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Verbal structure of numerals and digits handwriting: New evidence from kinematics

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Two experiments used a digitizing tablet to analyse the temporal, spatial, and kinematic characteristics of handwritten production of arabic numbers. They addressed a specific issue of the numerical domain: Does the lexical and syntactic structure of verbal numerals influence the production of arabic numerals (Experiments 1 and 2), even after enforced semantic processing in a comparison task (Experiment 2)? Subjects had to write multi–digit arabic numerals (e.g., 1200) presented in two different verbal structures: a multiplicative one (e.g., teen-hundred, *douze cents* (twelve hundred)) or an additive one (e.g., thousand-unit-hundred, *mille deux cents* (one thousand two hundred)). Results show differences in the inter-digit jumps that reflect the influence of the structure of verbal numerals, even after the semantic task. This finding is discussed with regard to different models of number transcoding (McCloskey, Caramazza, & Basili, 1985; Power & Dal Martello, 1990, 1997).

Numbers can be expressed by verbal numerals in a spoken or written form (e.g., fourteen) and by arabic numerals (digit strings, e.g., *14*). Besides being used for written calculation, arabic numerals are generally preferred for writing dates, prices, phone numbers, and so on, in written texts. Although there exists a long tradition of research on language writing, studies devoted to the production of arabic numerals remain very scarce. The experiments reported in this paper contribute to the development of this neglected area of research. Through the analysis of parameters related to the spatial, temporal, and kinematic characteristics of

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handwritten production of digits, we examined the production of arabic numerals in the specific case of transcoding—that is, upon the presentation of a verbal numeral. This situation offers the opportunity to test the way that verbal and arabic systems are likely to interact with each other or not. More specifically, we focused on complex numerals, which are assumed to require syntactic decomposition and composition mechanisms at the comprehension and production levels, respectively. Apart from one and two-digit numbers, which might be retrieved from lexicon as a whole,[1] arabic numerals indeed require a syntactic planification step, and we examined here whether it is influenced by the verbal structure of the presented numeral, either in a direct transcoding task or after a semantic task (i.e., comparison of two numbers).

Whereas all current cognitive models on number transcoding propose a distinction between lexical and syntactic mechanisms (the former allowing comprehension or production of isolated elements, words or digits; the latter allowing comprehension or production of the relationships between the elements and thus complex numbers), they disagree as to whether transcoding passes along asemantic (Deloche & Seron, 1982a, b; 1987), semantic (McCloskey, Caramazza, & Basili, 1985; Power & Dal Martello, 1990, 1997; Power & Longuet-Higgins, 1978), or multiple routes (Cipolotti, 1995; Cipolotti & Butterworth, 1995; Cohen, Dehaene, & Verstichel, 1994). The neuropsychological data have not been able to decide definitively between these alternative models (for a review, see Seron & Noël, 1995). Indeed, compelling evidence for asemantic transcoding would be a patient who cannot access semantics or perform semantic tasks while still writing correctly arabic numerals from verbal numerals. Such a patient has not yet been reported.

Asemantic or multiple routes models are insufficiently detailed and do not specify the mechanisms involved in the production of arabic numerals, nor do they directly address this question. In fact, only two models provide such a description, and both propose that the nature of representations used to trigger production mechanisms is semantic: *the semantic-base-10 model* (McCloskey, 1992; McCloskey & Caramazza, 1987; McCloskey et al., 1985; McCloskey, Sokol, Goodman-Schulman, & Caramazza, 1990) and the *semantic-verbal model* (Power & Dal Martello, 1990, 1997). We briefly describe here their main aspects regarding the writing of arabic numerals.

According to a very influential theory of the number-processing system (the semantic-base-10 model), verbal and arabic production processes in no way influence each other. This model posits several functional components of number processing (see Figure 1). At a general level, it distinguishes between mechanisms for number comprehension and those for number production. Within each of these systems, a further distinction is made between notation-specific modules: Lexical and syntactic mechanisms are different for processing arabic or verbal numerals. The comprehension mechanisms translate an entry form (arabic or verbal) into its semantic representation, and the production mechanisms convert this semantic representation into the target output code.

This model thus presents three main characteristics: (1) a complete separation between comprehension and production processes; (2) a complete separation between verbal and arabic

[1] In a multiplication task, Noel, Brysbaert, and Fias (1997) found that the activation of a decade–unit structure in the output phonological buffer does not lead to the independent activation of decade and unit names, but rather to a combined decade–unit structure. Thus, small and frequent numbers, like two-digit numbers, may be represented as a whole, without decomposition.

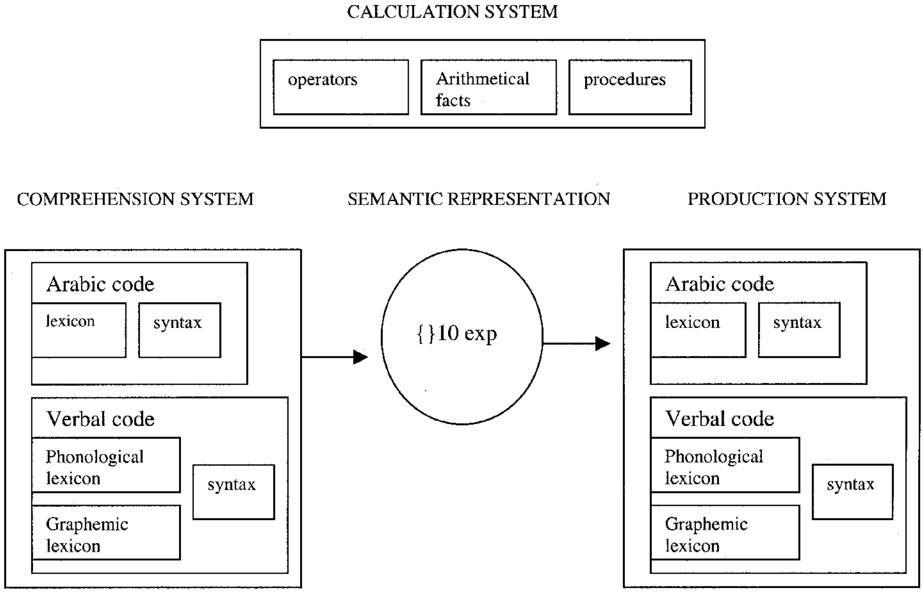

Figure 1. Semantic-base-10 model of McCloskey, Caramazza, and Basili (1985).

codes processing; and (3) a semantic bottleneck component between the comprehension and the production systems. The semantic representation is assumed to be abstract and code-independent (i.e., the semantic representation of a verbal numeral, say, "two hundred and sixty-five", and of its arabic counterpart, "265", is the same). Furthermore, it is considered to capture the base-ten organization of our numerical system, as it specifies the basic quantities in a number with the power of ten associated with each. A numeral such as "two hundred and sixty-five" or "265" is thus represented by the semantic formula "{2}10exp2; {6}10exp1; {5}10exp0". This representation activates syntactic and lexical production mechanisms. In the first step of the arabic production process, the highest power of ten of the semantic formula is identified, and on this basis a syntactic frame of the appropriate size is generated. For instance, this frame specifies that for a number in which 10exp2 is the highest power of ten, the arabic form will be a sequence of three digits: [- - -]. Each basic quantity in the semantic representation is then assigned to the appropriate slot in the frame[2] [{2} {6} {5}]. This filled frame constitutes a plan for the production of the sequence of digits, as it specifies the arabic representations (i.e., the digits) that are to be retrieved from the arabic production lexicon, as well as their position in the sequence [265] (McCloskey, 1992; McCloskey et al., 1985).

We would like to underline one of the main aspects of this model, as it has consequences on the transcoding processes: The semantic base-10 representation logically implies that the peculiarities of the verbal stimulus presented do not exert any influence on the arabic production mechanisms.

[2]As the abstract semantic representation does not include a representation for {0}, the corresponding slot is not filled in the frame, and an empty slot indicates that the digit 0 has to be retrieved.

The semantic-verbal model (Power & Dal Martello, 1990; 1997) also distinguishes between comprehension, production, and semantic processes. The main difference with the semantic-base-10 model lies in the nature of the semantic representations that are assumed to guide arabic production. In the present conception they are also abstract, but their internal structure is tied to the verbal code. For instance, “two hundred and sixty-five” would be represented by the corresponding primitive numerical concepts (noted by “C”) and their additive and multiplicative relationships, thus by: “⟨C2 × C100⟩ + ⟨C60 + C5⟩>”.[3]

The arabic production mechanisms require the application of different rules activated by the additive and multiplicative semantic relationships. When the primitive concepts are in a sum relationship, an overwriting operator (symbolized by “#”) is requested: “one hundred and two”, represented by “⟨C100⟩ + ⟨C2⟩”, activates the overwriting operator “100 # 2” in order to produce the final output form “102”. This rule thus requires zero(s) to be deleted from the right of the sequence and replaced by the digits corresponding to the added unit (or teen, or decade). When numerical concepts are in a product relationship, a concatenation operator (symbolized by “&”) is activated. Thus, “two hundred” would be represented by “⟨C2⟩ × ⟨C100⟩, and the multiplicative relationship activates the concatenation operator: “2 & 00” to produce “200”. This operator specifies that zeros have to be added to the right of the digit standing for the multiplying unit (or teen, or decade): Two zeros in the case of “hundred”, three zeros in the case of “thousand”, and so on.

