Semantic priming in number naming

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The issue of semantic and non-semantic conversion routes for numerals is still debated in numerical cognition. We report two number-naming experiments in which the target numerals were preceded by another numeral (prime). The primes and targets could be presented either in arabic (digit) notation or in verbal (alphabetical) notation. The results reveal a semantically related distance effect: Latencies are fastest when the prime has the same value as the target and increase when the distance between prime and target increases. We argue that the present results are congruent with the idea that the numerals make access to an ordered semantic number line common to all notations, as the results are the same for within-notation priming (arabic–arabic or verbal–verbal) and between-notations priming (arabic–verbal or verbal–arabic). The present results also point to a rapid involvement of semantics in the naming of numerals, also when the numerals are words. As such, they are in line with recent claims of rapid semantic mediation in word naming.

Arabic digits (1, 2, 3, . . .) and verbal word numerals (one, two, three, . . .) are the two main formats in which numbers can be represented. Both have been the subject of a substantial body of research in the last decade (see Butterworth, 1991; Dehaene, 1997, for reviews). However, so far only a few studies have looked directly at the interactions between the two formats (Fias, Reynvoet, & Brysbaert, 2001; Koechlin, Naccache, Block, & Dehaene, 1999). Links between the verbal and the arabic notation have remained largely at a theoretical level, although confronting digits and words may be a fruitful approach to get further insights into the dynamics of number processing.

Possible benefits of contrasting word numerals and arabic digits may be illustrated by looking at the differences between word and picture processing. One of the main differences between these two types of stimulus is that words can be named without semantic mediation, whereas pictures cannot. Virtually all models of word naming consist of at least one non-semantic conversion between orthographic input and phonological output. In some models, this conversion depends on direct grapheme–phoneme translations (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Parry, Langdon, & Ziegler, 2001); in other models, it consists of a connectionist type of conversion between letters and sounds (Plaut, McClelland, Seidenberg, & Patterson, 1996), and in other models still, it additionally consists of a direct link between an orthographic input lexicon and the speech output system (e.g.,

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Besner, 1999). In contrast, nearly all models of picture naming (e.g., Glaser, 1992; Humphreys, Price, & Riddoch, 1999; Sitton, Mozer, & Farah, 2000; Theios & Amrhein, 1989) assume that pictures cannot be named if their meaning is not understood. Neuropsychological evidence for this position was reported by Hodges and Greene (1998). Only a few researchers (e.g., Brennen, 1999) defend the idea that there is a direct, non-semantic route from pictorial input to speech output.

Part of the evidence for the difference between pictures and words comes from the picture–word interference task, a variant of the original Stroop task (Stroop, 1935; for reviews, see Glaser, 1992; MacLeod, 1991). In this task, a word and a picture are presented together and participants are asked either to read the word or to name the picture. The general finding is that words interfere with picture naming, but that word naming is hardly affected by the presence of an incongruent picture. Further evidence comes from the priming paradigm. In this paradigm, two stimuli are presented after one another, and the processing of the second stimulus (target) is analysed as a function of the first stimulus (prime). In the word-processing literature, it is well documented that the processing of a target word like *nurse* is faster when it follows the semantically related prime *doctor* than when it follows an unrelated word like *ball* (Meyer & Schvaneveldt, 1971; see Neely, 1991, for a review). The priming is observed with primes presented for a few tens of milliseconds (Marcel, 1983). So, a semantic relationship between the prime and the target can very rapidly improve the processing of the target, although there is a continuing debate over to what extent this semantic relationship is based on shared semantic features or on the fact that both words often co-occur in the language (i.e., associative priming rather than pure semantic priming; see Balota, 1994; Lucas, 2000, for reviews).

