Cross-Notation Number Priming Investigated at Different Stimulus Onset Asynchronies in Parity and Naming Tasks

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Abstract. In this paper, a parity judgment task and a number naming task were used to investigate cross-notational number priming. Primes and targets could be verbal (e.g., *seven*) or Arabic numbers (e.g., 7), and were always presented in a different notation within the same trial (either a verbal prime and an Arabic target or an Arabic prime and a verbal target). Previous experiments showed that response latencies increase when the distance between prime and target increases (for example, in a naming task, *seven* is pronounced faster after 6 than after *5*). This semantic distance priming effect was the same for Arabic and verbal targets and was the same for within-notation trials as for cross-notation trials. In the present experiments, we wanted to investigate whether the cross-notational priming effect also occurs at SOAs shorter than the ones used in previous experiments. Therefore, we used SOAs of 43, 57, 86, and 115 ms. Semantic distance effects were indeed present at these shorter SOAs: Processing times in the semantic parity judgment task and in the non-semantic naming task increased when the distance between prime and target increased. The results are discussed and integrated within an interactive dual-route model of number processing that postulates that the impact of the semantic and the non-semantic route depends on the task and the notation of the stimuli.

Key words: number processing, priming, stimulus onset asynchrony

Research with the semantic priming paradigm goes back a long way and has revealed many insights in the processing of different kinds of stimuli. In the semantic priming paradigm, two stimuli are presented shortly after each other and the processing time of the second stimulus (target) is analysed as a function of the first stimulus (prime). The paradigm was used first in the language literature in which it was found that a target word (e.g., doctor) was processed faster after a related prime word (e.g., nurse) than after an unrelated prime word (Meyer & Schvaneveldt, 1971). The semantic priming paradigm was later used with other stimuli as well, including numbers. The first authors to investigate the processing of numbers with the priming paradigm were Den Heyer and Briand (1986). In a letter-digit classification task, they showed that RTs to Arabic targets were faster when immediately before a prime with a close value (distance of 1) had been presented than when a more distant prime had been presented (distance of 2 or 4). In line with this result, Brysbaert (1995) found that naming times of digits were faster when the target was preceded by a prime of a close magnitude. Both Den Heyer and Briand (1986) and Brysbaert (1995) interpreted these results as evidence for the hypothesis that the prime makes access to an abstract ordinal number line on which activation spreads from one representation to the magnitudes nearby.

It should be noted, however, that the stimulus onset asynchronies (SOAs) in these studies were quite long so that strategic effects on the RTs cannot be ruled out. In order to answer the question of whether the semantic priming effect in number processing arises auto-

Bert Reynvoet is a post-doctoral researcher of the Fund for Scientific Research-Flanders (Belgium). The authors wish to thank Wim Fias, Glen Bodner, and an anonymous reviewer for valuable comments on a previous version of this paper.

DOI: 10.1027/1618-3169.51.2.81

matically, one should make the SOAs shorter and present the prime stimulus very briefly so that it becomes difficult for the subjects to detect the prime (Neely, 1991). The latter can be realized by masked priming (e.g., Forster & Davis, 1984; Marcel, 1983). This technique was used, for instance, in an fMRI study by Dehaene et al. (1998) in which subjects classified numbers as smaller or larger than 5 by pressing on the left or the right response button. Before the target number, a prime was presented for 43 ms embedded between a pre-mask and a post-mask. Participants could not see the prime. Prime-target pairs could be congruent (i.e., prime and target evoked the same response, e.g., "smaller" as in 4 – 1) or incongruent (i.e., prime and target evoked different responses, e.g., 4 – 6). The results from brain imaging and ERP measurement showed that a stream of perceptual, semantic, and motor processes was initiated by the unconsciously presented prime, directly leading to a facilitation for congruent compared to incongruent trials. In addition to this congruency effect, RTs to trials in which the prime and the target evoked the same responses also revealed a semantic distance effect: Latencies were faster for identical prime-target pairs (e.g., 4 – 4 or four – 4) than for response-congruent but non-identical prime-target pairs (e.g., 4 – 1 or four – 1). This semantic distance priming effect was visualized in a reanalysis of the imaging data by Naccache and Dehaene (2001b), who reported a decrease in activation in the left and right intraparietal sulcus when prime and target were identical. Several reports have since replicated and extended these findings, and shown (1) that the RTs in congruent trials are longer when the distance between prime and target increases from one to two (Koechlin, Naccache, Block, & Dehaene, 1999; Naccache & Dehaene, 2001a; Reynvoet & Brysbaert, 1999), (2) that the distance priming effect is the same for within-notation priming (i.e., prime: Arabic digit – target: Arabic digit) and cross-notation priming (i.e., prime: Arabic digit – target: word numeral) (Naccache & Dehaene, 2001a; Reynvoet, Brysbaert, & Fias, 2002; but see Koechlin et al., 1999), and (3) that the distance priming effect shows up not only in semantic tasks such as number comparison (Dehaene et al., 1998; Koechlin et al., 1999; Naccache & Dehaene, 2001a) and parity judgment (Reynvoet & Brysbaert, 1999; Reynvoet, Caessens, & Brysbaert, 2002), but also in nonsemantic tasks such as number naming (Reynvoet & Brysbaert, 1999; Reynvoet, Brysbaert, et al., 2002). All this evidence suggests that in number processing, a notation-independent semantic representation for digits and verbal numerals is automatically activated, from which activation spreads to nearby numbers on the ordered continuum.

