Encoding numbers: Behavioral evidence for processing-specific representations

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The aim of this study was to test the hypothesis of a complex encoding of numbers according to which each numerical processing requires a specific representational format for input. In three experiments, adult participants were given two numbers presented successively on screen through a self-presentation procedure after being asked to add, to subtract, or to compare them. We considered the self-presentation time of the first number as reflecting the complexity of the encoding for a given planned processing. In line with Dehaene's triple-code model, self-presentation times were longer for additions and subtractions than for comparisons with two-digit numbers but longer for subtractions than for additions and comparisons with one-digit numbers. The implications of these results for different theories of number processing are discussed.

A large part of our cognitive resources is allocated daily to number processing. Seldom does a day pass without one's having to read numbers, to perform calculations, or to retrieve numbers from memory. Counting, estimation, and comparison can also be added to this nonexhaustive list of activities that involve numbers. It has been suggested that the numbers we have to deal with differ not only in the format in which they are presented (e.g., number words, digits, patterns of dots on dice) or in the nature of the task in which they are involved, but also in the format of representation with which they are encoded and mentally manipulated. In the present study, to obtain behavioral evidence that humans use a variety of number representations, we tracked this variety in the very first steps of cognitive processing—the encoding stage.

Several theories have been advanced to account for this variety of number representations in humans. These theories differ mainly in how they conceive the cognitive architecture for number processing and the existence of notation-specific processes. McCloskey's (e.g., 1992) *abstract-modular* model assumes that numerical inputs of different forms (e.g., digits, number words) are converted by notation-specific comprehension modules into a common abstract format. This abstract quantity code provides the basis for any subsequent processing in pro-

duction or calculation modules. Thus, the amodal representation would constitute an unavoidable bottleneck in number processing (McCloskey, 1992; McCloskey, Caramazza, & Basili, 1985). By contrast, Campbell and Clark (1988; Clark & Campbell, 1991) proposed an *encoding complex* hypothesis, in which it is assumed (1) that number processing may be mediated by modality-specific processes rather than abstract codes, (2) that different surface forms can influence strategies, and (3) that a single numerical function can involve several codes. According to this model, number skills would be based on multiple forms of internal representations and could be realized in many ways. It is even suggested that these different ways in which number processing can be realized could vary as a function of cultural or idiosyncratic experience. According to this general hypothesis of a variety of codes for number processing, Noël and Seron (1993) proposed their *preferred entry code* model, which states that certain representations may be more suitable to certain tasks and, moreover, that individuals may prefer certain representations for idiosyncratic reasons.

The most specified and precise theory relying on the encoding complex hypothesis is probably Dehaene's *triple-code* model of number processing (1992, 1997, 2001; Dehaene & Cohen, 1995, 1997). According to this model, numerical information can be mentally manipulated in three different representation formats: an analogical quantity or magnitude code, a verbal code, and a visual Arabic code. Each activity involving numbers would rely on one of these specific codes (Dehaene & Cohen, 1997). Magnitude comparison would rely on an analogical representation of numbers or, in other words, a language-independent spatial representation of numbers on a mental line. The numbers'

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quantitative meaning would be retrieved and positioned on a left–right oriented mental number line without being transcoded into a verbal code. On the contrary, this transcoding would be necessary for the resolution of simple operations such as $7 + 2$. It is known that the frequent use of such operations allows children's number processing to evolve gradually, from a resolution via algorithmic computing to a direct retrieval of the answer from a network-like structure stored in long-term memory (Ashcraft & Battaglia, 1978; Ashcraft & Fierman, 1982; Ashcraft & Stazyk, 1981; Barrouillet & Fayol, 1998; Siegler, 1996; Siegler & Shrager, 1984). In Dehaene's model (Cohen & Dehaene, 2000; Dehaene & Cohen, 1997), the network-like organization for additions takes the form of tables stored as verbal associations ("seven plus two is nine") in an auditory verbal word frame. Whereas activities such as magnitude comparison or simple operation solving rely on a simple and direct transcoding (i.e., in an analogical format and in a verbal format for comparison and retrieval, respectively), multidigit number operations, such as the addition $37 + 22$, would require more complex processes and the coordination of several representational codes. According to Dehaene and Cohen (1995, 1997; Cohen & Dehaene, 2000), such problems are solved via the mental manipulation of a spatial image of the operation in the Arabic notation. The authors qualify this manipulation as a "semantic elaboration," because "it requires a good understanding of the quantities involved in the original problem" (Dehaene & Cohen, 1995, p. 102). Naturally, solving these problems requires a large amount of controlled attention to go carefully through a series of steps to reach the answer. Neuropsychological studies show indeed that the prefrontal areas of the brain that control nonautomatic activities are activated for such complex calculations (Roland & Friberg, 1985; Zago et al., 2001). Accordingly, we showed in a previous study that operand manipulations via mental decompositions are required in order to achieve complex calculations (Thevenot, Barrouillet, & Fayol, 2001). In our example, participants could decompose 37 and 22 into $30 + 7$ and $20 + 2$, respectively, add 20 to 30, temporarily store this intermediate result (50), then compute or retrieve $7 + 2$, and finally add 9 to 50. Therefore, in Dehaene's model, multidigit calculations involve the mental manipulation of spatial images of the operation in Arabic notation as well as verbal representations, which are necessary to retrieve intermediate results in long-term memory.

