$, $p = .0052$, $MSE = 60$, and a Group × Distance interaction, $F(3, 66) = 5.16$, $p = .003$, $MSE = 12$. Participants in the larger–left group made slightly more errors than those in the larger–right group, and this effect was especially notable for close targets (see Dehaene et al., 1990).

Discussion

The main purpose of Experiment 2B was to replicate the priming effects observed in Experiment 2A and to study how they generalized to dot patterns. Overall, the results confirmed our predictions. First, in the one condition that was identical to Experiment 2A, when both the prime and the target were presented in Arabic notation, the effect of quantity priming was replicated. Participants responded increasingly faster as the numerical relation between prime and target decreased. This confirms that an Arabic digit, even when masked and presented for 66 ms, can be processed at a semantic level and can influence the processing of nearby numbers.

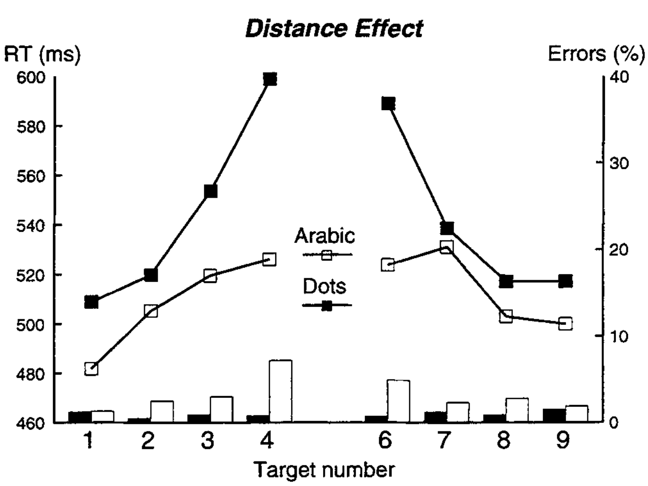

Figure 12. · Distance effect with target numbers presented as Arabic digits or as dot patterns in Experiment 2B. The graph shows the response times (RTs; curves) and error rates (bars) to the target numbers 1, 4, 6, and 9 (making up 75% of trials) as well as to the distractor numbers 2, 3, 7, and 8 (25% of trials).

Second, as in Experiment 2A, we found no transfer of quantity priming across notations. When the prime and target appeared in different notations, one as a dot pattern and the other as a digit, the numerical relation between them had no influence on response times. The lack of quantity priming when the prime was in Arabic notation and the target in dot notation (Arabic–dot trials) is particularly noteworthy, given the presence of quantity priming on Arabic–Arabic trials. This brings further support to the hypothesis that the quantity representation associated with Arabic digits is partially distinct from the one used to process the numerosity of dot patterns.

The evidence from dot–Arabic trials is more ambiguous, because there was no quantity priming when both the prime and the target were dot patterns. In itself, this might suggest that the masked dot primes were simply not perceived by the participants. That interpretation, however, is challenged by the results of the response-priming analysis. As in Experiment 2A, notation-specific quantity priming was accompanied by a nonspecific effect of response priming. In all conditions of prime and target notations, participants responded faster when the prime and target were both larger or both smaller than 5 than when they fell on different sides of 5. In Experiment 2B, this effect was now partially modulated by notation, being maximal in Arabic–Arabic trials, of intermediate size in Arabic–dot and dot–Arabic trials, and minimal and marginally significant in dot–dot trials. Nevertheless, its occurrence with primes in either notation indicates that all primes were processed at least up to a level at which they were categorized as smaller or larger than 5. Participants were apparently applying the comparison instructions to the prime number as well as to the target number. In that respect, our results fit with the notion that conscious factors such as task instructions can influence the unconscious processing of masked primes (Carr & Dagenbach, 1990; Dagenbach, Carr, & Wilhelmsen, 1989).

Given the presence of a significant response-priming effect with dot primes, the absence of quantity priming on dot–dot trials is surprising. One possibility that we envision is that, although the representation of the masked dot primes was sufficiently accurate for them to be categorized as larger or smaller than 5 on a significant proportion of trials, it was not sufficient for them to be precisely represented so that different primes on the same side of 5 could have a differential effect on target processing. For instance, it could be the case that the dot primes 6, 7, 8, and 9 are merely coded as "some numerosity around 7 or 8" and hence have no differential effect on the subsequent processing of a dot pattern of numerosity 9 (no quantity priming). This explanation might predict that, for numbers in the subitizing range 1–4, which participants might perceive more accurately, quantity priming might be obtained on dot–dot trials. Unfortunately, a reanalysis of the relation effect with prime size (larger or smaller than 5) as an additional factor did not confirm this prediction.