The semantic distance priming effect in the naming of verbal numerals (Reynvoet, Brysbaert, et al., 2002) at first sight seems contradictory to results obtained by Fias, Reynvoet, and Brysbaert (2001) and Fias (2001). In a stroop-like task, Fias, Reynvoet, et al. (2001) simultaneously presented a verbal and an Arabic numeral on a display. Both numbers either referred to the same magnitude (e.g., five – 5: congruent trials) or to different magnitudes (e.g., five-6: incongruent trials). Subjects had to ignore one of the numerals (distractor) and name the other numeral (target). The results showed that the presence of an incongruent Arabic digit did not interfere with the naming of a verbal target, whereas the naming of an Arabic target was hindered by an incongruent verbal distractor, suggesting that Arabic targets are named via the semantic system, whereas verbal numbers can bypass the semantic system and can be named through a set of nonsemantic orthography-to-phonology conversions (see also Brysbaert, Fias, & Reynvoet, 2000). Other evidence for nonsemantic processing of verbal numerals was offered by Fias (2001). In this paper, Fias made use of the finding that in Western cultures the semantic magnitude representations of small numbers are associated with left-hand responses and those of large numbers with right-hand responses (Dehaene, Bossini, & Giraux, 1993). Fias (2001) first showed that when participants have to decide whether a verbal target is odd or even, they are faster to react to small numbers with their left hand and to large numbers with their right hand. Next, he showed that no such association exists in a phoneme monitoring task in which participants had to indicate whether the verbal target contained the /e/ sound or not. This result was particularly interesting, because in a previous experiment, Fias, Brysbaert, Geypens, and d'Ydewalle (1996) had found that when participants have to decide whether the name of an Arabic digit contained the /e/ sound, they did show the associations left/small, and right/large.

Although these results seem contradictory, they can easily be reconciled if one assumes an interactive cascaded model of number processing with a semantic and an nonsemantic route, and a continuous, graded propagation of activation between the different parts of the model (Cipolotti & Butterworth, 1995; Dehaene, 1992). In healthy participants, there is a lot of evidence that the semantic route from Arabic input to verbal output is more important than the nonsemantic route. Evidence for nonsemantic processing of Arabic targets is rare and limited to some neuropsychological reports (Cipolotti & Butterworth, 1995; Dehaene & Cohen, 1997; Noel & Seron, 1995) and inconclusive evidence from brain imaging (Chochon, Cohen, Van der Moortele, Dehaene, 1999).[1] On the other hand, previous experiments

[1] The authors reported no activation in parietal cortex during digit naming. This was in contrast with some behavioral experiments in which the mere presentation of a

have revealed that digits address their semantic representation very rapidly (Dehaene et al., 1993; Dehaene & Akhavein, 1995; Fias et al., 1996), even when the digits are task-irrelevant (Fias, Lauwereyns, & Lammertyn, 2001; Lammertyn, Fias & Lauwereyns, 2002). The results described above indicate that verbal numerals, just like other words, can be named without semantic mediation (Fias, 2001; Fias, Reynvoet, et al. 2001). However, as soon as a prime number, either verbal or Arabic, is presented shortly before the verbal target (more than 100 ms), processing times of the target are mediated by the magnitude of the prime (Reynvoet, Brysbaert, et al., 2002). A possible interpretation of these findings is that the impact of the semantic system in verbal numeral naming is limited because of a more important nonsemantic route, and that the semantic system can only exert its influence when it is pre-activated by a prime. This idea of a dual-route model for verbal numbers is in line with the assumptions of several authors (Butterworth, Cappelletti, & Kopelman, 2001; Cappelletti, Butterworth, & Kopelman, 2001; Cohen, Dehaene, & Verstichel, 1994) and with current models of written word naming, which all consist of multiple routes from alphabetic input to spoken output (Besner, 1999; Coltheart, Rastle, Parry, Langdon, Ziegler, 2001; Plaut, McClelland, Seidenberg, & Patterson, 1996).