Although the triple-code model's conception of a variety of formats of representations for numbers is widespread, we have surprisingly little behavioral evidence underpinning this view. On the one hand, much evidence stems from brain-imaging studies or neuropsychological reports of selective impairments in brain-damaged patients. Indeed, patients who show impairments in one domain of competence relying on one of the three codes while other domains of competence remain largely intact constitute evidence for the triple-code model (Cohen & Dehaene, 1995, 1996, 2000, 2001; Dehaene, 1997; Dehaene & Cohen, 1991, 1997; Delazer & Benke, 1997; Seymour, Reuter-Lorenz, & Gazzaniga, 1994; Warrington, 1982). Further evidence

has been provided by brain-imaging studies that have made it possible to associate anatomical circuits with each node of the triple-code model (Dehaene, Spelke, Stanescu, Pinel, & Tsivkin, 1999; Dehaene et al., 1996; Plodowski, Swainson, Jackson, Rorden, & Jackson, 2003; Roland & Friberg, 1985). On the other hand, varieties in the format of representation are inferred from variations that affect complex treatments such as learning (Spelke & Tsivkin, 2001) or problem solving (Dehaene, Dupoux, & Mehler, 1990), but, Campbell (1999) has stressed, studies that address this problem more directly are rare. Moreover, Szűcs and Csépe (2004) have recently noted that a critical point in former studies investigating the effect of format of representation in arithmetic (Blankenberger & Vorberg, 1997; Campbell, 1994, 1999; Noël & Seron, 1997; Noël, Fias, & Brysbaert, 1997) is that "the effects of modality-specific coding . . . or amodal processes cannot be separated perfectly" (p. 21). The aim of the present study is to fill this gap by taking advantage of the known properties of encoding.

Although the encoding process has been described as unavoidable because attention to an object or event is sufficient to commit it to memory (Logan, 1988), it is clearly established that this encoding does not correspond to a simple mental snapshot. As Logan has suggested, the attributes of the stimulus are filtered by attention, and only those that are relevant to the task at hand are represented explicitly in the memory instance (Logan, Taylor, & Etherton, 1996). Thus, if the way in which a given stimulus is represented depends on the nature of the task, and if Dehaene is correct in assuming that there are a variety of representations of numbers related to specific uses and tasks, then the encoding of numbers should be systematically affected by the nature of the task in which these numbers are involved. More precisely, in the following experiments, we investigated the time required by participants in order to encode numbers of different sizes as a function of the subsequent activity (addition, subtraction, or comparison) for which these numbers were encoded and maintained. Our general prediction was that encoding a given number in view of a subsequent use would be faster when there existed a definite representational format into which the number could be coded that would permit a direct solution to the problem at hand. The encoding would take longer when such an appropriate representation could not be directly constructed, leading to complex coding processes. We tested this hypothesis in two experiments. The first was conducted using large two-digit numbers, whereas the second involved one-digit numbers. For both experiments, very clear predictions were drawn from Dehaene's hypothesis of a variety of representations.

EXPERIMENT 1A

Because it is highly improbable that additive and subtractive problems could be solved by direct retrieval of the answer from memory when they involve two-digit numbers (e.g., $45 + 23$), these numbers have to be manipulated mentally and understood, for example, as 4 tens and 5 units on the one hand and 2 tens and 3 units on the

other. Thus, a possible following step toward a solution would be to transcode 5 and 3 from their Arabic to their verbal form in order to retrieve the appropriate additive fact stored in verbal code. Because subjects must switch mentally between the two notations in the course of complex calculations, the encoding process would be complex and would involve at least two different codes (Dehaene, 1992). Thus, encoding large numbers with a view to complex calculations requires the coordination of at least the visuospatial Arabic and verbal codes because there is no possibility of directly representing the numbers in such a way that a solution can be reached directly. By contrast, according to the triple-code model, the comparison of a number with another is possible within an analogical code that permits one to reach an answer (Dehaene, 1997). Therefore, encoding a two-digit number for comparison with another number involves a simple coding and thus would take less time than would representing the same number in order to engage in the algorithmic procedures required by additions or subtractions.

To test this hypothesis, we measured the time that adult participants took to read and store numbers after being informed of their subsequent use. Participants were presented with series of three two-digit numbers that successively appeared on a computer screen. They were informed about the precise nature of the task that they had to perform by a word (*addition*, *subtraction*, or *comparison*) that appeared on screen before the first number. In the addition condition, the participants were asked to decide whether or not the third number presented was the sum of the two numbers previously displayed. In the subtraction condition, they had to decide whether this third number corresponded to the difference between the first two. Finally, in the comparison condition, they had to decide whether or not this third number fell between the two previous numbers. The three numbers were displayed using a self-presentation procedure. Once she or he had read a number, the participant pressed a key to make it disappear and display the next one. We assumed that the self-presentation time of the first number was indicative of the complexity of the sole encoding process, because no other processing could be applied before the presentation of the second number.

According to Dehaene's triple-code model, we expected shorter self-presentation times of the first number in the comparison than in the addition and subtraction conditions, with no difference in presentation times between the latter two conditions. Although the numbers in this experiment were presented sequentially instead of being displayed together as is usually the case when one is performing arithmetic operations, the complex encoding processes that we described above are needed to perform additions and subtractions with large numbers. Because there is no code through which the answers to additions or subtractions of large numbers can be reached directly, encoding those numbers necessarily requires their analysis in tens and units, probably using a visuospatial Arabic code as well as a verbal code to access stored arithmetic facts, possibly with additional analogical codes in view of

algorithmic computation if related arithmetic facts prove to be unavailable.