Another possibility that we envision is that dot primes and dot targets might not be processed as separate visual events, at least in some trials. If so, the dot pattern prime would tend to fade into the dot pattern target rather than be processed as a distinct pattern. As a result, both response and quantity priming would dramatically decrease when both the prime and the target are dot patterns, but response priming would remain when either the prime or the target appears in Arabic notation. Indeed, this pattern of results was precisely found in Experiment 2B. There was a lack of quantity priming and marginal response priming in dot–dot trials and strong response priming in both dot–Arabic and Arabic–dot trials. Thus, it remains a highly plausible interpretation that needs to be tested in further experiments.

General Discussion

The aim of our experiments was to explore to what extent the mental pathways for number processing are segregated according to the numerical notation used for input. Chronometrical and neuropsychological evidence suggests that Arabic numerals, verbal numerals, and the numerosity of dot patterns are initially extracted by partially distinct visual identification systems (Cipolotti & Butterworth, 1995; Cipolotti, Warrington, & Butterworth, 1995; Dehaene, 1996; Dehaene & Akhavein, 1995; Macaruso et al., 1993; McCloskey & Caramazza, 1987). Do these systems converge onto a single, common representation of quantity, however, as postulated by McCloskey (1992; McCloskey & Caramazza, 1987) and Dehaene (1992) or only at a later stage of processing? Previous experiments had shown that the distance effect on response times in the number comparison task remains essentially the same when numbers are presented as Arabic digits, spelled-out number words, or random sets of dots (Buckley & Gillman, 1974; Foltz et al., 1984; Tzeng & Wang, 1983). These findings were generally considered as evidence for a unique representation of quantities involved in numerical comparison (Dehaene, 1992; McCloskey et al., 1992). As aforementioned, however, these results are logically consistent with multiple representations with a similar internal organization. In fact, the present data suggest both a partial dissociation between distinct notation-specific representations of quantity and a convergence at a later stage of processing when participants engage in a number comparison task. In this discussion, we try to outline how current models of number processing must be modified to account for these results.

Internal Representation of Quantities

When two numbers are presented in close temporal succession, responses to the second number are facilitated to a variable extent depending on its numerical relation to the first number (Brysbaert, 1995; den Heyer & Briand, 1986; Marcel & Forrin, 1974). Our main finding is that this quantity-priming effect also depends on the notation in which the prime and target numbers are presented, as well as on the conditions of presentation of the prime. In Experiment 1, primes were presented for 200 ms and were subjected to the same number comparison task as the target numbers. Under these conditions, quantity priming was found both within each notation (Arabic, verbal, and dot patterns) as well as across the Arabic and verbal notations, but not across the Arabic and dot pattern notations. In Experiment 2, primes were presented for only 66 ms, were masked, and were not explicitly responded to by the participants. Under these conditions, quantity priming was still observed when the numbers were both in Arabic notation or both in verbal notation, but no cross-notation priming was found.

These results are hard to reconcile with models postulating a single unified representation of quantities (Dehaene, 1992; McCloskey, 1992; McCloskey & Caramazza, 1987). Although the original McCloskey's model did not include an input module for the numerosity of sets, Macaruso et al. (1993) have used dot patterns for input and output and have claimed that these also access the central abstract representation. Likewise, the triple-code model (Dehaene, 1992) posits a unique representation of the magnitude of numbers, accessible by Arabic numerals, verbal numerals, or extraction of the numerosity of sets. The new data indicate that this postulate is oversimplified. Although participants, when given enough time, can obviously relate dot numerosity with Arabic or verbal numerals, in speeded comparison tasks the quantity representation appears to dissociate into multiple format-specific components. In these models, the only stage at which quantity priming can occur is the common quantity representation. Indeed, only at this stage is the distance and relation between numbers explicitly represented. However, because this stage is postulated to be independent of input format (be it Arabic, verbal, or dot patterns), these models should have predicted identical amounts of quantity priming, both across and within notations. On the contrary, the results indicate that quantity priming does not necessarily occur across notations.

None of the available models seems to readily account for this finding. The closest model is Campbell and Clark's encoding-complex model (Campbell, 1994; Campbell & Clark, 1988, 1992), in which the different input notations are assumed to activate highly variable internal analog, digital, finger, verbal, and other representations of numbers. Even this model, however, did not specifically predict that different input notations would yield similar distance effects, but no cross-notation priming effects, in some conditions.

