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Naming Two-Digit Arabic Numerals: Evidence From Masked Priming Studies

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The authors investigated how 2-digit Arabic numerals are named by looking at the effects of masked primes on the naming latencies. Target numerals were named faster when prime and target shared a digit at the same position (e.g., the target 28 primed by 18 and 21). In contrast, naming latencies were slower when prime and target shared 1 or 2 digits at noncorresponding places (e.g., the target 28 primed by 82, 86, or 72). Subsequent experiments showed that these priming effects were situated at the level of the verbal production of the Arabic numerals. The data point to a nonsemantically mediated route from visual input to verbal output in the naming of 2-digit Arabic numerals.

Keywords: naming, two-digit Arabic numerals, masked priming

Recent years have witnessed a dramatic increase in the number of studies examining number processing. Unfortunately, for some topics this increase has not been accompanied by a growing consensus about the processes involved. In the current article, we address what arguably should be one of the simplest questions in numerical cognition: How are Arabic numerals named?

Four different models have been proposed by various authors, depending on the answers to the following two questions: Is semantic mediation required for the naming of Arabic numerals? Are two-digit numbers processed holistically or through a process of syntactic decomposition into 10s and units?

The issue of semantic mediation addresses the question of whether Arabic numerals can be named without first activating their meaning. For visually presented words within an alphabetic language, there is plenty of evidence that such nonsemantically mediated naming is possible. In fact, many existing models of written word naming do not even include an implemented semantic route (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Plaut, McClelland, Seidenberg, & Patterson, 1996). Such a route is assumed to exist but has not yet been properly examined because it does not seem necessary to account for word-naming latencies. These can be explained by a direct letter–sound conversion route (assembled phonology) or a route in which the visual input activates a presentation in the input lexicon, which, in turn, activates a representation in the phonological output lexicon (addressed phonology).

In contrast, most researchers assume that objects and pictures of objects cannot be named without first activating their meaning (e.g., Levelt, Roelofs, & Meyer, 1999). Damian, Vigliocco, and Levelt (2001) provided particularly convincing evidence for the difference between word reading and picture naming. They asked participants to repeatedly name pictures in a semantically homogeneous block (e.g., cat, goat, rat, beaver, tiger, swan) or in a semantically heterogeneous block (e.g., cat, hand, ferry, skirt, broom, leek). Damian et al. observed that participants needed more time to name the pictures in the homogeneous condition than in the heterogeneous condition. They attributed this interference effect to an increased competition in the retrieval of lexical entries in the homogeneous condition because of the semantic overlap among the various stimuli. The interference effect was not present when the pictures were replaced by words and participants were asked to repeatedly read the words. With these stimuli, the researchers found even faster reading times in the homogeneous block than in the heterogeneous block, in line with the associative priming effect usually found in word reading. The difference was not due to the type of stimuli, because the semantic interference effect reappeared when participants were asked to start their response with the correct article of the noun that was depicted (the experiment happened in German, a language in which nouns get different articles depending on their gender). Previously, Kroll and Stewart (1994) had shown a semantic interference effect when bilingual participants were asked not to read the stimulus words but to translate them into their second language. The extraction of gender information and the translation of words, unlike the naming of words, are thought to require semantic mediation. Other evidence for the distinction between picture and word naming was reviewed

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by Glaser (1992). For instance, pictures take substantially longer to name than words but induce shorter semantic decision times.

Researchers have disagreed whether Arabic digit naming resembles word naming or picture naming. In one of the first influential models, McCloskey, Caramazza, and Basili (1985) argued in favor of obligatory semantic mediation. Later, Brysbaert (1995), Fias (2001; Fias, Geypens, Brysbaert, & d'Ydewalle, 1996; Fias, Reynvoet, & Brysbaert, 2001), and Damian (2004) joined this position. Brysbaert (1995) did so after he observed that reading times of Arabic numerals between 1 and 99 primarily depended on the logarithm of the number magnitude, which is a characteristic of the meaning of the numbers. Fias et al. (1996; see also Fias, 2001) defended obligatory semantic mediation in Arabic number naming because they found that participants reacted faster with their left hand to small numbers and with their right hand to large numbers (i.e., the so-called SNARC effect, reflecting semantic access to the mental number line, which is thought to be oriented from left to right; Dehaene, Bossini, & Giraux, 1993) not only when they had to indicate whether the number was small or large but also when they had to indicate whether the name of the Arabic numeral contained an /e/ sound or not. Fias et al. (2001) presented other evidence for obligatory semantic mediation in Arabic number naming. They observed that the naming of Arabic digits was faster when a distractor number word on the display referred to the same magnitude as the digit (e.g., 6–six) than when it referred to a different magnitude (e.g., 6–four). No such Stroop-like interference effect was seen when participants were asked to name a number word in the presence of a digit distractor (e.g., naming times were the same for six–4 as for six–6). Finally, Damian (2004) reported that number words are named faster than digits, whereas magnitude judgment is faster for digits than for number words, mimicking the asymmetries observed between pictures and words.

Another group of authors, however, defends the idea that the semantically mediated route is supplemented by a direct connection between the Arabic input and the verbal output, which is faster than the semantically mediated route. Although such a route is sometimes presented as a substitute of the semantic route, McCloskey (1992) rightly indicates that a direct number-naming route cannot replace the semantically mediated route, because the most important task of number processing is number understanding and not number naming. Similarly, we must be able to name numbers on the basis of conceptual information and not only on the basis of visual input. So the existence of a semantically mediated route is pivotal in any model of number processing, and a direct route from Arabic input to verbal output requires an additional processing pathway. One of the first researchers to defend such an asemantic route for number naming was Coltheart (1978), who claimed that digits, just like punctuation marks and abbreviations, form part of the orthographic input lexicon. Other authors who defended the idea were Deloche and Seron (1987), Dehaene (1992), and Roelofs (in press). Roelofs (in press), for instance, replicated Fias et al.'s (2001) Stroop interference task. However, he matched the area covered by the digit to the area covered by the word (Fias et al. presented words and digits in the same font). Using this simple manipulation, Roelofs showed that the Stroop interference effect of Arabic digits was the same as that of words and significantly different from that of dice faces representing numerals. On the basis of this finding, Roelofs claimed that dice faces require conceptual identification before they can activate lemmas and word forms, whereas Arabic digits (just like words) can activate the lemmas and word forms directly. Meeuwissen, Roelofs, and Levelt (2003) made a similar claim for multidigit Arabic numbers, after having observed that the number-naming times were mostly influenced by word form characteristics (the whole-word frequency, the frequency of the constituent morphemes, and the length of the numeral in phonemes) and not by the magnitude of the number.

A second issue in Arabic number naming on which researchers disagree is whether two-digit Arabic numerals are processed as a whole or are decomposed into 10s and units. No one questions that decomposition is needed for numerals like 781,524.08. Similarly, there is little evidence that the number 781 would be recognized as a whole (unless it has a nonquantitative meaning for the participants, for instance, because it is the number of a room in which they regularly meet; see later). However, with respect to two-digit numbers, there is evidence that these may be recognized as a whole. Dehaene et al., for instance, claimed that the semantic number magnitude system can be thought of as a modality-independent number line on which all numbers are ordered from small to large. Empirical evidence for this view came from the distance effect in number comparison (Dehaene, Dupoux, & Mehler, 1990). When participants are asked to indicate whether stimuli are larger or smaller than a standard (e.g., 5 or 65), they can do so faster for numbers with distant magnitudes (e.g., $1 < 5$, $27 < 65$) than for numbers with close magnitudes (e.g., $4 < 5$, $64 < 65$). Dehaene et al. (1990) observed that this distance effect was a function of the logarithm of the difference between the comparison stimulus and the standard, and that the effect did not show a discontinuity when there was a difference in the decade[1] digits of the standard and comparison numbers. That is, participants were faster to decide that $59 < 65$ than $60 < 65$, but this difference did not seem to be larger than expected on the basis of the logarithm of the distance between the numbers. Dehaene et al. (1990) proposed that two-digit stimuli are converted into analog magnitudes before they are compared.