At first sight, these two models seem very similar as both posit comprehension and production mechanisms and a central semantic representation. What distinguishes them is that only the semantic-verbal model predicts an influence of the verbal structure of numerals on the arabic numeral production rules.

Converging data seem to favour the psychological pertinence of this last proposition, and, more specifically, they show the relative difficulty of the overwriting rule. In the neuropsychology field, the patient L.R., described by Noël and Seron (1995), showed an influence of the syntactic structure of the verbal numeral on the nature of errors in writing arabic numbers. He wrote correctly the arabic numeral “1200” when presented with a spoken numeral with a multiplicative structure (*twelve hundred*: 12 × 100), whereas he erred in writing the same four digits when the presented numeral was an additive structure (*one thousand two hundred*: 1000 + 200); in this case, he produced a syntactic error like “1000200”. The authors interpreted this pattern of errors within the framework of the semantic-verbal conception, as reflecting a deficit in the application of the overwriting rule in the case of “thousand” in an additive relationship. The patient D.M. studied by Cipolotti, Butterworth, and Warrington (1994) showed the same difficulty with the overwriting rule: All his errors consisted in inserting zeros at places corresponding to the additive relationship with thousand. Recently, the patient R.R. produced the same kind of errors—that is, insertions of zeros, when producing arabic numerals upon the presentation of a written verbal code (Macoir, Audet, & Breton, 1999). Delazer and Denes' study (1998) showed the parallel between neuropsychological

[3]Let us note that in the 1990 conception, teens (eleven to nineteen) and tens (twenty to ninety) are not represented as lexical primitives : <<Twenty>> is represented by C2 × C10, and is thus very similar to the base-10 representation ({2} 10 exp2). This assumption differs in their 1997 conception, where the primitive numerical concepts include the units, teens, and tens. We consider this last conception and thus assume that <<twenty>> is represented by C20, or <<fourteen>> by C14 (“C” standing for “primitive numerical concept”).

recovery and developmental acquisition of arabic script. They examined a patient, C.K., who also produced syntactic errors when writing arabic numerals, and who recovered over the three testing sessions. Her evolution showed at the beginning that she used a misleading rule consisting of writing all digits different from zero on the left, and all zeros on the right. During the second session, the errors reflected the verbal number form, as they consisted of lexicalization (i.e., insertion of zeros at places of additive relationships) due to a lack of the overwriting rule. At the third session, she had almost completely recovered. Like children, she mastered the product relationship (i.e., UH, *two hundred*) before the sum relationship (i.e., HU, *one hundred- and six*; HD, *one hundred and sixty*; HT, *one hundred and sixteen*) (Power & Dal Martello, 1990; Seron, Deloche, & Noel, 1991; Seron & Fayol, 1994), showing the difficulty in correctly applying the overwriting rule compared to the concatenation one. Within sum relations, developmental data have also shown that children first master the HU forms (106), and apply the same "rule" to HD (one hundred and sixty, 1060) or HT (one hundred and sixteen, 1016) forms (Seron & Fayol, 1994). Contrary to children, C.K. showed no gradual recovery of the sum relationships with hundred, all of them being wrong during the second session, but correct during the third.

In the present study, Experiment 1 looks for further evidence for the semantic-verbal model and the difficulty of the overwriting operation in normal adult subjects, by studying the kinematics of handwriting identical series of digits produced upon the presentation of different verbal forms.

EXPERIMENT 1

Specific cases of some verbal numeral systems allow examination of the production of identical arabic numbers corresponding to different verbal structures: In French, the quantities between 1100 and 1999 may correspond to two types of verbal structures (in Dutch or in English, the same is also true for quantities above 2000). For instance, the arabic numeral 1200 may correspond to *one thousand two hundred* (*mille deux cents* in French) or to twelve hundred (*douze cents* in French). The first expression will be referred to as a ThUH structure (Thousand–Unit–Hundred), and the second as a TH structure (Teen–Hundred). Within the semantic-base-10 model, the two types of stimulus should eventually generate the same semantic representation, which should thus activate the same production procedures (see Figure 2). Even if lexical-semantic representations are not excluded at the verbal comprehension or production levels (McCloskey & Macaruso, 1995), these intermediary representations should not influence the arabic production process as it takes place solely on the basis of the semantic-base-10 representation. In contrast, within the semantic-verbal conception, it is assumed that numerals presented as TH and ThUH should lead to the construction of two distinct semantic structures, which, in turn, should trigger distinct production rules in order to construct the arabic numeral (see Figure 2).

We based the present empirical test on the assumption that the distribution of inter-digit jumps in the arabic numeral output (i.e., the jump above the paper or connection stroke between two digits) could reflect the characteristics of the representations and operations involved in the processes underlying the production of arabic numerals. We derived this assumption from a number of results obtained in the study of the kinematics of handwriting words or sentences. Parameters such as movement time, writing size, writing fluency, and pen

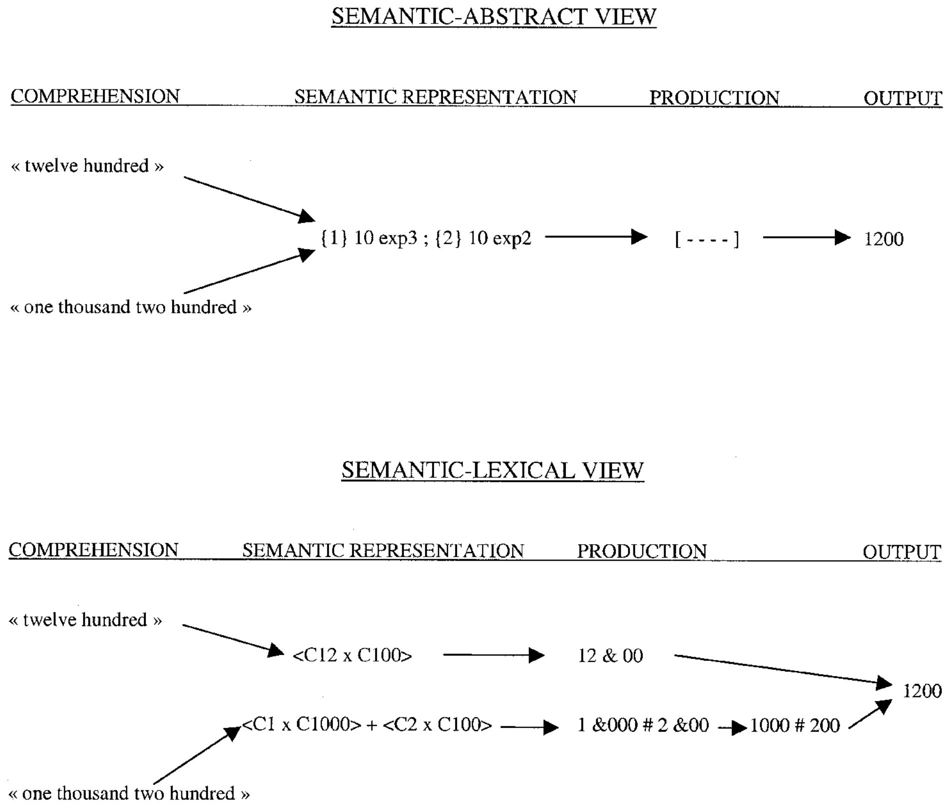

Figure 2. Predictions of the semantic-base-10 and of the semantic-verbal models for the processing of the two verbal forms contrasted.

pressure have been shown to vary not only with biomechanical conditions of a trajectory, but also with cognitive and motor demands (Schomaker & van Galen, 1996; Van der Plaats & van Galen, 1990; van Galen, 1991; Van Gemmert & van Galen, 1997). Studies on the kinematics of handwritten production of words showed that variables assumed to be related to different levels of the production process, such as the lexical status of words or trigrams (Zesiger, 1995; Zesiger, Hauert, & Mounoud, 1993), the spelling uncertainty (Orliaguet & Boë, 1993), the word length and the serial position of letters within the word (van Galen, Meulenbroek, & Hylkema, 1986), the stroke and letter repetition (van Galen, Smyth, Meulenbroek, & Hylkema, 1989), and the syllable repetition (van Galen, 1990), influenced the dynamic production of handwriting in terms of various parameters (movement duration, writing trajectory, velocity, dysfluency), at a point in time in advance of the real–time production of the corresponding segment.