The priming paradigm has not been limited to word–word conditions, but has also included pictorial stimulus materials. This leads to three extra conditions: one within-notation condition (picture–picture) and two between-notations conditions (word–picture and picture–word). When a target picture has to be named, a semantically related prime picture presented a few tens of milliseconds before the target reduces the naming latency (Carr, McCauley, Sperber, & Parmelee, 1982; Dell'Acqua & Grainger, 1999; Glaser & Düngelhoff, 1984). When, on the other hand, a word prime is presented shortly before the picture, picture naming is not affected or even hindered by a related word (Alario, Segui, & Ferrand, 2000; Glaser & Düngelhoff, 1984; La Hey, Dirckx, & Kramer, 1990; Starreveld & La Hey, 1996). In particular, word primes that belong to the same semantic category seem to result in prolonged picture–naming times (Alario et al., 2000). With picture–word pairs, there does not seem to be a priming effect from the picture on the word–naming latencies (Dell'Acqua & Grainger, 1999; Glaser & Düngelhoff, 1984; but see Peterson & Savoy, 1998, in a slightly different paradigm).

The issue of semantic versus nonsemantic naming of words/pictures can easily be extended to the number domain. There are no a priori reasons to believe that verbal numerals would be named differently from other words. So, on the basis of the current models of word naming, we can safely assume that there are two routes for naming verbal numerals: a semantic and a non-semantic one. The big issue that still remains concerns the relative speed of these two pathways, with some models assuming a rather slow semantic pathway (Coltheart et al., 1993) and others assuming very rapid semantic influences (Plaut et al., 1996). On the other hand, the issue of semantic versus nonsemantic naming is much more debated with respect to the naming of arabic numerals. Some authors strongly defend the idea that digits, just like pictures, require semantic mediation to be named (Brysbaert, 1995; McCloskey, 1992), whereas others argue for the existence of a non-semantic digit–sound conversion system in addition to a semantically mediated pathway (Cipolotti & Butterworth, 1995; Dehaene, 1992).

Evidence for obligatory semantic mediation in arabic numeral naming has been found both in research with brain-damaged persons and in research with healthy participants. McCloskey, Sokol, and Goodman (1986), for instance, showed that the lexical substitution errors made by a brain-damaged patient in the naming of arabic numerals fell into three separate, semantically meaningful clusters—units, teens, and tens—indicating that some kind of lexico-semantic representation had been activated in the naming of the numerals. Working with healthy university undergraduates, Brysbaert (1995) showed that number-naming times were faster when arabic target numerals were preceded by arabic primes with a close magnitude than when they were preceded by primes with a more distant value. Reynvoet and Brysbaert (1999) replicated the finding with tachistoscopically presented primes. They reported that participants named targets like *4* faster when 115 ms previously the primes *3* or *5* had been presented than when the primes *2* or *6* had been presented. This finding can be explained by assuming that numbers are semantically represented on an ordered continuum and that the activation spreads along the continuum.

Evidence in favour of a non-semantic route for the naming of arabic numerals mainly comes from research with patients and from brain-imaging studies. Dehaene and Cohen (1997), for instance, described a patient (MAR) who could name digits perfectly but made 20% errors when asked to indicate which of the two digits was the larger. In a functional Magnetic Resonance Imaging (fMRI) study with normal participants, Chochon, Cohen, van de Moortele, and Dehaene (1999) reported very little activation in the parietal cortex during digit naming, even though this part of the cortex is heavily involved in semantic numerical tasks.

On the basis of this evidence, a viable working hypothesis seems to be that both verbal and arabic numerals can be named with and without semantic mediation, but that the non-semantic route is usually faster for the naming of verbal numerals, whereas the reverse is true for the naming of arabic numerals. A first test of this hypothesis was reported by Fias et al. (2001). They used a digit/word variant of the picture/word interference paradigm (see earlier) and showed that the naming of a verbal numeral in this Stroop-like task was not hindered by the presence of an incongruent arabic distractor, whereas the naming of an arabic digit was hindered by the presence of an incongruent verbal distractor. This is in line with the idea that for verbal numerals the non-semantic letter–sound conversion pathway dominates the semantically mediated route, but that for arabic numerals the non-semantic route is a rather slow conversion pathway.