Other evidence that two-digit numbers are processed as a whole comes from number-priming studies. A number is recognized faster when immediately before a number of a close magnitude (e.g., 9–8, 66–65) has been processed than when a number of a more distant magnitude has been processed (e.g., 2–8, 61–65). Crucially, the priming effect is the same across decades as within decades (i.e., the priming effect of 7 on 9 is the same as that of 11 on 9; Brysbaert, 1995, Experiments 1 and 2; Reynvoet & Brysbaert, 1999). This too seems to suggest that two-digit numbers are processed as a whole and that there is continuity of the semantic representations across decades.

The assumption of holistic two-digit number processing has figured less prominently in models with a direct route between Arabic input and verbal output, but it is not absent. Cohen, Dehaene, and Verstichel (1994), for instance, postulated a lexicon for familiar Arabic numerals to explain why a deeply dyslexic patient could read well-known multidigit numbers (e.g., 1945) but not unfamiliar numbers (e.g., 4159). Delazer and Girelli (1997) came

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[1] Note that in this context the concept *decades* refers to "10s" and not to "ten years."

across a similar finding, when their patient was unable to name multidigit numbers (e.g., 164) unless these were preceded by an associated prime word (*Alfa Romeo*; the patient had such a car). Alameda, Cuetos, and Brysbaert (2003) replicated this priming effect in healthy participants using briefly presented masked primes to reduce deliberate expectancy and guessing strategies. Finally, Seron and Noël (1995) ventured that frequently used expressions, such as number names, are preassembled at the level of the phonological output lexicon. This would explain why neuropsychological patients with severe deficits remain capable of reciting well-learned word sequences (including number sequences).

Not all researchers defend holistic representations of two-digit numbers, however. McCloskey (1992), for instance, hypothesized that number magnitudes are not represented by a position on a number line but by a combination of powers of 10. So the number 28 is thought to be represented as $\{2\} \times \{10^1\} + \{8\} \times \{10^0\}$. Grossberg and Repin (2003) made a similar claim and argued that the precision of the number line can be increased by postulating a two-dimensional number map rather than a unidimensional number line. In the two-dimensional map, the 10s, 100s, and 1,000s are situated on the same strip as the units (e.g., 10, 100, and 1000 share the strip of 1 but are extended in the second dimension). Grossberg and Repin (2003) made a case of how a unidimensional number line can evolve into a two-dimensional map, when there are interactions between the number line and the number words used to refer to quantities (e.g., in English, all 10s are formed by adding the suffix *–ty* to a number; this regularity can be exploited to create a band of decades along the number line that represents the units).

The discussion between holistic and decomposed semantic representations of two-digit numbers turns around the question whether in two-digit number comparisons there is any evidence for decomposition. Dehaene et al. (1990) claimed there was not, but very detailed examinations since have indicated that this may have been a premature conclusion. Nuerk, Weger, and Willmes (2001; see also Ratinckx, Nuerk, van Dijck, & Willmes, in press), for instance, asked their participants to select the larger of two simultaneously presented two-digit Arabic numbers. Half of the trials were unit–decade compatible, half were incompatible. A trial was defined as compatible if the decade magnitude comparison and the unit magnitude comparison of the two presented numbers led to the same response (e.g., 52 and 67 are compatible because $5 < 6$ and $2 < 7$) and as incompatible if this was not the case (e.g., 47 and 62 are incompatible because $4 < 6$ but $7 > 2$). The authors obtained a significant unit–decade compatibility effect (in addition to the usual distance effect), suggesting that the 10s and the units had been compared in parallel. Grossberg and Repin (2003) noticed a similar compatibility effect when they simulated double-digit number comparisons within their computational model based on the two-dimensional number map. Other authors (e.g., Verguts & De Moor, 2005) failed to find a distance effect of the units when the decades differed (i.e., participants were not faster to decide that $41 < 57$ than to decide that $45 < 57$, although the difference between the numbers is larger in the former case than in the latter). In contrast, such a distance effect was clearly present when the decades were the same (deciding that $51 < 57$ occurred faster than deciding that $55 < 57$).

Decomposition of the input is also central to Meeuwissen et al.'s (2003) direct route of number naming. This is because the Weaver++ model of word and picture naming on which the direct Arabic number route is based (Levelt et al., 1999) holds that complex numerals are constructed and represented as composites of 1,000s, 100s, 10s, units, and teens (these are the numbers between 11 and 19 that have a deviating name). In their view, the naming of the numeral 78 involves retrieval of the constituting lemmas (*seventy* and *eight*) in the correct syntactic order (e.g., in Dutch the units precede the 10s). Once the lemmas are activated and ordered, the appropriate expression is constructed by retrieving the relevant morphemes and segments (e.g., in Dutch the morpheme *-en* [and] must be inserted between the units and the 10s: *acht-en-zeventig* [eight-and-seventy]). Then the appropriate phonological syllables are constructed and the motor programs for these syllables retrieved. Decomposition was also present in the direct route of Dehaene's (1992) triple-code model. In this model, Arabic numerals of more than one digit are recognized by a visual Arabic number form system (based on a visuospatial grid) that is capable of translating the input into a verbal output. This translation is assumed to be a complex process involving separate steps of syntactic composition and lexical retrieval (Deloche & Seron, 1987).

Below we try to clarify the literature by making use of a new manipulation, for which the four types of interpretation (semantically mediated, holistic; semantically mediated, decomposed; direct route, holistic; and direct route, decomposed) make divergent predictions. This manipulation is based on the masked distance-related priming effect, described previously and pioneered by Koechlin, Naccache, Block, and Dehaene (1999) and Reynvoet and Brysbaert (1999). On the basis of this effect, we can predict that the number 85 will prime the naming of 86. All models converge on this prediction. A model based on obligatory semantic mediation and holistic representations on a number line predicts it, because the prime and the target are closely represented on the number line and are coactivated in the very first stages of number processing. A model with obligatory semantic mediation and composite, power-of-10 magnitude representations also predicts priming, because prime and target share the same entry in the 10s slot and have adjacent numbers in the units slot. The same reasoning explains why the priming occurs in a nonsemantic model based on the online concatenation of the words for units and 10s. Finally, a nonsemantic model with a visual input lexicon for familiar Arabic numerals and a verbal output lexicon for familiar complex number names can account for the priming by pointing to the fact that 85 and 86 are strongly associated with each other (the first associate that comes to mind when seeing the number 85 probably is 86).

Predictions start to diverge, however, when it comes to forecasting a possible priming effect of 81 on the naming of 86. Models based on decomposition of the numbers would still predict priming because of the overlap of the 10s. However, much less priming is predicted by models based on holistic representations of two-digit numbers; Reynvoet and Brysbaert (1999; see also Reynvoet, Brysbaert, & Fias, 2002) observed that the distance-related priming effect of masked primes does not extend beyond distances of +3 or –3. Similarly, the association strength between the numerals 81 and 86 is likely to be too weak to induce significant priming.

Very similar predictions hold for the situation in which the target number 86 is primed by the number 96. Because of the overlap in the unit slot, composite models predict a priming effect, whereas holistic models do not.

Finally, there are the intriguing cases of digits in noncorresponding positions. What will happen to the naming of the target number 86 when it is preceded by the primes 62, 58, or 68? Holistic models predict no priming effects; composite models might predict an interference effect because of the overlap of the lexical items in the different slots.

Six masked priming experiments were run to shed light on the issues of semantically mediated versus direct Arabic number naming and holistic versus decomposed two-digit processing. Experiments 1 to 3 were designed to investigate whether two-digit Arabic numerals are processed holistically or in a decomposed way. The remaining Experiments 4 to 6 were run to demarcate the origin of the masked priming effects obtained in Experiments 1 to 3.

