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Two routes for the processing of verbal numbers: evidence from the SNARC effect

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Abstract The functional locus of the semantic system is an important issue in number processing. In the present article, the necessity of addressing a central semantic magnitude system in the processing of printed verbal number words is evaluated by looking at the presence of a spatial-numerical association of response codes or SNARC effect. This effect consists of an association of number magnitude and response-preference (preferred responses to small numbers with the left hand and to large numbers with the right hand) and reflects semantic access. Two experiments were run. In Experiment 1, participants performed a parity judgment task which requires access to number semantics. A SNARC effect was observed. In Experiment 2 a phoneme monitoring task was used, which can, in principle, be performed through direct asemantic transcoding. No SNARC effect occurred. Apparently, written number words access the semantic system only if this is necessary for correct task completion. Hence, a semantic and an asemantic route can be postulated for the processing of word numerals. These observations contrast with the processing of Arabic numerals for which semantic effects are omnipresent. Implications of this explicit demonstration of a dissimilarity between the processing of digits and of number words are discussed.

Introduction

The key function of mental number processing is to express quantities of elements, abstract or concrete, and their mutual relations. Evidence is now accumulating that the mental representation of quantity or magnitude is best conceived of as a left-to-right oriented, compressed, analogue number line (Dehaene, 1992), although alternative possibilities have been proposed (see e.g., McCloskey, 1992, for a base-ten representation of number magnitude). The compressed nature of the number line follows from the finding that number magnitude effects usually are not linearly related to the magnitude itself, but to some compressive function of the magnitude (e.g., the logarithm, Brysbaert, 1995; or a power law with exponent less than one, Krueger, 1989). The analogue characteristic follows from the finding that, at least for Arabic numbers of up to two digits, the time to compare two numbers in terms of magnitude decreases as a function of the numerical distance between the two numbers and cannot be explained by making reference to the constituting digits (Dehaene, Dupoux, & Mehler, 1990). Finally, the left-to-right orientation follows from the observation that small numbers are preferentially responded to with the left hand, whereas the reverse is true for large numbers (Dehaene, Bossini, & Giraux, 1993; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). Of course, numbers have other semantic attributes than magnitude, e.g., parity status, whether or not a number is a prime number, arithmetic tables, encyclopedic knowledge, etc. How this information is mentally represented and how it relates to magnitude information is still unclear.

This internal semantic information can be externally represented by a variety of surface forms, of which Arabic (digits) and verbal numbers (number words) are the most frequently used. Number comprehension, then, comes down to locating the number at the appropriate position on the number line. The Arabic and the verbal notational system share the general feature of being a non-ideographic, symbolic system. Both make use of symbols that are arbitrarily related to the concepts they express. Furthermore, both notational systems allow for the construction of an infinite number of stimuli on the basis of a small, finite set of symbols and rules.

Despite these commonalities, however, there are essential discrepancies between the notational systems.

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The Arabic system is a logographic notational system. This implies that the smallest units of representation (i.e., digits) are themselves related to a meaningful concept. In alphabetic systems, like the verbal notational system, the smallest representational units (i.e., letters) are not directly related to a concept. Only specific combinations of letters convey meaning. The logographic-alphabetic distinction can be expected to cause fundamental differences in the processing of Arabic and written verbal numbers. The fact that a digit pops out between letters and vice versa (Jonides & Gleitman, 1972) is indicative in this respect, as are electrode recording of human extrastriate visual cortex who show early segregation of letter and digit processing (Allison, McCarthy, Nobre, Puce, & Belger, 1994) and the performance of pure alexic patients who often show a relative sparing of reading Arabic numerals as compared to reading alphabetic characters (see e.g., Cohen & Dehaene, 1995).

The lexico-syntactic principles underlying the construction of larger numbers from the basic elements is a further difference between the Arabic and verbal notational system (Butterworth, 1999). The Arabic system uses place-value for powers of ten: from right to left in a multidigit number, each digit represents a multiplicative relationship with increasing powers of ten. This is essentially different from the name-values for powers of ten (ten, hundred, thousand, etc.) used in the verbal number system. Moreover, the place-value system guarantees a perfect regularity in the Arabic number system, whereas number words of most European languages are characterized by a relatively frequent occurrence of irregularities [for instance, 2,000 in Dutch is 'twee duizend' (two thousand) whereas 1,000 is 'duizend' (thousand) and not 'een duizend' (one thousand)]. Due to such irregularities, the decimal structure of the verbal number system is not as transparent as it is for digits.

Given these basic differences, one might expect substantial differences in the processing characteristics of Arabic numbers and number words. In this context, it is surprising to observe that all available models on numerical cognition (Cipolotti & Butterworth, 1995; Dehaene, 1992; McCloskey, 1992) are characterized by a high degree of similarity for Arabic and verbal number processing. None of these models incorporates differences in available processing pathways. Nor do they explicitly postulate differential processing properties within the available pathways.

