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Automatic activation of multiplication facts: Evidence from the nodes adjacent to the product

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Adult observers are widely assumed to be equipped with a specific memory store containing arithmetic facts. The present study was aimed at exploring the possibility of obtaining an automatic activation of multiplication facts by using the number-matching paradigm (LeFevre, Bisanz, & Mrkonjic, 1988), in which mental arithmetic is task irrelevant. In particular, we were interested in exploring whether the nodes that precede or follow the product node in the multiplication table can also be automatically activated as a consequence of the mere presentation of two numbers. In Experiments 1 and 2, we showed that participants were slower in responding "no" to probes that were numbers adjacent to the product in the table related to the first operand of the initial pair than to probes that were unrelated to the initial pair. In Experiments 3 and 4, we showed a similar pattern for probes that were numbers adjacent to the product in the table related to the second operand of the initial pair. Experiments 5 and 6 ruled out alternative accounts and confirmed the results of the previous experiments. Taken together the present findings suggest that multiplication facts are stored in a highly related network in which activation spreads from the product node to adjacent nodes.

Recent cognitive models of mental calculation (see Ashcraft, 1995, for a review) share the assumption that, at least for those operations whose operands are represented by single digits, adult subjects retrieve solutions from stored knowledge representations, generally known as *arithmetic facts*.

Neuropsychological research has shown that arithmetic facts can be selectively lost after brain injuries (e.g., Cohen & Dehaene, 1994; Hittmair-Delazer, Sailer, & Benke, 1995; McCloskey, Aliminosa, & Sokol, 1991; Sokol, McCloskey, Cohen, & Aliminosa, 1991;

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Warrington, 1982; Whetstone, 1998) and can also selectively resist decay in patients suffering from dementia (e.g., Girelli, Luzzatti, Annoni, & Vecchi, 1999; Remond-Besuchet, Noël, Seron, Thioux, Brun, & Aspe, 1999). Such results can be interpreted as showing that arithmetic facts are stored independently of either other semantic knowledge or other mathematical skills.

The cognitive implementation of arithmetic facts is part of the calculation system of the modular model of number skills proposed by McCloskey, Caramazza, and Basili (1985; McCloskey, 1992). Other models have been developed, which assume that arithmetic facts are retrieved from an interrelated network of associative links in long-term memory (e.g., Ashcraft, 1992; Campbell, 1995; Dehaene & Cohen, 1995; Geary, Widaman, & Little, 1986; Miller, Perlmutter, & Keating, 1984; Siegler, 1988).

The present paper tries to replicate and extend the results reported by Thibodeau, LeFevre, and Bisanz (1996), who showed that, using a non-arithmetic task, it is possible to trigger an automatic retrieval process involving number facts related to multiplication. Thibodeau et al.'s experimental paradigm is based on a modified Stroop procedure developed by LeFevre, Bisanz, and Mrkonjic (1988) for investigating the obligatory activation of addition facts. The rationale is quite similar to that underlying experimental paradigms adopted in semantic priming studies and will be illustrated in the next paragraph. Before that, we review some of the pertinent literature concerning the issue of priming and automatic activation in the domain of numbers, which is directly related to the issue we investigated in the present study.

Interference and priming in cognitive arithmetic

Automaticity in cognitive arithmetic has been investigated by focusing on two main phenomena: cross-operation interference and within-operation interference.

