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Low working memory capacity impedes both efficiency and learning of number transcoding in children

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Abstract

This study aimed to evaluate the impact of individual differences in working memory capacity on number transcoding. A recently proposed model, ADAPT (a developmental asemantic procedural transcoding model), accounts for the development of number transcoding from verbal form to Arabic form by two mechanisms: the learning of new production rules that enlarge the range of numbers a child can transcode and the increase of the mental lexicon. The working memory capacity of 7-year-olds was evaluated along with their ability to transcode one- to four-digit numbers. As ADAPT predicts, the rate of transcoding errors increased when more production rules were required and when children had low working memory capacity, with these two factors interacting. Moreover, qualitative analysis of the errors produced by high- and low-span children showed that the latter have a developmental delay in the acquisition of the production rules.

Keywords: Working memory; Number transcoding; Procedural system; Individual differences

Introduction

Working memory is considered to be the “workbench of cognition” (Jarrold & Towse, 2006; Klatzky, 1980). Indeed, working memory capacity refers to the ability to hold

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information in mind while maintaining other information to achieve a cognitive task. Thus, variation in this capacity is related to performance in any cognitive activity. However, individual differences in working memory capacity are studied mostly in complex activities such as problem solving, reasoning, and text comprehension. The current study aimed to evaluate the impact of individual differences in a relatively simple task, namely, number transcoding. Although transcoding from a verbal form to an Arabic number chain is an everyday activity, children exhibit specific errors, especially at the beginning of the learning process. However, very few studies have investigated the development of this activity. A new model called ADAPT (a developmental asemantic procedural transcoding model) was proposed recently to account for these errors and to describe the ongoing processing steps in transcoding (Barrouillet, Camos, Perruchet, & Seron, 2004). The aim of the current article is to document number transcoding in children and to examine how individual differences in working memory capacity could affect this process.

Individual differences in working memory capacity

A large number of studies have shown that working memory spans, measures of an individual's working memory capacity, reliably predict performance in national curriculum tests evaluating both language and mathematical skills (e.g., Gathercole & Pickering, 2000; Gathercole, Pickering, Knight, & Stegmann, 2004; Lépine, Barrouillet, & Camos, 2005). Furthermore, some of the academic difficulties encountered by children with or without learning disabilities could result from their low working memory capacities (Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; Geary, Brown, & Samaranayake, 1991; Geary, Hoard, & Hamson, 1999; McLean & Hitch, 1999).

Three major accounts have been proposed to explain why working memory capacity measures are such a good predictor of human cognitive functioning (Cowan, 2005; Jarrold & Towse, 2006). First, some models suggest that working memory measures evaluate the efficiency of processing. Daneman and Carpenter (1980), and Case, Kurland, and Goldberg (1982) proposed that the reading or counting span—that is, the number of items that can be maintained for further recall while reading sentences or counting arrays of dots—depends on the cognitive demands of the reading or counting process. Second, some studies have shown that working memory capacity measures reflect variations in individuals' storage capacity independently of processing efficiency (Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Fry & Hale, 2000; Oberauer, Süβ, Wilhelm, & Wittmann, 2003). Third, recent accounts of working memory equate its capacity with the amount of attentional resources. These resources could be allocated specifically to retrieve information from long-term memory (Cowan, 1999; Lovett, Reder, & Lebière, 1999), to engage in both processing and storage (Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2001), to control attention in the face of interference (Engle, Tuholski, Laughlin, & Conway, 1999; Hasher, Zachs, & May, 1999; Kane & Engle, 2003; Saito & Miyake, 2004), or to hold multiple items simultaneously (Cowan, 2001).

Usually, the impact of individual differences in working memory is evaluated in high-level cognitive tasks because they involve multiple-step processing for which the duration and efficiency of each step determine overall performance and because they require both the retrieval of large amounts of information and the storage of information in the face of interfering and distracting inputs. Thus, even simpler tasks that rely on the retrieval and storage of information, such as number transcoding, should also be affected by individual differences in working memory, and individuals with high working memory capacity should outperform those with lower capacity on this type of task. This effect must be especially clear at the beginning of learning this new skill because each step of processing is then more attentionally demanding.

Number transcoding in children

In mathematical cognition, the learning and use of verbal number systems have been widely studied (Fuson, 1988; Fuson, Richards, & Briars, 1982; Gelman & Gallistel, 1978; Siegler & Robinson, 1982). Most verbal number systems rely on a limited lexicon from which only few quantities could be designated by a single word and a syntax that rules the combination of words in a sequence for larger quantities. The verbal lexicon is organized into different lexical classes. In French, there are the units (U) from *un* (one) to *neuf* (nine), which represent the basic numbers from 1 to 9. There are the decades (D) from *dix* (ten) to *quatre-vingt-dix* (ninety), which represent the basic numbers multiplied by 10. There are the particulars (P) from *onze* (eleven) to *seize* (sixteen), which represent the basic number values plus 10; this category corresponds approximately to the teens in English.[1] Finally, there are *cent* (hundred, H) and *mille* (thousand, M), which represent number values but also enter into syntactic relations with other elements of the lexicon. Two syntactic rules govern the notation of the addition and multiplication relations between the elements of the lexicon. For example, *deux cents* (two hundred) means the number value two times hundred, whereas *cent-deux* (one hundred and two) refers to the number value hundred plus two. Thus, any number value is expressed by a set of product and sum relations.

Contrary to the verbal system, the number system written in digits is formally simple. Indeed, the written decimal system consists of only 10 elements (0, 1, 2, 3, 4, 5, 6, 7, 8, and 9) and a single principle, namely, the positional notation. According to this principle, the value of a digit is determined entirely by its position in the sequence, starting from the right, and it increases by a power of 10 at each step to the left. When there is no value for a given power of 10, the corresponding position is occupied by 0 so as to maintain the value as a power of 10 of the next-to-the-left digit. In the Arabic system, all sequences of digits are acceptable except those starting with 0 when the form refers to a number value (e.g., 007).