Broadly speaking, two theoretical positions have been taken according to the functional locus that is attributed to the internal semantic magnitude information. Central semantics models, with McCloskey's (1992) model as prototype example, assign a central role to semantic information. After modality-specific encoding by specially devoted encoding modules for Arabic and verbal numbers, numbers are necessarily translated to an amodal representation of numerical meaning, which is the basis for all numerical operations. For output, this information can be sent to modality-specific output modules for the production of Arabic or verbal numbers. In one of his reports McCloskey suggests the existence of a direct connection between written verbal input and spoken verbal output, following the literature on word recognition (1992, pp. 114). However, this assumption was not directly empirically investigated and was not incorporated in the model.

Opposed to the central semantics view are those models that assume additional asemantic processing routes. For instance, Cipolotti and Butterworth's (1995) multiple route model extends McCloskey's model with asemantic connections. Such connections are postulated between all possible surface forms (Arabic, written verbal and spoken verbal). Unless differences in relative strength of available pathways are explicitly defined, this model reflects a close functional parallelism in the processing of Arabic and verbal numerals. Dehaene's triple code model postulates connections between three types of stored numerical knowledge: Arabic, auditory verbal and abstract magnitude information (Dehaene, 1992). Again, no fundamental structural differences are incorporated. It should be noted, however, that in a recent anatomo-functional elaboration of the triple code model (Dehaene & Cohen, 1995) an explicit difference exists in the sense that the verbal number system is only represented in the left hemisphere, whereas Arabic and magnitude information are bilaterally represented. However, due to the speed and efficiency of callosal connections no clear functional difference is expected under normal circumstances.

So far, the encoding-complex hypothesis introduced by Campbell (e.g., Campbell, 1994; Campbell & Clark, 1992) is the only theory that capitalizes on modality-specific processes. Different types of numerical representations (phonological, graphemic, visual, semantic, lexical, articulatory, imaginal, and analogue) are assumed to be directly interconnected and to form an associative encoding complex that is activated during numerical processing. As the encoding complex that is activated differs due to task requirements, the theory predicts idiosyncratic and task-related variability (e.g., different performance patterns for problems presented in verbal and Arabic mode). At this point, however, this hypothesis is not yet sufficiently constrained to generate testable predictions.

The balance of the evidence seems to be in favor of a central semantic system, at least for digits. For verbal number words the available evidence is insufficient to draw justified conclusions. Semantic access has been evaluated with a variety of magnitude-related effects. These effects have been mainly observed in numerical comparison tasks. This validates their status as markers of semantic access, but what is more important in the context of the functional locus of magnitude information is the fact that these effects have also been observed in tasks that do not draw on semantic information for correct performance. In this respect, Brysbaert (1995) observed a logarithmic size effect (increase in processing time as a function of the logarithm of number magnitude) in retention and naming of Arabically presented numerals. Another magnitude-related effect is the congruity effect: When numbers have to be compared in terms of their physical size, the numerical value of the numbers (congruent or incongruent with the numerical dimension) has repeatedly been shown to affect the comparison process, and vice versa (e.g., Henik & Tzelgov, 1982; Foltz, Poltrock, & Potts, 1984, see e.g., Algom, Dekel, & Pansky, 1996, for an analysis of the conditions for the congruity effect to occur). The distance effect is another robust finding in numerical comparison: Indicating which of two numbers is larger becomes easier as the numerical distance between the two numbers increases. Duncan and McFarland (1980) and Dehaene and Akhavein (1995) found an effect of distance if the two numerals had to be compared physically, although magnitude is not needed. Den Heyer and Briand (1986) found distance-dependent priming effects of successively presented digits in a magnitude-irrelevant digit-letter classification task. Another indication of semantic access is the SNARC effect (Dehaene et al., 1993). It demonstrates a spatial-numerical association of response codes: Small numbers are responded to preferentially with the left hand compared to the right hand, whereas the reverse holds for large numbers. Fias et al. (1996) found an SNARC effect not only in a semantic parity judgment task (as Dehaene et al.), but also in an asemantic phoneme monitoring task: A digit was presented and participants had to indicate whether a particular phoneme (i.e., /e/ sound) was present in the corresponding number name. Taken together, the omnipresence of semantic effects with Arabic numbers in tasks that do not require semantic information strongly argues in favor of a central semantic system. One has to be careful, though, not to confuse a central semantic system with automatic access to this system. A central semantic system means that the semantic system is accessed if a number is processed further than its physical characteristics. Whether these further processes occur automatically is another issue (see Pansky & Algom, 1999, for arguments against automaticity in number processing). Additional constraints need to be satisfied to make the strong conclusion of automaticity, as automatic processes are generally defined as fast, effortless, unconscious and autonomous (see e.g., Logan, 1980; Shiffrin & Schneider, 1977).