In this paper we examine the impact of the semantic and the nonsemantic routes in cross-notational priming in a parity judgment task and a number naming task. Until now, all priming experiments used SOAs of more than 100 ms and all found evidence for semantic processing, whereas in the Fias, Reynvoet, et al. (2001) study, where evidence for nonsemantic processing was reported, target and distractor were presented simultaneously (SOA = 0 ms). In the present experiments, we will further investigate semantic number priming across a range of SOAs between 43 ms and the previously used 115 ms. We have chosen to use cross-notation trials only (verbal prime – Arabic target or Arabic prime – verbal target) because previous experiments showed that within-notation and cross-notations number priming evoke the same effects (Naccache & Dehaene, 2002a; Reynvoet, Brysbaert, et al., 2002). By using cross-notation prime-target trials, we can exclude the presence of low-level, perceptual priming effects and priming effects due to associative relations in the input lexicon. The impact of SOA on the magnitude of the priming effect is likely to provide us with important information about the interaction of the semantic and the nonsemantic processing pathway in the naming of verbal and Arabic targets.

digit suffices to influence reaction times. Therefore, they re-examined the presence of parietal activation during naming by lowering the significance level. This analysis showed indeed an increase in parietal activation during digit naming compared to letter naming.

Experiment 1: Parity Judgment Task

In Experiment 1, we made use of a parity judgment task to find semantic numerical influences at very short SOAs (43, 57, 86, and 115 ms). The advantage of the parity judgment task is that it is a semantic task that cannot be performed without accessing number meaning (see Dehaene et al., 1993; Fias et al., 1996). Reynvoet and Brysbaert (1999, Experiment 2) obtained a robust semantic priming effect with this task when both prime and target were Arabic numerals and when the SOA was 132 ms (prime presentation duration = 66 ms): Participants were faster to indicate that a target numeral was odd or even, when the prime had a value close to the target than when the prime had a more distant value (e.g., response time to the target *4* was faster when the prime was *6* than when the prime was *8*). In a stroop-like task with simultaneous presentation of both numerals, Fias et al. (2001) also reported evidence for semantic mediation in parity judgment. Accordingly, we expected that distance priming effects would show up even at the shortest SOAs.

Method

Participants

Forty-eight native Dutch-speaking first-year psychology students participated in the experiment for partial fulfillment of a course requirement.

Apparatus

Stimuli were presented on a 15-inch color screen connected to a computer running the MS-DOS operating system. RTs were measured with an external button box connected to the game port of the PC.

Stimuli and Procedure

All participants saw two blocks of 192 trials. In one of the blocks, the targets were digits between 2 and 9, accompanied by two "=" signs to the left of the digit and two to the right in order to make the width of the Arabic stimuli approximately the same as that of the verbal stimuli. Primes were verbal numerals between two and nine (i.e., in Dutch: twee, drie, vier, vijf, zes, zeven, acht, negen). In the other block, the modalities of primes and targets were reversed. As our main interest was semantic priming and as we have shown before that semantic distance priming in a parity judgment task is obtained with compatible trials only (e.g., even prime and even target; Reynvoet, Caessens, et al., 2002), we limited our stimulus set to compatible trials. In total, there were 32 combinations of primes and targets. All combinations were repeated six times per block. Before each block, 32 practice trials were given. In these trials, the target ranged from 2 to 9 and was preceded by the same number in a different modality. Primes and targets in the practice block were in the same modality as in the test block. Stimuli were presented in yellow on a black background and were centred on the screen. All characters were presented in triplex font and were between 0.5° to 0.7° wide and 1° high. The order of the blocks was counterbalanced over participants.

Each trial consisted of the following sequence. First, a forward mask was shown for 71 ms (synchronized with the refresh cycle of the screen). This mask consisted of six hash marks (#) of the same size and font as prime and target. Then the prime was presented for 43 ms. The onset asynchrony between prime and target was 43, 57, 86, or 115 ms. The SOA was manipulated by inserting a backward mask of six hash marks between prime and target for different periods of time. When the SOA was equal to 43ms, the target was presented immediately after the prime, whereas in the in the other conditions, the backward mask was presented for respectively 14, 43, and 72 ms. The target remained on the screen for 200 ms. A postexperimental study was conducted to check the visibility of the primes in the different SOA conditions. The study showed that the primes were not visible in the 43 ms and the 57 ms condition, but could be detected slightly above chance in the 86 ms and the 115 ms SOA condition.[2]