Experiment 1

In Experiment 1, participants named targets ranging from 1 to 99, which were all preceded by two-digit Arabic number primes. Only a specific part of the targets ranging from 18 to 93 (test trials) was analyzed; the other targets belonged to the filler trials. We included five different (related) prime conditions in which primes shared at least one digit with the target. In two conditions, target and prime shared a digit at the same position (position-congruent overlap; e.g., the prime 13 or 28 preceded the target 18), whereas in the three other conditions one or both of the digits swapped places between prime and target (position-incongruent overlap; e.g., the prime 81, 83, or 31 preceded the target 18). Each of the five (related) prime conditions was compared with a matched unrelated prime in which there was no overlap between the prime and the target (see also Appendix A).

Method

Participants. Sixteen first-year psychology students (age range: 18–19 years) at Ghent University participated for course credit. They were all native Dutch speakers. Note that in the Dutch language number names beginning from 21 are named in a reversed order (e.g., *een-en-twintig* [one-and-twenty]; for more information on the Dutch number-naming system see later discussion). Participants were unaware of the purpose of the experiment and had normal or corrected-to-normal vision. Informed consent and ethics approval were obtained before the start of the experiment according to the American Psychological Association (APA) guidelines.

Stimuli. All Arabic numbers from 1 to 99 were presented as targets for a total of 990 trials (see Appendix A for the full set of stimuli used). Part of these trials was considered test trials (470 in total), whereas the remainder were filler trials (520 in total). We included the filler trials to create a more natural experimental environment in which all targets between 1 and 99 had to be named instead of merely a specific part (i.e., only the test trials).

For each target in the test trials, five related and five unrelated primes were chosen. Two related primes had always one position-congruent digit overlap with the target (e.g., target 18, primes 13 and 28), whereas three primes had at least one overlapping digit on incongruent positions (e.g., target 18, primes 83, 31, and 81). For each target in the test trials, we also selected five unrelated primes (e.g., target 18, primes 23, 29, 79, 92, and 32), so that on average their numerical distance to the target was the same as that of the related primes to the targets. This resulted in a total of 235 test trials with related primes (5 primes × 47 targets) and 235 test trials with unrelated primes (5 primes × 47 targets).

Procedure. Stimuli were presented on a 15-in. color screen. Presentation was controlled by a PC-compatible Pentium 233, which had a microphone connected to the game port. Reaction times (RTs) were measured to the nearest millisecond. First, a forward mask was shown for 80 ms (synchronized with the refresh cycle of the screen). This mask consisted of two hash marks (##) that were of the same size and font as the Arabic targets. Then the prime was presented for 50 ms followed by a backward mask for another 50 ms. The backward mask was the same as the forward mask. Finally, the target was presented during 200 ms, resulting in an stimulus onset asynchrony (SOA) of 100 ms (for an overview of the procedure, see Figure 1). To reduce the physical overlap between prime and target, we made the primes (Arial font 11) smaller than the targets (Arial font 12). All stimuli were presented in white on a black background and were centered on the screen.

To investigate how visible the primes were under these presentation conditions, we ran an additional experiment on 12 new participants. Presentation of the stimuli was the same as that described previously, but participants were asked to judge whether the masked prime and the target shared at least one digit or not. We included 10 trials in each of the 10 priming conditions (five types of overlap, related and unrelated primes). The mean success rate was 58%, $t(11) = 3.5$, $p < .005$, indicating that the primes were not completely invisible. Discrimination performance, as measured by d', deviated significantly from 0 ($d' = 0.46$), $t(11) = 4.4$, $p < .005$. This means that our priming conditions do not fulfill the requirements for unconscious processing, although any effect we obtain is still going to be an automatic effect. Neely (1991) showed that strategic expectancy effects require SOAs of more than 250 ms. In addition, because full identification of the primes was not required in the experiment, the control experiment was able to discover the smallest possible degree of discrimination of the primes.

Participants in the main experiment were asked to name the target number as quickly and accurately as possible. After the microphone was triggered, the word "OK" was presented centered at the bottom of the screen. The experimenter typed the participant's answer on the computer keyboard and noted whether the time registration had worked properly. Then the screen was cleared, and the next trial started after 1,200 ms. The experiment started with 20 training trials randomly chosen from the 990 experimental trials. A short pause was provided after the training session and after every 165 trials of the experimental session. In each break, the participants were informed about their mean RTs and errors to stimulate the participants to perform at best and to avoid too much loss of data. Because the experiment was run in Dutch, the number names from 11 to 14 were irregular (i.e., *elf* [eleven], *twaalf* [twelve], *dertien* [thirteen], *veertien* [fourteen]). The names from 15 to 19 were regular but different from the rest (i.e., *vijftien* [fifteen], *zestien* [sixteen], *zeventien* [seventeen], *achttien*

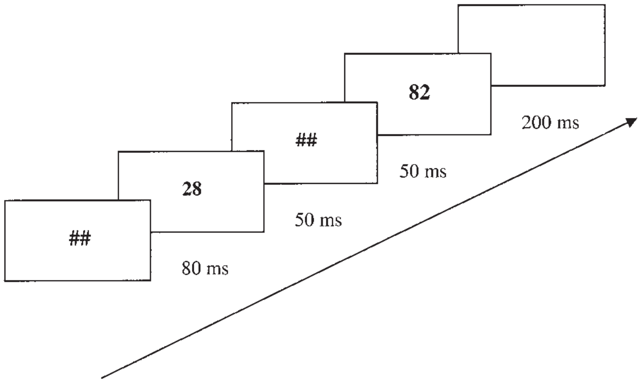

Figure 1. General outline of the masked priming procedure in Experiment 1.

[eighteen], *negentien* [nineteen]). The number names from 21 on were reversed (e.g., *een-en-twintig* [one-and-twenty], *twee-en-twintig* [two-and-twenty]). Further information about this characteristic of the Dutch (and the German) number-naming system can be found in Brysbaert, Fias, and Noël (1998).

Results

Mean percentage of naming errors and unreliable measurements resulting from coughs or noise was 3.6%. Only average RTs of correct responses in the range of 150 to 1,200 ms were analyzed. There were virtually no outliers in the correct responses.

Except for the priming condition in which the units of the prime matched the 10s of the target (31–18 [491 ms] vs. 32–18 [484 ms]), $t(15) = 1.72$, $p = .11$, all effects were significant (Table 1): 13–18 (471 ms) versus 23–18 (479 ms), $t(15) = -2.59$, $p < .05$; 28–18 (470 ms) versus 29–18 (476 ms), $t(15) = -2.64$, $p < .05$; 81–18 (506 ms) versus 79–18 (487 ms), $t(15) = 6.99$, $p < .01$; 83–18 (502 ms) versus 92–18 (487 ms), $t(15) = 4.72$, $p < .01$. Notice that the sign of the difference is positive (facilitation) in the conditions with position-congruent digits and negative (inhibition) in the conditions with position-incongruent digits. Also notice that in the current study, no genuine neutral condition (e.g., two hash marks as a prime instead of a two-digit Arabic numeral) was included so that the use of the terms *facilitation* and *interference* is strictly speaking not justified (see Experiment 6 for such a condition). However, in this experiment, in using the terms *facilitatory priming* and *inhibitory priming,* we refer to faster and slower RTs, respectively, in the related condition relative to the unrelated condition.

Discussion

Experiment 1 was designed to discriminate between a range of alternative hypotheses about how two-digit Arabic numerals are named. The results were quite clear. There was a significant priming effect of 7 ms when prime and target shared one digit on a corresponding position (13–18 and 28–18) and a significant interference effect when prime and target shared digits on different positions. The interference was more clearly present when both digits swapped places (81–18) and when the 10s of the prime agreed with the unit of the target (83–18) than when the unit of the prime agreed with the 10s of the target (31–18; see Table 1).

These findings allow us to reject two of the hypotheses mentioned early in this article because they do not agree with the predictions of the holistic models, according to which two-digit Arabic numerals are processed as wholes. Such models only predict priming from numerals with a nearby magnitude; in addition, they do not predict interference. The findings are in line with the models that stress the syntactic decomposition of two-digit Arabic numerals into a combination of 10s and units (Deloche & Seron, 1987; Grossberg & Repin, 2003; McCloskey, 1992; Meeuwissen et al., 2003; Nuerk et al., 2001). The Arabic numeral 18 is rapidly recoded as a combination of a 10 and a unit, and position-incongruent overlaps seem to create confusion.