Evidence in favor of asemantic processing possibilities mainly comes from the neuropsychological literature: Brain-damaged patients have been described who show impaired transcoding from one surface code to the other, with preserved number comprehension (Cipolotti & Butterworth, 1995; Cipolotti, Butterworth, & Warrington, 1994; Cohen & Dehaene, 1995; for a review, see Seron and Noël, 1995). The reverse dissociation has recently been described in a patient with Gerstmann syndrome (Dehaene & Cohen, 1997) who showed an impairment in quantitative number knowledge with a preserved ability to read Arabic numerals (but see Mayer, Martory, Pegna, Landis, Delavelle, & Annoni, 1999, for a case of Gerstmann syndrome with both reading and comprehension of Arabic numbers impaired). Despite the possible strength of a double dissociation (Shallice, 1988; Teuber, 1955), it cannot be considered as decisive evidence in this issue. The reason is that patients involved in the double dissociation were unilaterally lesioned, whereas semantic magnitude information has been shown to be bilaterally represented, as is evident from the performance of split-brain patients (Seymour, Reuter-Lorenz, & Gazzaniga, 1994) and from brain imaging studies (Chochon, Cohen, van de Moortele, & Dehaene, 1999; Pesenti, Thioux, Seron, & De Volder, 2000). Therefore, the possibility cannot be ruled out that the residual reading abilities rely on the spared magnitude representation in the hemisphere opposite to the lesion. Thus, a definite answer to the question of asemantic transcoding mechanisms should come from the performance of a patient with bilateral damage to the areas underlying the processing of number magnitude. Unfortunately no such a patient has been described so far. Moreover, there is general agreement that neuropsychological findings should be supported by data from normal individuals (e.g., De Haan, 1994). Otherwise, the possibility exists that patients use strategies which are available but rarely used in normal functioning because they are slow and error-prone.

In sum, the above findings provide evidence that number magnitude has a profound effect on Arabic number processing. There are no behavioral data that unequivocally urge to incorporate asemantic pathways. The question, then, is if the semantic system fulfills an equally central role in the processing of verbal numbers. So far, there is not sufficient empirical evidence to draw strong conclusions on this point. Nonetheless, there are indirect indications that suggest a less central status of semantic information for verbal numbers. A non-semantic route for the naming of verbal numerals has been postulated to account for format-specific effects in multiplication and addition (Blankenberger & Vorberg, 1997; Noël, Fias, & Brysbaert, 1997), so that a difference in the necessity of semantic transcoding may be expected between verbal and Arabic numerals. Also, the existence of an asemantic route for the naming of written verbal numerals can be defended on the basis of many models of visual word recognition (see e.g., Coltheart, Curtis, Atkins, & Haller, 1993; Seidenberg & McClelland, 1989). An explicit demonstration of an asemantic route for words, however, is to my knowledge not available in the numerical domain.

It is the purpose of the research reported here to directly evaluate the possibility of asemantic processing of verbal numbers. We will make use of our previous work on the SNARC effect (Fias et al., 1996) and examine whether number magnitude is as pivotal for verbal numerals as it is for Arabic numerals. As indicated above, Fias et al. reported a SNARC effect not only when participants had to perform a task that required access to the meaning of the numbers (parity judgment), but also when participants were asked to perform a task that in principle could be completed without access to the semantic information. Thus, when participants were presented with a digit and asked whether its name contained an /e/ sound or not, they reacted faster with their left hand to small digits and with their right hand to large digits. This finding presented strong evidence for indispensable semantic transcoding in the processing of Arabic numerals (see also Huha, Berch, & Krikorian, 1995). In the present article, exactly the same reasoning will be followed to find out whether verbal numerals require semantic mediation to the same extent as Arabic numerals. Experiment 1 looks for a SNARC effect as an indication of semantic access in a parity judgment task, Experiment 2 in a phoneme monitoring task.

Experiment 1

Before accepting the SNARC effect as an indication of access to magnitude information, it is well worth evaluating the validity of this assumption. Three findings are important in this respect. First, the SNARC effect appears to depend on magnitude relative to the interval of numbers used, rather than on non-numerical characteristics of numbers (e.g., visual appearance, frequency, etc.). This has been demonstrated by examining the SNARC effect in two partly overlapping intervals (Dehaene et al., 1993, Experiment 3; Fias et al., 1996, Experiment 1). In the interval 0–5, the two largest numbers (4 and 5) were responded to preferentially with the right hand. In the interval 4–9, however, the preferred side of response for 4 and 5 was left, as they are the smallest numbers of this interval. Second, Dehaene et al. (1993, Experiment 4) used letters instead of numbers to investigate whether it could be the sequential ordering of numbers, rather than their magnitude, that causes the SNARC effect. Letters are sequentially ordered, just like numbers, but they do not share the magnitude ordering with numbers. The fact that no SNARC effect was obtained for letters rejects sequential order as an origin of the SNARC effect, and further supports the magnitude-related interpretation. Third, SNARC effects have been obtained in comparison tasks, which obviously rely on magnitude information (Brysbaert, 1995, Experiment 3; Dehaene et al., 1990, Experiment 2).