We see at least four ways in which the present data might be reconciled with past models of number processing, though none is devoid of problems. First, one might postulate that, although the same quantity representation is accessed by numbers in both Arabic and verbal notations, it is reliably preactivated by a masked prime only when this prime is presented in the same notation as the target. For instance, the change of notation on Arabic–verbal or verbal–Arabic trials might result in a resetting of the quantitative activation left over by the prime, thus preventing quantity priming from appearing. Alternatively, one might invoke a cooperative effect on same-notation trials, by which the quantitative activation left over by the prime would be enhanced when the prime and target share the same notation.

Such possibilities, however, although presumably within the range of the complex notation-specific effects that can emerge from connectionist implementations of number processing (Campbell & Oliphant, 1992), are clearly little more than ad hoc suppositions at this stage. Note that in the present Experiment 2, notation change by itself had no effect on reaction times but rather interacted significantly with quantity priming, because quantity priming was found on only same-notation trials; conversely, in Experiment 1A, notation change had a significant influence on response times (responses being faster on same-notation than on different-notation trials) but no influence on the amount of quantity priming. Thus, the data provide no support for the view that the change in notation is causally related, through resetting or cooperative effects, to the presence or absence of quantity priming.

A second possibility is that the quantity-priming effect observed under masked-priming conditions does not arise from an internal semantic representation of numbers as quantities but rather from associations between lexical items. The word *one* might be associatively related to the word *two,* itself related to the word *three,* and so on; likewise for the digits 1 and 2, 2 and 3, and so on. Through spreading activation across such multiple associative connections, a masked number word may thus supply a decreasing level of activation to successively more distant lexical items. It seems plausible that such associative connections would exist only within a given input lexicon (Arabic or verbal) and that no association would exist between, say, the lexical representations of the digit 1 and of the word *two.* Thus, this hypothesis may explain the absence of cross-notation priming. In addition, because there are no lexical representations associated to random dot patterns, it might also explain why no quantity-priming effect was found in Experiment 2B, even on dot–dot trials.

In spite of its seductive simplicity, this lexical association hypothesis has problems too. First, in a same–different judgment task, Dehaene and Akhavein (1995) explicitly tested and rejected the hypothesis that effects of the distance between numbers could be due to lexical associations. They selected pairs of numbers such as 18/20 and 80/12 in which, according to theories of the number lexicon (Deloche & Seron, 1984; McCloskey, Sokol, & Goodman, 1986), the lexical distance is constant while the numerical distance obviously varies, and they still obtained a significant distance effect. Second, the lexical hypothesis cannot explain why within- and cross-notation quantity priming was found in a nonmasked, double-comparison task or even why quantity priming was found with dot patterns (Experiment 1). If lexical associations exist within only the Arabic and verbal lexicons, as must be postulated to account for the masked-priming results, then they cannot be held responsible for the quantity-priming effects observed on dot–dot, Arabic–verbal, and verbal–Arabic trials in Experiment 1. One would then have to suppose that the quantity-priming effects in both experiments, although they are of similar size, have completely different origins, a lexical one in the former case and a semantic one in the latter case—a logically plausible but clearly not a very economical hypothesis.

Furthermore, if lexical associations accounted for masked quantity priming within the Arabic and verbal lexicons, asymmetric quantity priming should be predicted. Because both notation systems consist of an ordered series of symbols, priming should occur preferentially in the forward, ascending direction (as was indeed found by Marcel & Forrin, 1974, in a number-naming task). For instance, THREE should prime FOUR to a greater extent than TWO should prime ONE. However, the present data do not support this prediction. A reanalysis of the masked priming in Experiment 2A, which compared trials in which the prime and target were in ascending or in descending order, revealed neither a significant main effect of priming direction, $F(1, 24) = 2.94$, $p = .10$, $MSE = 3{,}320$, nor a significant Priming Direction × Quantity Priming interaction when both the primes and targets were either Arabic or verbal numerals, $F(3, 72) = 0.56$, $p = .64$, $MSE = 1{,}481$. Similar results were obtained in the unmasked-priming experiment (Experiment 1A). All in all, our results rule out a pure lexical association interpretation of quantity priming in binary numerical comparison judgments, although one cannot exclude that, in addition to semantic processing, lexical associations also contributed to the global quantity-priming effect.

