Single-digit and two-digit Arabic numerals address the same semantic number line

Bert Reynvoet[*], Marc Brysbaert

Department of Experimental Psychology, University of Gent, H. Dunantlaan 2, 9000 Gent, Belgium

Abstract

Many theories about human number representation stress the importance of a central semantic representation that includes the magnitude information of small integer numbers, and that is conceived as an abstract, compressed number line. However, thus far there has been little or no direct evidence that units and teens are represented on the same number line. In two masked priming experiments, we show that single-digit and two-digit Arabic numerals are equally well primed by an Arabic numeral with the same number of digits as by an equally distant Arabic numeral with a different number of digits (e.g. the priming effect of 7 on the target 9 is the same as the priming effect of 11 on the target 9). The finding was obtained both with a number naming task and with a parity judgement task. This is in line with the hypothesis that units and teens are part of a continuous number line. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

There is quite some evidence that when humans process small integer numbers, they address a semantic magnitude system that varies according to the logarithmic function or a root function of the number magnitude (e.g. Krueger, 1989). For instance, Brysbaert (1995) showed that number processing times for Arabic numerals from 1 to 99 increase with the logarithm of number magnitude. Other evidence comes from experiments in which participants have to indicate which of two presented numbers is the smallest. Participants react faster and more accurately when both numbers are small (e.g. it is easier to indicate that $2 < 3$ than that $8 < 9$), and when there is a large distance between the two numbers (e.g. it is easier to indicate that $4 < 8$ than that $4 < 5$). Both effects can nicely be described if one assumes a logarithmic number line (Dehaene, Dupoux & Mehler, 1990; Dehaene, 1989).

* Corresponding author. Tel.: + 32-9-264-6432; fax: + 32-9-264-6496.
E-mail address: bert.reynvoet@rug.ac.be (B. Reynvoet)

However, the compressed number line is not accepted by all authors. McCloskey (1992), for instance, put forward a model of numerical cognition in which the semantic representation is not a continuous number line, but an abstract representation consisting of powers of 10. So, a number such as 13 is represented as one time 10 to the first power, and three times 10 to zeroth power. According to this model, one might expect a discontinuity between the numbers 9 and 10. A similar distinction between units (i.e. the numbers 0–9) and teens (10–19) has been made by Deloche and Seron, (1987) in their asemantic model of Arabic numeral pronunciation.

Although a lot of research on number representations has been done recently, there is still little or no direct evidence whether or not units and teens make access to a single number line. Most researchers avoid the problem by using unit numbers only. To our knowledge, there are but two studies that addressed the question, and both yielded equivocal results. Dehaene, Bossini and Giraux (1993) showed that in a parity judgement task, small numbers are reacted to faster with the left hand than with the right hand, whereas the reverse is true for large numbers. They called this phenomenon the SNARC (spatial-numerical association of response codes) effect, and in one of their studies, they examined the effect for numbers ranging from 0 to 19 in Arabic and verbal modality. They obtained the SNARC effect, but it was substantially smaller than the effect obtained with units only, and the difference was largely due to the units. In another study, Brysbaert (1995) claimed that processing times of Arabic numerals are a function of the logarithm of number magnitude, but he admitted that the data could as well be described by an equation based on number frequency and an extra time cost for the processing of two-digit numerals.

In this article, we used the priming paradigm to examine the transition from units to teens. Den Heyer and Briand (1986) showed that RTs to Arabic numerals are faster when immediately before a prime is shown with a close magnitude (distance of 1) than when a prime is shown with a magnitude farther apart (distance of 2 or 4). Den Heyer and Briand interpreted this finding as evidence for the hypothesis that single-digit numbers are represented on an ordered continuum and that the activation of the prime spreads along the continuum. Koechlin, Naccache, Block and Dehaene (1999) recently reported similar results with masked priming. This is a technique in which the prime is presented tachistoscopically so that the priming effect cannot be due to strategic expectations. An intriguing aspect of the masked priming technique, however, was that priming could only be obtained within a certain modality (e.g. Arabic prime – Arabic target; or verbal prime – verbal target). When the prime was clearly visible, cross-modal priming was possible as well (e.g. Arabic prime – verbal target; Koechlin et al., 1999).