An objection against Experiment 1, however, might be that the priming effects we obtained had little to do with the relative position of the digits in a two-digit numeral but were caused by the perceptual overlap of the prime and the target when they shared a digit on the same position. This view could account for the facilitatory priming on Trials 31–18 and 28–18 but seems less likely to provide an explanation for the inhibitory priming on Trials 81–18, 83–18, and 31–18. Nevertheless, we decided to run a new experiment in which the physical overlap between target and prime was manipulated.

Experiment 2

In this experiment, we shifted the prime to the left in half of the trials, so that the units digit of the prime was presented at the same location as the 10s digit of the target. In the other half of the trials, the prime was shifted to the right, so that the 10s digit of the prime

Table 1
Overview of the Mean Priming Effects (in Milliseconds) as a Function of the Different Priming Conditions in All Experiments

	Naming task					Nonnaming task	
Priming condition	Exp. 1	Exp. 2	Exp. 3	Exp. 6A (digits)	Exp. 6B (letters)	Exp. 4	Exp. 5
Position-congruent overlap							
10s + unit overlap 18–18				30*	30*		
10s overlap 13–18	8*	8*	8*	15*	9*	4	3
Unit overlap 28–18	6*	11*	7*	–2	4	3	5
Position-incongruent overlap							
10s–unit + unit–10s overlap 81–18	–19*	–12*	–10*	–24*	–18*	–1	0
10s–unit overlap 83–18	–15*	–11*	–6*	–12*	–4	–3	0
Unit–10s overlap 31–18	–7	–1	6	–2	–1	–2	–4

Note. Because we had to control the distances between primes and targets, 6 of the 47 prime–target controls in the position-congruent 10s overlap condition (e.g., 13–18) were related (see Appendix A). To make sure that the facilitation effect for the 10s overlap in Experiments 1–3 was not due to the related trials in the controls, we reanalyzed the data without these trials. The results remained the same. Over the three experiments, the facilitation effect for the 13–18 trials was 6 ms, $t(44) = -5.43$ $p < .0001$. In addition, we replicated this facilitation effect with primes of the type 1# that was not subject to this problem (Experiment 6a). "+" = facilitation; "–" = inhibition. Exp. = experiment.
* $p < .05$.

was presented at the location of the units digit of the target. If the priming effects of Experiment 1 were due to an overlap in the physical position, then we should observe priming when the units–10s digits of the prime agree with the 10s–units digits of the target and not when the units–10s digits of the prime agree with the units–10s digits of the target (which are presented at different locations). Only the test trials (see Appendix A) of Experiment 1 were run.

Method

Participants. Fifteen first-year psychology students (age range = 18–26 years) at Ghent University participated for course credit. They were all native Dutch speakers and had not taken part in Experiment 1. Participants were unaware of the purpose of the experiment and had normal or corrected-to-normal vision. Informed consent and ethics approval were obtained before the start of the experiment according to the APA guidelines.

Stimuli. Only the test stimuli from Experiment 1 were presented, which resulted in a total of 470 items (47 targets × 10 primes; see Appendix A).

Procedure. The equipment was the same as in Experiment 1. This time, however, the mask consisted of four hash marks (####) instead of two. The target was presented centered, corresponding to the positions of the two inner hash marks. The position of the prime varied between two locations: One corresponded to the two leftmost hash marks and the other to the two rightmost hash marks. Each participant saw both versions (i.e., the position of the prime was a within-subject variable). The experiment started with 20 training trials randomly chosen from the 940 (2 prime positions × 470 items) experimental trials. Everything else was exactly the same as in Experiment 1.

Results

Mean percentage of naming errors and unreliable measurements resulting from coughs or noise was 3.1%. Only average RTs of correct responses in the range of 150 to 1,200 ms were analyzed. There were virtually no outliers in the correct responses.

The data were analyzed using a 2 × 2 analysis of variance (ANOVA) that included the variables prime position (left vs. right) and prime relatedness (related vs. unrelated primes). The same priming effects, which were significant in Experiment 1, were also significant in Experiment 2 (see Table 1). Facilitatory priming effects were found for the condition in which the decade of the prime was equal to the decade of the target (13–18 [452 ms] vs. 23–18 [460 ms]), $F(1, 14) = 25.62$, $p < .01$, and for the condition in which the units of the prime were equal to the units of the target (28–18 [449 ms] vs. 29–18 [460 ms]), $F(1, 14) = 14.47$, $p < .01$. Inhibitory priming effects were found in the condition with swapped digits (81–18 [477 ms] vs. 79–18 [465 ms]), $F(1, 14) = 8.17$, $p < .05$, and in the condition in which the 10s of the primes were the units of the targets (83–18 [478 ms] vs. 92–18 [467 ms]), $F(1, 14) = 28.60$, $p < .01$, but not in the condition in which the units of the primes were the 10s of the targets (31–18 [466 ms] vs. 32–18 [465 ms], $F < 1$). No other main or interaction effect was significant, meaning that the position of the prime relative to the target did not make a difference.

Discussion

The results of Experiment 2 were straightforward. The priming effects depended on the relative positions of the digits within the two-digit Arabic numerals and not on the screen location at which they had been presented. This is further evidence for the idea that the numerals had been syntactically decomposed before being named, and that cross-talk between identical multipliers in the 10s slot and the units slot slowed the process.

Experiment 2 also replicated another aspect of Experiment 1, namely that overlapping prime units and target 10s (72–28, 43–32) caused less interference than overlapping prime 10s and target units (86–28, 25–32). One explanation might be that Arabic multidigit numerals are processed in a left-to-right manner, so that the first digit in the prime has a faster impact than the second. Another explanation might be that because of the Dutch number-naming system, in the 86–28 and 25–32 condition, the overlapping digit was the digit with which the response started (eight-and-twenty, two-and-thirty), whereas in the former condition the overlapping part was toward the end of the response (eight-and-twenty, two-and-thirty). A similar phenomenon was observed by Brysbaert et al. (1998) in Dutch but not in French (see also Ferreira & Swets, 2002, for the interpretation of that effect). Experiments in English (or French) may help to decide between these alternative explanations. If the interference effect is due to the way in which multidigit numbers are processed, the findings in English should duplicate those of the current experiment. Alternatively, if the effect is due to the way in which two-digit numbers are named, then the digit-interference effect in English should be stronger for trials like 72–28 and 43–32 than for trials like 86–28 and 25–32 (i.e., the reverse pattern of Dutch).

Experiment 3

In both Experiments 1 and 2 we used an SOA of 100 ms between prime and target. To find out how long it takes to build up the syntactic decomposition of the number, we decided to run another experiment with the shortest possible SOA and without changing the presentation time of the prime. Therefore, Experiment 3 was an exact replication of Experiment 2, except that the SOA was reduced to 67 ms (50-ms prime + 17-ms postmask). This SOA was comparable to the SOA of 66 ms in Greenwald, Abrams, Naccache, and Dehaene (2003), who claimed that the two digits of an unconsciously presented masked two-digit prime were processed separately. By reducing the prime presentation time to 67 ms, we could examine whether the effects we obtained required a reasonably long time to build up and were preceded by a stage in which the digits of the prime were processed independently. A control experiment on 12 participants similar to the one in Experiment 1 showed that the primes were not completely invisible when participants did their best to see a relationship between the prime and the target (58% correct), $t(11) = 3.5$, $p < .01$; $d' = 0.44$, $t(11) = 3.5$, $p < .005$.

Method

Participants. Fourteen first-year psychology students (age range = 18–23 years) at Ghent University participated for course credit. They were all native Dutch speakers and did not participate in Experiments 1 or 2. Participants were unaware of the purpose of the experiment and had normal or corrected-to-normal vision.

Procedure. Everything was the same as in Experiment 2 except that the backward mask was presented for 17 ms instead of 50 ms, resulting in an SOA of 67 ms.