As a matter of fact, Dehaene et al. (1993, Experiment 8), using parity judgment as task, have already reported a SNARC effect for the verbal numerals 0–9 in French, although it was weaker than for Arabic numerals. So, Experiment 1 was essentially a replication study to check the robustness of the finding, and to have a comparison for the evaluation of the findings with the phoneme monitoring task in Experiment 2.

Method

Participants

Twenty Dutch speaking first-year psychology students (2 male, 18 female) participated in the experiment. Average age was 18.6 years (SD = 1.8 years). Two participants were left-handed.

Instructions

Participants were asked to judge the parity of written verbal numerals by pressing a button with the left or the right hand. They were explicitly informed about the range of numbers; both speed and accuracy were emphasized.

Stimuli

The numbers we used ranged from 0 to 9 and were presented as written Dutch number names (“nul”, “een”, “twee”, “drie”, “vier”, “vijf”, “zes”, “zeven”, “acht”, and “negen”) in Borland C’s simplex font (VGA card in graphics mode).

Procedure

Participants took part in two blocks of trials, one with the even response assigned to the left hand and the odd response assigned to the right hand, and one with the assignment reversed. The order of the blocks was counterbalanced across participants. Each block started with a training session in which all numbers were presented once. In the test blocks, the numbers were presented 54 times, in randomized order with the restriction that each number followed all other numbers six times. This resulted in a total of 540 trials per block. There was a short resting period between the blocks. A response board, with the two buttons separated 25 mm from one another, was connected to a PC-compatible computer (486 processor). Reaction times (RTs) were measured to the nearest millisecond.

Each trial started with an empty rectangular frame (520 mm × 250 mm) presented in the center of the screen for 300 ms. Thereafter, the target number appeared (width: from 220 mm to 350 mm – depending on the number of letters in the number name –, height: 110 mm) for 1,300 ms. During this period responses were registered. The frame and the number were then erased and the screen remained blank for an interstimulus interval of 1,500 ms.

Results and discussion

Error rate did not exceed 11.6% per subject (average = 3.9%). There was no speed accuracy trade-off, as indicated by the positive correlation between RT and number of errors computed over the 20 cells of the design (10 numbers, separately for left and right responses): $r = 0.69$, $n = 20$, $P < 0.001$. RTs of the correct responses are depicted in Fig. 1.

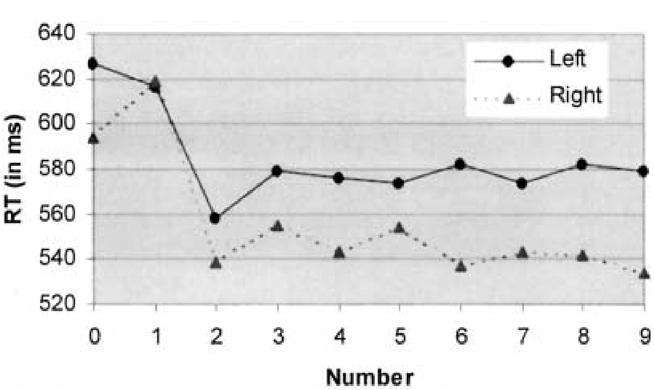

Fig. 1 RTs as a function of number magnitude and side of response in parity judgment (Experiment 1) (*RT* reaction time)

‘Following Dehaene et al. (1993), the presence of a SNARC effect is evaluated by the Magnitude × Side of response interaction in a 2 (Parity: odd or even) × 2 (Side of response: left or right) × 5 (Magnitude: 0–1, 2–3, 4–5, 6–7 or 8–9) ANOVA on medians of correct responses. This interaction reached significance [$F(4, 76) = 4.23$, MSE = 598.7, $P < 0.005$]. No other interactions were significant. The following main effects were significant: Side of response [$F(1, 19) = 36.23$, MSE = 2304.7, $P < 0.0005$] and Magnitude [$F(4, 76) = 31.80$, MSE = 1515.0, $P < 0.0005$]. The effect of Magnitude results from the slow responses to numbers 0 and 1. This was also observed in parity judgment with Arabic numerals (Fias et al., 1996). Apparently, the parity status of these numbers is not as clear as it is for other numbers. In fact, some participants explicitly asked for the parity status of the number 0. Therefore, the ANOVA was repeated with omission of 0 and 1. The same results were obtained with exception of the main effect of Magnitude which did not reach significance: a main effect of Side of response [$F(1, 19) = 44.22$, $MSE = 1873.7$, $P < 0.0005$] and an interaction effect of Magnitude × Side of response [$F(3, 57) = 5.55$, $MSE = 348.7$, $P < 0.005$].