In the remainder of this article we look for further interactions between arabic and verbal input by turning to the priming technique. By having arabic and verbal targets preceded by either arabic or verbal primes, we can get further insights into the relative speed of the different pathways for both types of input.

EXPERIMENT 1

In Experiment 1, we investigated the effects of arabic and verbal primes on the naming of arabic digits. A similar comparison of within- and across-notation priming has previously been reported by Koechlin et al. (1999) and Naccache and Dehaene (2001), who used a magnitude judgement task (i.e., is the target larger or smaller than *5/five*?). In the first experiment by Koechlin et al., primes were clearly visible (participants also had to respond to them); in the second experiment, the primes were presented tachistoscopically and were masked (prime duration = 66 ms; stimulus-onset asynchrony, SOA, between prime and target = 133 ms). In Experiment 1, Koechlin et al. obtained a distance-related priming effect (i.e., responses were faster when the prime and target had a close value than when they had a more distant value) both when prime and target had the same notation and when they had a different notation. However, in Experiment 2, only within-notation priming was observed, leading the authors to conclude that under speeded response conditions the masked priming occurred in a notation-specific subsystem.

However, Naccache and Dehaene (2001) failed to replicate the latter finding of Koechlin et al. and reported a cross-notation priming effect of the same magnitude as that of the within-notation priming effect even though the primes were presented tachistoscopically and masked. Naccache and Dehaene gave some reasons why the findings of Koechlin et al. may have been misinterpreted, and they concluded that the distance priming effect was indeed due to interactions within an amodal, notation-independent, semantic number system.

The experiments of Koechlin et al. (1999) and Naccache and Dehaene (2001) show how within- and across-notation priming conditions can be used to get some insight into the issue of semantic mediation in the naming of arabic numerals. If the naming is semantically mediated, one would expect the same effect from verbal numeral primes (across notation) as from arabic numeral primes (within notation). In addition, the distance-related priming effect should be symmetrical, as the spreading of activation happens simultaneously downward and upward (see also Reynvoet & Brysbaert, 1999). On the other hand, if the priming effect is due to notation-specific associative priming within an arabic form recognizing system, then no across-notation priming should be observed, and the priming effect should be larger in the forward direction (e.g., *3*–target *4*) than in the backward direction (e.g., *5–4*). The latter prediction follows from the observation that the number 4 is much more likely to be reported in a word associative generation task after the prompt 3 than after the prompt 5.

Method

Participants

A total of 20 native Dutch-speaking first-year psychology students participated in the experiment (18 females, 2 males).

Apparatus

Stimuli were presented on a 17" colour screen connected to a computer running under the MS-DOS operating system (Pentium 133). Reaction times (RTs) were measured with a microphone connected to the game port. After each response, the experimenter typed the participant's answer on the computer keyboard and noted if the time registration had been successful.

Stimuli and procedure

Targets were arabic digits between 4 and 9, and primes were arabic or verbal numerals ranging from the target minus three to the target plus three. In total, there were 42 combinations of primes and targets. All participants saw four blocks of 126 trials. In each block, the prime–target combinations were shown three times in a random order, making a total of 12 observations per prime–target combination. Before the first block, 20 practice trials were given. In these trials, the target ranged from 18 to 22, and the prime was always 20. Primes and targets in the practice block were in the same modality as those in the test blocks.