Results and Discussion

Mean percentage of naming errors and unreliable measurements resulting from coughs or noise was 7%. Only average RTs of correct responses in the range of 150 to 1,200 ms were analyzed. There were virtually no outliers in the correct responses.

The results of the current experiment replicated those of Experiments 1 and 2 (see Table 1). All effects were significant except for the condition in which the units of the prime were equal to the 10s of the target: 13–18 (476 ms) versus 23–18 (484 ms), $t(13) = -3.51$, $p < .05$; 28–18 (474 ms) versus 29–18 (481 ms), $t(13) = -2.28$, $p < .05$; 81–18 (501 ms) versus 79–18 (491 ms), $t(13) = 2.78$, $p < .05$; 83–18 (495 ms) versus 92–18 (489 ms), $t(13) = 2.64$, $p < .05$; and 31–18 (485 ms) versus 32–18 (491 ms), $t(13) = -1.56$, $p = .14$. The only difference between Experiments 2 and 3 was that the interference effect of position-incongruent digits in Experiment 3 tended to be smaller than in Experiment 2. This may be in line with Greenwald et al.'s (2003) claim that repeatedly presented unconscious primes can activate the constituting digits. However, the main finding for our purposes is that, for the naming of two-digit Arabic numerals, a syntactic decomposition seems to be involved.

Experiment 4

The results of Experiments 2 and 3 rule out an account of the facilitatory and inhibitory priming effects in terms of low-level visual processing. This adds further credit to the hypothesis that the priming effects are caused by a decomposition of the two-digit Arabic numbers during naming. This hypothesis rules out the holistic accounts but still leaves open the question whether the decomposition occurs at the semantic level or in a direct number-naming route. To address this question, we followed two tracks. First, we examined whether similar effects could be found in number decision tasks (the current experiment and Experiment 5). Then we assessed whether similar priming effects can be obtained in the naming of nonnumerical stimuli (Experiment 6).

In the current experiment, we asked participants to decide whether the target stimuli formed a number (e.g., 18) or a number–letter combination (e.g., A8, 1M). This task has been used before by Alameda et al. (2003) and produces RTs that are comparable to number-naming times. Notice that we could not use number magnitude or parity judgment tasks, because these tasks are influenced by the congruency of the responses elicited by the primes and the targets (Dehaene et al., 1998; Reynvoet, Caessens, & Brysbaert, 2002), an issue that interferes with the questions addressed here (e.g., because a number magnitude task requires that both the related and the unrelated prime are response compatible with the target).[2]

Method

Participants. Twenty-two first-year psychology students (age range = 19–27 years) at Ghent University participated for course credit. They were all native Dutch speakers and did not participate in the previous experiments. Participants were unaware of the purpose of the experiment and had normal or corrected-to-normal vision. Informed consent and ethics approval were obtained before the start of the experiment according to the APA guidelines.

Procedure. A total of 940 trials were presented. Half of the trials were the test stimuli from Appendix A (47 targets × 10 primes). The other half consisted of nonnumber trials that were constructed by changing one digit into a letter. For half of the nonnumber trials, the first digit was replaced by their corresponding uppercase letter (e.g., 1 was replaced by A, 2 by C, and so on for D, F, G, H, K, M, and P). For the other half of the nonnumber trials, the second digit of the target was replaced in the same way. Participants were instructed to indicate whether the target stimulus was a valid two-digit number or not. Manual responses were measured with an external two-key response box connected to the gameport of the PC. Half of the participants were instructed to press the left button when the target was a valid number and the right button when the target was a nonnumber. The other half of the participants received the reverse response instructions.

Results and Discussion

Only average RTs of correct responses to the real two-digit numbers ($N = 470$) in the range of 150 to 1,200 ms were analyzed. The mean percentage of errors was 5%. There were virtually no outliers in the correct responses.

The results of the current experiment did not replicate the priming results of the previous naming tasks. Planned comparisons did not yield a single significant effect: 13–18 (466 ms) versus 23–18 (470 ms), $p = .26$; 28–18 (468 ms) versus 29–18 (471 ms), $p = .31$; 81–18 (471 ms) versus 79–18 (470 ms), $p = .69$; 83–18 (474 ms) versus 92–18 (471 ms), $p = .39$; 31–18 (473 ms) versus 32–18 (471 ms), $p = .65$ (see Table 1). This is a first indication that the priming effects of Experiments 1 to 3 are limited to naming tasks. In Experiment 5, we addressed the same question with a different task.

Experiment 5

To investigate whether the absence of the priming effects in the number–letter decision task would generalize to other nonnaming tasks, we conducted a new experiment in which participants had to decide whether the target number was presented in italics or not. Fias, Lauwereyns, and Lammertyn (2001) showed that the magnitude of a number is automatically accessed in an orientation discrimination task (but not, for instance, in a color discrimination task).

Method

Participants. Ten new first-year psychology students (age range = 19–23 years) at Ghent University participated for course credit. They were all native Dutch speakers. Participants were unaware of the purpose of the experiment and had normal or corrected-to-normal vision. Informed consent and ethics approval were obtained before the start of the experiment according to the APA guidelines.

Procedure. Participants had to decide whether the target two-digit number was presented in italics or not (number-orientation detection). This experiment was an exact replication of Experiment 4 except that the nonnumbers (e.g., 9A, 1H) were now replaced by real two-digit numbers (i.e., the test stimuli of Appendix A) in italics.

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[2] For instance, if the task is to judge whether the target is larger or smaller than 55, then both the related and the unrelated prime must be larger than 55 when the target is larger. In addition, both the related and the unrelated prime would have to be unit-decade compatible relative to the comparison number (Nuerk et al., 2001).

Results and Discussion

Only average RTs of correct responses to all numbers (both in italics and normal font; $N = 940$) in the range of 150 to 1,200 ms were analyzed. The mean percentage of errors was 6%. There were virtually no outliers in the correct responses.

As in Experiment 4, planned comparisons yielded no significant effects: 13–18 (474 ms) versus 23–18 (477 ms), $p = .29$; 28–18 (472 ms) versus 29–18 (477 ms), $p = .35$; 81–18 (477 ms) versus 79–18 (477 ms), $p = .99$; 83–18 (475 ms) versus 92–18 (475 ms), $p = .99$; 31–18 (478 ms) versus 32–18 (474 ms), $p = .19$ (see also Table 1). As in Experiment 4, the current null effects are in line with the hypothesis that the priming effects in Experiments 1 to 3 are limited to the naming task.

Experiment 6

Because the kind of number decision tasks one can design are rather limited (as a result of the requirement that the related and the unrelated prime–target trials must not differ in response congruency costs), we decided to test the other side of the direct-route hypothesis. If the effects are due to a general word production route that is used for all types of symbolic stimuli, then the facilitatory and inhibitory priming effects we observed in Experiments 1 to 3 should not be limited to numerical stimuli but should generalize to other symbolic stimuli. Therefore, we asked participants to name consonant pairs (e.g., GT, QM), which were preceded by primes, that shared part of the target either in the same or in the alternative position. For this experiment we made use of the finding that letter priming is possible across letter cases (i.e., the target GT is primed by gt; Bowers, Vigliocco, & Haan, 1998). In this way, we circumvented the problem of physically overlapping letters. If the priming effects in the two-letter naming task are similar to those in the two-digit naming task (i.e., facilitation for position-congruent overlap and inhibition for position-incongruent overlap), then we have strong evidence that the priming effects in the two-digit number naming studies are indeed due to a nonsemantic route for the naming of symbolic stimuli.

We introduced a further change because we wanted to have better control of the nonoverlapping letter–digit in the prime and we wanted to create a truly neutral condition. Therefore, we introduced the presence of hash marks in the primes. The target TG could be preceded by the primes tg, t#, #g, g#, #t, gt, or ##. Three of these primes preserve the positions of the letters, three swap the positions, and one is completely neutral.

Because of the changes we introduced, we decided to also run the experiment with Arabic numerals to make sure that the findings of Experiments 1 to 3 can be generalized to the current presentation conditions. So the target 18 could be preceded by the primes 18, 1#, #8, 8#, #1, 81, or ##.