[2] In a detection study, 10 new participants were told what they were about to see and had to apply the same instructions as in the experiment to the primes. Trial presentation and stimuli were exactly the same as in the experiments, with the exception that now also incompatible trials (e.g., 6–7) were included. Participants performed in 64 Arabic–verbal trials and 64 verbal–Arabic trials (each preceded by 16 practice trials) and in all SOA conditions (which were counterbalanced across subjects). Correct classifications of even primes were treated as hits and wrong classifications as misses to enabled the computation of *d*'. Correct and wrong classifications of odd primes were respectively treated as correct rejections and false alarms. Average *d*' for the 43, 57, 86, and 115 ms SOA condition were respectively 0, −0.02, 0.27 and 0.32. The *d*' at the two shorter SOAs did not statistically deviate from zero, whereas the *d*' in the condition with the 86 ms SOA (one-sided $t(9) = 2.12$, $p < .05$) and the 115 ms SOA (one-sided $t(9) = 2.11$, $p < .05$) were significantly larger than zero. This means that the primes could be identified above chance-level in the longer SOA conditions.

Participants were assigned randomly to one of the four SOA conditions (twelve participants per condition). They were asked to judge the targets on their parity status and were told that a trial would be announced by six hash marks. Half of the participants were asked to press the left key on the response box when the target was even and the right key when the target was odd. The other half performed the task with the reversed response assignment.

Results

To be consistent with our previous paper (Reynvoet & Brysbaert, 1999), we limited our analysis to the RTs at distance 0 (prime and target had the same value), distance 2 (the absolute difference between prime and target equaled 2) and distance 4. The selected couples were 2–2, 2–4, 2–6, 3–3, 3–5, 3–7, 4–4, 4–6, 4–8, 5–5, 5–7, 5–9, 6–6, 6–4, 6–2, 7–7, 7–5, 7–3, 8–8, 8–6, 8–4, 9–9, 9–7, 9–5. In this way, each target contributed equally to each distance and the priming direction was controlled for, as on half of the couples the prime was larger than the target, and on the other half it was smaller. The remaining trials were treated as fillers.

Mean percentage of errors was 4.8%. RTs smaller than 250 ms and larger than 1000 ms were excluded from the analysis, resulting in a loss of 1.2% of the data. A 4 (SOA) × 2 (Notation of the Target) × 3 (Distance Between Prime and Target) ANOVA was performed on the mean RTs with SOA as a between subject variable and the other two variables as within-subject variables. The same ANOVA was also run on the mean percentages of error, but we chose not to report this analysis since not one effect approached significance.

The ANOVA of the RTs revealed an effect of stimulus notation: Arabic targets were responded to 26 ms faster than verbal targets, $F(1, 44) = 12.61$, MSE= 3885, $p < .001$. More importantly, the effect of distance between prime and target was also significant (see Figure 1): Latencies were fastest when prime and target had the same value and increased when the distance between prime and target increased, $F(2, 88) = 23.42$, MSE = 238, $p < .001$. RTs increased by 7–8 ms when the distance between prime and target increased by two. A linear contrast over all distances showed a significant increase in RTs when the distance increased, $F(1, 44) = 30.32$, MSE = 361, $p < .001$. Even at the shortest SOA (43 ms), this linear contrast was significant, $F(1, 44) = 9.33$, MSE = 361, $p < .01$. The distance effect did not interact with notation, $F(2, 88) = 2.29$, MSE = 184, $p > .10$. Neither the main effect of SOA, $F < 1$, nor the interaction of SOA with notation, $F < 1$, or with distance, $F(6, 88) = 1.02$ MSE = 238, $p = .43$, reached significance. The distance priming effect did not differ under the various conditions as revealed by the nonsignificant triple interaction of Distance × Notation × SOA, $F(6, 88) = 1.06$, MSE = 138, $p = .39$.

Discussion

In line with our expectations, the results replicate and extend earlier findings (Reynvoet & Brysbaert, 1999; Reynvoet, Caessesns, et al., 2002) by showing that parity judgments are fastest when prime and target have the same value and slowly increase as the distance between prime and target increases. In addition, the present data show that the effect can be obtained when prime and target are presented in a different notation (in line with Naccache & Dehaene, 2001a; Reynvoet, Brysbaert, et al., 2002; and contrary to Koechlin et al., 1999). The pattern of results can be interpreted as evidence for the hypotheses that Arabic and verbal primes make access to a notation-independent number line on which activation spreads to nearby numbers. We also observed faster RTs for parity judgments on Arabic targets than on verbal targets. This is in line with other experiments investigating parity judgment on Arabic and verbal targets (Dehaene et al., 1993).

The most important finding of Experiment 1, however, is that the distance priming is similar at all SOAs and for both notations, extending the cross-notation priming effect to shorter SOAs, which is evidence for the fact that semantic mediation in processing verbal and Arabic targets is very similar at different SOAs.