In the experiments reported below, we make use of the masked priming technique, and examine whether the priming effect of 9 on 10 is equally strong as the priming effect of 11 on 10. That is, we compare prime-target pairs in which both prime and target are single-digit numbers or two-digit numbers, with prime-target pairs in which one of the numerals consists of a single digit and the other consists of two digits. If Arabic numerals with one and two digits access the same semantic number line, there is no reason why spreading of activation would stop at the border between 9 and 10. However, if units and teens are represented differently, priming may be confined to

the category of the prime, or at least it should be largely attenuated. In Experiment 1, we examined priming in a number naming task; in Experiment 2, we used a parity judgement task.

2. Experiment 1

2.1. Method

Targets ranged from 5 to 15, primes from the target minus three to the target plus three. This made a total of 77 combinations. All participants saw four blocks of 154 trials. In each block, the prime-target combinations were shown twice in a random order, making a total of eight observations per prime-target combination. Before the first block started, 20 practice trials were given. In these trials, the target ranged from 18 to 22, and the prime always was 20.

The experiment was run on a PC-compatible Pentium 233 and a 17'' colour screen. Each trial consisted of the following sequence of events. First, a forward mask was shown for 66 ms (synchronised with the refresh cycle of the screen). This mask consisted of two cardinal signs that were of the same size and font as the Arabic targets. Then, the prime was presented for 66 ms, followed by a backward mask for another 66 ms. The backward mask was the same as the forward mask. Finally, the target was presented and remained on the screen until a response was made. In order to reduce the physical overlap between prime and target, we made the primes (6×8 mm high) smaller than the targets (8×10 mm high). This procedure was the same as the one introduced by Koechlin et al. (1999). All stimuli were presented in yellow on a black background and were centred on the screen. Characters were presented in a triplex font. Participants were told to name the target as quickly as possible. RTs were measured with a microphone connected to the game port. After each response, the experimenter typed the participant's answer on the computer keyboard and noted if the time registration had worked properly.

Participants were 10 first-year psychology students (7 female, 3 male) of the University of Gent. They were all native Dutch speakers.

3. Results

No naming errors were made. Mean percentage of unreliable measurements due to coughs or noise was 2.7%. In a first analysis, the medians of the correct responses were analysed with a 11 (target) $\times$ 7 (distance prime-target) ANOVA (see Table 1). All effects were significant. Targets 6, 7, 10 and 11 had slower RTs than the other targets ($F(10, 90) = 4.83$; $P < 0.001$), and there was a significant main effect of the prime-target distance ($F(6, 54) = 68.97$, $P < 0.001$). RTs were fastest when prime and target were the same and slowest when the distance between prime and target equalled three. Post-hoc comparisons indicated that RTs differed significantly for the primes T-3 and T-1 ($P < 0.01$), as did RTs for the primes T + 1 and T + 3

Table 1
RT as a function of the distance between prime and target (Experiment 1: naming)

Target	Prime						
	T-3	T-2	T-1	T	T + 1	T + 2	T + 3
5	475	464	456	438	469	489	479
6	508	488	480	461	501	518	521
7	516[a]	505	495	464	491	514	530[b]
8	488[a]	481[a]	466	455	475	483[b]	482[b]
9	502[a]	473[a]	477[a]	429	483[b]	475[b]	482[b]
10	508[b]	501[b]	491[b]	450	489[a]	493[a]	500[a]
11	492[b]	495[b]	496	451	498	492[a]	503[a]
12	480[b]	481	462	428	477	459	488[a]
13	497	477	479	438	463	480	492
14	481	506	476	435	461	486	496
15	494	472	453	432	477	479	485
Mean	495	486	476	444	480	488	496

[a] Selected trials within-decade.
[b] Selected trials between-decade.