Despite the ease of this system, transcoding numbers from their verbal forms to their digital forms induces specific difficulties. A large number of studies have reported specific impairments in patients, mostly brain-damaged adults (e.g., Cipolotti & Butterworth, 1995; Delazer & Denes, 1998; McCloskey, Caramazza, & Basili, 1985; Noël & Seron, 1995; Singer & Low, 1933). However, only four studies have evaluated transcoding from verbal to Arabic forms in children. The first one, by Power and Dal Martello (1990), showed that Italian 7-year-olds transcoded one- and two-digit numbers perfectly, produced errors on three- and four-digit numbers (54% errors), and were unable to transcode five- and six-digit numbers at all (for similar results in Belgian French-speaking children,

[1] However, in French, 17, 18, and 19 are expressed using the decade unit (DU) forms dix-sept, dix-huit, and dix-neuf (literally ten-seven, ten-eight, and ten-nine), respectively.

see Noël & Turconi, 1999). In a related study, Seron, Deloche, and Noël (1992) distinguished two types of transcoding errors in Belgian French-speaking 8- and 9-year-olds: lexical errors consisting of substitutions of digits (e.g., 134 for *cent vingt-quatre* [one hundred and twenty-four]) and syntactic errors resulting from the addition or suppression of 0s (e.g., writing 10024 for the previous example). Thus, the lexical errors maintain the length of the chain, whereas the syntactic errors reduce or increase it. Moreover, children produced more syntactic errors than lexical errors (40 vs. 5% at 8 years and 15 vs. 1% at 9 years). These results were replicated by Sullivan, Macaruso, and Sokol (1996), who observed that more than 90% of the errors in English-speaking 7- to 12-year-olds were syntactic in nature. Overall, the previous studies categorized errors mainly as lexical versus syntactic, but they are rather limited because they involved small numbers of children and used only a limited set of numbers. More important, no further attempt has been made to evaluate and account for individual differences, although Sullivan and colleagues (1996) noted the inconsistency of the errors among children. Recently, the new model ADAPT was proposed to account for the development of number transcoding (Barrouillet et al., 2004).

ADAPT: A Developmental Asemantic Procedural Transcoding model

ADAPT is a developmental, asemantic, and procedural model of transcoding. The developmental and asemantic characteristics of the model are presented only briefly here because they are not the focus of the current study and have been described extensively elsewhere (Barrouillet et al., 2004). ADAPT follows Deloche and Seron's (1982) proposal by assuming that transcoding from a verbal code to an Arabic code does not require any semantic representation of the numbers. In other words, transcribing "two hundred and twenty-seven" into "227" does not necessitate representing the number as the sum of 2 hundreds, 2 tens, and 7 units. ADAPT is also the first developmental model of transcoding because it explains how new rules are learned and created from old ones and how new representational units are stored in long-term memory when numbers are transcoded. Namely, it is assumed that each number or part of a number transcoded is associated with its verbal form in long-term memory, thereby creating a new representational unit within the mental lexicon. The strength of the association is proposed to vary with the frequency of the form; frequent numbers result in stronger associations and stable representational units, whereas rare associations are soon forgotten. These units in turn direct the subsequent transcodings. Within this framework, two processes contribute to improved performance with age and practice: the evolution of the procedural system and the increasing number of representational units in the mental lexicon.

To test the developmental aspect of ADAPT, more than 400 8- and 9-year-olds transcoded nearly 100 two- to four-digit numbers (Barrouillet et al., 2004). As already observed by previous studies, the older children exhibited fewer errors than did the younger children (9 vs. 56%), and syntactic errors were more frequent than lexical errors (73 vs. 12%). More important, the percentage of errors was highly correlated with the number of rules predicted by ADAPT to transcode numbers ($r > .90$).

ADAPT is a procedural model because the heart of the model is a production system that manages the transcoding from the verbal form to the digital form (Fig. 1). ADAPT supposes that, after the encoding of the verbal input, a parsing system parses the verbal chain from the start of the auditory signal to the end. The elements issued from this pars-

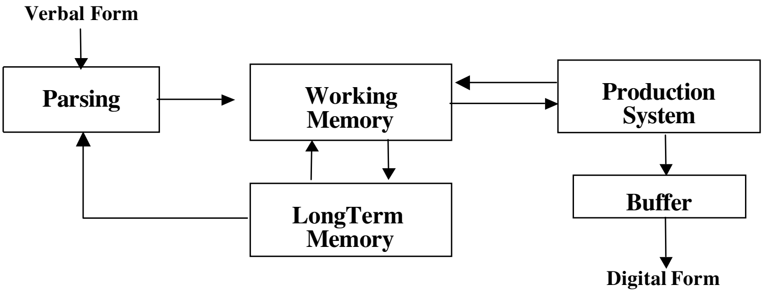

Fig. 1. Schematic view of different components in ADAPT model.

ing are sequentially sent to working memory, where they are stored temporarily before being processed. Following Anderson's (1993) ACT-R (adaptive control of thought–rational) model, this production system is composed of "condition–action" rules. Each rule is fired when the current content of working memory corresponds to its conditions. These rules generally aim at constructing the digital chain, which is produced at the end of the transcoding process (Table 1). More specifically, some rules (P1 in ADAPT) are devoted to the retrieval of information from long-term memory, for example, retrieving that *deux* (two) in the verbal form corresponds to the symbol "2" in the digital form but also "25" for *vingt-cinq* (twenty-five) or "500" for *cinq cents* (five hundred). Other rules manage the size of the digital chain and the number of slots. For example, in *deux mille trois* (two thousand and three), one rule is in charge of constructing a frame of three slots after "2" (2???). Those rules are called P2 and P3 when they manage chains or subchains containing *cent* (hundred) or *mille* (thousand), respectively. At the end of the transcoding process, P4 rules fill empty slots (if any) with intermediary 0s and issue the Arabic chain to be transformed in written output through grapho-motor procedures (Table 2). Moreover, the presence of information stored in working memory (yes or no) and the presence of a frame in the Arabic chain under construction (yes or no) constitute the conditions that define four different kinds (a–d) of P2 and P3 rules and three kinds of P4[2] rules (Table 1).