We further reasoned that inter-digit jumps in arabic numeral writing output should be longer at places corresponding to increased difficulty in composition operations, that is in the Power and Dal Martello (1990, 1997) model, to the application of overwriting rules. First, when comparing identical arabic numerals corresponding to TH or ThUH types, we expected the first inter-digit jump (1_XXX) to be longer in the ThUH than in the TH forms, as there is

	Processes in transcoding TH forms	Processes in transcoding ThUH forms
Input	"Twelve hundred and forty eight"	"One thousand two hundred and forty eight"
Lexical-semantic level	<C12 x C100> + <C40 + C8>	<C1000 > + (<C2> x <C100> + <C40 + C8>)
Production rules	(12 & 00) # (40 # 8)	1000 # ((2&00) # (40 # 8))
	1200 # 48	1000 # (200 # 48)
		1000 # 248
Output	1248	1248

Figure 3. Processes in transcoding Teen–Hundred (TH) and Thousand–Unit–Hundred (ThUH) forms in the semantic-verbal perspective.

an overwriting operation located between the first and second digit in the former case (see Figure 3), whereas the first two digits correspond to a lexical primitive in the latter. Second, when contrasting forms containing, or not, an additive relationship in their final structures—that is, forms with a decade–unit in an additive relationship (e.g., *twelve hundred and forty-eight* or *one thousand two hundred and forty-eight*: 12*48*, –DU hereafter),[4] or forms that end after the word "hundred" in a multiplication relationship (e.g., *twelve hundred* or *one thousand two hundred*: 12*00*, –00 hereafter)—we expected the second inter-digit jump (1X_XX) to be longer in the former case as a decade–unit structure has to be overwritten on the initially programmed zeros, whereas in the latter case the double zeros are programmed by a concatenation operation (see Figure 3).

In contrast, according to McCloskey's model (McCloskey et al., 1985), neither the type nor the final structures of a presented verbal numeral should have an effect on the production process of arabic numerals, and thus, according to our assumptions, they should lead to similar dynamics of handwriting across conditions.

As inter-digit jumps might also reflect motor programming, we had to introduce some control conditions. In the handwriting of letters, it was found that the repetition of the same pattern, such as in the case of double letters, had an impact on the handwriting movement of the letter that precedes the doubling of a consonant (Portier, van Galen, & Thomassen, 1993; van Galen et al., 1989): Its velocity is slower and it contains more dysfluencies. Furthermore, inter-digit jumps might also vary according to the grapho-motor complexity of the to-be-written digits. For instance, it was shown that the starting jump (preceding the initiation of the writing gesture) had a longer trajectory if the first letter was more complex—that is, with more similar strokes (*m* vs. *p*, Van der Plaats & van Galen, 1990). With regard to the complexity of digits, we have shown in another study (Lochy, Zesiger, & Seron, in press) that the digit zero was the fastest to be produced and thus the easiest grapho-motor pattern amongst digits. Therefore, when comparing the handwriting of different final structures, three factors might be confounded. The inter-digit jump preceding the –00 final structures might be *shorter* than the –DU structures because (1) the transcoding process is less demanding, and also because (2) the pattern of the digit zero is the easiest to programme, whereas (3) the doubling of the pattern could *lengthen* this same inter-digit jump. In order to control for a possible motor effect of the doubling of zeros in –00 forms, we introduced –DU forms consisting of two similar digits (–DUs)

[4] Standing for decade–unit, as teens and tens begin with the same letter.

close in complexity to zero (e.g., *sixty-six*: 66). Furthermore, in order to test what could be due solely to motor effects, we presented control stimuli that isolated the motor aspects of the handwriting of digits by removing any possible influence of the syntax of the verbal form. They consisted of the same sequence of digits as in the TH and ThUH forms, but the verbal input form contained no syntactic structure—that is, it consisted of four unit-words that we will call hereafter "*no-syntax forms*" (NS, e.g., *one two six six*, corresponding to *twelve hundred and sixty-six*, and to *one thousand two hundred and sixty-six* for the arabic sequence, *1266*).

Method

Participants

A total of 12 right-handed, French-speaking volunteers (6 females, 6 males) at the Catholic University of Louvain participated in this experiment. Their mean age was 27 years 8 months (range 22–52 years).

Material

Productions were recorded by means of a digitizing tablet (WACOM–UD, sampling frequency 200 Hz, spatial accuracy 0.12 mm) monitored by a PC.

Stimuli

The first part of the experiment consisted of the NS forms—that is, subjects had to write arabic numerals presented verbally as four unit-words. These NS forms were presented in the written verbal format and embodied three different final structures, with six items for each structure. These final structures corresponded to double zeros (–00, e.g., *one three zero zero*), same digits (–DUs, e.g., *one three two two*), or different digits (–DUd, e.g., *one three four six*). The 18 trials were presented four times in four different blocks, for a total of 72 experimental trials. They were mixed with filler items of three (12 items), four (12 items), or five digits (24 items). Each block thus contained 30 items: 18 experimental and 12 fillers.

The second part of the experiment consisted of syntactic experimental forms ($n = 36$), also presented in the written verbal format (see Table 1): Half of them were TH (e.g., *twelve hundred*); the other half were ThUH (e.g., *one thousand two hundred*). Each type involved three different final structures: six double zeros (–00, e.g., *thirteen hundred vs. one thousand three hundred*, *1300*), six decade–unit with different digits (–DUd, e.g., *thirteen hundred and forty-seven vs. one thousand three hundred and forty-seven*, *1347*), and six decade–unit with the same digits (–DUs, e.g., *thirteen hundred and sixty-six* vs. *one thousand three hundred and sixty-six*, *1366*).

The 36 experimental forms were mixed with 72 filler items, consisting of 18 three–digit numbers (6 HU, 6 HD, 6 UHDU), 18 four–digit numbers (6 ThH, 6TD, 6 ThUHUDU), and 36 five–digit numbers (6 TThU, 6 TThD, 6 DThU, 6 DThD, 6 DUThU, 6 DUThD). All the stimuli were presented four times in consecutive blocks, each block thus comprising 54 items. In each block, trials were presented in a different fixed order, to avoid repeating the same arabic sequence successively. These four blocks were presented in one of two order lists counterbalanced across participants. There was thus a total of 216 items, among which 144 were experimental.

Procedure

Stimuli were displayed in the centre of a computer screen (Dell Ultrascan 17FS–LR), 80–90 cm from the participant, who was asked first to read aloud the numeral and then to write it down in arabic form. This procedure was chosen in order to ensure that the whole written sequence had been read before

TABLE 1
Stimuli of Experiment 1

Final structures	*Arabic numeral production*	*Verbal forms presented*		
		TH	*ThUH*	*NS*
–00	1200	Douze cents	Mille deux cents	Un deux zéro zéro
	1300	Treize cents	Mille trois cents	Un trois zéro zéro
	1400	Quatorze cents	Mille quatre cents	Un quatre zéro zéro
	1500	Quinze cents	Mille cinq cents	Un cinq zéro zéro
	1600	Seize cents	Mille six cents	Un six zéro zéro
	1800	Dix-huit cents	Mille huit cents	Un huit zéro zéro
–DUd	1234	Douze cent trente-quatre	Mille deux cent trente-quatre	Un deux trois quatre
	1367	Treize cent soixante-sept	Mille trois cent soixante-sept	Un trois six sept
	1428	Quatorze cent vingt-huit	Mille quatre cent vingt-huit	Un quatre deux huit
	1593	Quinze cent nonante-trois	Mille cinq cent nonante-trois	Un cinq neuf trois
	1639	Seize cent trente-neuf	Mille six cent trente-neuf	Un six trois neuf
	1842	Dix-huit cent quarante-deux	Mille huit cent quarante-deux	Un huit quatre deux
–DUs	1266	Douze cent soixante-six	Mille deux cent soixante-six	Un deux six six
	1322	Treize cent vingt-deux	Mille trois cent vingt-deux	Un trois deux deux
	1466	Quatorze cent soixante-six	Mille quatre cent soixante-six	Un quatre six six
	1522	Quinze cent vingt-deux	Mille cinq cent vingt-deux	Un cinq deux deux
	1622	Seize cent vingt-deux	Mille six cent vingt-deux	Un six deux deux
	1866	Dix-huit cent soixante-six	Mille huit cent soixante-six	Un huit six six

starting to write and that differences between the types of verbal form could not be attributed to encoding differences—otherwise participants could read only part of the numeral (in the TH form, the teen *twelve*; in the ThUH form, *one thousand*), then write it down (TH, *12*; ThUH, *1*), before reading and writing the rest of the sequence. Once the stimulus had been read aloud, it was erased from the screen, and the writing of the arabic numeral began. The participants wrote on a lined sheet of paper fixed on the digitizing tablet (that they could position in the way that was the most natural for them). They had to position the pencil on a fixed starting point, 2 cm on the left of the line they had to write on; this was done in order to have identical starting positions and starting jumps before initiating the writing of the number. When the participants had finished writing a trial, they had to position their pencil on the next starting point, and the next trial would then appear on the screen. Each participant could rest between blocks if so desired.