Method

Participants. Fourteen first-year psychology students (age range = 18–20 years) at Ghent University participated for course credit. They were all native Dutch speakers and did not participate in the previous experiments. Participants were unaware of the purpose of the experiment and had normal or corrected-to-normal vision. Informed consent and ethics approval were obtained before the start of the experiment according to the APA guidelines.

Procedure: Experiment 6A (two-digit naming). Everything was the same as in Experiment 2 except for the following changes. Targets were two-digit numbers taken from the set of all combinations of the digits 1 to 9. Numbers with identical digits were excluded, which resulted in 72 target numbers ranging from 12 to 98. Seven priming conditions were created: one baseline condition (e.g., ##-18), three prime conditions with a position-congruent overlap (e.g., 18–18, 1#-18, and #8–18), and three priming conditions with a position-incongruent overlap (e.g., 81–18, 8#-18, and #1–18). Prime position relative to the target (left or right) varied randomly. The experimental session consisted of 504 trials (i.e., 72 targets × 7 prime conditions). A short break was provided after every 96 trials in the experimental session.

Procedure: Experiment 6B (two-letter naming). Everything was the same as in Experiment 2 except for several details. The targets consisted of two letters in uppercase format, which were all the combinations of the consonants B, D, G, H, M, N, Q, R, and T. Repetition of letters in the same letter string were excluded (i.e., $9 \times 8 = 72$ combinations). Only meaningless letter strings (in the Dutch language) were used, which resulted in 52 remaining targets (see Appendix B for a complete list of the targets). Participants were asked to name the target beginning with the first letter. The primes consisted of letters in lowercase format. The primes were the same font size as the targets (Arial font 12). As in Experiment 6A, seven priming conditions were included: one baseline condition (##-TG), three prime conditions with a position-congruent overlap (tg–TG, t#–TG, and #g–TG), and three priming conditions with a position-incongruent overlap (gt–TG, g#–TG, and #t–TG). Prime position (left or right) varied randomly. The experimental session consisted of 364 trials (i.e., 52 targets × 7 prime conditions). A short pause was provided after every 96 trials in the experimental session.

Both Experiments 6A and 6B were administered in a single session of about 1 hr. The order of the experiments was counterbalanced across participants.

Results

Experiment 6A: Two-digit naming. Mean percentage of naming errors and unreliable measurements resulting from coughs or noise was 5%. Only average RTs of correct responses in the range of 150 to 1,200 ms were analyzed. There were virtually no outliers in the correct responses.

An ANOVA was run with the factor prime condition consisting of seven prime types. The main effect of prime condition was significant, $F(6, 78) = 53.44$, $p < .0001$: 18–18 = 447 ms, 1#-18 = 462 ms, #8–18 = 479 ms, 81–18 = 501 ms, 8#–18 = 489 ms, #1–18 = 479 ms, ##–18 = 477 ms (see Figure 2 and Table 1). Planned comparisons between each prime type and the baseline (e.g., ##–18) revealed the following significant effects: Facilitation effects of 30 ms and 15 ms were observed for the position-congruent prime conditions 18–18 and 1#–18, respectively (both ps $< .0001$), whereas inhibition effects of 24 ms and 12 ms were observed for the position-incongruent prime conditions 81–18 ($p < .0001$) and 8#–18 ($p < .005$), respectively. The effects of the position-congruent prime condition #8–18 ($p = .59$) and the position-incongruent prime condition #1–18 ($p = .34$) were not significant. Excluding the teens (12–19) from the analysis did not alter the results.

Experiment 6B: Two-letter naming. Mean percentage of naming errors and unreliable measurements resulting from coughs or noise was 6%. Only average RTs of correct responses in the range of 150 to 1,200 ms were analyzed. There were virtually no outliers in the correct responses.

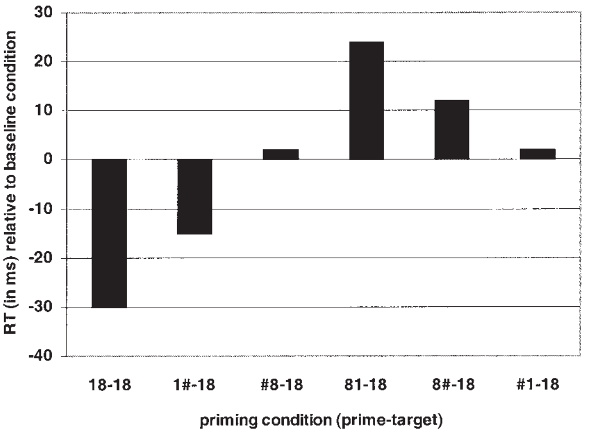

Figure 2. Main effect of priming in Experiment 6A (two-digit naming) showing facilitation with position-congruent overlap between prime and target and inhibition with position-incongruent overlap (in relation to the neutral baseline, i.e., prime–target: ##–18). RT = reaction time.

An ANOVA was run with the variable prime condition, which had seven levels. The main effect of prime condition was significant, $F(6, 78) = 16.98$, $p < .0001$: tg–TG = 477 ms, t#–TG = 481 ms, #g–TG = 486 ms, gt–TG = 508 ms, g#–TG = 494 ms, #t–TG = 491 ms, ##–TG = 490 ms (see Figure 3 and Table 1). Planned comparisons between each prime type and the baseline (e.g., ##–TG) revealed the following significant effects: Facilitation effects of 30 ms and 9 ms were observed for the position-congruent prime conditions tg–TG ($p < .05$) and t#–TG ($p < .05$), respectively, whereas an inhibition effect of 18 ms was observed for the position-incongruent prime condition gt-TG ($p < .005$). The facilitation effect of 4 ms for #g–TG ($p = .22$) and of 4 ms ($p = .30$) and 1 ms ($p = .86$) for g#–TG and #t–TG, respectively, were not significant.

Discussion

The results of Experiment 6A (two-digit naming) replicated the findings of Experiments 1 and 3, showing faster RTs for position-congruent primes and slower RTs for position-incongruent primes. The priming conditions with a single corresponding digit in the second position (e.g., #8–18 and #1–18) did not show reliable priming, indicating that the first digit in a two-digit number has a larger impact. This suggests that Arabic multidigit numerals are processed in a left-to-right manner because this gradient was now also present in the position-congruent trials. The fact that we used a neutral prime (e.g., ##–18) as a baseline allowed us to be firmer that the position-congruent priming effects were indeed facilitatory and the position-incongruent effects inhibitory.

Similar results were obtained in the letter-naming task (Experiment 6B). Facilitatory priming was observed with position-congruent primes (e.g., tg–TG and t#–TG) and inhibitory priming with position-incongruent primes (e.g., gt–TG). The only exception with the number-naming task was that we did not see a reliable effect when the first letter of the prime was the second letter of the target (i.e., g#–TG). As in the number-naming task, the first letter in the prime had a larger impact on the processing of the target than the second letter, indicating a left-right gradient in reading letter strings. This left–right direction in digit and letter naming has an analog in word naming, in which it has been found that primes facilitate target word naming when they share the first phonemes but not when they share the last phonemes. This is the so-called masked-onset priming effect, first reported by Forster and Davis (1991). So the target word *PAIR* is named faster when it is preceded by the prime *pole* but not when it is preceded by the prime *fair* (see also Schiller, 2004, for a series of experiments on this issue).

Altogether, the similarities between two-digit priming and two-letter priming are in line with the hypothesis that the priming effects in two-digit number naming are situated at the level of the number name production and have little to do with the activation of the meaning of the stimuli. This is in line with the claims defended by Meeuwissen et al. (2003) and Roelofs (in press).

General Discussion

The current experiments were designed to obtain more information about how two-digit Arabic numerals are named. As stated early in this article, numerous theories exist, distinguished from one another based on whether two-digit Arabic numerals are processed holistically or through a process of syntactic decomposition and whether semantic mediation is pivotal for the naming of Arabic numerals.