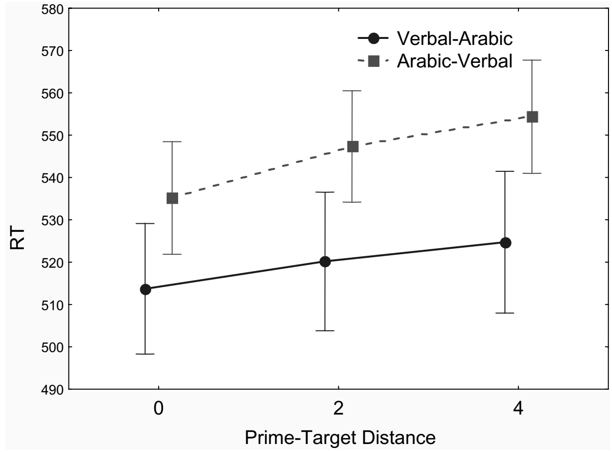

Figure 1. Mean RTs (averaged over all SOA conditions) in Experiment 1 plotted as a function of distance between prime and target for verbal and Arabic targets. The error bars indicate the 95% confidence intervals.

Experiment 2: Number Naming Task

Experiment 1 showed that cross-notation distance priming in a parity judgment task is not modulated by the SOA. However, this finding could be due to the fact that in order to make a parity judgment, one needs to have access to the semantic representation of numbers (Dehaene et al., 1993). In contrast, naming can be done without semantics. Hence, the question is whether the distance priming effect can be observed at short SOAs when Arabic and verbal targets have to be named. It is not unlikely to assume that semantic effects in number naming are restricted

Table 1. Mean RTs and Error Rates (Standard Errors in Parentheses) for Parity Judgments in Experiment 1

SOA	Prime-Target Distance 0 RT	Prime-Target Distance 0 Error	Prime-Target Distance 2 RT	Prime-Target Distance 2 Error	Prime-Target Distance 4 RT	Prime-Target Distance 4 Error
Verbal–Arabic Trials						
43	510 (11)	4.3 (1.2)	514 (11)	4.0 (0.8)	516 (13)	2.7 (0.6)
57	517 (15)	4.5 (1.1)	517 (16)	5.2 (1.4)	523 (17)	5.0 (1.0)
86	526 (18)	6.4 (1.7)	533 (16)	6.1 (2.1)	542 (16)	6.3 (2.4)
115	502 (16)	4.0 (1.3)	516 (20)	5.5 (1.6)	517 (20)	2.9 (1.4)
Arabic-Verbal trials						
43	521 (11)	4.9 (0.9)	543 (10)	4.5 (1.0)	548 (9)	3.8 (1.2)
57	547 (14)	2.4 (0.5)	552 (12)	5.2 (1.3)	558 (12)	4.7 (0.8)
86	543 (14)	5.9 (2.0)	550 (13)	5.4 (2.2)	555 (15)	4.3 (1.3)
115	529 (14)	4.0 (1.1)	544 (16)	5.9 (1.8)	556 (16)	5.6 (1.3)

to rather long prime-target SOAs. In a series of priming experiments (Reynvoet & Brysbaert, 1999; Reynvoet, Brysbaert, et al., 2002), we found that a close prime presented 115 ms before a verbal target facilitated naming times. On the other hand, Fias, Reynvoet, et al. (2001) showed that a simultaneously presented (SOA = 0 ms) Arabic distractor did not influence the naming of a verbal target. In the light of these findings, it could be that the semantic distance effect gradually increases when the SOA is longer.

Method

Participants

Forty native Dutch-speaking first-year psychology students participated in the experiment for partial fulfillment of a course requirement.

Apparatus

Stimuli were presented on a 15-inch color screen connected to a computer running under the MS-DOS operating system. RTs were measured with a microphone connected to the game port of the PC. After each response, the experimenter typed in whether the participant's answer had been correct and if the time registration had worked properly.

Stimuli and Procedure

The stimuli and the sequence of a trial were the same as in Experiment 1. All participants were assigned to one of the four SOA conditions (10 per condition). Again, participants completed two blocks; one block with verbal primes and Arabic targets, and another block with Arabic primes and verbal targets. The order of the blocks was counterbalanced over participants. In total there were 64 combinations of primes and targets (8 targets × 8 primes) and each combination was administered 5 times, leading to a total of 320 trials per block. Before each block, 32 practice trials were given. In these trials, targets ranged from 2 to 9 and were preceded by the same numeral, but in a different modality. Primes and targets in the practice block were in the same modality as in the test block. Participants were asked to name the target as fast as possible and were told that each trial would be announced by a series of 6 hash marks.