Each trial consisted of the following sequence of events. First, a forward mask was shown for 57 ms (synchronized with the refresh cycle of the screen). This mask consisted of six hash signs (#) of the same size and font as the arabic targets. Then the prime was presented for 57 ms, followed by a backward mask for another 57 ms. The backward mask was the same as the forward mask. Finally, the target was presented and remained on the screen until the participant named it. In order to reduce the physical overlap between prime and target, the font of the primes (6 mm wide × 8 mm high for arabic primes and 13 to 26 mm wide × 8 mm high for verbal numerals) was smaller than that of the targets (8 mm wide × 10 mm high). All stimuli were presented in yellow on a black background and were centred on the screen. Characters were presented in triplex font. Participants were asked to name the arabic digits between 4 and 9 and they were told that a trial would start with six hash signs displayed on the screen.[1]

Half of the participants saw trials in which the prime was a verbal numeral and the target an arabic numeral; the other half saw trials in which both prime and target were arabic numerals.

Results

No naming errors were made. Mean percentage of unreliable responses due to coughs or noise was 1.5%. A 2 (notation of the prime) × 6 (target) × 7 (distance between prime and target) analysis of variance (ANOVA) was run with median RTs as dependent variables. Target and distance between prime and target were within-subject variables; notation of the prime was a between-subjects variable.

The ANOVA revealed a significant main effect of target, $F(5, 90) = 9.13$; $MSE = 2280.42$; $p < .001$. The mean RTs for the targets 4 to 9 were, respectively, 506, 496, 508, 516, 490, and 483 ms. There was also a main effect of distance between prime and target, $F(6, 108) = 46.08$; $MSE = 396.17$; $p < .001$. RTs were fastest when prime and target had the same value, and they increased when the distance between prime and target increased. A planned comparison showed that there was a significant increase in RT, when the absolute distance between prime and target increased from one to two, $F(1, 18)= 228.97$; $MSE = 290.54$; $p < .001$. This increase was only marginally significant when the distance increased from two to three, F(1,

[1]To find out how visible the primes were under these presentation conditions, we conducted a control experiment. The procedure was the same as that in the experiment, and 10 new participants were asked to judge whether the masked prime was a digit or a letter. The digit or letter was presented for 14, 29, 43,or 57 ms. The target was replaced by a filled circle. In total, there were 768 trials (192 per presentation duration), half with a letter and half with a digit. Participants had to indicate the nature of the prime. Discrimination performance scopes, measured by d', were, respectively, –.03, 0.03, 0.48, and 0.94 for the 14-, 29-, 43-, and 57-ms presentation conditions; d' began to deviate from chance for a prime duration of 43 ms, $t(9) = 3.76$; $p < .01$, and 57 ms, $t(9) = 3.98$; $p < .01$, condition. This indicates that the primes were not completely invisible in the present studies and, hence, that we are not addressing the issue of nonconscious priming. However, this does not mean that the priming effects were not automatic, as Neely (1991) showed that strategic expectancy effects require SOAs of more than 250 ms to influence the results.

18) = 4.07; $MSE = 241.24$; $p < .06$. Post hoc comparisons showed that the priming effects were highly symmetric, as the differences between T – 1 (target minus one) and T + 1, T – 2 and T + 2, and T – 3 and T + 3 were all far from significant ($p > .93$). There was also an interaction between target magnitude and distance, $F(30, 540) = 3.06$; $MSE = 286.41$; $p < .001$.[2]

There was an interaction between notation of the prime and target magnitude, $F(5, 90) = 24.22$; $MSE = 2280.42$; $p < .01$, because all targets, except the target 9, were named slightly faster after a verbal prime. There was also an interaction between notation of the prime and distance between prime and target, $F(6, 108) = 2.43$; $MSE = 396.17$; $p < .05$. As can be seen in Figure 1, this interaction only slightly modulated the distance priming effect.