$(P < 0.01)$. The picture of Table 1, however, is slightly complicated because of the significant interaction between target and prime $(F(60, 540) = 2.11; P < 0.001)$.

To find out whether the interaction between target and prime was due to the conditions in which the border between units and teens had been transgressed, we limited the observations to those couples that allowed an orthogonal variation between distance and same/different category. That is, we limited the analysis to the prime-target combinations 4–7, 10–7, 5–8, 11–8, 6–8, 10–8, and so on, making a total of 24 combinations per participant (see Table 1). We tested in a 3 (absolute distance between prime and target) × 2 (within and between decade trials) ANOVA whether the distance effect was the same for within and between-decade trials ($RTs_{within-decade}$ = 483, 485, 499 ms for an absolute distance of 1, 2, 3 respectively; $RTs_{between-decade}$ = 487, 488, 496 ms for an absolute distance of 1, 2, 3 respectively). We obtained a main effect of distance $(F(2, 18) = 9.71; P < 0.01)$, indicating that RTs were faster when the prime was close to the target, and no effect of within or between-decade trials $(F < 1)$. No significant interaction effect emerged between distance and within or between-decade trials $(F < 1)$. However, as can be seen in the RTs above, the distance effects tended to be smaller for the between-decades trials than for within-decade trials. Tested separately, the distance effect was significant for within-decade trials $(F(2, 18) = 14.60; P < 0.001)$; the effect for between-decade trials was in the same direction but non-significant $(F(2, 18) = 1.37; P = 0.28)$.

4. Discussion

In Experiment 1, we replicated the masked priming effect and showed that an

Arabic numeral is named faster when immediately before a tachistoscopic prime with a close magnitude was presented. The priming effect was strongest when prime and target were the same number (repetition priming), but was still reliable when an absolute distance of one was compared to a distance of 2 or 3. The effect was in the order of 7–10 ms per unit of distance. Although the priming effect was slightly stronger for within-decade trials (8–9 ms) than for between–decade trials (5 ms), the same pattern was observed in both conditions and no interaction effect emerged. This is in line with the idea of units and teens being represented on the same number line.

A criticism against the experiment might be, however, that our naming task did not involve the semantic system and, hence, that the priming effect could be situated at another, possibly lexical, level. Although this interpretation is contradicted by findings reported by Fias, Brysbaert, Geypens and d'Ydewalle (1996), it could offer an explanation why masked priming is only possible within a particular notation and not across notations (see the Introduction). To counter this criticism, we repeated the experiment with parity judgement. Parity judgement requires access to the semantic system in order to produce the correct response. In addition, the semantic mediation can be verified by checking the presence of a SNARC-effect (Fias et al., 1996; Dehaene, Bossini & Giraux, 1993).

5. Experiment 2

5.1. Method

To avoid response interference, we only included prime-target combinations which asked for the same response (i.e. both prime and target were odd or even)[1]. Targets ranged from 7 to 12. Primes were either the same as the target, the target $\pm$ 2, or the target $\pm$ 4, making a total of 30 combinations. Participants were tested twice: once with the even response assigned to the right hand and once with the even response assigned to the left hand, in a counterbalanced order. Each of the sessions started with a practice block in which all combinations were presented once. Then, the participant had to perform three blocks of 120 trials in which each prime-target combination was shown four times. This made a total of 12 observations per combination per hand. There was a short break between sessions.

Stimulus presentation was the same as in Experiment 1. Participants had to indicate whether the target was odd or even by pressing one of the keys. Participants were 12 students from the same population as in Experiment 1.

6. Results

Mean percentage of errors was 4,0%. First, we ran a 2 (side of response) × 6

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[1] Using PET-data, Dehaene et al. (1998) showed that even tachistoscopically presented words are processed up to the response modality, so that primes and targets with a different parity can lead to interference at the output level, thereby obscuring the semantic distance effect.