Within this framework, working memory maintains throughout the transcoding process the verbal units issued from the parsing of the verbal chain, the retrieved digital forms, and the digital chain under construction. Thus, because the amount of information that can be actively maintained is limited, working memory capacity should be an important constraining factor to account for errors in number transcoding. For example, the patient "L.R." described by Noël and Seron (1995) suffered from a reduction of his working memory capacity and showed specific transcoding difficulties. By computing the number of items stored (i.e., the load in working memory[3]) at each step of the transcoding process, and by interrupting it when this load exceeded a threshold (i.e., the working memory span measured during the clinical evaluation), ADAPT simulated 78% of the forms written by L.R. (Barrouillet et al., 2004). This example shows that working memory capacity affects transcoding, at least in an adult for whom the rules were acquired and the reduction of

[2] At the end of the transcoding, when P4 rules are used, there is always some information stored and/or a frame.

[3] The load is evaluated by adding the number of verbal units to maintain for further processing to the size of the chain under construction. One is added if a digital form is retrieved from long-term memory.

Table 1
Transcoding rules in ADAPT model

Rule	Condition			Actions
	Verbal unit	WMS	Frame	
P1	*Lexic*	—	—	Find value in LTM Store value in WMS
P2a	Cent	—	—	Chain = 1??
P2b	Cent	Yes	—	Chain = wms + ??
P2c	Cent	—	Yes	Chain = left [chain, length (chain − 3)] Chain = chain + 1??
P2d	Cent	Yes	Yes	Chain = left [chain, length (chain − 3)] Chain = chain + wms + ??
P3a	Mille	—	—	Chain = 1???
P3b	Mille	Yes	—	Chain = wms + ???
P3c	Mille	—	Yes	Chain = left [chain, length (chain − 2)] Chain = chain + 00???
P3d	Mille	Yes	Yes	Chain = left [chain, length (chain − 2)] Chain = chain + wms + ???
P4a	End	Yes	—	Chain = chain + wms
P4b	End	—	Yes	Change all ?s by 0s
P4c	End	Yes	Yes	Chain = left [chain, length (chain − wms)] Chain = chain + wms

Note. Lexic is a representational unit stored in long-term memory (LTM). WMS is the working memory store, a buffer for short-term storage. When information is stored in WMS, the WMS condition is "yes." When some slots are empty in the chain (represented by ?), the Frame condition is "yes." The action "Chain = left [chain, length (chain − wms)]" means to select the left part of the current chain for a length equal to the length of the chain minus the length of the information stored in WMS.

Table 2
Example of transcoding in ADAPT: The transcoding of *sept mille neuf cent quarante-sept* (seven thousand nine hundred and forty-seven)

Verbal input	Rule	Retrievals from LTM	Chain in progress
Sept	P1	7	
Mille	P3b		7???
Neuf	P1	9	
Cent	P2d		79??
If DUs are retrieved:			
Quarante-sept	P1	47	
End	P4c		7947
If DUs are algorithmically transcoded:			
Quarante	P1	40	
Sept	P1′	7	7940
End	P4c		7947

Note. The transcoding differs depending on whether the Arabic forms of the one- and two-digit numbers are directly retrieved from long-term memory. P1′ is a rule dedicated to the transcoding of DUs when they are not available in long-term memory (see $ADAPT^{LD}$ in Barrouillet et al., 2004).

working memory capacity was abnormal. However, the question remains open in children who differ in their working memory capacity and who are still in the process of learning transcoding.

The current study

In the current study, 7-year-olds transcoded numbers from the French verbal form to the Arabic digital form. Most of the numbers required three or four digits to be transcoded, although one- and two-digit numbers were also used to detect abnormal difficulties, as suggested by Noël and Turconi (1999). Indeed, such small numbers should be perfectly transcoded at 7 years of age. Moreover, because two-digit numbers frequently are encountered in isolation or as part of larger numbers, ADAPT predicts that their Arabic forms should be stored in and directly retrieved from long-term memory.

According to ADAPT, the dictated numbers required two to six procedural rules to be transcoded (Table 3), and the number of errors produced by the children should be predicted by the number of rules required. Moreover, as already observed in more complex activities, children with low working memory capacity should produce more errors than should children with high working memory capacity. Indeed, we assume that working memory capacity affects the efficiency of both the algorithmic processing and the retrieval from long-term memory, as well as storage capacity and the amount of available attentional resources, with all of these factors having an impact on transcoding efficiency, according to ADAPT. Finally, children with low working memory capacity should exhibit even more errors when the attentional demand of the task increases. That is, when the numbers require more transcoding rules, these children's limited working memory capacity would impede every single step of processing. It should be noted that a conception purely in terms of individual differences in storage capacity would also predict such an interaction between the working memory span and the number of transcoding rules because the load depends entirely on the number of rules.

Concerning the types of errors the children would make, two alternative hypotheses could be made. It might be suggested that the errors produced by children with high working memory capacity would differ only in their rate, but not in their nature, from those produced by children with low working memory capacity. Indeed, if both groups had acquired the same rules, a reduction of working memory capacity would affect the overall efficiency of transcoding by slowing down the retrievals and the processing of the rules and by increasing the forgetting of forms, but it would produce the same types of errors. On the contrary, if the two groups did not reach the same level of learning of the transcoding rules, they would differ in both the rate and the nature of their errors. In the latter case, individual differences in working memory capacity would be responsible for differences in both the efficiency and the learning of the transcoding rules.

Method

Participants

A total of 71 French second graders (40 girls and 31 boys) participated in this study. Their mean age was 7 years 11 months ($SD = 5$ months). They came from three different middle class schools, and informed consent was received from their caregivers. An additional 4 children were eliminated from the sample because they attended only one of the two experimental sessions.