As the priming seemed to consist of a distance-related priming effect and a repetition priming effect (i.e., when prime and target referred to the same magnitude), we ran a multiple regression analysis for repeated measures (Lorch & Myers, 1990, Method 3) involving these two variables. The analysis was restricted to the distances 0, 1, and 2, because of the small difference in RT at the distance 3 and for reasons of comparability with the next experiment. Both repetition priming and distance priming had a significant effect on the RTs. The regression weight for distance was 8.37 ms, $t(19) = 5.41$; $p < .001$, indicating that the RTs increased by 8.37 ms when the absolute distance between prime and target increased by one unit. The regression weight of the repetition effect was 15.10 ms, $t(19) = 4.19$; $p < .001$, indicating that RTs were an extra 15 ms faster when prime and target referred to the same value. There were no differences between the regression weights for the two prime notations ($F < 1$).

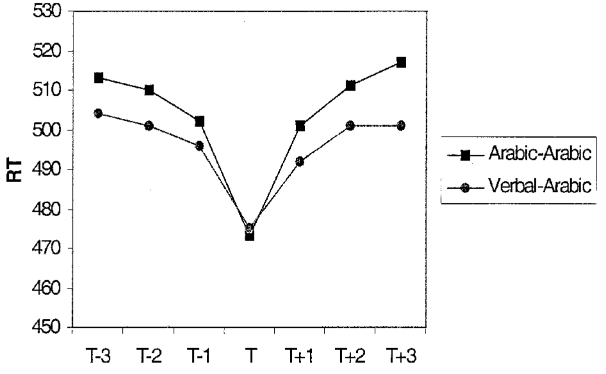

Figure 1. RTs of the arabic-number-naming priming task with arabic and verbal primes (Experiment 1).

[2]The significant interaction between target and prime recurs in all our experiments. (Also in an earlier paper, Reynvoet & Brysbaert, 1999, we obtained a significant interaction effect.) When we looked closer into the data, it turned out that the interaction is largely due to the relatively small targets being accompanied by small primes that only co-occur with that particular target (e.g., prime "1" only co-occurs with target "4"). This induces a distance priming effect that is to some extent smaller than the average priming effect. The same holds for relatively large targets (e.g., 12 only co-occurs with 9).

Discussion

We found that naming times of arabic numerals were fastest when the prime had the same value as the target and then slowly increased when the distance between prime and target increased. This is consistent with previous priming experiments (Brysbaert, 1995; Den Heyer & Briand, 1986; Reynvoet & Brysbaert, 1999), and can be interpreted as evidence for the fact that the prime is represented on an ordered number line and that activation spreads along the continuum. In line with Naccache and Dehaene (2001; but contrary to Koechlin et al., 1999), the notation of the prime (arabic or verbal) was not involved in any important interaction, indicating that the effects did not originate from a notation-specific representation, but rather from a common semantic system, which is the same for all notations. These data support the hypothesis that the semantic route is faster than the non-semantic conversion in normal arabic digit naming. Naming times were a function of the distance between the target and the prime (semantic relatedness), independent of the notation of the prime. Also, the effect did not seem to depend on differences in association strength between prime and target.

In addition to the semantic distance effect, there was a repetition priming effect: Target-naming latencies were an additional 15 ms faster when prime and target referred to the same quantity. This was not only the case when prime and target were presented in the same (arabic) notation, but also when the prime was presented in verbal notation and the target in arabic notation. We believe that this repetition priming effect is due to a combination of overlap in perceptual processes (in the arabic–arabic condition) and direct activation of the number name by the verbal prime (in the verbal-arabic condition). We return to this issue in the discussion of Experiment 2.[3]

EXPERIMENT 2

Experiment 2 was designed to find out to what extent the priming effects in the naming of verbal numerals differ from those in the naming of arabic digits. On the basis of current models of visual word recognition and the findings of Fias et al. (2001), we know that the non-semantic pathway is more important for the naming of verbal numerals than for the naming of arabic numerals (see earlier). The present experiment was run to find out what consequences this has for within-notation and across-notation priming. The only difference with Experiment 1 is that verbal target numerals were used instead of arabic target numerals.