The other theories do not lead to these definite predictions. According to McCloskey's abstract-modular model, whatever the planned processing, the comprehension modules would convert the Arabic form displayed on screen into the same abstract format. This model does not therefore predict any differences in encoding time among the three experimental conditions. As for Campbell's encoding complex hypothesis, it would not necessarily predict equivalent durations of encoding among the three experimental conditions because different specific codes could be involved, depending on the subsequent use of numbers. However, even if it acknowledges possible differences, this model does not make precise predictions about the relative time course of the encoding processes in view of additions, subtractions, or comparisons. Nonetheless, this theory, like Noël and Seron's (1993) preferred entry code model, would account for important individual differences in encoding time patterns.

Method

Participants. Twenty-four undergraduate students from the Université de Bourgogne took part in this experiment as volunteers.

Materials and Procedure. In order to trigger a number encoding appropriate to complex calculation when participants were presented with the addition and subtraction conditions, the pairs of numbers were constructed to optimize the probability of an algorithmic solution. Thus, 32 pairs of numbers were chosen randomly in the set of 96 pairs that fit the following constraints: their addition (inferior to 70) always required a carry, their difference was always larger than 10, and none of the two operations (addition and subtraction) had an answer ending with a 0 (see the Appendix). Each of these 32 pairs of numbers was presented in the addition, subtraction, and comparison conditions, resulting in 96 experimental trials presented randomly. In the addition condition, the participants had to decide whether a third number corresponded to the sum of the first two, whereas in the subtraction condition, they had to decide whether this third number corresponded to the difference of the first two. Finally, in the comparison condition, the participants had to decide whether this third number fell between the two numbers previously presented. Half of the trial was associated with a third number eliciting a "yes" response (the sum of the two operands for additions, their difference for subtractions, and a random number lying between them for comparisons), whereas the remaining trials were associated with a third number eliciting a "no" response. For additions and subtractions, this number was constructed by adding or subtracting 1 to the correct answer. Indeed, we know that when the proposed answer is too distant from the correct answer, the participants are able to solve such a problem by approximation rather than by calculation (Ashcraft & Battaglia, 1978). For comparisons, this number corresponded in half of the cases to the smaller operand minus 1, and in the other half, to the larger plus 1. In order to familiarize the participants with the task, six training trials were presented, one in each condition, before the experimental trials: 3 (addition, subtraction, comparison) $\times$ 2 (eliciting a "yes" vs. a "no" response). The six pairs of numbers used for this training phase were different from the pairs used in the experimental phase and were drawn randomly from the set of 96 pairs of numbers described above.

The experiment was carried out on a Macintosh computer running PsyScope software. The stimuli were presented on the computer screen. Each trial began with a 1-sec presentation of a word that indicated the type of task (addition, subtraction, or comparison) that was replaced by the first two-digit number. By pressing a key on a button box, the participant removed this number from the screen and

displayed the second number and then the third one by pressing the same key again. When the third number was displayed, the participants were asked to give their answer (*yes* or *no*) by pressing one of two labeled keys on the button box. The “yes” response was required when the third number corresponded to the sum of the first two numbers or to their difference or fell between them, for the addition, the subtraction, and the comparison conditions, respectively. The task was presented as a mental arithmetic task; there was no mention of speed of responding when the participants read the operands; and the participants were not informed that the self-presentation time of the first operand was recorded by the computer.

Results

The rates of correct responses to the problems were particularly high (.914, .931, and .953 for additions, subtractions, and comparisons, respectively), providing evidence that the participants paid attention to the task and encoded the numbers properly.

Mean self-presentation times. The mean time of self-presentation of the first operands was calculated for each participant in each condition after having discarded the times that exceeded the individual mean by more than three standard deviations, a procedure that led to the rejection of 2% of the recorded times (Table 1). A one-way ANOVA performed on these mean times revealed a significant effect of tasks [$F_1(2,46) = 8.62$, $MS_e = 36,821$, $p < .001$, by participants, and $F_2(2,62) = 16.42$, $MS_e = 25,286$, $p < .001$, by items]. In line with our hypotheses, the presentation times were higher for additions and subtractions (1,446 and 1,490 msec, respectively) than for comparisons (1,273 msec) [$F_1(1,23) = 9.28$, $MS_e = 36,314$, $p < .01$, $F_2(1,31) = 19.90$, $MS_e = 23,948$, $p < .001$; and $F_1(1,23) = 13.28$, $MS_e = 42,646$, $p < .01$, $F_2(1,31) = 30.59$, $MS_e = 24,184$, $p < .001$, respectively], whereas the difference between subtractions and additions was not significant [$F_1 < 1$; $F_2(1,31) = 1.04$, $MS_e = 27,728$, $p = .32$].

Nonparametric analyses indicated that 17 participants out of the 24 had longer self-presentation times for additions than for comparisons ($p < .05$, binomial test), and that 20 participants had longer self-presentation times for subtractions than for comparisons ($p < .01$). By contrast, there was no tendency for faster self-presentation in additions than in subtractions (10 participants, $p = .271$). A total of 15 participants presented the entire expected pattern of longer self-presentation times for both additions and subtractions than for comparisons ($p < .001$). As far as items were concerned, the mean self-presentation time was longer in addition than in comparison for 23 numbers out of 32 ($p = .01$), and longer in subtractions than in

comparisons for 25 numbers out of 32 ($p < .01$), with no significant trend when additions and subtractions were compared ($p = .43$).