Table 3
The 78 one- to four-digit numbers dictated in the transcoding task according to the categories defined by ADAPT

Category	P1	P2	P3	P4	Total	Dictated numbers	
U	1	0	0	1	2	3	4
P	1	0	0	1	2	14	13
D	1	0	0	1	2	40	20
DU	1 (2)	0	0	1	2 (3)	62	27
H	0	1	0	1	2	100	100
HU	1	1	0	2	4	108	105
HP	1	1	0	1	3	112	116
HD	1	1	0	1	3	150	160
HDU	1 (2)	1	0	1	3 (4)	164	122
UH	1	1	0	1	3	800	400
UHU	2	1	0	2	5	705	303
UHP	2	1	0	1	4	613	715
UHD	2	1	0	1	4	230	420
UHDU	2 (3)	1	0	1	4 (5)	768	632
M	0	0	1	1	2	1000	1000
MU	1	0	1	2	4	1008	1001
MP	1	0	1	2	4	1012	1014
MD	1	0	1	2	4	1020	1060
MDU	1 (2)	0	1	2	4 (5)	1089	1057
MH	0	1	1	1	3	1100	1100
MHU	1	1	1	2	5	1104	1102
MHP	1	1	1	1	4	1114	1115
MHD	1	1	1	1	4	1130	1160
MHDU	1 (2)	1	1	1	4 (5)	1181	1159
UM	1	0	1	1	3	8000	5000
UMU	2	0	1	2	5	4003	5001
UMP	2	0	1	2	5	2011	7012
UMD	2	0	1	2	5	6060	2010
UMDU	2 (3)	0	1	2	5 (6)	7035	9049
UMH	1	1	1	1	4	2100	7100
UMHU	2	1	1	2	6	8101	5104
UMHP	2	1	1	1	5	3111	6113
UMHD	2	1	1	1	5	4130	6180
UMHDU	2 (3)	1	1	1	5 (6)	3147	5127
UMUH	2	1	1	1	5	7600	2700
UMUHU	3	1	1	2	7	3708	6503
UMUHP	3	1	1	1	6	8216	2914
UMUHD	3	1	1	1	6	6980	2660
UMUHDU	3 (4)	1	1	1	6 (7)	7947	5635

Note. For each category, the number and type of procedural rules required to transcode numbers are specified when the DUs are retrieved from long-term memory. Shown in parentheses are the numbers of rules if the DUs are algorithmically transcoded. U, unit; P, particular; D, decade; H, hundred; M, thousand. P1 rules are responsible for retrievals from long-term memory, P2 rules are responsible for managing hundreds (H), P3 rules are responsible for managing thousands (M), and P4 rules are stop rules.

Materials and procedure

During the first session, a counting span task was administered individually to evaluate the capacity of working memory. In a recent study about the relations between numerical cognition and working memory, Barrouillet and Lépine (2005) used a reading letter span task and a counting span task. Although the counting span task relies on mathematical knowledge, this study showed that it was slightly less correlated with arithmetical abilities than the non-numerical span task (i.e., reading letter span task). However, the poor mastery of reading in second graders meant that it was not possible to use this latter task. During the second session, which took place approximately 1 month later, the transcoding ability of each group of children was evaluated through a collective test in their own classroom.

Counting span task

Children were presented with arrays of red and green dots and were asked to point at the red dots with a finger and to count them out loud. The arrays contained 5 to 12 red dots, with twice as many green dots (0.6 cm diameter) randomly displayed on cardboard squares with sides of 14 cm. Children were instructed that they needed to maintain the number of targets in each array for further recall. When a card with the word "Recall" was presented to them, they needed to recall these numbers aloud in their order of appearance on the arrays. In the case of errors in counting, recall was scored correct if children recalled the erroneous count. Series of arrays were presented in a booklet, the pages of which were turned by the experimenter. They increased from two to six, with three series of each length.

Two one-item and two two-item training series preceded the experimental series. Testing was terminated when children failed to recall the items of all three series at a particular length. Each experimental series correctly recalled was given a score of one-third, and the thirds were added together to provide a span score (Barrouillet et al., 2004; Kemps, De Rammelaere, & Desmet, 2000; Smith & Scholey, 1992). Because the counting span task started at length 2, we added 1 to the sum of thirds. For example, the correct recall of all three series of two items, and of two three-item series, resulted in a span of 2.67, that is, $1 + [(3 + 2) \times 1/3]$.

Transcoding task

A total of 78 one- to four-digit numbers were dictated in a fixed random order. Overall, 2 numbers were one digit, 6 were two digits, 20 were three digits, and 50 were four digits (Table 3). According to ADAPT, these numbers require two to seven different transcoding rules. The association of these different rules defines 39 categories of numbers. For example, the category HU (hundred unit) requires one P1 rule, one P2 rule, and two P4 rules, whereas the category HP (hundred particular) requires one P1 rule, one P2 rule, and only one P4 rule (Table 3). For each category, two numbers were randomly chosen except for *cent* (one hundred) and *mille* (one thousand), which are the only exemplars of their respective categories. These two exceptions were then repeated to have an identical number of items in each category.

Each child received a nine-page leaflet in which they needed to write their answers on successive lines. At the beginning of each line, a drawing helped children to keep track of the dictation. Before dictating each number, the experimenter specified where to write (e.g., "Now, it is the pig, eight thousand"). Each number was repeated twice. To reduce errors due only to the forgetting of the verbal dictated forms, and to make sure that children wrote down their answers on the correct line, the verbal form of each number was printed after the drawing on each line. The experimenter verified that children had sufficient time to write down their answers before dictating the next number. This second session took place on 3 successive days, with 26 numbers dictated each day.

Results

Descriptive data

On average, children produced 2006 errors, that is, 36.2% errors ($SD = 27.8$) on the 78 numbers, including 1.9% nonresponses ($SD = 5.4$). Due to the fairly small amount of nonresponses and the fact that all effects were identical when analyses were performed without the nonresponses, only results on the total number of errors (including nonresponses) are reported here.

Children did not produce any errors on one-digit numbers, and only 9 children produced an error on two-digit decade unit (DU) numbers. These errors were lexical, for example, writing "26" for *vingt-sept* (twenty-seven) or "72" for *soixante-deux* (sixty-two). The latter was the main error (2 occurrences) on two-digit numbers and is quite understandable because "72" (*soixante-douze*, literally sixty-twelve) is phonologically similar to *soixante-deux*. Thus, the children involved in this study did not present any abnormal difficulties in number transcoding. As previous studies observed, children produced significantly fewer errors on three-digit numbers (22.4%, $SD = 23.7$) than on four-digit numbers (47.2%, $SD = 34.8$), $t(70) = 8.51$, $p < .0001$.