Data analysis

The handwriting samples were filtered by a low-pass filter with a 10-Hz cut-off frequency. The resulting trajectory and absolute velocity pattern were displayed on a monitor. On this velocity profile, digits and inter-digit jumps were isolated at points of minimum velocity—that is, at maximal curvature. Each digit was defined by a pen–down criterion (thus a positive pressure function), and approaching movements were excluded. The inter-digit jumps were characterized by a zero pressure and a positive velocity function, as they correspond to the movement above the paper made by participants between two digits.

Three parameters were measured on each inter-digit jump and digit: duration of the writing movement (in milliseconds), trajectory length of the written trace (in millimetres), and dysfluency (number of extremes on the velocity curve). Dysfluency represents the number of changes in direction during the movement, and thus it assesses the number of strokes in a written pattern. As these parameters may be correlated, we carried out Pearson's correlation in order to choose the appropriate statistical analysis method—that is, to avoid inflated Type I error due to multiple tests of correlated variables (Cooley & Lohnes, 1971; Tabachnick & Fidell, 1989).

On inter-digit jumps, duration and length were positively correlated ($R_{xy} = .55$, $p < .0001$), as well as duration and dysfluency ($R_{xy} = .77$; $p < .0001$), and length and dysfluency ($R_{xy} = .43$, $p < .003$). On digits, the same pattern of results emerged: Duration and length were positively correlated ($R_{xy} = .58$, $p < .0001$), as well as duration and dysfluency ($R_{xy} = .75$, $p < .0001$), and length and dysfluency ($R_{xy} = .47$, $p < .002$). In order to take into account these correlations, we decided to undertake principal component analyses on inter-digit jumps and digits separately. On inter-digit jumps, one principal component emerged with an eigenvalue above 1 (2.18), accounting for 72.91% of the variance. The factor loadings were quite similar for the three variables: duration, .62; length, .51; and dysfluency, .59. On digits, there was also only one principal component with an eigenvalue above 1 (2.20), accounting for 73.38% of variance. The factor loadings were as follows: duration, .61; length, .52; and dysfluency, .58. We then performed ANOVAs separately for digits and inter-digit jumps on these principal components. Results are presented separately for inter-digit jumps and digits, and then discussed together.

Results

The mean error rate was 2.32%. These errors were excluded from the following analyses.

Analysis of the inter-digit jumps

The principal component was analysed independently for each position of the inter-digit jump (1, 2, or 3) with a 3 (types: TH, ThUH, NS) × 3 (final structures: –00, –DUd, –DUs) ANOVA. Types and final structures were within-subject factors.

At the first inter-digit jump, located between the first and the second digit (1_XXX), the ANOVA revealed a significant effect of type, $F(2, 22) = 10.08$, $p < .0001$ (see Table 2). Post hoc comparisons showed that NS forms were significantly different from TH forms, $F(1, 11) = 13.12$, $p < .004$, as well as from ThUH forms, $F(1, 11) = 7.35$, $p < .02$. TH and ThUH forms differed significantly as well, $F(1, 11) = 14.42$; $p < .003$. As can be seen from Table 2, duration for a TH was shorter than that for a ThUH, which was shorter than that for NS forms (135, 144 and 166 ms, respectively); a similar pattern was seen for trajectory length (5.27, 5.46, and 6.11 mm, respectively), and dysfluency (1.21, 1.30, and 1.61, respectively). There was no significant effect of the final structure, $F(2, 22) = 1.25$; $p < .3$, nor any interaction between type and final structure, $F(4, 44) < 1$.

The second inter-digit jump differed significantly as a function of type, $F(2, 22) = 8.27$, $p < .002$, and of the final structures, $F(2, 22) = 12.1$, $p < .0003$, and an interaction between these two factors was also significant, $F(4, 44) = 4.42$, $p < .004$. Post hoc comparisons were performed to assess the effect of final structure on each of the three types of verbal form. On the NS forms, final structure did not have a significant effect, $F(2, 22) = 3$, $p < .08$; however, this factor was significant for the TH forms, $F(2, 22) = 10.73$; $p < .0006$, as well as for the ThUH forms, $F(2, 22) = 12.26$; $p < .0003$. On the TH forms, –DUs and –DUd structures did not significantly differ, $F(1, 11) = 1.26$; $p < .2$, whereas they both differed from the –00 final structure: –00 and –DUs, $F(1, 11) = 15.55$; $p < .002$; –00 and –DUd, $F(1, 11) = 11.35$; $p < .006$. The same results were found on the ThUH forms—that is, –DUs and –DUd did not differ, $F(1, 11) < 1$, whereas –00 structure differed from that of –DUs, $F(1, 11) = 13.75$, $p < .003$, and from that of –DUd, $F(1, 11) = 13.67$, $p < .003$. As can be seen in Table 2, when a –DUs or –DUd was written in the TH and ThUH forms, the duration, length, and dysfluency were higher than when a –00 final structure was produced. On the NS forms on the contrary, the inter-digit jump did not vary according to the next structure to be produced.

The third inter-digit jump was also influenced by type, $F(2, 22) = 7.27$, $p < .003$ and by final structure, $F(2, 22) = 8.26$, $p < .002$, but the interaction between these factors was not significant, $F(4, 44) = 1.07$; $p < .3$. Post-hoc comparisons showed that TH and ThUH forms did not significantly differ, $F(1, 11) < 1$, whereas TH and ThUH forms differed from NS forms: $F(1, 11) = 5.64$, $p < .03$; $F(1, 11)$ 12.1, $p < .005$. The final structure effect was also examined by post hoc comparisons. –DUs and –DUd final structures did not significantly differ, $F(1, 11) = 2.07$; $p < .1$, whereas –00 final structures generated a shorter inter-digit jump than did –DUs structures, $F(1, 11) = 12.2$, $p < .005$, or –DUd structures, $F(1, 11) = 9.6$, $p < .01$.

Analysis of the digits

We did not expect any difference between structures for the first and second digits of the written arabic numbers as they were the same under all conditions, whereas the third and fourth corresponded to different digits under each condition. The principal component was analysed independently for each position of the digit (1, 2, 3, or 4) with a 3 (types: TH, ThUH, NS) × 3 (final structures: –00, –DUd, –DUs) ANOVA. Types and final structures were within-subject factors.

As expected, there was no effect of type or structure on the first and second digits (see Table 3), whereas structure had a significant effect on the third, $F(2, 22) = 14.82$, $p < .0001$, and fourth digits, $F(2, 22) = 48.66$, $p < .0001$.

TABLE 2

Experiment 1: Mean duration, length, dysfluency, and values of the principal compound for inter-digit jumps, for each type of verbal form and final structure

		Duration[a]				*Trajectory length*[b]				*Dysfluency*[c]				*Principal component*			
		Type				*Type*				*Type*				*Type*			
Inter-digits jump	*Structure*	*TH*	*ThUH*	*NS*	*Mean*	*TH*	*ThUH*	*NS*	*Mean*	*TH*	*ThUH*	*NS*	*Mean*	*TH*	*ThUH*	*NS*	*Mean*
1	00	131	142	166	146	5.19	5.37	5.97	5.51	1.18	1.32	1.61	1.37	–0.537	–0.372	0.246	–0.221
	DUd	137	145	163	148	5.27	5.58	6.08	5.64	1.25	1.33	1.54	1.37	–0.482	–0.332	0.182	–0.210
	DUs	136	144	170	150	5.34	5.44	6.20	5.69	1.20	1.25	1.68	1.38	–0.418	–0.303	0.348	–0.124
	Mean	135	144	166	148	5.27	5.46	6.11	5.61	1.21	1.30	1.61	1.37	–0.479	–0.335	0.259	–0.185
2	00	136	126	170	143	4.82	4.62	6.12	5.19	1.53	1.41	2.01	1.64	–0.445	–0.617	0.321	–0.247
	DUd	164	160	177	167	6.01	5.85	6.68	6.18	1.87	1.80	1.88	1.85	0.234	0.170	0.550	0.318
	DUs	163	157	177	166	6.50	6.30	7.07	6.62	1.80	1.71	1.84	1.78	0.421	0.132	0.637	0.396
	Mean	154	148	174	158	5.77	5.59	6.62	5.99	1.73	1.64	1.90	1.75	0.070	–0.104	0.503	0.155
3	00	124	124	143	130	4.92	5.02	5.84	5.26	1.15	1.27	1.47	1.30	–0.709	–0.630	–0.218	–0.519
	DUd	155	153	169	159	5.96	5.97	6.74	6.23	1.60	1.54	1.89	1.68	0.165	0.001	0.352	0.173
	DUs	145	139	154	146	6.08	5.94	6.32	6.11	1.52	1.43	1.70	1.55	–0.137	–0.188	0.230	–0.032
	Mean	141	139	155	145	5.65	5.64	6.30	5.86	1.43	1.41	1.68	1.51	–0.227	–0.272	0.121	–0.126

[a]In ms. [b]In mm. [c]No. of extremes.