A regression analysis, however, captures the essence of the SNARC effect in more detail. Because the SNARC effect stems from an association between the position of the number on the left-right oriented number line and the side of the response, it predicts a negative relation between number magnitude and the difference in RT between right hand and left hand responses (dRT). For small numbers, responses will be faster with the left hand, resulting in a positive dRT, whereas for large numbers responses will be faster with the right hand, resulting in a negative dRT. It is important to realize that a SNARC effect may be present, even when all dRTs are negative. This can be the case when a large majority of the participants is right-handed, which can result in overall faster right-hand responses. In this situation, the SNARC effect consists of a modification of this right-hand advantage as a function of the magnitude of the presented number. The most straightforward way to examine this inverse relation between dRT and number magnitude is to regress dRT on number magnitude and to test the reliability of the regression slope (see Fias et al., 1996, for a more detailed explanation).

This was done by means of the regression analysis for repeated measures data recommended by Lorch and Myers (1990, Method 3). In a first step, for all participants, the median RT of the correct responses was computed for each number, separately for left and right responses. On the basis of these medians, dRTs were computed by subtracting the median RT for left-hand responses from the median RT for right-hand responses. In a second step, for each individual participant a multiple regression analysis was computed with number magnitude and practice as predictor variables. The latter variable was included because dRTs may also be influenced by the order in which participants had to press the response buttons: If they first had to press the left button in response to even numbers, their left-hand responses may overall be slower than their right-hand responses due to practice, while the reverse holds for subjects who had to respond to even numbers with their right hand first. Those numbers that were responded to with the left hand first were coded as −0.5, those that were responded to with the right hand first were coded as +0.5, in order not to influence the magnitude of the intercept. In a third step, *t*-tests were performed to test whether the regression weights of the group deviated significantly from zero.

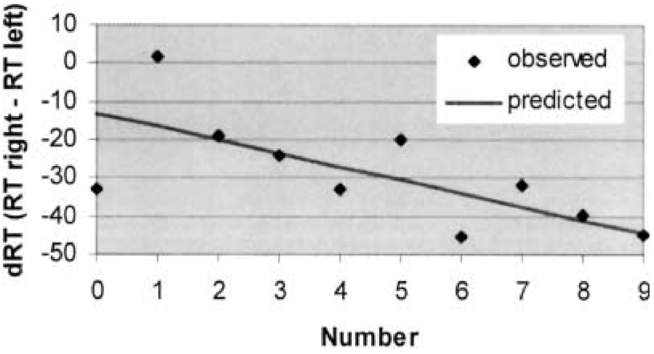

Fig. 2 Observed data and regression line representing RT differences between right-hand and left-hand responses as a function of number magnitude in parity judgment (Experiment 1)

From Fig. 2, it can be seen that there was indeed a negative relation between number magnitude and dRT, as predicted by the SNARC effect. The best fitting regression line is described by the following equation: $\mathrm{dRT} = -13.1 - 3.5\ (\mathrm{Magnitude}) + 13.3\ (\mathrm{Practice})$.

The magnitude coefficient differed significantly from zero, $t(19) = -2.72$, SD = 5.7, $P < 0.05$. The effect of practice did not reach significance [$t(19) = 1.19$, SD = 50.1].

Before accepting the presence of a SNARC effect, it is important to consider again the possible impact of the fact that the number 0, and to a lesser degree the number 1, deviated considerably from the predictions. To rule out any possible bias of these two numbers on the estimated contribution of Magnitude to the pattern of dRTs, the regression analysis was performed without 0 and 1; $\mathrm{dRT} = -10.9 - 3.73\ (\mathrm{Magnitude}) + 13.91\ (\mathrm{Practice})$.

The result is surprisingly similar: The magnitude coefficient differed significantly from zero, $t(19) = -3.53$, SD = 4.7, $P < 0.005$. The effect of practice did not reach significance [$t(19) = 1.3$, SD = 46.9].

Thus, in line with Dehaene et al. (1993), we found an SNARC effect when participants had to judge whether a written verbal numeral was odd or even. Also in line with Dehaene et al., this effect was smaller than the one with Arabic numerals (which returned a magnitude regression weight of more than 7; Fias et al., 1996, Experiment 1).

To evaluate whether the SNARC effect depended on elapsed processing time, I split up the data in two halves on the basis of response time to see whether there is an indication of accruing semantic elaboration when more time elapses. For each participant, for each number and for both sides of responses separately, the observations were split in a fast half and a slow half. Then median RTs, dRTs and regression equations were computed as before for the two sets of data. This resulted in the following equations: Fast: dRT $= -5.3 - 2.6$ (Magnitude) $+ 11.7$ (Practice), (with a mean RT of 498 ms); Slow: dRT $=$ $-17.1 - 3.0$ (Magnitude) $+ 12.9$ (Practice), (with a mean RT of 655 ms).

While Magnitude contributed (marginally) significantly in both regression analyses [Fast: $t(19) = -2.61$, SD $= 5.67$, $P < 0.05$; Slow: $t(19) = -1.35$, SD $= 10.03$, $P < 0.1$], the difference between the two Magnitude coefficients was not significant [$t(19) = -0.22$, SD $= 7.9$]. Thus, the size of the SNARC effect does not depend on elapsed processing time as it is equally strong in the fast half of the reaction times as in the slow half, despite a mean difference of more than 150 ms.