[3]It might be objected that our interpretation of semantic mediation in number naming is called into question by the observation that naming latencies were fastest for the target numeral “9”. On the basis of Brysbaert (1995) one would predict that the naming latencies increase as a function of the magnitude of the numbers. However, one must be cautious with this objection, as differences in naming latencies can have many different origins, going from the perceptual discriminability of the stimuli used to the sensitivity of the microphone to the onset phonemes of the number names (e.g., RTs were longest for the targets 6 and 7, the pronunciation of which starts with the phoneme “z” in Dutch).

Method

Participants

A total of 20 new native Dutch-speaking first-year psychology students participated in the experiment (17 females, 3 males).

Apparatus and instructions

These were the same as those in Experiment 3.

Stimuli and procedure

Targets were verbal numerals ranging from *four* to *nine* (in Dutch: vier, vijf, zes, zeven, acht, negen). Primes were verbal or arabic numerals ranging from the target minus three to the target plus three. In order to reduce the physical overlap between prime and target, we presented the primes in a smaller size than the targets.

Results

No naming errors were made. Mean percentage of unreliable measurements due to coughs or noise was 1.9%. The same ANOVA as that in the first experiment was run on the median RTs.

The results were similar to those in Experiment 1. There was a significant effect of target magnitude. $F(5, 90) = 4.75$; $MSE = 3236.04$; $p < .001$. The mean RTs for the targets 4 to 9 were, respectively, 475, 467, 479, 493, 463, and 469 ms. Also the distance between prime and target produced a significant effect, $F(6, 108) = 24.26$; $MSE = 403.09$; $p < .001$. RTs increased when the distance between prime and target increased up to a distance of two (Figure 2). Again, a planned comparison showed a significant difference between absolute distances of one and two, $F(1, 18) = 17.64$; $MSE = 563.66$; $p < .001$, whereas this difference was no longer significant between absolute distance, of two and three ($F < 1$). The priming effects were symmetric, indicated by non-significant pairwise comparisons of T – 1 and T + 1, T – 2 and T + 2, and T – 3 and T + 3 (all $p > .99$). Again, the interaction between prime and target was significant, $F(30, 540) = 1.68$; $MSE = 417.74$; $p < .05$ (Footnote 2). In addition, one interaction effect

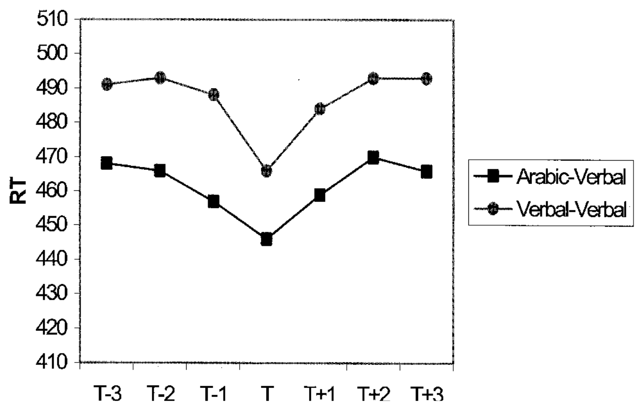

Figure 2. RTs of the verbal-number-naming priming task with arabic and verbal primes (Experiment 2).

with prime notation was obtained. RTs were slightly faster when an arabic prime preceded the target, except for the target 9, inducing a significant interaction between notation of the prime and target magnitude, $F(5, 90) = 7.56$; $MSE = 3236.04$; $p < .001$.

Just as in Experiment 1, we performed a multiple regression analysis on the data to find out the relative importance of the priming due to semantic distance and to repetition. In this analysis we only included values up to a distance of two, because the distance priming effect seemed to be limited to this range. The regression weight of absolute distance was 9.10 ms, $t(19) = 4.24$; $p < .001$, indicating that RT increased by 9 ms when the distance between prime and target increased by one unit. The regression weight of repetition priming was only marginally significant, regression weight = 6.66 ms; $t(19) = 2.016$; $p < .06$, indicating that the RTs were an additional 7 ms faster when the prime and the target had the same value. However, contrary to Experiment 1, there was a marginally significant difference between the repetition regression weights of the two notations, $F(1, 18) = 3.89$; $MSE = 188.08$; $p < .07$. There was no real repetition priming when arabic numerals preceded the verbal targets, whereas there was a substantial effect of repetition priming when verbal primes preceded the verbal targets (mean regression weights of 0.56 ms vs. 12.66 ms). There was no difference between the regression weights of absolute distance as a function of prime notation.