TABLE 3

Experiment 1: Mean duration, length, dysfluency, and values of the principal component for digit, for each type of verbal form and final structure

		Duration[a]				Trajectory length[b]				Dysfluency[c]				Principal component			
		Type				Type				Type				Type			
Digit	*Structure*	*TH*	*ThUH*	*NS*	*Mean*	*TH*	*ThUH*	*NS*	*Mean*	*TH*	*ThUH*	*NS*	*Mean*	*TH*	*ThUH*	*NS*	*Mean*
1	00	210	210	250	223	10.15	10.19	9.82	10.05	2.62	2.66	3.35	2.87	–1.216	–1.190	–0.762	–1.056
	DUd	211	217	253	227	9.87	10.16	9.88	9.97	2.68	2.77	3.42	2.95	–1.251	–1.097	–0.721	–1.023
	DUs	209	216	254	226	9.91	10.21	10.02	10.04	2.62	2.80	3.40	2.94	–1.239	–1.067	–0.707	–1.004
	Mean	210	215	252	225	9.98	10.18	9.90	10.02	2.64	2.74	3.39	2.92	–1.235	–1.118	–0.730	–1.027
2	00	314	316	338	322	11.39	11.56	11.59	11.51	5.66	5.77	5.88	5.77	0.465	0.533	0.646	0.548
	DUd	324	319	332	325	11.53	11.33	11.53	11.45	5.81	5.68	6.06	5.85	0.602	0.467	0.697	0.589
	DUs	326	323	334	327	11.66	11.55	11.70	11.63	5.81	5.75	5.83	5.79	0.633	0.607	0.757	0.666
	Mean	321	319	335	325	11.53	11.48	11.60	11.53	5.76	5.73	5.92	5.80	0.567	0.536	0.700	0.601
3	00	230	231	241	234	9.43	9.68	10.10	9.73	4.36	4.52	4.72	4.53	–0.683	–0.551	–0.386	–0.540
	DUd	309	310	317	312	10.59	10.60	10.61	10.60	5.50	5.53	5.66	5.56	0.294	0.240	0.384	0.306
	DUs	278	277	288	281	11.11	11.03	11.15	11.09	4.84	4.86	4.90	4.85	0.053	0.076	0.080	0.080
	Mean	273	273	282	275	10.38	10.44	10.62	10.48	4.90	4.97	5.09	4.98	–0.111	–0.077	0.036	–0.050
4	00	233	233	240	235	10.39	10.53	10.70	10.54	4.30	4.29	4.31	4.30	–0.501	–0.521	–0.443	–0.489
	DUd	346	351	362	353	12.64	12.74	12.75	12.71	5.96	5.87	6.21	6.01	1.040	0.995	1.190	1.075
	DUs	281	283	299	288	11.86	11.85	11.82	11.84	4.88	4.91	4.97	4.92	0.215	0.206	0.276	0.233
	Mean	287	289	300	292	11.63	11.71	11.74	11.69	5.05	5.02	5.16	5.07	0.251	0.226	0.341	0.272

[a]In ms. [b]In mm. [c]No. of extremes.

The post hoc contrasts revealed that –00 and –DUs digits differed, in the third, $F(1, 11) = 15.67$, $p < .002$, and fourth positions, $F(1, 11) = 24.73$, $p < .0004$. The –DUd and –DUs digits also differed in the fourth position, $F(1, 11) = 39.04$, $p < .0001$, but there was only a tendency in the third position, $F(1, 11) = 3.67$, $p < .06$. Finally, –00 and –DUd digits were also significantly different, in the third, $F(1, 11) = 18.83$, $p < .001$, and fourth position, $F(1, 11) = 68.16$, $p < .0001$. The digit zero was always shorter in duration and in trajectory length, and contained less dysfluency than digits from –DUs or –DUd structures (see Table 3).

In conclusion, although the writing movements for the third and fourth digits differed as a function of the final structure (as they corresponded to different digits), final structure did not influence all the parameters of the preceding inter-digit jumps. The simpler (shorter duration, length, and dysfluency) was always the zero, followed by the repeated digits (6 or 2), and finally by different digits.

Discussion

This experiment showed several results that go against the assumption that planning of handwritten movement is entirely determined by an abstract semantic representation independent of the verbal form. First of all, let us note that the no-syntax forms always generated longer inter-digit jumps than did syntax forms (TH or ThUH). This was true for all inter-digit jumps, and may be due to the fact that subjects processed these forms as four elements and thus wrote four separate elements, whereas they wrote an integrated arabic numeral when the input was a syntax form, thus leading to movements that were shorter and more fluent. Another factor that may have influenced these writing times is that the NS forms were written in the first part of the experiment, whereas the TH and ThUH forms were produced in the second part, thus a general speeding-up effect on these forms might be due in part to training and habituation to the task and apparatus.

On the syntax forms TH and ThUH, the first inter-digit jump, located between the first digit "1" and the next digit, was influenced by the type of verbal form: It was shorter when part of a teen form (e.g., *twelve*) in a TH type of verbal form, than when it was in ThUH forms, where an overwriting operation is supposed to take place between *thousand* and the rest. In contrast, the first two digits did not vary with the verbal form: The lengthening of the inter-digit jump in ThUH cannot thus be attributed to motor differences of the second digit.

The second inter-digit jump was influenced by final structures: A longer inter-digit jump was observed before a decade–unit structure (–DUs or –DUd) than before a double-zero structure. As we found an interaction with the type of verbal form, showing that there was no such effect of final structure on the NS forms, it allows us to reject the idea that this effect could stem only from the digit zero being simpler to programme, and we can thus interpret the lengthening of this inter-digit jump in the case of –DUs and –DUd as being due to the overwriting operation.

The third inter-digit jump was also influenced by the final structures: It was shorter between two zeros that are concatenated at the same time (XX & *00*), than between other digits—that is, when there is an overwriting operation between the decade and the unit (60 # 6; 30 # 4).

In summary, our findings clearly show that the type of verbal structure of numerals has an impact on the handwritten production of arabic numerals: Inter-digit jumps are longer when they correspond to an additive relationship in the verbal numeral and thus to an overwriting operation in the production of arabic numerals.

The preceding discussion is based on the assumption that the writing of an arabic numeral is initiated only after a complete semantic representation of the presented verbal numeral has been computed. However, some authors have proposed that transcoding numbers is an asemantic process (Cipolotti, 1995; Cohen & Dehaene, 1991; Dehaene, 1992; Deloche & Seron, 1987; Seron & Deloche, 1983). Indeed, some patients have shown a deficit in producing numerals in transcoding tasks, while being able to produce the same numerals in semantic tasks. In order to account for this dissociation, Cipolotti (1995) and Cipolotti and Butterworth (1995) proposed the existence of multiple routes for transcoding: Semantic and asemantic ones, which are activated by task demands and which inhibit each other once activated. The existence of semantic or asemantic pathways to transcode numbers is also suggested within Dehaene's triple code model (1992), where three types of representation of numbers are postulated: a visual-arabic number form, an auditory–verbal word frame, and an analogue magnitude representation of quantities. Transcoding familiar numbers activates a semantic and lexical pathway, as suggested by a patient unable to read unfamiliar arabic numbers while being able to read familiar numbers of equivalent complexity (i.e., *1789*, French revolution, vs. *1897*, unfamiliar, Cohen et al., 1994). On the contrary, transcoding unfamiliar numbers from the verbal to the arabic code or vice versa is an asemantic process via direct pathways between these two codes. These pathways are not specified but the authors refer to the Deloche and Seron (1987) asemantic model of transcoding. This model posits an asemantic algorithm to transcode numbers, containing a series of rules triggered by the lexical nature of the verbal primitives identified after segmentation of the verbal form. The rules are applied on the lexical primitives from the left to the right and insert digits in a three-position recurring frame. However, this model's algorithm does not include a rule allowing to transcode TH forms and is thus not directly testable here.

From an asemantic view, an interpretation of our effects could be to argue that the first digits might be written on the basis of a word-to-digit mapping procedure bypassing the syntactic and semantic analysis of the entire verbal string. In such a perspective, the inter-digit jumps in the writing of arabic numerals would not necessarily reflect aspects of the structure of a semantic–verbal representation. Rather, they would reflect some points in the time-course of the writing process where the word-to-digit mapping procedure is not sufficient to produce a correct arabic number and has to wait for the results of the other ongoing syntactically based transcoding processes. This objection is reasonable, given the existence of strong regularities in the mapping between the two notational systems, which might motivate a strategy where the first digits are written as soon as possible in transcoding tasks, and this would present the advantage of reducing memory load.[5] In English and French, it is always possible to write digits corresponding to the first word of a verbal numeral. Any multi-word verbal numeral begins either with a lexical primitive (a unit, *two*; a teen, *twelve*; or a decade, *twenty*), in which case the corresponding arabic numerals (2, 12, and 2–, respectively) could be immediately written

[5]Multi-word verbal numerals are difficult to hold in phonological short-term memory because they come from a small lexicon of words that are connected through a small number of syntactic relationships without strong semantic or pragmatic constraints. Given this memory load, it is thus economical to alleviate as soon as possible the information kept in working memory in order to avoid transcoding mistakes.

down, or else with a multiplier such as "hundred" or "thousand": In those cases the arabic numeral "1" can also be written down immediately.[6] The presence of a longer inter-digit jump between the first and second digits in the writing of ThUH than in the writing of TH forms would thus reflect such a two-step processing. In TH forms, the first two digits correspond to the first word: In a numeral like "1200", "12" is written through the direct word-to-digit mapping procedure before a complete representation of the input structure has been computed, whereas in the case of the ThUH forms, only "1" can be written immediately. Thus, in a ThUH verbal form, the longer inter-digit jump after the digit "1" may be due to the fact that the writing of the next digit <2> requires the completion of the syntactic analysis of the sequence,[7] whereas in the case of a TH structure this waiting point comes only after the writing of the first two digits "12". The influence of final structures on inter-digit jumps 2 and 3 can also be explained in the perspective of a word-to-digit mapping procedure activated in parallel with the syntactic composition. Indeed, when a verbal sequence ends with the word "hundred", two zeros can always be written, whereas when the final structure consists of a decade–unit, the writing of the last two digits necessitates a further syntactic analysis of the verbal form. The supplementary step in the latter case may explain the longer inter-digit jumps before and between the digits corresponding to the decade–unit.