As far as the self-presentation times for the second and the third numbers are concerned, the results replicated those observed by Thevenot et al. (2001). Additions and subtractions that involved calculations elicited longer self-presentation times for the second number (3,144 and 3,175 msec, respectively) than did the comparisons that did not require algorithmic processes (1,525 msec). Moreover, the decision times related to the third number (i.e., the proposed answer to the problem) were roughly the same in the three conditions (1,518, 1,443, and 1,496 msec for additions, subtractions, and comparisons, respectively).

Discussion

In this first experiment, we inferred the time required by participants to encode a two-digit number involved either in a comparison or in a calculation (addition or subtraction) from its time of self-presentation. We hypothesized, on the basis of Dehaene's triple-code model, that this encoding would take longer in the case of complex calculations than in the case of comparison. Indeed, in the former situation, a complex coding would be required, whereas in the latter, a simple transcoding of the numbers into an analogical code would enable the task to be solved. The results confirmed this view. The time to encode a two-digit number that would be involved in a comparison was significantly shorter than the time to encode the same number in order to engage in an arithmetic mental algorithm. This encoding time did not significantly vary with the algorithmic procedure (addition or subtraction). These facts suggest that the encoding process goes far beyond the simple registration and maintenance of the Arabic form of the number presented on screen with a view to subsequent use. As the encoding complex hypothesis predicts, the encoding process is affected by the nature of the planned activity. Even before any task-related processing, the numbers are encoded right from the start in an adapted representation format in order to permit and optimize further treatments.

Before the implications of these results can be discussed, two alternative hypotheses should be discarded. First, it could be argued that the differences between comparisons on the one hand and additions and subtractions on the other are due not to processing-specific ways to encode numbers but merely to encoding strategies elicited by the particular setting that we used. For example, one could imagine that, in order to compare numbers,

Table 1
Mean Self-Presentation Times (in Milliseconds), With Standard Deviations, for the First Operand As a Function of Its Size and the Type of Task in Which It Was Involved

Number Size	Addition		Subtraction		Comparison	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Two digits (Exp. 1A)	1,446	594	1,490	618	1,273	470
One digit (Exp. 2)	915	324	1,019	426	943	348

participants use an approximate quantity representation of the stimulus, whereas to add or subtract numbers, an exact representation is necessary. An approximate quantity representation could suffice for comparisons, because the distance between the first two numbers and the third was sometimes quite large. Thus, the higher self-presentation times for additions and subtractions would be due to an additional cost of activating an exact representation. However, this hypothesis cannot account for our results, for at least two reasons. The first is that an exact representation was needed at least for comparisons in the “no” trials, in which the third number was very close to the first two numbers (the smaller number minus 1 or the larger plus 1). An approximate representation would have led to a high rate of errors, but the rate of correct responses to comparisons was particularly high (.953). Second, there is direct behavioral evidence about the quality of encoding. Indeed, Thevenot et al. (2001) used the same design and the same numbers to study the operands–answer associations in long-term memory that result from solving additions and subtractions. The authors compared operand recognition following addition and subtraction solving with recognition of the same numbers involved in a mere comparison. After having added, subtracted, or compared the numbers, participants were presented with a target number and had to decide whether this number was involved in the problem or not. The key point here is that the rate of correct recognition was higher after comparisons (.98) than after an addition (.88) or a subtraction (.92), discarding any possibility of an approximate quantity representation for comparisons. Interestingly, the authors observed that, exactly as in the present experiment, comparisons elicited shorter self-presentation times of the first number (1,298 msec) than additions and subtractions (1,549 msec in both operations). As a consequence, the shorter self-presentation times for comparisons cannot have resulted from the construction of a less exact representation of quantities.

Following the second alternative hypothesis, it could be argued that the difference observed in our first experiment was due not to differences in the encoding process per se, but to additional processes specific to calculation activities. For example, the longer presentation times for addition and subtraction might result from the preactivation of some knowledge involved in arithmetic operation solving. Specifically, in an equation verification task, Roussel, Fayol, and Barrouillet (2002) showed that resolution times are shorter when the “+” sign is presented at least 150 msec before the operands than when the sign and the operands are presented simultaneously. The authors concluded that the “+” sign has the effect of priming the additive procedure. The time reduction would indicate that the procedure was already activated when the numbers to be added were displayed. In our experiment, we could therefore assume that the larger self-presentation times of the first two-digit numbers in the addition and subtraction conditions did not result from differences in the encoding times but rather from the necessary activation of a procedure that was not required for the comparison task. To rule

out this alternative hypothesis, we carried out a control experiment in which the presentation time of the word that indicated the type of task (addition, subtraction, or comparison) was controlled by the participant. The logic behind this control experiment was to discriminate between the procedure activation time and the encoding time. This would be possible if we obtained an effect of the task on the self-presentation times of the words as well as on the self-presentation times of the first numbers. Indeed, if in this second experiment we obtained the same effects on the self-presentation times of the words as we had obtained on the self-presentation times of the first numbers in the previous experiment, then they would necessarily be caused by the activation of a procedure or more trivially by a mental preparation in view to a specific and/or difficult task. If the same effects were moreover obtained on the self-presentation times of the first numbers, it could not reasonably be concluded that they were still the result of a mental preparation. When participants control the presentation times of the words specifying the task to be achieved, longer self-presentation times of the first numbers in the addition and subtraction conditions than in the comparison condition would therefore be undoubtedly attributable to differences in the encoding times.

EXPERIMENT 1B

Method

Participants. Forty-three undergraduate students from the University of Sussex took part in this experiment as volunteers.