We also compared the regression weights of Experiments 1 and 2 for repetition priming and distance priming. This analysis showed that there were no differences between the distance regression weights of the four conditions ($F < 1$), whereas a marginally significant difference between the regression weights of repetition priming showed up, $F(3, 36) = 2.51$; $p < .08$, due to the absence of a repetition effect in the condition of a verbal numeral preceded by a digit.

Discussion

The most striking finding from Experiment 2 is the resemblance of the data to those of Experiment 1, certainly given the findings of Fias et al. (2001), who reported that verbal numerals can be named through a direct non-semantic pathway. The present results indicate that when the semantic route is preactivated for some 115 ms, the semantic system can exert an influence on the naming of verbal numerals. In addition, the effect is not limited to the within-notation word–word condition, but is also observed with cross-notation digit–word stimuli and is not significantly smaller than that observed in the naming of arabic numerals.

The only reliable difference we observed between the priming effects on the naming of arabic and verbal target numerals was the absence of a repetition effect in the arabic–verbal condition. In our view, this finding fits well within our working hypothesis that for arabic numerals the non-semantic digit–sound conversion route is too slow to be involved in normal number naming. If we assume that the repetition priming effect is partly due to phonological priming (see the discussion of Experiment 1), then it is not surprising to find that there is no repetition priming when an arabic prime precedes a verbal target, because the non-semantic phonological route for arabic numerals cannot influence the naming of the verbal target. An arabic prime can only influence target naming semantically.

Finally, the faster RTs in the arabic–verbal condition are a strange observation. Nevertheless, the same semantic effects show up in this condition. It could be that the faster latencies are due to characteristics of the display. The prime was physically smaller than the target, which could cause less interference in the naming process and induce faster naming times.

GENERAL DISCUSSION

In this paper, we investigated the extent to which the naming of arabic and verbal numerals is semantically mediated when the semantic pathway is pre-activated by a prime. Our results show that naming latencies for both arabic and verbal target numerals (e.g., *5/five*) are faster when preceded by a prime that is close in magnitude (*4/four*) than when preceded by a prime that is more distant in magnitude (e.g., *3/three*; see also Brysbaert, 1995; Koechlin et al., 1999; Naccache & Dehaene, 2001; Reynvoet & Brysbaert, 1999). The present results offer further evidence against Koechlin et al.'s suggestion that the effect originates from a notation-specific number system, because the magnitude of the priming effect was the same across notation as within notation (see also Naccache & Dehaene, 2001). We argue that the present results are congruent with the idea that the prime makes access to an ordered semantic number line, which is common to all notations, and in the process of doing so activation is spread along the continuum (Brysbaert, 1995; Dehaene, 1992).

The obtained effects were identical for the naming of arabic and verbal numerals, except for the repetition effect. This is not in line with the expectations we had on the basis of our previous research with the digit/word interference paradigm (Fias et al., 2001) in which we observed that the naming of verbal numerals was not hindered by an arabic distractor, whereas the naming of an arabic target was impeded by the presence of an incongruent verbal numeral. The present data show that presenting a numeral shortly before the target (i.e., about 115 ms) is enough to have a semantic impact, even for the naming of verbal input.