Thus, it seems that the distribution of inter-digit jumps that we found here could be interpreted as the difficulty of the overwriting rule within the framework of the semantic-lexical model, or by positing the use of an immediate word-to-digit mapping procedure in parallel with a syntactic processing in an asemantic view. The next experiment attempts to disentangle these two interpretations by guaranteeing that a complete semantic representation of the verbal numeral is constructed before initiating the writing of the arabic numeral.

EXPERIMENT 2

The aim of this experiment was to enforce semantic processing of the presented verbal numerals before the written production task. For this purpose, pairs of written verbal numerals (sharing a lexico-syntactic structure or not) were presented to subjects who had to compare them, decide which was the larger, and then write down their answer in the arabic form. This task could help to clarify the previous alternative interpretation of our results, as a direct mapping between the first word of the verbal numeral and the first digits of the arabic numeral. This asemantic transcoding process could not be applied in the present experiment as the semantic representation had to be accessed before initiating the writing. Furthermore, regarding propositions in the literature of numerical transcoding, this experiment could clarify two issues: The existence of different routes for transcoding as a function of the task and the existence of intermediary semantic representations.

First, as mentioned earlier, neuropsychological studies have reported patients who were impaired in transcoding but who were able to produce the same numerals in semantic tasks (Cipolotti, 1995; Cipolotti & Butterworth, 1995). To account for this dissociation, the authors

[6] In French, the unit multiplying "cent" or "mille" is not specified if this unit is one.

[7] In the ThUH forms, no decision can be taken on the second word "mille *deux* . . ." as it could lead either to 1002 if the sequence ends at that point, or to 1200 if the word "cent" follows the first two words.

proposed the existence of multiple transcoding routes in McCloskey's general architecture. These routes may be semantic or asemantic, and once one is activated, as a function of the task, then it inhibits the others. In this regard, the type of representation activated in a semantic task and used for production of numerals is different from that in a direct transcoding task. If the production of arabic numerals is based on the semantic representation computed for the comparison task, we should not find differences between TH and ThUH at the arabic numeral production level. Indeed, the semantic representation would be of the same format for the two verbal forms contrasted (base-10 representation, e.g., {1}10exp3, {2} 10exp2, for "twelve hundred" as well as for "one thousand two hundred"), and thus it should lead to the same production steps and to the same characteristics in the kinematics of handwriting whatever the type of verbal form.

Second, the existence of Intermediate Semantic Representations (ISR, i.e., representation of the input lexical primitives and their relationships) has been proposed to explain an influence of the entry code upon a variety of tasks, among which was a comparison task (Noël & Seron, 1997). Subjects were faster when comparing pairs of numerals sharing the same syntactic structure (i.e., "twelve hundred/thirteen hundred") than when they were comparing numerals with different syntactic structures (i.e., "twelve hundred/one thousand three hundred"). The authors attributed this difference to ISR: For pairs of numerals sharing the same lexico-syntactic structure, the magnitude comparison could be performed directly on the ISR (e.g., <12> × <100> vs. <13> × <100>) . On the contrary, for pairs differing in their lexico-syntactic structure, the ISR generated would not allow such a direct comparison of magnitude (e.g., <12> × <100> vs. <1000> + <3> × <100>) and would involve a supplementary step of transforming them into a common representation, leading to a longer RT.

We tested the idea that the ISR computed for the comparison task could also be the basis for the production of arabic numerals by presenting pairs of numerals sharing the same lexico-syntactic structure (TH/TH or ThUH/ThUH) or differing in their lexico-syntactic structures (TH/ThUH and ThUH/TH). We reasoned that if ISR can be used for comparison in similar pairs, these representations[8] (in the case of TH forms, <12> × <100> and in the case of ThUH forms, <1000> + <2> × <100>) would also be the basis for the production of arabic numbers, thus leading to the differences between types that we found in the preceding experiment. On the contrary, in the case of different lexico-syntactic structures, the comparison cannot be made with ISRs: There is a need to access a common representation of both forms, either by transforming one of the two forms into the other, or by accessing a common abstract representation for both. This abstract representation could be either of the type McCloskey proposed (i.e., a base-10 representation; McCloskey et al., 1985), or an analogue magnitude representation as suggested by Dehaene (1992). In both of these conceptions, the lexico-syntactic structure plays a role at the encoding stages only and does not affect the comparison process itself. However, if in McCloskey's model, the basis for production of arabic numerals is the representation used for the comparison (i.e., the base-ten formula), in Dehaene's triple code model, it seems that the production of arabic numbers could not be made upon the analogue magnitude representation. Paths to and from the magnitude representation are not

[8]Actually similar to Power and Dal Martello (1990, 1997) verbal-semantic representations in our experiments—that is, upon a verbal entry form.

supposed to be syntactically sophisticated (Dehaene & Mehlier, 1992), but on the contrary, they would work by direct labelling: To each portion of the number line corresponds one or more labels (e.g., to the quantity <9> correspond the labels "9", "nine", "about 10"). Non-familiar and large numbers, like 212, are necessarily rounded off to a more familiar quantity, "200", and thus the magnitude representation is not suitable for precise transcoding of arbitrary numerals (Dehaene & Cohen, 1995, p. 87). In the present experiment, either the comparison of large numbers is made upon other types of representations and processes that are not stipulated by the model, or the approximate magnitude representations of the two numbers are activated by direct labelling on the number line. In the latter case, once the largest is identified, the pathway from the magnitude representation to the arabic representation would not suffice to produce the precise form required. One has to suppose that the verbal representations are maintained temporarily during the comparison, and that the analogue magnitude representation allows selection of the desired item in the auditory verbal word frame, in order to transcode the precise verbal numeral presented into an arabic numeral. The model does not make clear predictions on the effects of activating a semantic representation before writing, and is thus not suited to test such effects as it is not possible to produce a complex arabic numeral from an approximate representation with a non-syntactically sophisticated pathway.

To sum up, our hypotheses are that if a comparison is made upon ISR when possible, an effect of the type of numeral (TH/ThUH) should be found in the same lexico-syntactic condition, but not in the different lexico-syntactic condition. On the contrary, if the comparison is made in all cases on the basis of a common base-ten representation of the two stimuli, no difference between types should emerge at all, even when the syntax of the pair is the same. This finding, compared to that of Experiment 1, would furthermore support the proposition stemming from neuropsychological data: the existence of two different transcoding routes activated by task demands.

Method

Participants

A total of 8 right-handed, French-speaking subjects volunteered to participate in this experiment (4 males, 4 females). The mean age was 25 years old (range 21–29 years).

Material

The same material as that in Experiment 1 was used.