In a classic study, Winkelman and Schmidt (1974) showed that adult observers performing a verification task with simple additions and multiplications are very slow in rejecting false equations in which the stated result is the correct answer for the other operation. This cross-operation interference phenomenon represented some of the first behavioural evidence of the presence of associative processes in simple mental arithmetic. Miller et al. (1984) further demonstrated that subjects performing production tasks make a higher percentage of associative confusion errors than other kinds of error. Zbrodoff and Logan (1986) further explored the level of automaticity of the processes underlying mental arithmetic by means of the associative confusion effect discovered by Winkelman and Schmidt. Participants were to verify simple addition and multiplication equations. Results for half of the false equations were the correct answer for the other operation (*associative lures*; e.g., $3 + 4 = 12$; $3 \times 4 = 7$). The remaining false problems contained *non-associative lures* (i.e., responses not related to the operands by means of any conventional arithmetic operation). Zbrodoff and Logan found that latencies in false problems were significantly slower for associative than for non-associative lures (the *associative confusion effect*). More interestingly, the authors also found that the processes producing the associative confusion can be inhibited if participants are given certain temporal parameters. Zbrodoff and Logan concluded that single digits are directly linked to their sums and products and that these associations are generally activated automatically, thus leading to the associative confusion phenomenon. However, it is worth noting that this study provides only limited support for obligatory activation of arithmetic facts because participants had been instructed to perform an arithmetic operation, although a different one. Therefore, the associative confusion may reflect processing that is obligatory only if participants are in an "arithmetic mode": that is, when the context is that of performing an arithmetic task. Stazyk, Ashcraft, and Hamann (1982) examined whether the interference effect was also present within multiplication (within-operation interference) and found that participants were significantly slowed in verifying confusion problems (in which the stated result of the problem was a multiple of the first operand), relative to non-confusion problems (in which the stated result was not related to any of the operands of the problem; also see Lemaire, Abdi, & Fayol, 1996; Lemaire, Fayol, & Abdi, 1991).

Campbell (1987, Experiment 2; also see Campbell, 1991; Koshmider & Ashcraft, 1991) explored the effects of priming in a production task based on multiplication. His participants were given a neutral condition, in which a neutral stimulus was presented prior to the to-be-solved problem, and a correct-prime condition, in which the correct answer was shown before a problem was presented. There were also two false-prime conditions, in which the false prime was a high-frequency (related condition) or a low-frequency (unrelated condition) error for the following problem. Each of the four conditions had the same probability. Thus, participants could not use prime information to reliably predict the answer. The prime appeared for 300 ms and was immediately followed by the problem. Campbell found that when the prime was the correct answer, participants performed significantly more accurately and showed a clear advantage in latencies than in the neutral condition. Latencies in the false-prime related condition were significantly slower than those for the false-prime unrelated condition, which in turn were slower than reaction times for the neutral condition.

Campbell (1991; also see Meagher & Campbell, 1995) interpreted these findings by proposing two alternative accounts, based on an automatic-retrieval priming process or a familiarity-checking strategy. The retrieval-priming account claims that numerical primes are able to influence retrieval performance by increasing or decreasing the relative activation of the correct stored item. Following this hypothesis, facilitating and inhibiting priming effects automatically emerge as a consequence of encoding a prime before retrieval. It is also important to note how the multiplication priming effects are consistent with both the network-interference (e.g., Campbell, 1995) and the distribution-of-associations (e.g., Shrager & Siegler, 1998; Siegler, 1988) models of the memory for arithmetic facts. On the other hand, the familiarity-checking account states that priming effects could be the result of a strategy in which participants assess the familiarity produced by the prime-problem association (e.g., Lochy, Seron, Delazer, & Butterworth, 2000; Reder & Ritter, 1992). If familiarity is sufficiently high, participants state the prime as the response to the presented problem. Meagher and Campbell tried to distinguish between the two hypotheses by varying the delay between primes and problems, and they demonstrated that neither the retrieval-priming account nor the familiarity-checking account were able, alone, to explain all the results. Therefore, Meagher and Campbell concluded that both retrieval priming and a familiarity-checking strategy are involved in producing priming effects for multiplication.

LeFevre et al. (1988; also see LeFevre & Kulak, 1994; LeFevre, Kulak, & Bisanz, 1991; Lemaire, Barrett, Fayol, & Abdi, 1994) further explored within-operation interference in cognitive arithmetic by means of a modified Stroop procedure involving a number-matching task. Participants were shown a pair of single digits, which, after a variable time interval, was replaced by a probe digit. Participants were to decide whether the probe was one of the numbers presented previously or not. LeFevre et al. (1988) demonstrated that participants rejected significantly more slowly items in which the probe was the sum of the initial pair (e.g., 3 + 6 and 9) than items in which the probe was unrelated to the initial pair (e.g., 3 + 6 and 4). They also showed that such an interference effect emerged only at very short time intervals and did not depend on whether the "+" symbol was present in the initial pair. Neither did it depend on whether numbers appeared in arabic or written verbal format. LeFevre et al. (1988) interpreted the interference effect as evidence of obligatory activation of simple arithmetic facts, in the sense that activation of sums occurred even if mental arithmetic was completely task irrelevant.