Results

Not all data points were analysed. Previous experiments (Reynvoet & Brysbaert, 1999; Reynvoet, Brysbaert, et al, 2002) showed that the priming effects were most pronounced up to a distance of 2. Therefore, we only analysed the RTs of couples in which the absolute distance between prime and target was smaller than three (e.g., with target 4 we analyzed the trials 2–4, 3–4, 4–4, 5–4, 6–4). To be consistent with our previous experiments (Reynvoet & Brysbaert, 1999; Reynvoet, Brysbaert, et al., 2002) the analysis was limited to the four targets in the middle (4–7) to investigate the symmetric pattern of the priming effects. If subjects were using a number-representation-based continuum, then a symmetrical pattern is expected because activation would spread in both directions along this ordered continuum. On the other hand, if they were using an associative word-representation-based network to name the targets, then an asymmetrical pattern is expected. Number primes smaller than their targets would show more priming than number primes larger than their targets, because people are more likely to say "four" as the first associate of "three" than as the first associate of "five."

Mean percentage of unreliable measurements due to coughs, noise, wrong onsets, or a voice key that was not triggered immediately, was 7.4%. RTs smaller than 250 ms and larger than 1000 ms were excluded from the analysis, accounting for another 0.7% loss of data. A 4 (SOA) × 2 (Notation of the Target) × 5 (Distance Between Prime and Target) ANOVA was run on the mean RTs with SOA as a between participants variable and the other two as repeated measures.

The analysis revealed significant main effects of stimulus notation and distance between prime and target. Verbal numerals were named 21 ms faster than Arabic targets, $F(1, 36) = 16.57$, MSE = 2762, $p < .001$. Latencies also increased as a function of the distance between prime and target, $F(4, 144) = 39.56$, MSE = 208, $p < .001$. RTs increased by about 12 ms when the distance between prime and target increased with one (Figure 2). A linear contrast over the absolute prime-target distances 0 to 2 showed a significant increase in RTs when the prime-target distance increased, $F(1, 36) = 97.47$, MSE = 326, $p < .001$. Planned comparisons showed that the latencies of prime-target pairs with the primes smaller than the target and pairs with the primes larger than the target did not significantly differ from one another, $F < 1$. As in Experiment 1, SOA did not affect response latencies, $F(3, 36) = 1.71$, MSE = 23661, $p > .18$), and more importantly, SOA was not involved in an interaction with distance, $F < 1$, nor in a triple interaction with distance and notation, $F < 1$. Even in the 43 ms SOA condition, an increase in RTs was present when the absolute distance between prime and target increased as indicated by a significant linear contrast for verbal targets $F(1, 36) = 10.43$, MSE = 197, $p < .01$, and Arabic targets, $F(1, 36) = 8.26$, MSE = 367, $p < .01$. The only interaction with SOA that approached significance was the one with notation, $F(3, 36)=2.27$, MSE = 2762, $p < .10$. In general, latencies were faster for verbal targets than for Arabic targets. However, this advantage was not present in the 86 ms SOA condition, where Arabic targets and verbal targets were named equally fast. Unexpectedly, the interaction effect between stimulus notation and distance, $F(4, 144) = 2.14$, MSE = 231, $p < .08$, approached significance. This was due to a larger distance priming effect for Arabic targets than for verbal targets. The average increase in RT for the Arabic numerals was 15 ms when the distance between prime and target increased with one unit, whereas it was only 9 ms for verbal numerals.

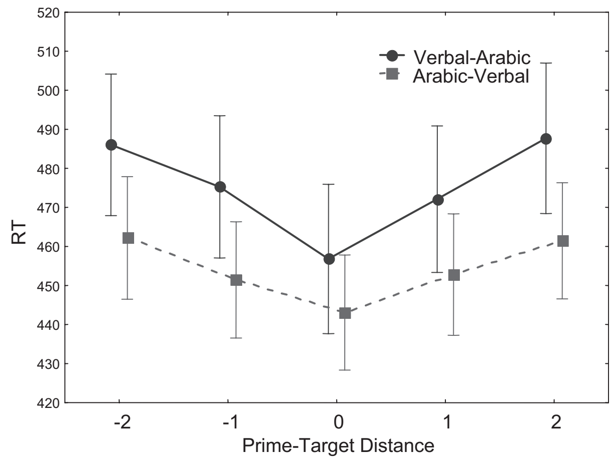

Figure 2. Mean RTs (averaged over all SOA conditions) in Experiment 2 plotted as a function of distance between prime and target for verbal and Arabic targets. The error bars indicate the 95% confidence intervals.