Stimuli

Experimental forms ($N = 40$) were presented in pairs in the written verbal format (see Table 4): Half of them were TH, the other half were ThUH. In half of the pairs, the two stimuli had the same lexico-syntactic structures (hereafter, SLS); (i.e., TH/TH: *thirteen hundred and sixty eight/twelve hundred and ninety four*; or ThU/ThUH: *one thousand three hundred and sixty eight/one thousand two hundred and ninety four*), and in the other half, the two stimuli had different lexico-syntactic structures (hereafter, DLS; TH/ThUH or ThUH/TH). The 40 pairs of experimental items were presented four times and were mixed with 80 fillers. We took care to present fillers beginning with the same first words as the experimental forms (i.e., "twelve", "thousand"), but integrated in other structures so that they were not

TABLE 4
Stimuli of Experiment 2: TH and ThUH pairs of verbal numerals in the two syntax conditions

Syntax condition	*Answer in arabic numerals*[a]	*Type of verbal numeral*	
		TH	*ThUH*
Same	**1236**/ 1142	Douze cent trente-six/ onze cent quarante-deux	Mille deux cent trente-six/ mille cent quarante-deux
	1368/ 1294	Treize cent soixante huit/ douze cent nonante quatre	Mille trois cent soixante huit/ mille deux cent nonante quatre
	1423/ 1379	Quatorze cent vingt-trois/ treize cent septante-neuf	Mille quatre cent vingt-trois/ mille trois cent septante neuf
	1572/ 1453	Quinze cent septante-deux/ quatorze cent cinquante-trois	Mille cinq cent septante-deux/ mille quatre cent cinquante-trois
	1619/ 1561	Seize cent dix-neuf/ quinze cent soixante et un	Mille six cent dix-neuf/ mille cinq cent soixante et un
	1225/ 1193	Douze cent vingt-cinq/ onze cent nonante-trois	Mille deux cent vingt-cinq/ mille cent nonante-trois
	1354/ 1278	Treize cent cinquante-quatre/ douze cent septante-huit	Mille trois cent cinquante-quatre/ mille deux cent septante-huit
	1436/ 1365	Quatorze cent trente-six/ treize cent soixante cinq	Mille quatre cent trente-six/ mille trois cent soixante-cinq
	1543/ 1429	Quinze cent quarante-trois/ quatorze cent vingt-neuf	Mille cinq cent quarante-trois/ mille quatre cent vingt-neuf
	1617/ 1546	Seize cent dix-sept/ quinze cent quarante-six	Mille six cent dix-sept/ mille cinq cent quarante-six
Different	**1236**/ 1142	Douze cent trente-six/ mille cent quarante-deux	Mille deux cent trente-six/ onze cents quarante-deux
	1368/ 1294	Treize cent soixante huit/ mille deux cent nonante quatre	Mille trois cent soixante huit/ douze cent nonante quatre
	1423/ 1379	Quatorze cent vingt-trois/ mille trois cent septante-neuf	Mille quatre cent vingt-trois/ treize cent septante neuf
	1572/ 1453	Quinze cent septante-deux/ mille quatre cent cinquante-trois	Mille cinq cent septante-deux/ quatorze cent cinquante-trois
	1619/ 1561	Seize cent dix-neuf/ mille cinq cent soixante et un	Mille six cent dix-neuf/quinze cent soixante et un
	1225/ 1193	Douze cent vingt-cinq/ mille cent nonante-trois	Mille deux cent vingt-cinq/ onze cent nonante-trois
	1354/ 1278	Treize cent cinquante-quatre/ mille deux cent septante-huit	Mille trois cent cinquante-quatre/ douze cent septante-huit
	1436/ 1365	Quatorze cent trente-six/ mille trois cent soixante cinq	Mille quatre cent trente-six/ treize cent soixante-cinq
	1543/ 1429	Quinze cent quarante-trois/ mille quatre cent vingt-neuf	Mille cinq cent quarante-trois/ quatorze cent vingt-neuf
	1617/ 1546	Seize cent dix-sept/ mille cinq cent quarante-six	Mille six cent dix-sept/ quinze cent quarante-six

[a]Correct in bold.

always the largest ones so as to avoid a strategy to look only at the first words. There was thus a total of 240 items, of which 160 were experimental ones.

All subjects started the task with the SLS conditions (TH/TH and ThUH/ThUH conditions were counterbalanced) and then the DLS conditions. The whole experiment lasted approximately 30 minutes.

Procedure

Stimuli were displayed one above the other (at 1/3 and 2/3 vertically, and centred horizontally) on a computer screen (Dell Ultrascan 17FS–LR), 80–90 cm from the participant, who was asked to decide which of the two numerals was the larger and to write down his answer in the arabic form. The rest of the procedure was similar to that of Experiment 1.

Data analysis

The recorded parameters were the same as those for the preceding experiment (movement duration, trajectory length, and dysfluency). We also recorded RTs (i.e., from the onset of the two verbal stimuli on the screen until the start of the writing gesture), but as this RT involves reading time, encoding time, comparison and decision times, and planification of writing, we do not think it will allow us to infer precisely about the underlying processes.

The data analysis was the same as that for Experiment 1. We decided to study only the first inter-digit jump (1_XXX), as no variations between the forms were manipulated at the second or third inter-digit jumps in the arabic numerals. We also performed Pearson's correlation on the three recorded handwriting parameters on inter-digit jumps, and a principal component analysis. Duration and dysfluency were positively correlated ($R_{xy} = .81, p < .0001$), as well as duration and length ($R_{xy} = .47, p < .0001$) and length and dysfluency ($R_{xy} = .46, p < .0001$). We thus decided to perform principal component analysis on the first inter-digit jump. Only one principal component emerged with an eigenvalue above 1 (2.17) accounting for 72.4% of variance, and variables were loaded with the following factor loadings: duration, .61; length, .49; and dysfluency, .61. We then performed a univariate test of variance (ANOVA) on this principal component (see Table 5).

Results

The mean error rate was 5.57% including the fillers (4.5% on experimental forms), and these items were excluded from the analysis. 34.6% of the errors concerned the comparison part of the task, with subjects choosing the smaller numeral. This error type did not differ as a

TABLE 5
Experiment 2: Mean duration, length, dysfluency, and values of the principal component for first inter-digit jump, for each type of verbal form and syntax condition

	Duration[a]			*Trajectory length*[b]			*Dysfluency*[c]			*Principal component*		
	Type			*Type*			*Type*			*Type*		
Syntax	*TH*	*ThUH*	*Mean*	*TH*	*ThUH*	*Mean*	*TH*	*ThUH*	*Mean*	*TH*	*ThUH*	*Mean*
SLS	132	147	140	4.87	5.10	4.99	1.19	1.36	1.28	–0.27	0.02	–0.12
DLS	135	142	138	4.69	4.89	4.79	1.31	1.35	1.33	–0.24	–0.10	–0.17
Mean	133	145		4.78	5.01		1.25	1.35		–0.25	–0.04	

[a]In ms. [b]In mm. [c]No. of extremes.

function of condition (7 vs. 6 errors on SLS and DLS, respectively). In 38.3 % of cases, errors concerned the lexical primitives of the numeral (16 lexical substitution errors, 16 intrusions from the other verbal numeral, and 9 omissions of a lexical primitive). A total of 16.8% of errors were syntactic and consisted mainly in the addition of intermediary zeros (13 out of 18 errors). The remaining 9.3% of errors comprised diverse error types (addition of digits, e.g., "1246" instead of "246", inversion of the production order of digits, etc. . .).

Analysis of the inter-digit jump

The principal component was analysed with a 2 (types : TH vs. ThUH) × 2 (syntax: SLS vs. DLS) ANOVA with repeated measures on each variable. The variable type represents the correct answer—that is, the largest of the two presented numerals. In the SLS condition, both numerals had the same structure, whereas in the DSL condition, they had different structures.

At inter-digit jump 1 (1_XXX), the ANOVA showed a significant main effect of type, $F(1, 7) = 10.51, p < .01$. As in Experiment 1, duration and length were shorter when subjects wrote a TH rather than a ThUH type of numeral, and it contained less dysfluency (see Table 5). There was no effect of syntax, $F(1, 7) < 1$, and no interaction between these two factors, $F(1, 7) = 1.94, p < .2$.

Analysis of RT

Median mean correct RTs were analysed with a 2 (types : TH vs. ThUH) × 2 (syntax: SLS vs. DLS) ANOVA with repeated measures on each variable. There was no significant effect of type, $F(1, 7) = 2.54; p < .15$ (TH, 2.84 s vs. ThUH, 2.95 s), no significant effect of syntax, $F(1, 7) < 1$ (SLS, 2.87 s vs. DLS, 2.92 s), nor any interaction between these two factors, $F(1, 7) = 1.82; p < .23$.

As already suggested earlier, many different processes occurred during these periods of almost 3 s: reading, comparison, decision, arabic numeral writing planification, and motor programming. In order to assess which factors influenced RTs, a stepwise regression analysis was run with RTs as the dependent variable. Four factors had a significant effect in this analysis (movement duration of the following arabic numeral, number of words in the pair of stimuli, numerical distance between the two stimuli, and trajectory length of the following arabic numeral) but explained only 13.46 % of variance.

Discussion

This experiment showed a clear influence of the type of verbal stimulus on writing arabic numeral after a comparison task: ThUH forms always generated a longer first inter-digit jump than did TH forms. This effect was found even when the lexico-syntactic structure of the two numerals was different. This result favours the idea that the type of representation used for the production of arabic numerals is one that keeps track of the verbal primitives and their relationships, triggering different production rules as a function of the additive or multiplicative semantic relationships, as the difficulty of the overwriting rule in the composition of arabic numerals is again confirmed by the present data.

In the present experiment, subjects had to access a representation of the quantity underlying the verbal forms in order to compare them. This representation could be a semantic-verbal one (or the ISR of Noël & Seron, 1997) when the lexico-syntactic structure of the pair was the same, but not when the syntax of the pair was different. In that case, subjects had to access a common representation, and the ISR hypothesis did not expect any difference in the handwritten production in this condition.