However, it has been argued (Baroody, 1994) that the interference effect might be a consequence of an automatically activated counting process rather than retrieval. Moreover, the examination of results from a study by LeFevre, Sadesky, and Bisanz (1996), who investigated participants' self-reports about selection of strategies in mental addition, allows one to claim that at least a subset of the stimuli used by LeFevre et al. (1988) might have triggered a counting strategy (however, see Kirk & Ashcraft, 2001, for important caveats on the use of self-reports for studying strategies in arithmetic).

Thibodeau et al. (1996) tried to extend the interference effect to multiplication by means of the same modified Stroop procedure used by LeFevre et al. (1988). They argued that any interference effect with multiplication facts would have been interpreted as strong evidence that participants were retrieving stored associations rather than adopting a "one-at-a-time" counting procedure. The authors found an interference effect that substantially replicated the results obtained in studies with addition facts (e.g., LeFevre et al., 1988), thus ruling out an automatic counting account (see Baroody, 1994), which appears to be untenable for multiplication (e.g., Miller et al., 1984).

The present study

According to the Consensus model (Ashcraft, 1995), a compound of various theories proposed for mental arithmetic (e.g., Ashcraft, 1992; Campbell, 1995; Siegler, 1988), numbers are stored as nodes in a network of associative links in long-term memory. Presentation of two numbers (operands) results in activation of the number nodes in the associative network. Activation then spreads from the presented nodes along associative links to related number nodes, such as the sum or the product. LeFevre at al. (1988) demonstrated that activation spreads from the presented nodes to the sum node in an obligatory manner (but see Baroody, 1994). In fact, activation of the sum node very plausibly occurred without any intention, being detrimental for the task at hand.

The modified Stroop procedure developed by LeFevre et al. (1988) was employed in six experiments to address the question of whether a given digit pair can involuntarily activate not only the product, but also the nodes adjacent to the product in the related table. We employed the same method as that used by Thibodeau et al. (1996), but we did not show the multiplication sign between the initial pair of numbers. This was motivated by the fact that the presence of the multiplication symbol might have cued participants to pre-activate the multiplication tables, even though, for addition, LeFevre et al. (1988, Experiment 2) showed that the presence of the sum symbol did not significantly affect interference.

In the present study, we focused on multiplication instead of addition because the former seems to be more closely related to retrieval than to the adoption of back-up procedural strategies. It is now clear that for single-digit addition, strategies evolve with practice from algorithmic computing to direct memory retrieval (Barrouillet & Fayol, 1998), whereas, generally, single-digit multiplication is learned directly by means of memory strategies. Also, it should be noted that several case studies are reported in the literature in which multiplication facts are particularly compromised compared to other simple operations (e.g., Dagenbach & McCloskey, 1992; Girelli, Delazer, Semenza, & Denes, 1996; Whetstone, 1998). This confirms the existence of a privileged link of multiplication with retrieval strategies. In fact, one may hypothesize that the usually consistent poorer performance observed for multiplication, with respect to addition and subtraction, is due to the fact that back-up strategies, such as counting, cannot be of great help with multiplication (for a similar argument, see Cohen & Dehaene, 1994).

In each of the six experiments that we performed, two kinds of trial were used: Matching trials were trials in which the probe matched one of the numbers in the cue (in which case participants were to respond "yes"); and non-matching trials were trials in which the probe did not match either number in the cue (in which case participants were instructed to respond "no").