Relations between the number of rules in ADAPT and the rate of transcoding errors

The observed pattern of results with a lack of errors in DU forms could indicate that the children directly retrieved the Arabic forms from long-term memory instead of algorithmically transcoding them. In ADAPT, the number of rules needed to transcode all of the dictated numbers was evaluated, with the DUs being either algorithmically transcoded or directly retrieved from long-term memory (Table 3). In the former, the transcoding of the 16 numbers that involved a DU required one more supplementary rule than was the case in the latter. Thus, the correlations between the number of errors and the number of rules were very similar and fairly high, $r = .787$, $p < .0001$ when DUs are algorithmically transcoded, $r = .789$, $p < .0001$ when they are directly retrieved. Nevertheless, a slightly higher correlation emerged when the two complex DUs specific to the French system from France (the *quatre-vingt*, the eighties) were supposed to be algorithmically transcoded, whereas the other DUs are retrieved, $r = .811$, $p < .0001$. Moreover, in a forward multiple regression analysis on the three- and four-digit numbers, the percentage of errors was positively correlated with the number of P2 to P4 rules, $r = .679$, $F(2, 67) = 58.31$, $p < .0001$, and with the number of P1 rules, $r = .751$ (R^2 change = .10), F enter = 15.60, $p = .0001$.

To summarize, ADAPT provided a good account of transcoding errors in children. Moreover, at 7 years of age, the French children probably have stored the Arabic forms of the smaller and most frequent DU numbers and directly retrieved them from long-term memory. However, the complex numbers specific to the French system are still algorithmically transcoded, thereby inducing the large number of errors observed (62.7% errors for the two four-digit numbers that included these complex forms vs. 46.6% for the other four-digit numbers). As Seron and Fayol (1994) observed, these complex forms specific to French in France are mastered late by children.

Relations between working memory capacity and the rate of transcoding errors

To evaluate the impact of working memory capacity on transcoding, three groups were defined using the z scores of their spans. In the entire sample, the spans varied from 1.00 to 3.33 ($M = 2.10$, $SD = 0.50$). Those children who obtained a z score greater than 0.67 comprised the high-span group, whereas those children who obtained a z score less than −0.67 comprised the low-span group. The procedure resulted in the selection of 21 children with low scores ($M = 1.56$, $SD = 0.19$), 15 children with high scores ($M = 2.85$, $SD = 0.21$), and the remaining 35 children in the medium-span group ($M = 2.10$, $SD = 0.19$).

An analysis of variance (ANOVA) was carried out on the percentage of errors made on three- and four-digit numbers with group as the between-subject factor and number of rules as the within-subject factor. The percentage of errors was significantly higher in low-span children (46.9%) and medium-span children (36.5%) than in high-span children (20.7%), $F(2, 68) = 4.61$, $p = .013$, $\eta_p^2 = .12$ (Fig. 2). It increased significantly with the number of rules required to transcode numbers, from 8.5% for two-rule numbers to 57.8% for seven-rule numbers, $F(5, 340) = 53.18$, $p < .0001$, $\eta_p^2 = .44$. As predicted, the interaction between the number of rules and the groups was significant, $F(10, 340) = 2.66$, $p = .004$, $\eta_p^2 = .07$. The percentage of errors increased with the increasing number of rules in the low-span group, $F(5, 100) = 23.13$, $p < .0001$, $\eta_p^2 = .54$, the medium-span group, $F(5, 170) = 42.68$, $p < .0001$, $\eta_p^2 = .56$, and the high-span group, $F(5, 70) = 6.16$, $p < .0001$, $\eta_p^2 = .31$, respectively. Moreover, the difference between the

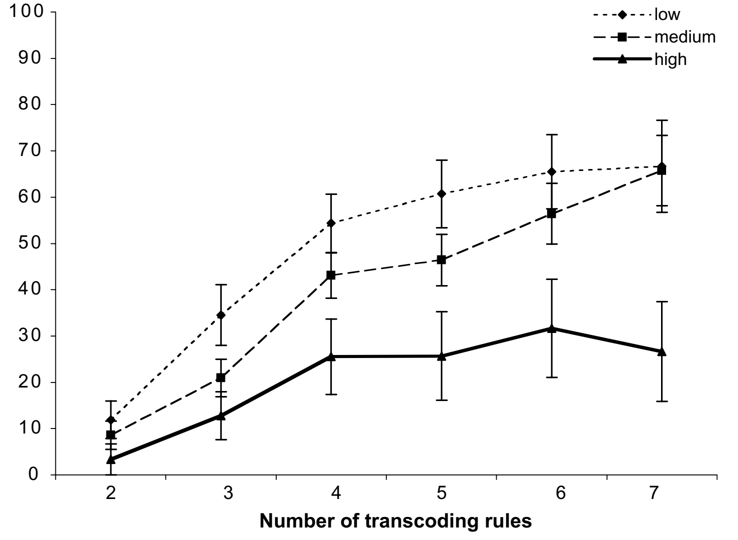

Fig. 2. Mean percentages of errors as a function of memory span group and number of rules (two to seven rules).

high- and low-span groups in error rate was significant for each number of rules, *p*s < .02, except for two rules, $p = .14$.

These results were confirmed by correlational analyses. Overall, working memory span correlated with the percentage of transcoding errors, $r = -.34$, $p < .01$, a correlation that reached significance for digits requiring three to seven transcoding rules, *r*s between −.250 and −.341, *p*s < .05, but not for two-rule digits, $r = -.127$, $p = .29$.

Qualitative analysis of transcoding errors in high- and low-span children

To complete these quantitative analyses, a qualitative analysis of the errors produced by the high- and low-span groups was performed on the three-digit numbers (43 and 132 erroneous forms, i.e., 14.3 and 31.4%, respectively) and four-digit numbers (197 and 632, i.e., 26.3 and 60.2%, respectively), for which the two groups differed significantly in the number of errors made, $t(34) = 2.16$, $p = .038$, and $t(34) = 2.96$, $p = .006$, respectively. The number of lexical errors was very small for both the low-span group (7 and 5 errors in three- and four-digit numbers, respectively) and the high-span group (2 and 6 errors in the corresponding numbers). All of the analyzed errors were syntactic. Furthermore, only the types of error that were made at least twice within a number category were classified, that is, not the types of error made twice for the same number because it would greatly reduce the amount of errors to analyze.