The results of the experiments converge to conclude that Arabic numerals are named in much the same way as words are named. That is, there is a direct, nonsemantic route from Arabic input to verbal output, which outperforms the semantically mediated route (see McCloskey's arguments about the necessity of a semantically mediated route, mentioned earlier). This route parses composite stimuli in a left-to-right sequence and retrieves the morphological and phonological information required for the correct output, as claimed by Meeuwissen et al. (2003) and Roelofs (in press) and foreshadowed by Deloche and Seron (1987) and Dehaene (1992).

Because the data force us to abandon a position we have defended in the past on the basis of other empirical findings (see prior discussion), we also need to reassess the interpretation of

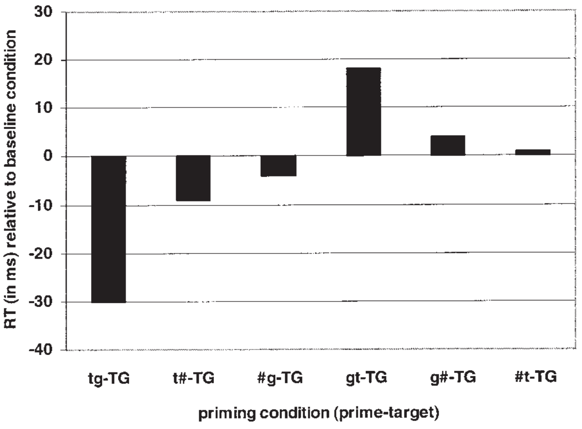

Figure 3. Main effect of priming in Experiment 6B (two-letter naming) showing facilitation with position-congruent overlap between prime and target and inhibition with position-incongruent overlap (in relation to the neutral baseline, i.e., prime-target: ##–TG). RT = reaction time.

these findings. The first evidence for pivotal semantic mediation in number naming was taken from Brysbaert's (1995) finding of a strong effect of the logarithm of number magnitude on number-reading times, together with priming effects that transgressed the decade borders. It is becoming increasingly clear, however, that this reading task involved other processes than those required for fast number naming. In the Brysbaert study, participants were asked to silently read four Arabic numerals and to indicate whether the last number was the same as one of the previous three numbers. Eye movements were tracked, and the experimenter measured how long participants looked at each number before going on to the next. Although this task is a simple, short-term memory task of the Sternberg type, it looks like participants use other, more semantically related strategies for good performance in this task than for the fast naming of Arabic numerals.

To some extent, the difference between Brysbaert's (1995) task and number naming was already becoming clear, because the logarithmic function described by Brysbaert has never been repeated for the naming of Arabic numerals (Duyck & Brysbaert, 2004; Meeuwissen et al., 2003; Ratinckx & Brysbaert, 1999). Although there is a slight effect because of number magnitude, it is an effect that can easily be accounted for by number frequency and number length. Of note is the fact that Duyck and Brysbaert (2004) failed to find a clear number magnitude effect when participants were asked to read number words or Arabic numerals from 1 to 12 but did observe a strong number magnitude effect when the participants were asked to translate number words of their native language into their second language. It is generally agreed that translation from the first language to the second requires the mediation of semantic information (Kroll & Stewart, 1994).

As mentioned early in this article, Fias, Reynvoet, and Brysbaert's (2001) findings with the Stroop interference effect have been called into question by Roelofs (in press). Although Fias, Reynvoet, and Brysbaert (2001) checked the validity of their presentation mode by showing a Stroop interference effect from Arabic numerals on number words in a parity judgment task under exactly the same stimulus presentation conditions, in light of Roelof's findings this particular evidence against the existence of a nonsemantic route in number naming becomes very thin. In addition, masked priming studies in which primes and targets are presented at the same location have shown more or less equivalent priming effects of number words on the naming of digits as vice versa (Reynvoet et al., 2002), even at SOAs as short as 43 ms (Reynvoet & Brysbaert, 2004). As Roelofs (in press) argued, this finding is more in line with his conclusion on the basis of the Stroop findings than with Fias, Reynvoet, and Brysbaert's (2001) interpretation.

Damian (2004) found faster naming times for number words than for Arabic digits and faster number magnitude decisions for digits than for words. The former could be due to the fact that word naming, unlike digit naming, can partly be achieved through direct letter–sound conversions, which may speed up the process of word naming relative to digit naming. The latter finding—that semantic tasks are easier with Arabic input than with verbal input—is a rather general finding and seems to indicate that the slowness of the semantically mediated route in the naming of (complex) Arabic numerals is not due to the part between the Arabic input and the semantic system but rather to the part between the semantic system and the production of verbal output. Researchers on number processing indeed seem to have underestimated the complexities involved in the production of verbal number words on the basis of conceptual (number magnitude) information. This is particularly true for multidigit numbers, which often have polymorphemic and multisyllabic names (or even consist of a concatenation of several words; e.g., one-hundred-seventy-seven).

The only finding that still fits uneasily within the dual-route model of Arabic digit naming is Fias et al.'s (1996; see also Fias, 2001) finding that a phoneme-monitoring task on digits is influenced by the meaning of the digits. Participants could indicate more rapidly that the name of a digit contained an /e/ sound with their left hand when the digit referred to a small number and with their right hand when the digit referred to a large number. A similar hand preference is observed when participants have to indicate whether a stimulus number is small or large, and this has been interpreted as evidence for the assumption that the number line is oriented from left (small) to right (large). Further research is needed to find out the true implications of this finding.

Our findings also present evidence against the suggestion that two-digit Arabic numerals are recognized in an input lexicon in which they are stored as unitary representations (Cohen et al., 1994). Why else would the numeral 18 be named faster after the prime 13 but slower after the prime 83? This evidence suggests that the associative priming between words and Arabic numerals (such as Alfa Romeo-164, Boeing-747, Barcelona, Spain-92) must be explained on grounds other than the word–number connections in the input lexicon.

In summary, our data have narrowed considerably the range of possible models of how Arabic numerals are named. There is now unequivocal evidence for a direct route in addition to a semantically mediated route, and this route is based on a syntactic decomposition of the Arabic input. We also hypothesize that the slowness of the semantically mediated route is due to the activation of the correct output on the basis of conceptual (magnitude) information rather than on the slowness of the activation of meaning on the basis of Arabic input.

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Appendix A

Stimuli of Experiment 1

The test (470 in total) and filler (520 in total) trials of Experiment 1 are presented in Table A1. The test trials are presented in bold. The unrelated primes are presented in parentheses. On average, the related primes equaled the unrelated primes with regard to the distance between prime and target. Target numbers consisting of a zero or of two equal digits were excluded from the test trials. Additionally, targets with units in the middle of a 10 (e.g., 35 or 36) were excluded from the test trials because it was difficult for these targets to find related and unrelated primes to be equaled on prime-target numerical distance (this also applied to targets smaller than 18 and targets ranging from 94 to 99).