Materials and Procedure. The material and the procedure were the same as in Experiment 1A, except that in order to avoid any influence on the word lengths, the words that indicated the type of task (addition, subtraction, or comparison) were replaced by their first letters: “A” for addition, “S” for subtraction, and “C” for comparison. The participants were instructed that when the letter “A” preceded the series of numbers, they would have to decide whether a third number corresponded to the sum of the two first numbers. If the letter “S” appeared on the screen, they would have to decide whether this third number corresponded to their difference. Finally, when a “C” preceded the numbers, they would have to decide whether this third number fell between the two numbers previously presented. Unlike in the previous experiment, the presentation time of the letter was not fixed by the experimenter. Instead, the participant removed the letter from the screen and displayed the first number by pressing a key on a button box. The self-presentation times of both the letters and the first numbers were recorded by the computer.

The experiment was controlled by a version of the TSCOP software (Norris, 1984) and carried out on a PC-compatible computer fitted with an Advantech PCLabCard, which provided millisecond timing of responses made via buttons attached to the card.

Results

The rates of correct responses to the problems were particularly high (.919, .927, and .951 for additions, subtractions, and comparisons, respectively), providing evidence that participants paid attention to the task and properly encoded the numbers.

Mean self-presentation times of the letters specifying the task. The mean time of self-presentation of the letters specifying the task was calculated for each participant in each condition after having discarded the times

that exceeded the individual mean for more than three standard deviations, a procedure that led to the rejection of 2% of the recorded times (Table 2). A one-way ANOVA performed on these mean times revealed a significant effect of tasks [$F_1(2,84) = 14.05$, $MS_e = 24,209$, $p < .001$, and $F_2(1,62) = 18.24$, $MS_e = 13,853$, $p < .001$]. The presentation times were higher for additions and subtractions (936 and 1,048 msec, respectively) than for comparisons (872 msec) [$F_1(1,42) = 5.38$, $MS_e = 16,338$, $p < .02$, $F_1(1,42) = 19.58$, $MS_e = 33,929$, $p < .001$, respectively, by participants, and $F_2(1,31) = 6.08$, $MS_e = 10,709$, $p < .02$, $F_2(1,31) = 35.57$, $MS_e = 14,686$, $p < .001$, respectively, by items]. Moreover, the times were higher for subtractions than for additions [$F_1(1,42) = 12.02$, $MS_e = 22,360$, $p < .001$; $F_2(1,31) = 12.36$, $MS_e = 16,165$, $p < .001$].

Mean self-presentation times of the first operands.

The mean time of self-presentation of the first number was calculated for each participant in each condition after having discarded the times that exceeded the individual mean for more than three standard deviations, a procedure that led to the rejection of 2% of the recorded times (Table 2). A one-way ANOVA performed on these mean times revealed a significant effect of tasks [$F_1(2,84) = 29.40$, $MS_e = 33,249$, $p < .001$; $F_2(1,62) = 18.24$, $MS_e = 13,853$, $p < .001$]. The presentation times were higher for additions and subtractions (1,297 and 1,260 msec, respectively) than for comparisons (1,019 msec) [$F_1(1,42) = 40.24$, $MS_e = 41,212$, $p < .001$, $F_1(1,42) = 34.27$, $MS_e = 36,311$, $p < .001$, respectively, and $F_2(1,31) = 140.70$, $MS_e = 8,751$, $p < .001$, $F_2(1,31) = 76.71$, $MS_e = 12,084$, $p < .001$, respectively]. However, the difference between subtractions and additions was not significant [$F_1(1,42) = 1.34$, $MS_e = 22,225$, $p = .25$; $F_2(1,31) = 1.78$, $MS_e = 12,132$, $p = .19$].

As far as the self-presentation times of the second and the third numbers are concerned, the pattern of results was quite similar to that in Experiment 1A. Additions and subtractions that involved calculations elicited longer self-presentation times of the second number (3,996 and 3,785 msec, respectively) than did the comparisons that did not require algorithmic processes (1,164 msec). Moreover, the decision times related to the third number (i.e., the proposed answer to the problem) were roughly the same in the three conditions (1,175, 1,206, and 1,316 msec for additions, subtractions, and comparisons, respectively).

Discussion

The results of Experiment 1B allow us to confirm that the higher self-presentation times of first two-digit numbers involved in additions or subtractions as opposed to comparisons are due to differences in encoding times rather than due to other processes such as a mental preparation or, more specifically, to the activation of a specific procedure (Roussel et al., 2002). Indeed, by giving the participants the opportunity to control the presentation time of the letter that indicated the type of task in which the first number would be involved, we gave them the possibility to control the time required for their mental preparation. It appears in accordance with Roussel et al.

that the letters "A" and "S," which represented addition and subtraction, respectively, were presented longer than the letter "C," which represented comparison. Interestingly, the letter "S" was presented longer than the letter "A," which could suggest that the mental preparation required in order to solve a two-digit subtraction is more demanding than that required in order to solve a two-digit addition, but this point is beyond the scope of the present article. The key point here is that despite the differences observed in the presentation times of the letters indicating the type of task to be achieved, the same results as those in the previous experiment were obtained for the presentation times of the first two-digits: They were higher for additions and subtractions than for comparisons. Because it would be difficult to argue that the participants continually prepared themselves for the task, the higher presentation times clearly reflect differences in encoding times.