Discussion

Experiment 2 yielded three important findings. First, the results were an exact replication of Reynvoet, Brysbaert, et al. (2002) and showed that cross-notation distance priming exists. This strongly suggests that the priming effect occurs at a notation-independent processing stage (see also Naccache & Dehaene, 2001a). Second, the distance priming effect was similar across SOA conditions (43, 57, 86, 115 ms). This means that even at short SOAs, the processing of targets is semantically mediated by a related prime. Finally, although significant distance priming effects were found with both notations, the analysis also revealed two notational effects: a first notational effect were the faster naming latencies for verbal targets as compared to the naming latencies of Arabic targets, which is consistent with Reynvoet, Brysbaert, et al. (2002). Another notational influence was reflected by the smaller prime-target distance effect for verbal targets. This effect is surprising because Reynvoet, Brysbaert, et al. (2002) did not observe this asymmetry. However, target notation was manipulated between subjects in Reynvoet, Brysbaert, et al. (2002), whereas it was a within-subject factor here, making the current experiment more powerful. The smaller distance priming effect in the naming of verbal targets is in line with our working

Table 2. Mean RTs with Standard Errors (in Parentheses) for Naming Responses in Experiment 2

SOA	Prime-Target Distance −2	Prime-Target Distance −1	Prime-Target Distance 0	Prime-Target Distance 1	Prime-Target Distance 2
Verbal-Arabic Trials					
43	491 (23)	479 (22)	470 (24)	479 (24)	492 (25)
57	481 (20)	466 (19)	446 (19)	469 (20)	480 (20)
86	455 (12)	448 (13)	428 (9)	443 (15)	458 (15)
115	518 (15)	508 (16)	484 (20)	498 (12)	521 (14)
Arabic-verbal trials					
SOA	Prime-Target Distance −2	Prime-Target Distance −1	Prime-Target Distance 0	Prime-Target Distance 1	Prime-Target Distance 2
43	448 (21)	443 (21)	429 (20)	441 (22)	446 (19)
57	454 (14)	448 (12)	441 (13)	452 (15)	465 (14)
86	453 (16)	439 (15)	434 (14)	442 (11)	448 (14)
115	494 (9)	476 (8)	468 (9)	475 (10)	487 (10)

hypothesis that more processing is occurring via the nonsemantic route when verbal targets have to be named than when Arabic targets have to be named (Brysbaert, 1995; Brysbaert et al., 2000; Fias, Reynvoet, et al. 2001).

General Discussion

The most important goal of this paper was to find out whether a number prime, presented in a different notation than the target, can semantically mediate the processing of Arabic and verbal number targets in a parity judgment task and a number naming task across a range of SOAs. It seems that this is indeed the case. Semantic mediation in number processing is manifested by a positive correlation between RTs and the distance between prime and target. The greater the difference between both numbers, the slower the RT. This prime-target effect can be interpreted as evidence that the prime automatically activates its corresponding magnitude on an abstract ordinal number line, causing activation to spread to neighboring numbers. In previous experiments, onset asynchronies always were more than 100 ms (e.g., Dehaene et al., 1998; Koechlin et al., 1999; Naccache & Dehaene, 2001a; Reynvoet & Brysbaert, 1999; Reynvoet, Brysbaert, et al., 2002; Reynvoet, Caessens, et al., 2002). We extended these findings by showing that at SOAs as short as 43 ms, the semantic system has already processed the prime sufficiently to affect the processing of the target. This is not surprising in a parity judgment task, which requires semantics for good task performance. However, our data show that this also applies to a task like number naming, which can be performed without semantic involvement, certainly when the input is verbal (e.g., Fias, Reynvoet, et al., 2001).

As we mentioned in the Introduction, a viable account of the issue of semantic mediation in number naming, both in Arabic and verbal format, seems to require a dual-route model for each notation, with one route directly going from the visual input to the phonological output, and the other route passing through the semantic system. The present data fit nicely within such a model and point to the rapidity with which the semantically mediated route starts to mediate processing times. The difference between the experiments of Fias, Reynvoet, et al. (2001) and the present experiments is minimal: Both tasks required the naming of a verbal target and all other stimuli (prime or distractor) could be ignored. The most important parameter that changed was the SOA (0 ms vs. 43 – 115 ms). Nevertheless, it seems that this minor difference is sufficient to allow distance priming effects to be observed. We think it is unlikely that targets are named via a nonsemantic route when the SOA is 0 ms, but via the semantic route when the SOA is 43 – 115 ms. Rather, we propose that both routes are activated at the same time when a prime or target is presented. The difference in the processing of verbal and Arabic targets then depends on the relative importance of the two routes, with the nonsemantic route being more important for the naming of verbal numerals than for the naming of Arabic numerals.