Concerning the three-digit numbers, 70% of the errors produced by the high-span group and 75% of those produced by the low-span group were classified (Table 4). Two main types of errors were made: adding 0s such that there was one or two 0s after the digit standing for the hundreds (e.g., adding two 0s for one hundred and twelve [written 10012], adding one 0 for one hundred and five [written 1005] or for seven hundred and fifteen [written 7015]) and adding one 1 (e.g., for six hundred and thirty-two [written 6132]). No significant difference appeared between the two groups on the distribution of the errors, $\chi^2(1) = 1.92$, $p > .10$.

Within the four-digit numbers, 37% (72/197) and 61% (383/632) of the erroneous numbers produced by high- and low-span individuals, respectively, were classified (Table 4).

Table 4
Percentage of errors committed for each type of error by the low- and high-span groups in the three- and four-digit numbers

Type of error	Three-digit numbers ($n = 20$)		Four-digit numbers ($n = 50$)			
			Hundred		Thousand	
	High ($n = 15$)	Low ($n = 21$)	High ($n = 15$)	Low ($n = 21$)	High ($n = 15$)	Low ($n = 21$)
Adding 0s	67	73	60	25	79	92
Adding 1	33	19	0	1	6	1
Discarding a digit			0	35		
Changing a digit	0	2	40	19	15	3
Committing complex errors			0	16		
Miscellaneous	0	4	0	4	0	4

Note. Complex errors involved placing one, two, or three 0s between the thousands digit and the hundreds digit and discarding the decade digit (e.g., eight thousand two hundred and sixteen written 80026).

Among them, 6 productions for the high-span group and 51 productions for the low-span group showed two different errors on the same number. More errors occurred for the thousands part (68 and 239 occurrences for the high- and low-span groups, respectively) than for the hundreds part (10 and 195 for the corresponding groups), especially in the high-span group, $\chi^2(1) = 28.40$, $p < .001$. These two types of errors were analyzed separately. Moreover, errors that did not affect the processing of the hundreds or thousands part also occurred (e.g., adding a 0 in DUs, writing only one or two digits), but they were rare, produced only by the low-span children, and classified as miscellaneous (Table 4).

Concerning the errors on the thousands part, the distribution of errors between the two main error types varied significantly between the two groups, $\chi^2(1) = 16.19$, $p < .001$ (Table 4). First, children in the high-span group changed the 0 after the digit standing for the thousands by 1 more frequently (e.g., seven thousand and thirty-five [written 7135], changing a digit in Table 4). This occurred only when *mille* was preceded by another verbal unit (i.e., when the number started with a digit other than 1) as in *quatre mille trois* (four thousand and three). In ADAPT, this error was simulated by a transformed rule P3b in which one 1 and two slots were added instead of three slots, that is, the action part of the rule P2d. Second, although both groups added 0s after the digit standing for the thousands, the low-span group differed from the high-span group by a greater variability on the number of added 0s. Indeed, in the low-span group, one 0 (13 errors), two 0s (65 errors), three 0s (115 errors), and even four 0s (28 errors) stood after the first digit, whereas in the high-span group, 42 of 54 such errors involved three 0s, $\chi^2(3) = 21.60$, $p < .001$. Having three 0s after the digit standing for the thousands (e.g., seven thousand and twelve written 700012, one thousand and one written 10001) was the main error in both groups, but the low-span individuals produced it twice as often as did the high-span individuals (11.0 vs. 5.6% of the written four-digit numbers). In ADAPT, this error is due specifically to an overload because of a restricted amount of working memory capacity. The dictation of the 50 four-digit numbers was simulated in ADAPT as for the patient L.R. (Barrouillet et al., 2004). By varying the span (i.e., threshold) from 0 to 5 by 0.1 steps, different proportions of the "having three 0s" error were obtained. The rate for this error was highly correlated with the span measure, $r = -.879$, $F(1, 49) = 166.06$, $p < .0001$, showing that the limit of working memory capacity is responsible for this specific and frequent error.

Finally, the second most frequent addition of 0s was to add four 0s (10 errors of 54 addition of 0s errors, i.e., 19%) after the digit standing for the thousands in the high-span group, whereas it was to add two 0s (65 errors of 221 addition of 0s errors, i.e., 29%) in the low-span group. However, the manipulation of working memory span in the simulation never produced such an occurrence of two or four 0s. These results show that the low-span group suffered both from an overload due to reduced working memory capacity and from a lack of acquisition of rules. These points are addressed in the following discussion.

Concerning the errors on the hundreds part within the four-digit numbers, the distribution of errors among the four main types differed significantly between the two groups, $\chi^2(3) = 10.85$, $p < .02$ (Table 4). As observed previously for the three-digit numbers, having two 0s after the digit for the hundreds was the major error in the high-span group (60% of errors) and also was rather frequent in the low-span group (25% of errors). This specific error always was combined with the addition of 0s for the thousands part. More often, three 0s were placed for the thousands part, for example, two thousand six hundred and sixty written 200060060, which led to the literal transcription of the numbers (4 of 6 errors for the high-span group and 30 of 47 errors for the low-span group). Variation in working memory span in the ADAPT simulation showed that the rate of making "having two 0s" errors was highly correlated with the span measure, $r = -.939$, $F(1, 49) = 368.54$, $p < .0001$. However, contrary to the children's productions, this error was not systematically associated with the addition of 0s after the thousands unit. On average across spans, only half of the erroneous forms produced by the simulation (50.9%) showed the two types of errors. Consequently, the difference in spans can partially account for this error.

In addition to the addition of 0s, other types of errors were produced by the low-span children. Interestingly, errors that seemed different from a purely descriptive point of view (Table 4) emerged from the same deficiency in ADAPT. Thus, a second type of error was discarding a digit, mostly one 0, that led children to write three digits instead of four digits. Some errors came from the disappearance of the 0 in the second position, and others affected the 0 in the third position (34 and 11 errors, respectively). Both types of errors were simulated by ADAPT. The former emerged when the rules for the thousands (P3) produced only two slots instead of three slots, that is, as the rules for the hundreds (P2). The latter came from erroneous P2c and P2d rules that govern the processing of the hundreds for numbers with a thousand in them for which one slot was added instead of two slots (e.g., for P2c, Chain = chain + 1?). Interestingly, these erroneous P2 rules also produced all of the errors involving the discarding of one 1. Moreover, by modifying the length of the chain selected to be processed by these P2 rules (e.g., Chain = left [chain, length (chain − 2)] for P2c), ADAPT simulated most of the "changing a digit" errors (i.e., changing 1 to 0: 2 errors in the high-span group and 28 of 36 errors in the low-span group) and half of the complex errors (16 of 32 errors). Most of the remaining complex errors were the conjunction of the erroneous P2 rule and the use of four slots instead of three slots in the P3 rules (9 errors). Overall, low-span individuals made more errors on the hundreds part in the four-digit numbers than in the three-digit numbers, with the reverse being observed in high-span individuals, $\chi^2(1) = 26.36$, $p < .001$.