In Experiments 1 and 2, we tested the hypothesis that the simple presentation of the initial digit pair was able to activate the nodes adjacent to the product in the table related to the first number of the pair. In the number-matching task, interference would have resulted in a slower rejection of probes that were the nodes adjacent to the product of the two numbers of the cue. In fact, participants would have to inhibit the detrimental obligatory activation of those nodes. In Experiments 3 and 4, we were interested in examining whether the same interference effect would have arisen for probes being the nodes adjacent to the product in the table related to the second number of the initial pair. Experiments 5 and 6 were carried out in order to rule out possible confounds arising from the set of stimuli that were employed in the previous experiments.

We have tested separately the interference effect produced by each kind of product-related probe separately for two important reasons. First, testing the different probes in the same experiment might have generated some co-activation phenomenon, which in turn might possibly have lead to overestimating the interference effect. Second, we could not find enough stimuli that fit the criteria for stimuli selection (see later).

In each experiment, we also systematically varied the time interval between the onset of the cue pair and the onset of the probe (*stimulus onset asynchrony* or *SOA*). LeFevre et al. (1988) proposed that the automatic activation of arithmetic facts is present at very short SOAs and then disappears at longer intervals due to either inhibition or decay of activation (e.g., Logan, 1980).

EXPERIMENT 1

In this experiment we tested the hypothesis that items for which the probe was the node below the product related to the first number of the initial number pair would be rejected more slowly than items that were unrelated to the initial pair (interference effect). According to LeFevre and Kulak (1994), the interference effect should be reliable only when the SOA is less than 60 ms for addition facts. Thibodeau et al. (1996), in trying to extend the interference effect to multiplication, found a significant interference effect at 100-ms and 120-ms SOAs, but not at 220-ms and 350-ms SOAs. This means that probably the interference effect has a different time course for addition and multiplication. However, a direct comparison is not possible because Thibodeau et al.'s study had a lower number of manipulations than the study by LeFevre et al. (1988).

Being concerned with a possible interference produced by the activation of the multiplication tables, we assumed the time course of the interference to resemble more the one showed by the product rather than the one showed by the sum. Therefore, we used a short SOA of 120 ms—that is, the one in which interference was the strongest in Thibodeau et al.'s (1996) study—and we also used longer SOAs (270 and 400 ms). Following Thibodeau et al.'s findings, we should have expected to find a significant interference effect at the shortest SOA but not at the longer ones. However, if one accepts the view that presentation of two numbers results in the activation of the product node, and then activation spreads from that node to other related nodes (see, e.g., Ashcraft, 1992), then we should expect the locus of interference to be found later for the node below the product. This means that the node below (as well as the node above) the product should not be activated directly by the presentation of the operands. If this is the case, then, any interference effect should be expected to become manifest only at the longer SOAs.

Method

Participants

A total of 21 undergraduates (9 males and 12 females) from the University of Padua, all right-handed, volunteered to take part in this experiment. Their age ranged from 19 to 26 years. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment.

Materials

Each trial was composed of the presentation of an initial digit pair cue (e.g., "8" and "3") followed by a digit probe (e.g., "16"). Participants were required to respond "no" if the probe did not match either number in the cue (non-matching stimuli) and to respond "yes" if the probe was one of the numbers of the initial pair (matching stimuli). Half were matching trials, the other half non-matching. Combinations of digit cues and probes that might have evoked activation on the basis of some relation among the items other than multiplication (e.g., addition, "8" and "3", and "11") were discarded from the stimulus set, in order not to generate associative confusions (e.g., Winkelman & Schmidt, 1974). Ties (e.g., "3" and "3") were excluded, primarily because they appear to have an easier access to the memory store than do other problems (e.g., Graham & Campbell, 1992; for a different view on the nature of the tie effect see Blankenberger, 2001). Digit cues and probes composed of 0 and 1 were also excluded because they seem to elicit the retrieval of rules, instead of the retrieval of results (e.g., Baroody, 1983; McCloskey et al., 1991). Each probe appeared the same number of times. Note that Thibodeau et al.'s (1996) constraints basically consisted of avoiding ties and eliminating 0 and 1 probes only.