(target magnitude) $\times 5$ (distance prime-target) ANOVA on the correct RTs. This yielded a significant main effect of target magnitude. Targets 8, 9 and 11 had slower RTs than the other targets ($F(5, 50) = 5.95$; $P < 0.001$). There was also a significant main effect of the distance between prime and target ($F(4, 40) = 30.19$; $P < 0.001$; see Table 2). RTs were fastest when prime and target were the same, but there was also a reliable difference ($P < 0.01$) between the distances 2 and 4. In addition, there was a significant interaction between side of response and target magnitude ($F(5, 50) = 4.55$; $P < 0.01$). Post-hoc comparisons indicated that even numbers were responded to faster with the right hand than with the left hand, whereas odd responses were responded to slower with the right hand than with the left hand ($F(1, 10) = 5.74$; $P < 0.05$). The association even/right and odd/left was only present for the participants who started with the opposite combination giving rise to a triple interaction between order of sessions, side of response and odd/even ($F(5, 50) = 4.42$; $P < 0.01$). Participants starting with the even/right and odd/left combinations did not show the effect ($F < 1$), whereas participants starting with the opposite combination did show this even/right and odd/left preference ($F(5, 25) = 29.49$; $P < 0.001$). This interaction could be due to practice effects. RTs in the first block were on average 20 ms slower than RTs in the second block. This practice effect is completely confounding with the even/right and odd/left association. Finally, we also tested whether there was a residual interaction of magnitude (a 3-level variable orthogonal to parity) with side of response. This revealed however no significant effect ($F < 1$).

In a 2 (distance between prime and target) x 2 (within and between-decade trials) ANOVA, we tested whether distance effects were the same in the conditions of within and between-decade trials ($RTs_{within-decade} = 422, 439$ ms for absolute distance of 2, 4 respectively; $RTs_{between-decade} = 423, 429$ ms for absolute distance of 2, 4, respectively). 20 combinations (see Table 2) were included in the analysis (i.e. 3–7 vs. 11–7, 4–8 vs. 12–8, 6–8 vs. 10–8, etc.). A significant main effect of distance ($F(1, 11) = 23.22$; $P < 0.001$) emerged, indicating that RTs were faster when a prime was presented with a close magnitude to the target. There was no

Table 2
RT as a function of the distance between prime and target (Experiment 2: parity judgement)

Target	Prime				
	T-4	T-2	T	T + 2	T + 4
7	420[a]	427	378	411	424[b]
8	457[a]	439[a]	399	418[b]	436[b]
9	438[a]	411[a]	402	435[b]	443[b]
10	424[b]	408[b]	371	406[a]	437[a]
11	425[b]	430[b]	391	438[a]	465[a]
12	425[b]	406	390	431	419[a]
Mean	431	420	388	423	437

[a] Selected trials within-decade.
[b] Selected trials between-decade.

effect of within or between-decade trials ($F(1, 11) = 1.39$; $P = 0.26$) nor an interaction effect ($F(1, 11) = 2.00$; $P = 0.19$). Like in Experiment 1, both effects were in the same direction but the distance effect was less strong for between-decade trials ($F(1, 11) = 2.52$; $P = 0.14$) than for within-decade trials ($F(1, 11) = 14.71$; $P < 0.01$). This does not necessarily mean that priming effects of between-decade trials are smaller than the priming effects of within-decade trials. As can be seen above, RTs of trials with an absolute distance of 2 are the same in both conditions, but the RTs for trials with an absolute distance of 4 are faster for between-decade trials than for within-decade trials, which is an indication that priming seems to last longer with trials across decades.