A third way of reconciling the present data with past models of number processing, which was suggested to us by Marc Brysbaert (personal communication, July 1998), is to assume that even though there is a common semantic representation for Arabic and verbal numerals, the speed of its convergence varies with input notation. Specifically, one might suppose that a numeral initially activates a rather broad range of semantic quantities and that this distribution is progressively narrowed down until a sharp peak is reached. As noted above, this final activation gradient would explain why quantity priming occured in Experiment 1. Assuming that the convergence occurs faster for Arabic numerals than for verbal numerals, at the short prime duration used in Experiment 2, the quantity representation might be placed in an intermediate state in which the distribution is sharper for Arabic than for verbal primes. This would readily explain why the Arabic–Arabic condition is the one in which the largest quantity priming is found in Experiment 2A. Unfortunately, this hypothesis should also predict strong quantity priming in the Arabic–verbal condition and little or no quantity priming in the verbal–verbal and verbal–Arabic conditions of this experiment. The evidence on this point, though admittedly somewhat weak, suggests that the contrary holds.

A fourth and final possibility is to assume that the internal representation of numerical quantities may be activated in a graded rather than an all-or-none fashion and that its initial activation may vary with input notation. Figure 13 depicts a hypothetical functional architecture for the number comparison task on the basis of this idea. This model assumes that the quantity representation normally functions as an undissociated whole but can, under some experimental conditions, be broken down into smaller notation-specific subsystems. When a number is presented in a given notation, say as an Arabic digit, it initially activates only a fraction of the

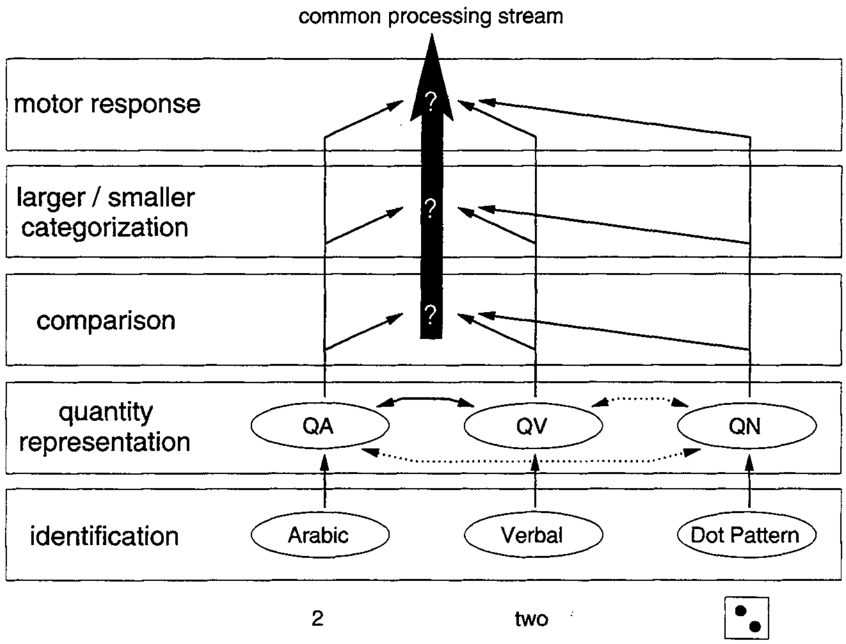

Figure 13. Tentative model of the levels of processing involved in the number comparison task and their interactions (see the text for further details). The quantity representation is tentatively separated into distinct subprocesses for representing the quantity of Arabic (QA) numerals, verbal (QV) numerals, and the numerosity (QN) of sets of objects. Quantity priming is supposed to occur at this level and may or may not transfer across notations depending on the speed of the lateral activations among QA, QV, and QN. Question marks indicate the various levels at which response priming may theoretically occur. A recent experiment suggests that the motor level is the locus of response priming (Dehaene et al., 1998).

quantity representation, namely the quantity subsystem devoted to Arabic inputs. Rapidly, the activation propagates to other quantity- and notation-specific subsystems. Eventually, the network falls down into a steady state of activity that represents numerical quantity independent of the notation that was initially used to activate it. However, the first stages of its activation depend on input notation.

This tentative model bears some similarity with Campbell and Clark's encoding-complex model (Campbell, 1994; Campbell & Clark, 1988, 1992). In both models, internal representations may be activated or interact in a graded fashion, although, in some conditions, they may behave like an undissociated whole. However, in contrast to Campbell and Clark's model, the present model does not assume that the differential activation of these internal representations of numerical quantity depends on the nature of the numerical task to be performed. Actually, it assumes that the representation of numerical quantity, which normally behaves as an undissociated whole as in Dehaene's (1992) triple-code model, may reveal, under extreme temporal conditions and independently of the numerical task to be performed, subtle differential activations depending on input format during the process of convergence toward a unified representation.