Following Thibodeau et al.'s (1996) study, three cue–probe association types were created. They varied in the relation between the probe and the cues and, therefore, also in the correct response (see Appendix A). For both *below-product* and *neutral* (unrelated) stimuli, the probe did not match either number of the digit cue. For below-product stimuli, the probe was equal to the number corresponding to the node below the product of the digits in the cue, in the table related to the first (i.e., the leftmost) number in the cue. Neutral stimuli had the same cues as the below-product stimuli. The single-digit numbers in the neutral cues did not match either number in the double-digit probes, in order to avoid partial matches. Neutral probes were not divisible by either number in the cue, to avoid table-related activation. However, we used neutral probes that in most cases were nodes belonging to some other multiplication table (see Appendix A). This means that neutral probes were part of the multiplication associative network.

It is worth remembering that the interference effect is estimated by comparing performance between the critical (below the product, in this experiment) node probe and the neutral probe. Therefore, choosing a unit of the multiplication network as a comparison term is very conservative. It is conceivable that the presentation of such a probe will by itself generate some activation, the number being involved in the same representational space. This reasoning is somewhat similar to the one underlying the choice of stimuli in a typical arithmetic verification task, in which participants are required to judge as true or false a problem with a stated result. One should not allow the observer to perform the task by applying non-retrieval strategies, like the odd–even rule (e.g., Lemaire & Fayol, 1995) or a plausibility/familiarity judgement (e.g., Campbell & Tarling, 1996; Zbrodoff & Logan, 1990).

On non-matching trials there were also *non-matching filler stimuli* with a double-digit number in both the cue and the probe (see Appendix A). These stimuli were chosen in order to have a condition in which participants saw non-matching stimuli having double-digit cues. Because the purpose of these stimuli was only to balance the other non-matching trials, they were not included in data analyses (see Thibodeau et al., 1996).

Three types of matching trial were included (see Appendix A). There were *probe-balancing stimuli*, in which the probe was the same probe as that used in the below-product trials but the probe was also one of the numbers in the cue. Also, there were *cue-balancing stimuli*, which had the same cues as the below-product stimuli, and one of the numbers in the initial pair was the probe. These stimuli were chosen so that participants saw matching trials consisting of two single-digit numbers in the cue. Finally, *matching filler stimuli* were included, which had a double-digit number in the cue. The probe always matched the single-digit number in the cue.

For the present experiment we prepared a list with 7 stimuli for each type, so that we had a list of 42 stimuli in total (see Appendix A). The SOA between cue and probe was 120, 270, or 400 ms. Each list was repeated three times for each SOA, for a total of 378 stimuli per participant. For half of the stimuli, the correct response was "yes", for the other half "no". Order of presentation was randomized for each subject, with the constraints that no more than three matching or non-matching stimuli, and no more than three SOAs of the same value appeared consecutively. The same criteria for stimuli selection and presentation were also used in all the subsequent experiments.

Apparatus

All testing was conducted in a sound-attenuated, dimly lit room. An IBM-compatible 486 computer running the MEL software (Schneider, 1988) connected to a 15-inch colour VGA monitor was used to control timing of events, generate stimuli, and record reaction times (RTs) and accuracy. The monitor was placed at eye level on a table in front of the participant. The participant sat with the head positioned on a headrest, so that the distance between the eyes and the screen was approximately 50 cm. The fixation point (an asterisk), as well as each single digit, was 50 mm in height and 30 mm in width.

Design

Three within-participants factors, matching condition (2 levels: matching and non-matching), probe type (3 levels: below product, neutral, and filler), and SOA (3 levels: 120, 270, and 400 ms) were considered. Each participant performed a single experimental session, which consisted of three blocks of 126 trials each.

Procedure

Participants were given an oral description of the stimuli and task and were encouraged to respond as quickly as possible, while maintaining accuracy.