Experiment 2

Contrary to parity judgment, phoneme monitoring does not require access to any kind of semantic information for correct performance: A mere translation from spelling to sound is sufficient to detect the presence of a particular phoneme in a string of letters. As a consequence, if an asemantic route is available for this translation, no SNARC effect is expected when participants have to indicate whether the name of a written verbal numeral contains an /e/ sound. On the other hand, if no such route is available, transcoding is necessarily semantically mediated, which will then result in a SNARC effect. As indicated above, Fias et al. (1996, Experiments 2 and 3) obtained evidence for the latter position with digits, as they found a SNARC effect for phoneme monitoring with Arabic numerals (digits) as input. Moreover, the size of the effect did not decrease with training, and was present for the faster half of the response times (Fias, 1998), thus effectively supporting the semantic transcoding models. The present experiment investigates whether the same is true for verbal numerals.

Method

Participants

Twenty first-year psychology students (7 male, 13 female) participated in the experiment. Mean age was 18.3 years (SD = 0.9). The majority ($n = 17$) was right-handed.

Instructions

Participants were told to judge whether there was an /e/ sound in the name of the written verbal numeral, by pressing one of two response buttons. Both speed and accuracy were stressed in the instructions, and the interval of numbers was explicitly mentioned.

Stimuli

The numbers ranged from 0 to 9 and were presented as Dutch written number names in Borland C's simplex font. The Dutch words for these numbers are "nul", "een", "twee", "drie", "vier", "vijf", "zes", "zeven", "acht", and "negen", with the /e/ phoneme present in 1, 2, 6, 7 and 9. It must be noted that the e sound in 6 is short, whereas it is long in all other cases. This fact was explicitly mentioned in the instructions. It may also be noted that two other verbal numerals "drie" and "vier" contain the letter "e" in the orthographic representation but not the sound /e/ in the phonological representation ("ie" is pronounced /I:/ in Dutch). As a consequence, the task could not be performed on the basis of visual letter search. Rather, a translation to the spoken word form was necessary.

Procedure

Procedural details were exactly the same as in Experiment 1.

Results and discussion

Error rate did not exceed 10.1% per subject (average = 2.9%). The absence of a speed-accuracy trade-off was indicated by a significant positive correlation between RT and number of errors computed over the 20 cells of the design (10 numbers, left and right response): $r = 0.77$, $n = 20$, $P < 0.001$. Mean RTs for the correct responses to the numbers 0 to 9 are presented in Fig. 3.

As in Experiment 1 the effect of number magnitude and side of response was first evaluated by means of an ANOVA, with a 10 (Magnitude) × 2 (Side of response) design (a $5 \times 2 \times 2$ design, analogous to Experiment 1, could not be used because the presence of an /e/ sound does not alternate for successive numbers). Both Magnitude and Side of response elicited a main effect [$F(9, 171) = 19.3$, MSE $= 959.5$, $P < 0.0005$ and $F(1, 19) = 9.2$, MSE $= 2608.2$, $P < 0.007$ respectively], but, more importantly, the interaction was not significant [$F(9, 171) = 0.50$; MSE $= 753.8$].

Figure 4 shows the difference in response time between right-hand and left-hand responses as a function of number magnitude. To assess the relationship statistically, regression weights were computed as in Experiment 1. This resulted in the equation: dRT $=$ $-16.66 + 0.23$ (Magnitude) $+ 5.02$ (Practice).

Neither magnitude nor practice differed reliably from zero [Magnitude: $t(19) = 0.3$, SD $= 3.2$; Practice:

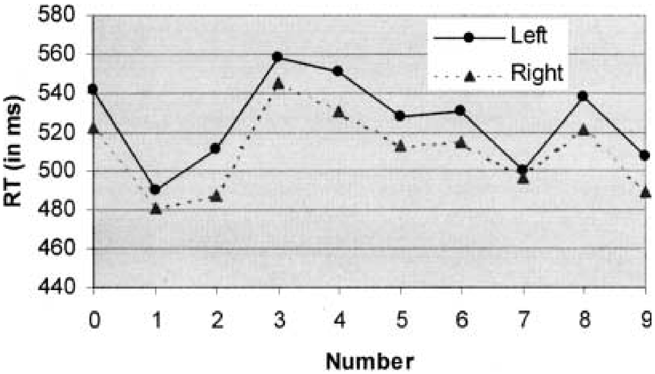

Fig. 3 RTs as a function of number magnitude and side of response in phoneme monitoring (Experiment 2)