The multiple routes proposition did not expect differences between TH and ThUH in the arabic forms after the semantic task in neither condition (whether the syntax was the same or not). Indeed, this task implied the computation of an abstract semantic representation, different from the one elaborated in direct transcoding tasks. This representation, whether a base-10 semantic representation or an analogue magnitude representation, could not generate differences in the production of arabic numerals as it is of the same format for all verbal forms presented. This result does not mean that the kind of representation is the same in transcoding or in comparison, but that effects on handwriting production of arabic numerals are not influenced by an access to an abstract representation of quantity. We postulate that the verbal-semantic representation (or ISR) was reactivated for triggering the arabic numeral production rules, or that subjects held the verbal stimulus in phonological short-term memory during the comparison task and computed the semantic-verbal representation in order to guide the writing of arabic numerals. We can thus conclude that the kind of representation used for producing arabic numerals keeps track of the semantic relationships between verbal primitives as it activates different composition rules that influence the handwritten production.

The fact that we did not find any effects on RTs is not really informative: This measure reflects unfortunately too many different processes (encoding time, reading time, comparison and decision times, handwriting programming, etc.) which does not allow us to draw conclusions from these results. Indeed, in the Noël and Seron study (1997), differences were found in RTs as a function of the similarity of the pair under comparison: Pairs sharing the same lexico-syntactic structures led to shorter RTs than pairs with different structures.

GENERAL DISCUSSION

The main goal of the present study was to examine whether the lexical and syntactic structure of the verbal numerals presented as stimuli influenced the kinematic characteristics of the handwritten production of arabic numerals in two different situations: either in direct transcoding (Experiment 1) or after semantic processing had been enforced by a comparison task (Experiment 2). Both experiments clearly indicated that there was such an influence. Actually, we observed that inter-digit jumps varied according to the syntactic structure of the verbal numerals, when the to-be-written arabic digits were exactly the same. This effect was similar in direct transcoding (Experiment 1) and after a semantic task (Experiment 2), suggesting that the type of representation used to trigger the arabic numeral composition rules was the same in the two tasks and kept track of the verbal primitives and their relationships.

More precisely, the influence of the syntactic and lexical structure of verbal numerals on the transcoding into arabic numerals was observed through the effects of the additive relationship in the verbal numeral on the kinematics of inter-digit jumps. The first inter-digit jump (i.e., X_XXX, Experiment 1 and 2) corresponded to an additive relationship in ThUH forms and to a lexical primitive in TH forms. These verbal forms thus differed in their syntactic and lexical components (*one thousand two hundred* vs. *twelve hundred*) but resulted in exactly the same arabic forms (1200). Strong evidence for the influence of the structure of the verbal form was observed, as the inter-digit jump was longer when the verbal form was of a ThUH type than when it was of a TH type. The second inter-digit jump (i.e., XX_XX, Experiment 1) corresponded to verbal numerals with different final structures: with a decade-unit structure in an additive relationship (e.g., 1266 or 1275) or not (e.g., 1200). It was again observed that the presence of an additive relationship in the verbal form resulted in the lengthening of the corresponding second inter-digit jump at the production level. Furthermore, it was demonstrated that this lengthening could not be explained by motor differences in the graphic movements (e.g., the doubling of the digit zero, which is simpler than the others in the –00 final structures). First, it remained present even if the –DU elements were composed of doubled digits (e.g., 66) that were simpler than non-doubled digits (e.g., 35). Second, it was not present when identical sequences of digits had to be written from a verbal form containing no syntax—that is, presenting a succession of unit words (e.g., 66 or 35 written from "six six" or "three five", respectively), and involving thus only the motor component of production.

These relationships between the structure of verbal numerals and the inter-digit jumps observed in the arabic written output cannot be explained within the semantic-base-10 model of McCloskey et al. (1985). This model proposes that production mechanisms operate exclusively on the basis of an abstract semantic representation, which does not keep track of the peculiarities of the presented stimuli. With regard to the present experiments, the model predicts that upon presentation of TH and ThUH verbal forms, the same semantic representation would be computed (see Figure 2), on the basis of which the same arabic composition mechanisms are planned, and no difference is expected in the output form. Where the final structures with (–DU) or without (–00) a decade–unit in additive relationship are concerned, one may argue that the differences in inter-digit jumps 2 and 3 (i.e., shorter before and between zeros than before and between other digits) might be due to their absence in the semantic representation and to the fact that digit retrieval might be based on different processes: One syntactically driven (for 0), the other semantically driven (for other digits). But it is not clear what consequences such a distinction should predict in terms of processing complexity and its reflection on handwriting kinematics.

In contrast, the semantic-verbal model of Power and Dal Martello (1990, 1997) can easily accommodate the findings of the present experiment. The difference on the first inter-digit jump, when comparing TH and ThUH forms, finds a straightforward explanation, given that the two verbal entry forms are assumed to be transformed into two different semantic representations (see Figure 2). In the case of a TH structure, the first inter-digit jump is located between digits corresponding to a verbal lexical primitive (e.g., twelve), whereas, in the case of a ThUH structure, it results from an overwriting operation (see Figure 2). Given that we observed a longer inter-digit jump when the arabic sequence corresponded to a ThUH structure, a tentative interpretation would thus be to consider that the application of an overwriting operation is more time consuming. This interpretation is furthermore supported by neuropsychological and developmental studies on transcoding: The overwriting operation required by an additive relationship seems to be more error prone in the case of a brain lesion (Cipolotti et al., 1994; Delazer & Denes, 1998; Noël & Seron, 1995) and is acquired later (Power & Dal Martello, 1990; Seron, Deloche, & Noel, 1991; Seron & Fayol, 1994), than the concatenation operation resulting from a multiplicative relationship.

However, there are propositions of asemantic transcoding processes in the literature (Cipolotti & Butterworth, 1995; Dehaene, 1992; Dehaene & Cohen, 1995; Deloche & Seron, 1987), and a plausible alternative explanation could be that subjects initiated writing before having computed a complete semantic representation of the verbal numeral, by a word-to-digit mapping procedure.

The second experiment of the present study guarantees that subjects had to access a semantic representation of the presented numerals because they had to compare their sizes. The fact that differences in the writing of TH and ThUH verbal forms remained at the production level, even when the two stimuli of the pair did not share the same lexico-syntactic structure, is compelling at first. Indeed, we had hypothesized, in the line of Noël and Seron's (1997) intermediate representation proposition (ISR), that we would find the TH/ThUH difference when the pair was similar, as the comparison could be made on the ISR, but not when the pair was different. Their proposal cannot therefore account simply for the effects we found here, except if we suppose that even if a common abstract semantic representation is accessed for the comparison task, it is not the basis for production, and that the ISR is reactivated when the composition of arabic numerals begins.

In Dehaene's conception, number comparison, at least for small numbers, is made on the basis of an analogue magnitude representation. This representation is conceived as an oriented number line obeying Weber–Fechner's law, which means that it is "compressed" for large numbers, and consequently their representation is less precise (Dehaene, 1989; Dehaene & Cohen, 1995; Dehaene, Dupoux, & Melher, 1990). However, in the present experiment, arabic numerals could not be produced on the basis of the magnitude representation accessed in the comparison task, as numbers are supposed to be approximately represented (especially large ones) and directly labelled. Thus, one has to postulate that the verbal representations of the presented numerals (e.g., "fourteen hundred and sixty five") labelled portions of the number line (e.g., "about 1400") in order to compare sizes, and that the magnitude representation allows selection of the correct verbal representation temporarily maintained in order to write the arabic numeral (e.g., 1465) corresponding to the precise verbal form required to be transcoded. The direct route between the verbal and arabic representations works on non-interpreted sequences of symbols, words, and digits, but apart from claiming its asemantic nature, the authors have never specified the processes underlying this transcoding route.

The present results do not favour the idea that the type of representation used for producing numbers is different in a semantic task and in a direct transcoding task (Cipolotti, 1995; Cipolotti & Butterworth, 1995). On the contrary, our results strongly support the idea that the type of representation used as a basis for arabic numeral production processes is the same whatever the task. This representation keeps track of the verbal primitives and their relationships (ISR of Noël & Seron, 1997, or the semantic-verbal representation of Power & Dal Martello, 1990, 1997), which trigger composition rules of different complexity, the overwriting rule being the more difficult and generating longer inter-digit jumps at the production level.

To sum up, this study used an original technique in the domain of transcoding numbers, recording the on-line temporal, spatial, and kinematic characteristics of the handwritten production. The data obtained shed some light and also raise some new questions on an unresolved debate in the literature, concerning the structure of the representations used during a transcoding task. First, we showed that there are differences between writing the same series of digits if the verbal form presented is a sequence of non-syntactically integrated elements compared to integrated verbal numerals. Second, our findings rule out the conception of a central representation losing all properties of the entry code and providing the sole basis for the arabic production mechanisms (McCloskey et al., 1985). On the other hand, they favour the idea that transcoding verbal forms into arabic digits operates on representations keeping track of their lexical and syntactic structure, and that the same type of representation is also the basis for the production of arabic numbers after a semantic task.

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