This model may explain why cross-notation priming is or is not obtained depending on the temporal conditions of the experiments. Quantity priming presumably occurs when the quantitative subsystem associated with the target has been activated by the prior presentation of the prime. When both the prime and the target are in the same notation, they always activate the same internal quantity subsystem, and hence quantity priming is predicted (provided that the prime has been accurately identified). When the prime and target are in different notations, however, the occurrence of cross-notation quantity priming will depend on the extent of the activation produced by the prime. If enough time is left for the prime to activate the entire quantity network, cross-notation priming is predicted. Such was the case in the double-comparison Experiment 1A with Arabic and verbal numerals. If, however, the prime is presented too briefly, only the corresponding notation-specific subsystem will have time to activate, and hence no cross-notation priming is predicted. This is presumably what occurred in the above masked-priming experiments.

In this framework, the propagation of activation need not occur with the same efficiency between all notation-specific subsystems. Indeed, the experimental evidence suggests that whereas the Arabic and verbal subsystems are tightly linked, the numerosity of dot patterns may be internally represented in a more autonomous fashion. As shown in Experiment 1, even when the prime is processed for a long period of time, no quantity priming is found between the Arabic and dot pattern notations. Obviously, participants can convert back and forth between Arabic digits and the numerosity of dot patterns. However, this conversion does not seem to be compulsory, at least in a number comparison task.

The tighter link between the Arabic and verbal subsystems may reflect the closer similarity of these two input formats—they are both lists of symbols—relative to dot patterns. Specific associations may exist between these two notational systems. For instance, associations between the lexical items coding for the Arabic digit 1 and the word ONE may enforce the two subsystems devoted to Arabic and verbal numerals to quickly converge to the same, common steady state, whereas the convergence would be slower and not compulsory for the Arabic digit 1 and the display of a single dot.

Convergence of Notation-Specific Processing Streams

Although the various input number notations may thus be processed in partially distinct streams, our data also provide unequivocal evidence for the convergence of these notation-specific processing streams at a later stage of the comparison process. In both masked-priming experiments, response priming was found both within and across notations. When the prime and the target fell on the same side of 5, and thus favored the same response (congruent trials), responses were faster than when the prime favored a different response than the target (incongruent trials). Comparison to a neutral case (prime = number 5) indicated that this effect was entirely due to inhibition on incongruent trials. Most important, this response-priming effect was clearly different from the quantity-priming effect in that it was significant even when the prime and target appeared in distinct notations (Arabic and verbal, or Arabic and dot pattern). This proves that distinct input notations eventually converge onto the same processing stream at some stage of the comparison process, beyond the quantity representation stage.

In theory, this convergence may occur at any of the levels shown in Figure 13. First, priming may arise from the motor level. The prime may go through the same stages as the target, all the way up to a final stage of motor preparation for the right or left hand. If the subsequent target requires a different motor response, this previous activation would have to be inhibited, resulting in a slowing down of reaction time. This hypothesis implies the strong and rather counter-intuitive prediction that a prime that is not consciously seen may nevertheless be processed through a series of visual, semantic, and motor preparation stages.

There are, however, at least two other prior stages at which response priming may occur. First, the input numbers may be categorized into those larger than 5 and those smaller than 5 at a level of processing more abstract than that of the motor preparation itself. For instance, suppose that the participants mentally label the input numbers with the words *larger* and *smaller.* Inhibition might then occur when the labels allocated to the prime and to the targets do not match. The second possibility is that the comparison process itself is common to all input number notations, although the quantity representation may not be. If a single-comparison process is used on both the prime and the target, it may begin to accumulate evidence in favor of, say, the larger side when the prime is presented and later have to counter this initial bias on incongruent trials.

In recent work, we have started using brain-imaging methods to disentangle these models of response priming (Dehaene et al., 1998). The results suggested that the motor-priming hypothesis is correct. We first showed that the response-priming effect could be replicated with an even shorter prime duration of 43 ms. As in Experiment 2A, we found complete transfer of response priming across Arabic and verbal notations. We then recorded covert response preparation signals from motor cortex, using either the temporal accurate method of event-related potentials or the spatially accurate method of event-related functional magnetic resonance imaging. Both methods revealed that motor activation was covertly influenced by the prime. The motor cortex that should have been active if participants were responding overtly to the prime was indeed transiently activated prior to the main overt target-induced motor activation. This provided direct evidence that, under stringent conditions of prime invisibility (Dehaene et al., 1998), numerical primes may nevertheless be processed according to arbitrary number comparison instructions, all the way down to a motor level of representation. In combination with the present results, these experiments indicate that the methodology of primed numbers is a promising new tool for clarifying the organization of the mental representations involved in number processing.

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