Yet it has to be noted that in Experiment 1B, the self-presentation times of the first operands were shorter than in Experiment 1A (i.e., -149, -230, and -253 msec for addition, subtraction, and comparison, respectively). It could therefore be concluded that in Experiment 1A, the self-presentation times of the first two-digit numbers constituted some portion of the time required for mental preparation. However, at least in the case of additions, the self-presentation time of the letter in Experiment 1B was also shorter than the 1-sec presentation time of the word in Experiment 1A, suggesting that the time allowed in Experiment 1A to read the operation was sufficient for mental preparation. The lower self-presentation times of the first numbers in Experiment 1B than in Experiment 1A might simply indicate that the self-controlled presentation of the letters allowed participants to be systematically ready to be presented with the first numbers.

Having discarded the possibility that the self-presentation times of the first numbers might reflect processes other than the encoding time, we conducted Experiment 2, using small instead of large numbers, which led to different predictions following the triple-code model.

EXPERIMENT 2

Unlike in Experiments 1A and 1B, the numbers that we used in this experiment did not exceed 10. In the previous experiments, we observed shorter encoding times of the first operands when they were later involved in an addition or a subtraction rather than in a comparison. Those results followed Dehaene's model, since multidigit calculations

Table 2
Mean Self-Presentation Times (in Milliseconds), With Standard Deviations, for the Letter Indicating the Task to Be Achieved and the First Operand As a Function of the Task in Experiment 1B

Stimuli	Addition		Subtraction		Comparison	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Letters	936	269	1,048	325	872	209
Two-digit numbers	1,297	417	1,260	408	1,019	356

are supposed to involve different formats of representation (i.e., at least verbal and Arabic formats), whereas magnitude comparisons rely on only a single format (i.e., analogical format). If the logic behind this argumentation is valid, then different results should be obtained when smaller numbers are involved.

As mentioned earlier, small additions are known to be solved by adults by direct retrieval of the answer from a network in long-term memory (Ashcraft & Battaglia, 1978; Ashcraft & Fierman, 1982; Ashcraft & Stazyk, 1981; Siegler & Shrager, 1984). In Dehaene's model (Cohen & Dehaene, 2000; Dehaene & Cohen, 1997), the network-like organization for additions takes the form of tables that are stored as verbal associations ("seven plus two is nine") in an auditory verbal word frame. The access to additive facts therefore requires a simple transcoding of the numbers in a verbal format. On the contrary, according to Dehaene and Cohen (1997; Cohen & Dehaene, 2000), subtraction problems are not commonly learned by rote and thus long-term memory does not contain subtractive arithmetic facts. As a consequence, exactly as multidigit operations, single-digit subtractions should require a complex encoding of the numbers or, in other words, the coordination of several representational codes. Indeed, because an algorithmic strategy is required in order to solve a simple subtraction, a more complex coding involving verbal labels as well as representations of the quantities to be manipulated has to be executed. Thus, and contrary to what the triple-code model predicted in the previous experiments, the same theory predicts that the encoding of small numbers would take longer when they are involved in subtractions rather than in additions. However, there would be no difference between addition and comparison conditions. Indeed, both treatments are permitted by appropriate representational formats that can be directly accessed, an analogical format for comparisons and a verbal format for additions.

As in Experiment 1A, and for the same reasons, McCloskey's abstract-modular model did not predict any differences in encoding time among the three experimental conditions. Although Campbell and Clark (1992) evoked "the hypothesis that arithmetic answers are represented as verbal-lexical codes" (p. 479), their encoding-complex view made no precise predictions about the relative time courses for encoding small numbers as a function of the task.

Method

Participants. Twenty-four undergraduate students from the Université de Bourgogne took part in this experiment as volunteers.

Materials and Procedure. The materials were constructed as in the previous experiments. The only difference concerned the pairs of digits used. In order to optimize the probability of a retrieval procedure in the case of addition, these pairs contained numbers strictly lower than 11 (see the Appendix). Owing to the rationale of the comparison task in which the third number either fell or did not fall between the first two, the difference between these two numbers was always higher than 1 and the number 0 was not used. Thirty-two pairs of numbers were chosen among the 36 possible pairs constructed, with the following constraints (i.e., 4 pairs constructed with the number 10 were removed from the pool). As in the previous experiments, each of the 32 pairs was presented in the addition, subtraction, and comparison conditions. In the addition and subtraction

conditions, the third number, on which the decision had to be made, corresponded in half of the cases to the sum or the difference of the operands. In the other half of the cases, this number corresponded to the correct answer ± 1 . Finally, in the comparison condition, half of the trials were associated with a third number lying between the first two numbers. As for the remaining trials, half of them corresponded to the smaller operand minus 1 and in the other half to the larger operand plus 1.

The procedure for the 96 experimental trials (32 pairs $\times$ 3 conditions) was the same as that in Experiment 1A. The participants were presented with six training trials before the experimental trials. The pairs of numbers used to construct these trials were drawn randomly from the list of 32 pairs used in the experimental phase. Indeed, it was impossible to use different pairs of numbers, considering the constraints to be respected (see the Appendix). The computer and software were the same as in Experiment 1A.

Results

As in the previous experiments, evidence for an accurate encoding of the first and second operands was provided by the high rates of correct responses to the problems (.956, .960, and .900 for additions, subtractions, and comparisons, respectively).