Finally, we ran a multiple regression analysis of repeated-measures data described by Lorch and Myers (1990, method 3), to test the SNARC-effect. Because the SNARC-effect stems from an association between the position of a number on the left-to-right-oriented number line and the side of response, it predicts a negative relation between number magnitude and the difference in RT between the right and the left hand (dRT). According to Fias et al. (1996), the most straightforward method to test this negative relation statistically is to regress dRT on number magnitude and to test the reliability of the regression slope. Due to the reliable odd/left and even/right association, we also included this variable. We coded odd targets as -0.5 and even targets as $+0.5$. As can be seen in Fig. 1a, there was no reliable evidence that the small numbers were reacted to faster with the left hand than with the right hand, and that the large numbers elicited faster right hand responses (regression weight = -1.4 ms; $t = 0.67$; df = 11). There was evidence that odd responses were responded to faster with the left hand than with the right hand, whereas the opposite was true for even numbers. We obtained a reliable regression weight = -43.62 ms, ($t = 1.92$; $P < 0.05$, one-tailed) indicating that dRTs increased when the target was odd an decreased when the target was even (see Fig. 1a).

Because the presence of a SNARC-effect would have been additional evidence that the parity task indeed requires access to the semantic number line, our failure to find the effect is not without importance. A possible reason for the failure, however, could be the uncertainty introduced by the difference between the value of the prime and the value of the target (because on some trials, participants had to react to a small number that was larger than the prime; on other trials, they had to react to a small number that was preceded by a prime that was on the high end of the scale; and so on). One way to circumvent all possible conflicts introduced by the difference between target and prime, is to limit our analysis to those trials in which prime and target had the same value (i.e. trials with repetition priming)[2]. This analysis revealed a SNARC-effect of -6.75 ms that approached significance ($t(11) = 1.70$; $P < 0.06$, one-tailed) indicating that the small targets were indeed reacted to faster with the left hand than with the right hand, and that the reverse was true for the targets at the high end of the scale. In addition, for the trials with repetition priming, there was some evidence that odd targets, which were coded as -0.5 in the analysis, were reacted to faster with the left hand than with the right hand, whereas the reverse was true for

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[2] The authors thank Wim Fias for this suggestion.
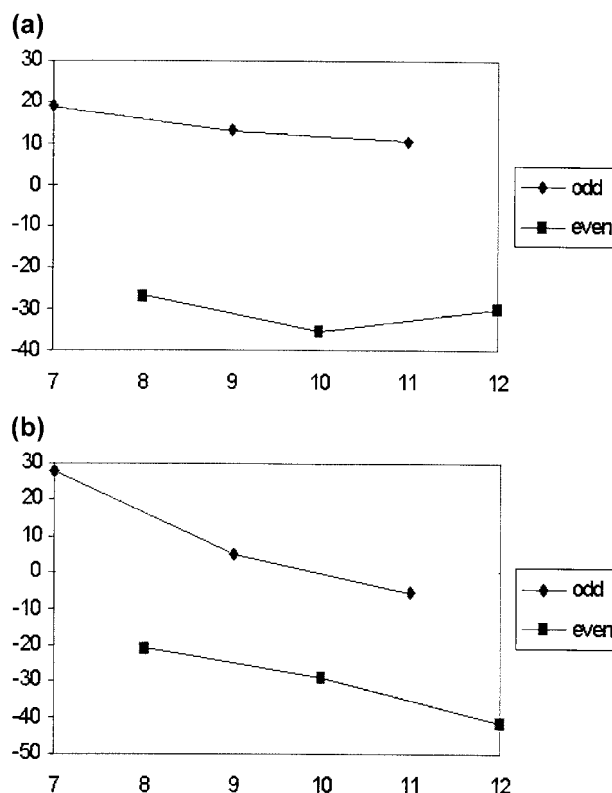
(a)

(b)

Fig. 1. (a) Observed data representing RT differences between right hand and left hand. All combinations are included in analysis. (b) Observed data representing RT differences between right hand and left hand. Only identity couples are included in analysis.

even targets, coded as $+0.5$ (regression weight $= -32.8$ ms; $t(11) = 1.53$; $P < 0.08$, one-tailed). Both effects are shown in Fig. 1b. There was no interaction between the two effects ($t = 0.65$; df $= 11$).