We believe that the distance effect is difficult to explain on the basis of associative relations within a non-semantic form-recognizing input system. First, the finding that the priming effects are similar for within-notation conditions (arabic–arabic and verbal–verbal) and for between-notation conditions (arabic–verbal and verbal–arabic) excludes the possibility of associative priming because arabic and verbal numerals cannot belong to the same input system. Second, as already argued by Koechlin et al. (1999), if the effects were due to associative relations between the stimuli, the naming times should not exhibit a symmetric pattern. The priming should be stronger in the forward direction. Finally, Reynvoet and Brysbaert (1999) obtained similar priming effects in a non-semantic naming task and a semantic parity judgement task, which indicates that the effects in the naming task are probably originating from the same semantic level as the effects in the parity task.

One might wonder what the present data mean for models of number processing? The most surprising finding was the strong across-notation priming in the naming of verbal numerals. In combination with the results of Fias et al. (2001), this tells us something about the relative speed of the different routes. In Fias et al., we argued that naming arabic numerals is always semantically mediated, without denying the possibility of a slow non-semantic conversion route for arabic numerals (Cipolotti & Butterworth, 1995; Dehaene & Cohen, 1997; Deloche & Seron, 1987). In contrast, for verbal numerals we argued that under unprimed presentation conditions the semantic route is outperformed by a non-semantic spelling–sound conversion system. The present data add to this picture, however, by showing that the semantic route for verbal numerals cannot be excessively slow because a small lead of 100 ms suffices to have influences from an arabic prime on the naming of a verbal numeral. Another important point is that the present data contradict Cipolotti's claim (1995; Cipolotti & Butterworth, 1995) that the chosen route is a function of task demands. According to Cipolotti, a non-semantic task, like naming, will activate the non-semantic conversion route and inhibit other conversion mechanisms, including the semantic route (Cipolotti & Butterworth, 1995). In this paper, we show that a verbal-numeral-naming task makes use not only of the non-semantic conversion route, but also of a semantically mediated route.

We believe that a strict modular model, with a semantic system and a non-semantic conversion mechanism as independent modules, cannot account for the present data. The present data are more in line with a cascade model of numerical processing that is based on a graded propagation of activation between the different parts of the model (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; McClelland, 1993; Plaut et al., 1996). When a verbal numeral is presented, the orthographic information will be sent simultaneously to semantic nodes and to phonological nodes. In addition, the semantic system is connected to the phonological system. Information spreads in parallel along the pathways. In the semantic system, numbers that are close in magnitude share some nodes (e.g., Dehaene & Changeux, 1993), so that the semantic representation of a number can be partly pre-activated by a number with nearby value. Under unprimed presentation conditions, the non-semantic orthographic–phonological connections have the largest impact due to the transparent grapheme–phoneme correspondences in Dutch verbal numerals. However, when the semantic route is already partly activated by a related prime, fewer activation changes will be necessary in this pathway to come to the activation pattern of the target word (e.g., Masson, 1999; Sharkey, 1990), so that the semantic route will be fast enough to influence the naming process. The input system of arabic numerals is connected to the same semantic system and has the same semantic priming effects. The present data do not allow us to say anything about the need of additional direct arabic–phonological connections (to explain the finding of neuropsychological patients who can still name digits but do not always understand them; e.g., Dehaene & Cohen, 1997), but if this route exists it is likely to be considerably slower than the semantically mediated conversion.

Because of the similarities between verbal numerals and words in general, our conclusions may also extend to the wider issue of visual word recognition. They provide evidence for automatic and relatively fast semantic mediation in word naming and, as such, contradict previous claims that semantic mediation is not involved in word naming when the language contains relatively consistent spelling-to-sound mappings (e.g., Dell'Acqua & Grainger, 1999). The generality of our findings, however, may depend on the extent to which the speed of semantic mediation is a function of the knowledge tested. If it turns out that the numerical meaning can be activated faster by visual verbal input than can the non-numerical meaning, then our findings may be limited to the numerical domain (see Thioux et al., 1998, for evidence that numerals may constitute a distinct category at the semantic level).

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