Mean self-presentation times. The mean time of self-presentation of the first operands was calculated for each participant in each condition after having discarded outliers using the same procedure as in Experiments 1A and 1B, leading to the same rate of rejected values (Table 1). A one-way ANOVA performed on the mean times revealed a main effect of tasks [$F_1(2,46) = 5.85$, $MS_e = 12,019$, $p < .01$; $F_2(2,62) = 6.76$, $MS_e = 14,094$, $p < .01$]. As we predicted, self-presentation times were longer for subtractions than for comparisons (1,019 and 943 msec, respectively) [$F_1(1,23) = 6.99$, $MS_e = 10,075$, $p < .05$; $F_2(1,31) = 5.71$, $MS_e = 17,172$, $p < .05$]. However, contrary to what we observed in Experiments 1A and 1B, self-presentation times were also longer for subtractions than for additions (915 msec) [$F_1(1,23) = 7.65$, $MS_e = 17,136$, $p < .05$; $F_2(1,31) = 12.23$, $MS_e = 14,410$, $p < .01$]. There was no significant difference between additions and comparisons [$F_1(1,23) = 1.05$, $MS_e = 8,848$, $p = .32$; $F_2(1,31) = 1.06$, $MS_e = 10,702$, $p = .31$].

Nonparametric analyses confirmed these results: 17 participants out of 24 considered the numbers for longer periods of time before subtractions than before comparisons ($p < .05$, binomial test), and 20 exhibited longer self-presentation times for subtractions than for additions ($p < .001$). Overall, 15 participants exhibited the expected pattern of longer self-presentation times before subtractions ($p < .001$). This expected pattern was observed on 18 out of 32 items ($p < .001$).

Concerning the self-presentation times of the second number, the three types of problems elicited short times of presentation (1,132, 1,186, and 1,172 msec for additions, subtractions, and comparisons, respectively). It is difficult to hypothesize what kind of processes underlay these times. Whereas the participants in Experiments 1A and 1B probably found it safer to engage in calculations as soon as they discovered the second number of additions and subtractions, the small numbers used in Experiment 2 were easier to maintain in short-term memory.

Thus, it is impossible to surmise what participants exactly did when processing this second number. Concerning the third number, the self-presentation times were higher for comparisons (1,188 msec) than for additions (954 msec) and subtractions (998 msec), which could suggest that it is more difficult to compare small numbers than to add or subtract them. It could have been due to the fact that small numbers are inherently close to each other and close number magnitude comparison is known to be a demanding activity (see, e.g., Moyer & Landauer, 1967).

Discussion

As already observed in Experiments 1A and 1B, we showed in Experiment 2 that the time required by participants to encode small numbers varies as a function of their subsequent use. However, the encoding of small numbers took longer for subtractions than for comparisons and for additions. This result lends strong support to the general encoding complex hypothesis and more precisely to the triple-code model, which assumes that additive number facts are readily available from long-term memory in mental tables but that there are no such tables for subtractions. Although the exact nature of the format in which additive facts are encoded cannot be inferred from our results, these results are compatible with the hypothesis of storage of additive facts in a verbal code. The triple-code theory assumes that comparisons require one to transcode the numbers presented in their Arabic form into an analogical format. Thus, the encoding for comparisons would require some time-consuming transcoding from the Arabic format of presentation. The fact that there was no significant difference in self-presentation times between the comparison and addition conditions suggests that such a transcoding is also required for additions, possibly from the Arabic form of presentation to a verbal code. The longer self-presentation times observed with subtractions suggest that the latter operations require more complex encoding processes and that there is no code in which the answer would be directly available.

GENERAL DISCUSSION

The aim of the present study was to provide behavioral evidence that the way in which numbers are encoded depends on the task in which they are involved, with some tasks requiring more complex encoding than others. We proposed that one could infer the existence of such different levels of complexity from the time that participants required in order to encode a number that was involved in an addition, a subtraction, or a comparison. We hypothesized that this time would be shorter when there was a representation code in which the number could be encoded and that allowed participants to reach an answer directly. Dehaene's triple-code model describes such codes in which numbers can be represented and processed. This theory assumes that the comparison activities would rely on an analogical code but that number facts would be stored in a verbal code (Cohen & Dehaene, 2000; Dehaene & Cohen, 1997). By contrast, algorithmic procedures would require

more complex representations as participants mentally manipulate the quantities to which the numbers refer and keep track of intermediary results. As a consequence, we hypothesized that adding and subtracting large numbers would require complex representations and thus longer encoding processes than would comparisons, the latter being made possible by a single coding through readily accessible analogical representations. However, adding small numbers would lead to faster number encoding than would subtracting them, because additive answers can be directly retrieved through a verbal format whereas subtractions more often require algorithmic computing (Campbell & Xue, 2001; Cohen & Dehaene, 2000; Dehaene & Cohen, 1997; Seyler, Kirk, & Ashcraft, 2003) and thus a more complex coding involving verbal labels as well as representations of the quantities to be manipulated. The results confirmed that the time required by participants to encode numbers varies as a function of their expected use. In other words, numbers are transcoded into the task-relevant representation in preparation for task execution. Moreover, even if our results do not permit one to infer any specific format of representation, the overall pattern of differences fit the predictions issuing from Dehaene's triple-code model perfectly.