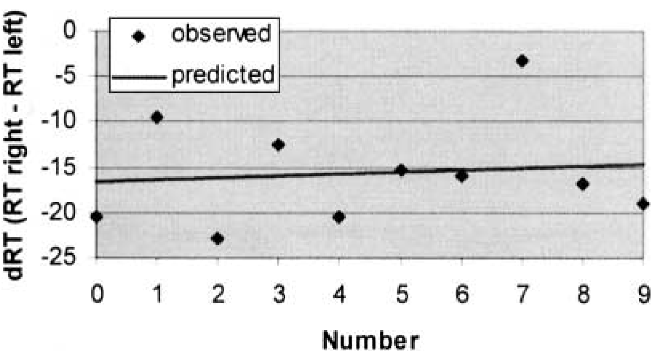

Fig. 4 Observed data and regression line representing RT differences between right-hand and left-hand responses as a function of number magnitude in phoneme monitoring (Experiment 2)

$t(19) = 0.4$, $\mathrm{SD} = 58.6$]. Moreover, the magnitude regression slopes differed significantly between Experiment 2 and Experiment 1 [$F(1, 38) = 6.4$, $\mathrm{MSE} = 21.7$, $P < 0.02$). Thus, no SNARC effect emerged from the present experiment with verbal numerals as stimuli, whereas Fias et al. (1996) in two different experiments reported a reliable SNARC effect for a phoneme monitoring task with Arabic numerals as input (ranging from −4.3 to −6.0). Apparently, semantic mediation is not necessary for the detection of an /e/ sound in printed verbal numerals. This suggests that there is a direct, asemantic route for naming written verbal numerals, as hypothesized by Noël et al. (1997) and Blankenberger and Vorberg (1997) and as predicted by most models of word processing.

To evaluate a possible influence of processing speed on the size of the SNARC effect, the data were split in a fast half and a slow half as in Experiment 1. This resulted in the following equations: Fast: $\mathrm{dRT} = -12.3 + 0.30$ (Magnitude) $+ 12.28$ (Practice), (with a mean RT of 455 ms); Slow: $\mathrm{dRT} = -12.6 - 1.16$ (Magnitude) -19.1 (Practice), (with a mean RT of 598 ms).

Magnitude was not significant in either of the data sets [Fast: $t(19) = 0.69$, $\mathrm{SD} = 2.44$; Slow: $t(19) = -0.62$, $\mathrm{SD} = 8.3$] and did not differ between the two groups [$t(19) = 0.9$, $\mathrm{SD} = 7.3$]. Thus, even in the slow group of responses there was no reliable SNARC effect, although considerably shorter processing times led to a SNARC effect in Experiment 1. Apparently, the translation of a written number word to its phonological equivalent is not semantically mediated.

The tendency of the Magnitude slope to become negative, although not significant, could be an indication of a weak automatic activation of the number line. The possibility of automatic activation of magnitude information from written number words has been argued by Dehaene and Akhavein (1995). They observed a distance effect when two number words had to be compared physically. Because physical matching does not require semantic elaboration, the distance effect shows that semantic elaboration occurred automatically. It is surprising to note, however, that the automatic activation of magnitude in Dehaene and Akhavein (1995) was observed with average RTs of about 500 ms. To the contrary, in the current experiment, 100 ms more was not sufficient to elicit a SNARC effect. The fact that so much time was needed for only a weak tendency of semantic activation to occur could be an indication of interpathway inhibition. Possibly, as suggested by Cipolotti and Butterworth (1995), active employment of the direct route inhibits processing along the semantically mediated route. Cipolotti and Butterworth (1995) invoked this hypothesis to explain why their patient should not make use of the intact semantic route for naming numbers when direct transcoding routes were impaired.

It is also worth noting that RTs for digits in a phoneme monitoring task (on average 591 ms and 548 ms in Experiment 2 and 3, respectively, Fias et al., 1996) were similar to or smaller than those observed here for slow responses to number words (598 ms). The fact that similar processing times elicit a SNARC effect for digits but not for number words, rules out the possible interpretation that Arabic-verbal transcoding is in fact asemantic and that the observed SNARC effect for digits was simply due to longer processing time available for activation to spread undeliberately to the number line. This strengthens the case we made in Fias et al. (1996) that Arabic-to-verbal transcoding obligatorily activates the number line.

General discussion

As in Fias et al. (1996), the SNARC effect was used as a measure of access to magnitude information with verbal numbers. This effect expresses an association of number magnitude and response side: Small numbers are preferentially responded to with the left hand, whereas large numbers are preferentially associated with right hand responses. In Experiment 1 we found a SNARC effect in a parity judgment task. As a number's parity status is a semantic attribute, this result by itself is not very surprising. Experiment 2, however, is of more critical importance. A phoneme monitoring task was used: Participants had to indicate whether the spoken equivalent of the visually presented number word contained an /e/ sound or not. No SNARC effect was observed. Because the task could not be performed on the basis of visual letter search (the Dutch numerals "drie" and "vier" contain the letter "e" in the orthographic representation but in these cases the letter "e" is not pronounced as /e/), this indicates that for verbal numbers there is a processing route that allows a written number word to be converted to sound, without involvement of the number line.