7. Discussion

Just like in Experiment 1 we found a reliable effect of absolute distance between prime and target. Although the distance effect tended to be larger for within-decade trials (8–9 ms) than for between-decade trials (4 ms), there is no indication that priming effects of absolute distance seems to be stronger in this first condition. On the contrary, priming effects seem to last longer for between-decade trials. Moreover, the patterns of results in both conditions were comparable and no interaction effect was found. This is further evidence that single-digit and two-digit Arabic numerals make access to the same semantic number line.

We further observed that even numbers tended to be associated with right hand responses and odd numbers with left hand responses. This effect has first been observed by Willmes and Iversen (1995), who called it a 'linguistic markedness association of response codes', or MARC-effect, and has since been replicated in several unpublished studies. In our study, the effect was largely limited to those participants who did not start with the preferred combination.

Finally, we found some evidence for a SNARC–effect when we limited our analysis to those trials in which no confusion was present due to the difference between target and prime (see Fig. 1b). Willmes and Iversen (1995) reported a similar combination of a SNARC and a MARC-effect in their experiment. Both the SNARC and the MARC-effect have been taken as evidence that the semantic number line is involved in parity judgement (Fias et al., 1996; Willmes and Iversen, 1995). This means that the findings of Experiment 1 can be explained without the need of a separate Arabic numeral lexicon as the origin of the priming effect.

8. General discussion

The research question of the present study was straightforward: do units and teens lie on the same semantic number line, so that one can be primed by the other to the same extent as they can be primed by other members of their own category. The answer turned out to be reasonably straightforward: yes (see Tables 1 and 2).

In two masked priming experiments, the effect of the prime on the processing of the target depended on the absolute distance between prime and target, and amounted to 6–7 ms per unit of distance. As in previous research (den Heyer and Briand, 1986), the priming effect was the same whether the prime was smaller than the target or larger. As can be seen in Tables 1 and 2, the distance priming effect is not absent in the between-decade condition. Therefore, we feel safe to conclude that the priming effect of absolute distance emerges both in the within-decade trials and in the between-decade trials.

This extends Brysbaert, (1995, Figs. 4 and 6) finding that priming with two-digit Arabic numerals can be obtained for prime-target distances up to 19 units. In addition, in line with Koechlin et al., (1999), the present findings show that the primes were processed to a high level despite their short presentation time (66 ms) and the presence of forward and backward masks. Because of the use of a decision task with response latencies and the use of a short prime duration, the priming effects we observed cannot be strategic (Neely, 1991), although a prime duration of 66 ms did not make the prime completely unconscious as well[3].

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[3] To find out how perceptible the primes were, we conducted a small experiment in which the target was shown for 500 ms, preceded by the forward mask, the prime and the backward mask for 66 ms. We asked three non-trained subjects from the same population as in the experiments, to report the target and the prime. The prime was identified in 45% of the trials, ranging from 38 to 52%. This number is probably an overestimate because of the instructions (i.e. to report the presentation of a prime) and correct guessing on the basis of partial information (e.g. because there were only 17 primes, participants had 6% chance of guessing the prime).

The most likely origin of the priming is semantic rather than lexical, because the effect was equally strong in the number naming (Experiment 1) as in the parity judgement task (Experiment 2), and because Experiment 2 provided independent evidence that the semantic number line had been addressed to make the odd/even decision (i.e. we found evidence for a SNARC and a MARC-effect in our data, at least when the analyses were limited to the proper conditions). These findings are in line with models that see the core of the numerical system as an analogue magnitude system with which all small integer numbers make contact during their processing (Brysbaert, 1995; Dehaene et al., 1998; Fias et al., 1996). The findings are less easily explained by models that put units and teens in different bins (e.g. Deloche and Seron, 1987; McCloskey, 1992).

Acknowledgements

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