Discussion

Although a large literature has described adult patients' deficiencies in transcoding numbers after various injuries, the current study is the first to investigate individual differences in children's number transcoding. Three main phenomena arose from the current results. First, the ADAPT model gave a fair prediction of transcoding performance in 7-year-olds. Second, children with low working memory capacity were poorer at transcoding than were children with high working memory capacity. Third, these two groups of children also differed on the types of errors made. These three issues are now discussed in turn.

Further evidence in favor of ADAPT

ADAPT is a procedural model that describes number transcoding as a multiple-step process relying on several procedural rules. For each number, a sequence of different rules is required. In the current study, the number of rules predicted the rate of errors, replicating previous findings in children of a similar age (Barrouillet et al., 2004). This sole factor accounted for more than 60% of the variance in the rate of errors. Moreover, the fit between the number of rules and the rate of errors was slightly better achieved by a version of ADAPT in which the DUs are directly retrieved from long-term memory rather than algorithmically transcoded. Although this point was tested more extensively elsewhere (Barrouillet et al., 2004), the current results converge in the same direction. From 7 years of age onward, French children have already stored the digital form of the DUs and retrieve them in their transcoding.

Finally, the error pattern brought some evidence against the semantic models of transcoding (McCloskey, 1992; McCloskey et al., 1985; Power & Dal Martello, 1990). Indeed, the types of errors committed in the hundreds part of the four-digit numbers are qualitatively different (Table 4) from those committed in the three-digit numbers, although the numerical meanings per se are identical. For example, "one hundred and twenty-two" represents the exact same quantity when it occurs in isolation as when it is inserted within "five thousand one hundred and twenty-two" (i.e., one hundred, two decades, and two units). However, some errors, such as discarding or changing a digit and committing complex errors (Table 4), occurred only in the four-digit numbers, whereas others, such as adding 1, occurred only in the three-digit numbers. This difference can be accounted for only if different processes underlie the transcoding of the hundreds part of a number when it is either inserted in a longer verbal expression leading to four-digit numbers or displayed alone. ADAPT is the only model that makes such a distinction, with P2a and P2b rules activated if the hundreds part is alone and P2c and P2d rules activated if it is inserted in larger numbers. It should be noted that adding 0s, and more specifically "having two 0s," occurred in both the three-digit numbers and the hundreds part of the four-digit numbers. However, it is rather difficult to use this fact as an argument in favor of a semantic view because this error is the most frequent one overall. It occurred even in the thousands part of the four-digit numbers, which involves a different numerical representation from the three-digit numbers.

Overall, the current set of data favors the ADAPT model in its procedural and asemantic aspects. More interestingly, the current study sheds light on the impact of individual differences in working memory capacity in number transcoding.

The efficiency of transcoding is affected by working memory capacity

As ADAPT predicts, children with low working memory capacity made more transcoding errors than did children with high working memory capacity. Furthermore, this difference between groups increased with the number of rules required. Such a difference between children and adults with high working memory capacity and those with low working memory capacity has already been observed in other cognitive tasks (for a review, see Jarrold & Towse, 2006), especially in mathematical cognition (Bull et al., 1999; Bull & Scerif, 2001; Case et al., 1982; DeStefano & LeFevre, 2004; McLean & Hitch, 1999). Most of these studies concern complex mental arithmetic. Quite recently, new data showed that such differences also occur in more elementary mathematical activities such as simple operation solving relying on the direct retrieval of the answer from long-term memory (Barrouillet & Lépine, 2005). Thus, the current study represents a further example of an elementary activity in which individual differences in working memory capacity affect performance.

Other transcoding models might predict an impact of working memory capacity on transcoding (Deloche & Seron, 1982; McCloskey, 1992; Power & Dal Martello, 1990). For example, they might agree that the verbal input needs to be maintained temporarily to be transcoded. However, they are underspecified in the cognitive processes that underpin such an effect. More specifically, none of these models has ever explicitly mentioned a potential role for working memory. In contrast, ADAPT predicts that the difference in performance between high- and low-span children arises from three loci. Because ADAPT describes transcoding as a multi-step process relying on the retrieval of information from long-term memory and requiring the storage of intermediary information issued from the parsing and the procedural rules, individual differences in working memory capacity could affect the efficiency of the procedural rules, the retrieval process, and the storage of the intermediary products.

High-span children could exhibit more efficient transcoding rules (e.g., less costly, faster) because their overall pool of cognitive resources is larger (Halford, 1993; Pascual-Leone, 1978) or because processing is less demanding (Case et al., 1982), thereby freeing some resources that could be dedicated to the maintenance of the intermediary products. High-span children could also have more attentional resources available for retrieval (Barrouillet & Camos, 2001; Gavens & Barrouillet, 2004). In a network of memory traces as described in ACT-R (Anderson, 1993), the spreading of more sources of activation would permit the retrieval of a better representation, and this could be retrieved faster as well (Cantor & Engle, 1993). Alternatively, high-span individuals could be more resistant to interference (Kane & Engle, 2003), and this also facilitates the retrieval of the digital forms among such a rather confusing network due to the high similarity of the representations. The capacity of the storage per se could also be greater in these children (Bayliss et al., 2003, 2005). Because the dictated verbal form, the products of the parsing, the retrieved digital forms, and the chain under construction need to be maintained more or less simultaneously, any reduction in storage capacity would impair the transcoding.