On the basis of our previous research with Arabic numerals (Fias et al., 1996), we had to conclude that asemantic transcoding did not happen for this modality. Making use of exactly the same experimental procedure, we now find that asemantic transcoding is possible for verbal numerals. This opposite pattern of findings points to a divergence between the processing of Arabic and verbal numerals.

None of the current models (e.g., Cipolotti & Butterworth, 1995; Dehaene, 1992; McCloskey, 1992) incorporates such a dissimilarity in available processing pathways. Either they do not incorporate asemantic processing facilities at all, either for Arabic numbers or for verbal numbers, or they posit asemantic routes, for Arabic and verbal numbers. It is clear that none of these models can account for the asymmetric pattern of our data.

The central semantics models should be extended with a direct route allowing for a direct and asemantic conversion of written number words in their spoken form. This results in a model that preserves a central position of the semantic system for digit processing, whereas a double route is available for the processing of written verbal numbers.

In principle, the architectural lay-out of the multiple route models is not falsified by the difference between Arabic and verbal number processing observed here. However, to account for the difference it is necessary to further constrain these models by explicitly determining the relative strengths of the postulated routes. The omnipresence of semantic effects with Arabic numbers leads to the conclusion that the semantic route is stronger than the asemantic route(s) and thus dominates it, such that under normal circumstances performance will not be affected by the direct connections. In exceptional cases, for instance after damage to the semantic pathway, effects from the asemantic route might be observable. In this case, comprehension of digits would be damaged, while reading abilities are preserved. However, as pointed out in the introduction, no patient with a specific and complete lesion of the semantic system has been described.

In addition, if multiple pathways are postulated, interpathway effects should be taken into account and the conditions for their occurrence precisely described. The hypothesis of inhibitory effects of active employment of the asemantic routes on the semantic ones has been put forward by Cipolotti and Butterworth (1995) to explain why their patient did not use the intact semantic route (no comprehension difficulties), while his asemantic routes were thought to be damaged (reading and writing difficulties). Experiment 2 supports this hypothesis in the sense that there was no automatic activation of the number line when the asemantic route was employed for the spelling to sound conversion, whereas automatic semantic access does occur in situations where there is no task-induced reason to use the asemantic route (Dehaene & Akhavein, 1995). Whether the inhibitory mechanism also operates in the other direction (active use of the semantic route leading to inhibition of the asemantic connection) can be doubted. Noël et al. (1997) showed that format-specific effects in mental multiplication can in principle be accounted for by direct transcoding of verbally presented written number words to phonology, whereas the actual retrieval of the multiplication problem is subserved by the semantic route.

Another important question is how precisely the asemantic conversion happens. From the literature on word recognition, two general mechanisms have been proposed: Either the recoding happens directly on the orthographic input without lexical involvement (assembled phonology), or the presented verbal numeral activates an entry in the orthographic input lexicon, which has direct connections to the verbal output system (addressed phonology; see Berent & Perfetti, 1995, and Frost, 1998, for reviews). By itself, the data reported here do not allow the two possibilities to be distinguished. However, it is worth noting that the present findings have been obtained in Dutch, which is a language with fairly straightforward and consistent mappings between the letters of the number words and the sounds they represent (i.e., a shallow language). Most theories of visual word processing recognize that such simple conversions can be achieved without semantic involvement. Things may be different, however, for languages with opaque, inconsistent correspondences between the letters of the number words and the sounds they represent (e.g., compare the pronunciation of "-one" in the number word "one" and in the word "zone"). For these languages, predictions differ between theories: some say that the inconsistent spelling-sound conversions will increase the contribution of the semantic system (Strain, Patterson, & Seidenberg, 1995; Van Orden, Pennington, & Stone, 1990), whereas others emphasize the involvement of an orthographic input lexicon (Coltheart et al., 1993). It would certainly be interesting to see whether a SNARC effect is obtained for the phoneme detection task in a language with opaque grapheme-phoneme correspondences. If so, this would considerably strengthen the former class of theories.

This shows that a good insight in the processing of verbally presented numbers is important, not only for understanding numerical cognition per se, but also because studies on numerical cognition can help extending our knowledge of word recognition in general. Indeed, research in the domain of numerical cognition can in principle take advantage of the fact that numerical information can be represented by means of two well-learned albeit fundamentally different symbolic systems. Thus, internal numerical information is accessible from two surface modalities. In principle, comparison of performance with digit stimuli and number word stimuli allows true semantic effects to be separated from effects at the level of input and/or output (see e.g., Noël et al., 1997; Brysbaert, Fias, & Noël, 1998). Moreover, words in the numerical domain have the additional advantage that their semantic meaning is strictly defined and highly constrained. There is no doubt that this situation, together with the new measures of semantic access (like the distance effect and the SNARC effect), can be beneficial for research on word recognition in general because it provides new experimental tools and theoretical perspectives. To gain profit from this privileged situation, it is of major importance to develop a detailed picture of how the processing of Arabic and verbal numerals relate to each other and of the differences that may exist between them.

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