According to the horse-race variants of the dual-route model (Coltheart, 1978; Paap & Noel, 1991), the importance of a route depends on its speed: The faster route (horse) determines the output. In interactive connectionist models with two routes (e.g., Plaut et al., 1996), the importance of a route depends on the change in activation it induces per processing cycle. In those models, one route is no longer faster than the other, but both change gradually the activation in the output level, until a stable state is reached. The amount of activation change induced by a route per processing cycle depends on the weight of connections *and* on the activation level of the units in the intermediate layers between the input and the output. So, the activation of the phonological representation /tU/ on the basis of the orthographic input *two* is gradually built up until a threshold value is reached. The steepness of the activation buildup due to the direct orthography-phonology route depends on the strengths of the connections between the orthographic word representation *two* and the phonological representation /tU/ (via a layer of hidden units). The steepness of the activation buildup due to the semantically mediated route, depends on the connection strengths of the orthographic input representation *two* and the magnitude representation |two|, on the connection strengths of the magnitude representation |two| to the phonological output representation /tU/, *and* on the activation level of the magnitude representation |two| at the beginning of the trial. The higher the initial activation of the magnitude representation, the more activation will be forwarded from the orthographic input to the phonological output via the semantically mediated route.

Our findings fit well within an interactive connectionist variant of a dual route model with a semantic and a nonsemantic route. For Arabic input the rise of activation is steeper in the semantic system than in the phonological output system, because the mapping from digits to meanings is simpler than the mapping from digits to sounds. A 2 has a very similar meaning, independent of its position in a number; however, its pronunciation varies (compare 2, 12, 20). In contrast, for verbal input the activation buildup will be faster in the phonological output system than in the meaning system. Words with a similar orthography, in general, have a similar phonology (e.g., two, to), but rarely have overlapping meanings.

Our conjecture of stronger links between digits and meaning than between words and meaning, and stronger links between letters and sounds than between digits and sounds is in line with the observations of a recent fMRI study conducted by Pinel, Dehaene, Rivière, and LeBihan (2001). They showed that subjects during a number comparison task showed a more pronounced increase in activation for verbal numerals compared to digits in areas close to those found in studies of word reading, and a greater increase in activation for digits relative to verbal numbers in bilateral inferior parietal and frontal areas, indicating more semantic involvement. It also agrees with the faster parity judgment times for Arabic input (Experiment 1) and the faster naming times for verbal input (Experiment 2). The different connection weights for Arabic and verbal input mean that the time needed to activate the correct number name up to threshold level will be determined to a larger extent by the semantically mediated route for Arabic input than for verbal input. However, because the contribution of the semantically mediated route not only depends on the connection weights but also on the activation level of the semantic units, preactivating the relevant semantic units is likely to increase the amount of activation contributed by the semantic route per processing cycle, both for Arabic and verbal numerals; hence the distance related priming effect.

At first sight, the stronger priming effect for the naming of Arabic targets than for the naming of verbal targets also seems to be in line with this model. However, given the confound between target notation and prime notation, the difference between Arabic and verbal targets here, could (partly) be due to the difference between verbal and Arabic primes.

Another factor that may be of importance in the interpretation of our findings is that we blocked the SOA in our experiments. Naccache, Blandin, and Dehaene (2002) showed that unconscious priming only occurred with a constant prime-target SOA in a block and not when the prime-target SOA changed from trial to trial. Apparently, in a block with a fixed SOA, participants were able to allocate attention to the time window during which the prime-target pair appeared. In the present experiments, participants took part in one SOA condition only and responded to the two target notations in different blocks. As noted by one of the reviewers, it is possible that the relation between the amount of priming and the SOA depends on at least two different and possibly counter-balancing effects: the activation of the semantic representation evoked by the prime which may gradually diminish over time, and attention to the temporal succession of a prime-target pair, which may be more easily to allocate when prime and target are a bit more separated in time. We indeed found that subjects could detect primes better when the SOA were longer, which might be evidence for the fact that top-down modulation might be more effective at somewhat longer SOAs. Together with the finding of Greenwald, Draine, and Abrams (1996) that unconscious semantic priming effects are stronger at short SOAs, a mixture of semantic and top-down attentional effects sounds plausible indeed. This mixture of both effects might be responsible for the lack of effect of SOA on the semantic priming effects.

In sum, we have shown that numbers that were masked to reduce their visibility nonetheless make access to the semantic system. From there, they facilitate the processing of a nearby target, even when this target is presented in another notation than the prime. The prime-target SOA does not seem to have a large impact on the amount of priming. The same priming is observed when the SOA is 43 – 115 ms. The latter finding may be peculiar to small integer numbers, as argued by Damian (2001) and Greenwald, Abrams, Naccache, and Dehaene (2003), who ventured that fast semantic mediation may be more difficult to obtain with other verbal stimuli. They argued that numbers elicit strong semantic effects because they have a simple, well-defined meaning.

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February 27, 2003
June 18, 2003
June 23, 2003

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