These results, which confirm the encoding complex hypothesis, seem to be at odds with McCloskey's model, which assumes that all numerical inputs are translated into an amodal and abstract representation of quantities (McCloskey, 1992; McCloskey & Caramazza, 1987). Such a model would not predict any variation in encoding time from one condition to another in our experiments. In each condition, the same Arabic form of presentation would have to be transcoded in the same amodal format of representation. Of course, it could be assumed that the differences that we observed resulted from some postencoding subsequent processes that could take place during the presentation of the first number, such as some kind of preactivation of the appropriate calculation procedures. It is possible that such processes would take longer for additions and subtractions than for comparisons, for example. However, these task-related processes, insofar as they did occur, would more probably have been triggered by the word indicating the nature of the task to be performed rather than the first number that appeared 1 sec later: Experiment 1B confirmed this interpretation. Therefore, time of presentation of the first operand could not reflect the activation of this procedure and could only reflect the time required for its encoding. Thus, it seems difficult to reconcile McCloskey's semantic models with our results, which are more in line with the general encoding complex hypothesis.

However, the latter hypothesis can underpin different theoretical proposals. For example, we have seen that Dehaene's triple-code model assumes that each numerical processing requires a specific numerical format for input. By contrast, other models that share the hypothesis of different representation codes for numbers are less constrained and admit that the combination of specific codes and functions can vary from individual to individual, leaving room for idiosyncratic variability. This is

the case of Noël and Seron's (1993) preferred entry code hypothesis or Campbell and Clark's (1988, 1992) encoding complex model, which assumes that the strength of specific code-function combinations can depend on an individual's idiosyncratic learning history and strategies. Is such variability reflected in our results?

Although the analyses based on central tendencies confirmed the predictions issued from the triple-code model, the nonparametric analyses revealed that some participants did not exactly conform to the predicted pattern. In Experiment 1A, a majority of participants conformed to the expected pattern of longer self-presentation times for additions and subtractions than for comparisons, but there were 2 participants who strongly diverged from it. Both exhibited significantly longer self-presentation times for subtractions than for additions and no difference between additions and comparisons. This pattern suggests that the first operand of the additions was stored in an Arabic format of presentation without any decomposition or semantic analysis. Such encoding could reflect adaptive idiosyncratic strategies. For example, postponing the semantic analysis of the first operand can allow participants to modulate this analysis and to choose the most appropriate decomposition according to the characteristics of the second operand. For example, when one adds either 15 or 12 to 29, it could be found more convenient to decompose 29 into 25 and 4 in the first case but into 20 and 9 in the second case. However, such a strategy requires one to wait for the second operand before any decomposition. In Experiment 2, in which small numbers were presented, most of the participants had longer self-presentation times for subtractions than for additions and comparisons. However, 1 participant exhibited the pattern usually observed with large numbers—that is, significantly longer self-presentation times for additions than for comparisons, with no difference between additions and subtractions. In this case, it could be assumed that this participant favored algorithmic strategies for solving both operations and thus encoded the numbers in the same way.

Thus, our results revealed some idiosyncratic variability. However, these divergent cases were rare and insufficient to negate the predicted effects. Moreover, these divergent cases can be explained, as we have seen, by individual differences in strategy choice that do not necessarily involve individual differences in the way numbers are encoded for a given subsequent process. For example, equivalent presentation times for additions and subtractions of small numbers in some participants are not at odds with Dehaene's model if these participants do not rely on the retrieval of arithmetic facts to solve additions and use algorithmic procedures for both types of operation. At the very least, our results suggest that individuals encode numbers in a goal-directed way, with the time required by the encoding process depending on both the planned use of these numbers and the available knowledge about number facts. We can surmise that this adapted encoding aims at allowing an optimal subsequent use of the numbers by means of the appropriate procedures. Among

the theories that endorse this encoding complex hypothesis, Dehaene's triple-code model proved to be the most heuristic and predictive.

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APPENDIX
List of the 32 Pairs of Numbers Used and Associated Answers

	Experiments 1A and 1B					Experiment 2				
	N1	N2	Answer			N1	N2	Answer		
			Add.	Sub.	Comp.			Add.	Sub.	Comp.
"Correct" trials	28	14	42	14	21	3	1	4	2	2
	29	15	44	14	20	5	2	7	3	3
	33	18	51	15	29	5	3	8	2	4
	33	19	52	14	24	6	2	8	4	4
	34	17	51	17	25	6	3	9	3	4
	36	15	51	21	26	6	4	10	2	5
	37	15	52	22	19	7	5	12	2	6
	38	15	53	23	22	8	1	9	7	4
	38	16	54	22	28	8	4	12	4	6
	38	25	63	13	32	8	5	13	3	6
	39	26	65	13	31	9	1	10	8	5
	39	27	66	12	30	9	2	11	7	6
	45	19	64	26	33	9	5	14	4	7
	47	15	62	32	23	10	2	12	8	5
	48	14	62	34	35	10	3	13	7	8
	48	19	67	29	41	10	4	14	6	7
"Incorrect" trials	27	14	42	14	28	4	1	4	2	0
	29	12	42	18	30	4	2	5	1	1
	29	16	44	12	15	5	1	7	5	6
	29	18	46	10	17	6	1	8	6	7
	32	19	60	12	18	7	1	7	5	0
	37	14	52	24	38	7	2	8	4	1
	38	13	50	24	12	7	3	9	3	2
	38	14	53	25	39	7	4	10	2	3
	38	24	61	13	23	8	2	11	7	9
	38	27	64	10	26	8	3	12	6	9
	39	15	55	25	40	8	6	15	3	9
	46	18	63	27	17	9	3	13	7	10
	47	18	66	30	48	9	4	12	4	3
	49	13	63	37	50	9	6	16	4	10
	49	17	65	31	16	9	7	17	3	10
	49	18	68	32	50	10	1	10	8	0

Note—For comparisons, *answer* refers to the third number presented, the participants being asked whether or not this answer fell between N1 and N2.

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