This study does not allow us to pinpoint the exact locus of the individual differences. It could even be suspected that not only one locus but actually several loci underpin these differences (Bayliss et al., 2003, 2005; Cowan et al., 2005). The interaction between working memory span and the number of rules could favor any of the three loci of individual differences (rules efficiency, storage, and retrieval). Indeed, each rule constitutes a further step in the transcoding process that increases both the number of items stored temporarily and the number of retrievals. However, the fact that the simulation in which the load is evaluated by the amount of information maintained simultaneously provided a good fit to the data suggests that storage capacity per se is a strong limit to transcoding. Further investigation is needed to test this point.

Finally, although the counting span task is not a better predictor of numerical cognition than are other non-numerical working memory span tasks (Barrouillet & Lépine, 2005), it remains possible that these results depend partly on the numerical nature of the processing component of the working memory span task we used. In the counting span and transcoding tasks, number words must be maintained for further recall and for processing by the production rules, respectively. However, the qualitative differences in the errors made by the two groups sheds some light on this issue. Because high- and low-span children differed in the transcoding rules they used, it is more probable that their difference is more general than being restricted to the storage of numerical information. This point is discussed in the following section.

The learning of procedural rules depends on working memory capacity

As in previous studies, very few lexical errors were made, and no major difference in the production of this type of error was observed between the children with high working memory capacity and those with low working memory capacity. Thus, the basic mental lexicon required in this task does not differ between the groups, at least at 7 years of age. It might be that differences will occur in preprimary school learning of the symbols, but as yet no work has been carried out in this area.

Concerning the syntactic errors, five main types of errors were described, and although high- and low-span groups differed in the number of errors in both the three- and four-digit numbers, it was only in the latter that they differed in the types of errors made. Interestingly, in ADAPT, errors that looked similar emerged from different sources, whereas different errors emerged from the same source. Overall, the errors emerged from only three main sources.

First, as shown by the computational simulation, adding two 0s in the hundreds part and three 0s in the thousands part of the four-digit numbers resulted from a cognitive overload due to a restricted capacity in working memory or, more specifically, to a restricted storage capacity during transcoding (i.e., the threshold parameter in the simulation). Cognitive overload represents the major source of errors in the high-span children (up to 58% of the classified errors vs. 40% in the low-span children). It could seem quite counterintuitive that the children with higher working memory capacity would suffer more from an overload than would the children with lower working memory capacity. However, it must be kept in mind that, overall, the low-span children made twice as many errors as did the high-span children (47 vs. 21%). Moreover, the results suggest that, at 7 years of age, high-span children have already acquired all of the transcoding rules (even for the four-digit numbers), with their difficulties coming from the load induced by recently acquired and demanding rules. Conversely, the children with low working memory capacity were still in the process of acquiring some of the rules. Thus, their errors came either from the inappropriate use of correct rules firing in the wrong situation or from the use of incomplete rules, as the analyses of the two other sources of errors showed.

The second source involves the management of the number of slots, and it induces discarding a digit in the hundreds part or adding four or two 0s in the thousands part of the four-digit numbers. These errors were more frequent in low-span children than in high-span children (36 vs. 16% of the classified errors). It should also be noted that the high-span children always set a larger number of slots than is required, whereas the low-span children used mainly a smaller number of slots than is required (e.g., when the P3 rule raised two slots instead of three slots, when the P2c or P2d rule raised one slot instead of two slots). This discrepancy suggests that the high-span children have already learned rules dedicated to four-digit numbers in which the number of slots is not yet settled, but they already know that the final chain must be more than two or three digits. In contrast, the low-span children set a number of slots as prescribed in the rules dedicated to smaller numbers. These children still do not have specific rules to produce four-digit numbers. Thus, because the current information partially matches the conditions of activation of previously acquired rules (rules dedicated to the two- and three-digit numbers), these rules fire in the wrong situation following a process of partial matching (Anderson, 1993).

The final source of error concerns the action part of the rules (e.g., a change in the length of the chain for the P2c rule). This type of error leads to a digit change in four-digit numbers and to the production of complex errors. We have seen that these errors are more frequent in low-span children than in high-span children. As already argued, low-span children suffer from a delay in rule acquisition. Even for the rules dedicated to the hundreds (P2 rule), the actions are not well established, although these rules are acquired before the P3 rule for the thousands. Finally, the conjunction of these two last sources of difficulty can occur in the same production (e.g., an error in the action of the P2 rule and in the number of slots). Interestingly, this conjunction was observed only in low-span children.

Thus, the results indicate that low-span children are late in the acquisition of the transcoding rules compared with high-span children. More specifically, the current data suggest that low-span children exhibit difficulties in the process of generating advanced rules (P3 rules) that manage the four-digit numbers, whereas the rules for the three-digit numbers are learned but their use is highly demanding. In line with the ACT-R model, ADAPT assumes that new procedural rules derive from declarative knowledge on which analogy processes apply. More advanced procedures would be constructed by coordinating already existing procedures. Thus, this coordination of procedural knowledge would be less efficient in children with low working memory capacity. As already mentioned, this difficulty could be restricted to numerical activities. However, the process of coordination is described as one of the key functions of the central executive and often is considered to be domain general (Baddeley, 1996; Miyake et al., 2000).

Conclusion

Working memory has an important impact on academic achievement in mathematics and numerical activities. For example, counting, addition problem solving, multidigit operations, and word problem solving all are affected by individual differences in working memory capacity (Barrouillet & Lépine, 2005; Bull & Scerif, 2001; DeStefano & LeFevre, 2004; Geary et al., 1991, 1999; Lépine et al., 2005). It was shown in this study that this relation between working memory and numerical activities extends to the simplest abilities such as transcoding numbers. This suggests that the impact of working memory capacity on mathematical academic achievement is at least partly mediated by the involvement of working memory in elementary skills and activities. Consequently, practitioners should be aware of the fact that individual differences arise from the very first numerical abilities taught to children. However, it should be noted that when transcoding relies on the retrieval of information from long-term memory (e.g., for the DUs), these differences disappear. Classically, working memory is highly involved in the procedural aspects of cognitive activities because they are highly demanding. In contrast, more automatized processes are less affected by working memory capacity except on their speed. Thus, practitioners should favor the automatization of transcoding by any teaching method that would quickly lead children to use a retrieval strategy for the simplest forms (i.e., the DUs) instead of applying algorithmic strategies. Relying on the direct retrieval of answers from long-term memory would diminish the cognitive demand of the transcoding and, thus, reduce the impact of individual differences.

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