Table A1
Stimuli of Experiment 1

	Primes				
	Position-congruent overlap		Position-incongruent overlap		
Target	10s overlap	Unit overlap	10s–unit + unit–10s overlap	10s–unit overlap	Unit–10s overlap
1	10 21	33 73	40 95	88 39	92 91
2	10 30	41 61	77 70	95 88	49 94
3	12 30	55 41	70 95	75 40	89 90
4	13 21	61 55	88 95	96 41	93 50
5	14 16	41 39	23 18	32 37	21 44
6	15 19	51 47	24 28	42 38	31 72
7	16 23	61 54	25 31	52 46	30 72
8	17 14	71 74	35 32	53 56	77 94
9	18 15	81 84	27 24	72 75	22 64
10	19 25	91 85	28 34	82 76	61 77
11	29 35	92 86	65 59	56 62	64 71
12	39 36	93 96	48 43	84 89	22 54
13	49 45	94 98	67 64	76 79	30 44
14	59 66	95 88	68 57	86 97	70 81
15	69 73	96 92	78 72	87 93	54 61
16	10 18	54 42	60 80	71 94	42 43
17	10 13	61 55	70 69	96 83	48 51
18	**13 (23)**	**28 (29)**	**81 (79)**	**83 (92)**	**31 (32)**
19	**14 (24)**	**29 (28)**	**91 (87)**	**94 (87)**	**41 (43)**
20	14 12	54 43	60 50	76 69	80 44
21	**27 (17)**	**31 (34)**	**12 (34)**	**15 (35)**	**32 (34)**
22	15 19	33 54	50 73	69 45	77 52
23	**28 (18)**	**13 (14)**	**32 (17)**	**34 (48)**	**42 (41)**
24	**29 (19)**	**14 (15)**	**42 (51)**	**46 (37)**	**52 (51)**
25	30 15	55 61	70 73	88 97	54 46
26	10 22	54 33	70 40	83 97	47 53
27	**23 (31)**	**17 (16)**	**72 (65)**	**75 (89)**	**62 (61)**
28	**21 (35)**	**18 (17)**	**82 (76)**	**86 (79)**	**72 (71)**
29	**24 (34)**	**19 (18)**	**92 (86)**	**95 (86)**	**82 (81)**
30	30 22	55 33	60 50	80 77	55 83
31	**34 (28)**	**21 (24)**	**13 (24)**	**16 (25)**	**23 (24)**
32	**38 (26)**	**42 (41)**	**23 (15)**	**25 (16)**	**43 (45)**
33	20 19	53 44	70 80	85 97	88 56
34	**39 (29)**	**24 (25)**	**43 (56)**	**41 (51)**	**53 (52)**
35	12 20	55 44	77 50	19 88	83 84
36	10 20	53 33	70 80	57 83	87 85
37	**32 (42)**	**47 (48)**	**73 (69)**	**71 (82)**	**63 (64)**
38	**31 (47)**	**48 (47)**	**83 (97)**	**85 (74)**	**73 (74)**
39	**37 (41)**	**49 (46)**	**93 (85)**	**91 (85)**	**83 (82)**
40	10 15	44 88	50 94	77 35	90 89

Table A1 (*continued*)

	Primes				
	Position-congruent overlap		Position-incongruent overlap		
Target	10s overlap	Unit overlap	10s–unit + unit–10s overlap	10s–unit overlap	Unit–10s overlap
41	**46 (37)**	**51 (56)**	**14 (23)**	**12 (23)**	**24 (23)**
42	**47 (39)**	**32 (31)**	**24 (18)**	**29 (19)**	**34 (31)**
43	**48 (38)**	**53 (51)**	**34 (28)**	**31 (29)**	**54 (56)**
44	20 20	53 48	70 90	20 99	33 36
45	12 11	44 87	50 90	91 99	38 58
46	30 22	53 77	70 88	21 15	34 79
47	**43 (51)**	**37 (38)**	**74 (81)**	**79 (69)**	**64 (62)**
48	**42 (52)**	**38 (39)**	**84 (95)**	**81 (91)**	**74 (67)**
49	**45 (53)**	**39 (32)**	**94 (78)**	**92 (83)**	**84 (83)**
50	11 10	48 49	60 50	22 88	80 78
51	**59 (43)**	**41 (43)**	**15 (26)**	**17 (26)**	**25 (26)**
52	**58 (46)**	**62 (61)**	**25 (16)**	**28 (34)**	**35 (36)**
53	**57 (49)**	**43 (42)**	**35 (29)**	**32 (27)**	**45 (46)**
54	14 10	77 55	88 60	90 99	31 59
55	20 13	44 49	50 50	91 98	60 77
56	11 20	33 38	40 77	23 91	81 76
57	**53 (61)**	**67 (69)**	**75 (82)**	**72 (84)**	**65 (68)**
58	**54 (62)**	**68 (67)**	**85 (92)**	**82 (93)**	**75 (73)**
59	**51 (67)**	**69 (68)**	**95 (84)**	**96 (81)**	**85 (87)**
60	11 22	36 55	40 90	25 (98)	37 30
61	**65 (57)**	**71 (72)**	**16 (25)**	**13 (28)**	**26 (25)**
62	**68 (58)**	**52 (53)**	**26 (31)**	**24 (13)**	**36 (37)**
63	**67 (59)**	**73 (71)**	**36 (27)**	**35 (21)**	**46 (42)**
64	17 13	48 36	65 49	90 66	74 75
65	30 22	44 38	50 63	99 89	73 27
66	11 10	57 33	66 40	89 98	26 61
67	**63 (71)**	**57 (59)**	**76 (58)**	**73 (59)**	**56 (58)**
68	**64 (72)**	**58 (57)**	**86 (75)**	**84 (75)**	**76 (75)**
69	**62 (75)**	**59 (58)**	**96 (42)**	**93 (78)**	**86 (85)**
70	16 30	37 44	40 49	87 94	99 62
71	**79 (65)**	**61 (64)**	**17 (32)**	**14 (32)**	**27 (28)**
72	**75 (69)**	**82 (86)**	**27 (19)**	**21 (14)**	**37 (35)**
73	**78 (68)**	**63 (62)**	**37 (12)**	**39 (18)**	**47 (48)**
74	12 26	45 44	52 63	65 89	91 63
75	22 30	47 36	55 52	62 66	99 92
76	**71 (81)**	**56 (52)**	**67 (59)**	**64 (54)**	**57 (59)**
77	22 16	45 55	49 60	52 89	78 14
78	**74 (82)**	**98 (96)**	**87 (93)**	**89 (96)**	**67 (65)**
79	**73 (86)**	**89 (85)**	**97 (68)**	**98 (58)**	**87 (86)**
80	17 20	36 45	40 60	68 89	80 99
81	**89 (74)**	**91 (93)**	**18 (43)**	**19 (35)**	**28 (29)**
82	**86 (76)**	**92 (94)**	**28 (13)**	**23 (15)**	**38 (39)**
83	**87 (79)**	**93 (92)**	**38 (52)**	**36 (41)**	**48 (49)**
84	12 20	47 51	62 63	78 79	13 94
85	21 22	45 56	65 67	80 94	72 99
86	**81 (91)**	**96 (97)**	**68 (57)**	**62 (71)**	**58 (57)**
87	**82 (92)**	**97 (95)**	**78 (64)**	**74 (64)**	**68 (69)**
88	16 11	57 56	63 66	79 90	18 99
89	**84 (96)**	**79 (76)**	**98 (74)**	**97 (76)**	**78 (76)**
90	11 20	45 56	58 60	65 98	17 71
91	**95 (87)**	**81 (82)**	**19 (32)**	**18 (36)**	**29 (27)**
92	**98 (84)**	**72 (74)**	**29 (35)**	**27 (17)**	**39 (38)**
93	**97 (85)**	**83 (84)**	**39 (45)**	**37 (46)**	**49 (47)**
94	25 21	33 66	40 78	67 93	79 10
95	11 21	46 58	60 80	90 98	12 67
96	12 27	33 66	40 90	47 93	65 16
97	26 11	51 63	66 80	11 99	69 68
98	26 26	59 33	60 40	99 63	70 66
99	11 27	63 46	78 66	90 80	66 64

Note. Test trials are denoted in bold; the unrelated primes are presented in parentheses.

Appendix B

Stimuli of Experiment 6B

The two-letter targets (uppercase format) and the corresponding prime (lowercase format) with a position-congruent overlap of both the first letter and the second letter are presented in Table B1 (Experiment 6B).

Table B1
Stimuli of Experiment 6B

Target	Prime	Target	Prime	Target	Prime	Target	Prime
BM	bm	GR	gr	MT	mt	QR	qr
BQ	bq	GT	gt	ND	nd	QT	qt
BR	br	HD	hd	NG	ng	RB	rb
DG	dg	HG	hg	NH	nh	RD	rd
DH	dh	HN	hn	NM	nm	RG	rg
DM	dm	HQ	hq	NQ	nq	RH	rh
DN	dn	HR	hr	NR	nr	RN	rn
DQ	dq	HT	ht	NT	nt	RQ	rq
DR	dr	MB	mb	QB	qb	TG	tg
GD	gd	MD	md	QD	qd	TH	th
GH	gh	MG	mg	QH	qh	TM	tm
GM	gm	MN	mn	QM	qm	TN	tn
GN	gn	MQ	mq	QN	qn	TQ	tq

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