The sequence of events on each trial is shown in Figure 1. The background was black, and stimuli appeared in white. Each trial began with a 100-ms, 500-Hz tone as a warning signal. At the same time, the fixation point appeared, centred on the screen, lasting for 400 ms. Immediately after the offset of the fixation point, a digit pair (the cue) was presented for 60 ms and was then masked for 40 ms by means of seven asterisks. After the cue and the mask were turned off, a variable interstimulus interval (ISI) followed (20, 170, or 300 ms), resulting in three SOAs (120, 270, and 400 ms). After this sequence, the probe number was presented and remained visible until the participant's response or 2500 ms elapsed. The participant responded by pressing one of the two designated keys on the keyboard.

Half of the participants pressed the "P" key for matching trials and the "Q" key for non-matching trials. The other half did the opposite. RTs were recorded by the computer with millisecond precision. At the end of each trial, participants were given visual feedback concerning their performance. When they responded correctly, no feedback was given. The feedback for incorrect responses was the display message "error". If a response was not produced within 2500 ms, the display "missed response" was presented. All the stimuli appeared centred on the screen.

Before the experiment began, participants performed practice trials until they felt confident with the task. Each experiment consisted of three blocks. At the end of each block, participants were encouraged to take a short break.

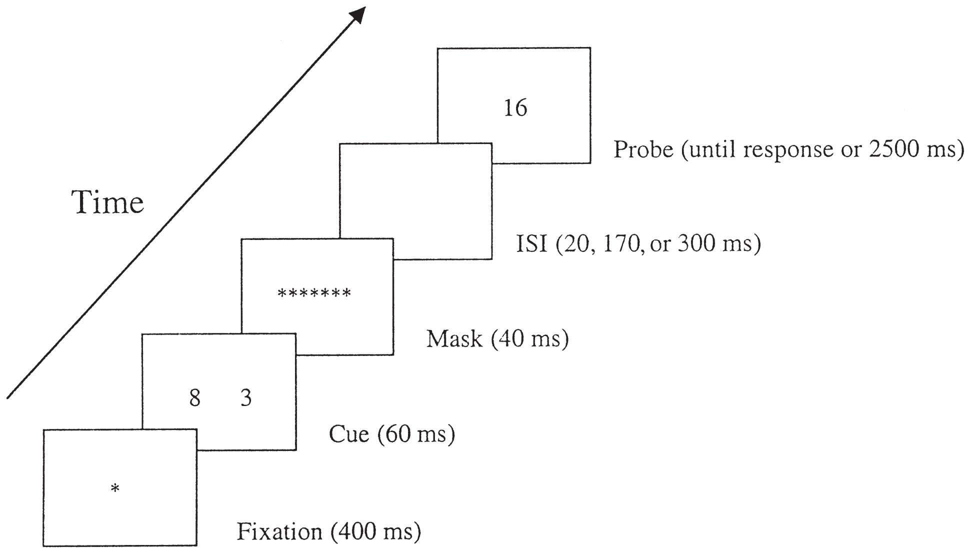

Figure 1. Sequence of events on a single trial in Experiments 1–6. A non-matching "below product" trial related to the first operand (Experiment 1) is illustrated.

Results and discussion

RT data

In this and all subsequent experiments, outliers were removed from the data before analyses were carried out. Outliers were defined as RTs faster or slower than 2.5 standard deviations above the mean. This resulted in the removal of approximately 2.5% of all observations in the present experiment.

Data analyses were focused on non-matching trials, as the matching trials did not address our hypotheses. However, a first within-participants two-way analysis of variance (ANOVA) was performed on mean correct RTs, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors. Participants responded more rapidly to matching trials ($M = 547$ ms, $SD = 101$) than to non-matching trials ($M = 592$ ms, $SD = 108$), which resulted in a main effect of matching condition, $F(1, 20) = 45.784$, $p < .0001$. We interpret the advantage for matching trials over non-matching trials as an instance of a more general phenomenon, on which basis, in a wide variety of tasks, participants are usually faster in responding "yes" than "no"[1] (see, e.g., Ratcliff, 1987). The effect was not considered further.

Participants also responded more rapidly as cue–probe SOA increased (120-ms SOA: $M = 623$ ms, $SD = 105$; 270-ms SOA: $M = 554$ ms, $SD = 97$; 400-ms SOA: $M = 531$ ms, $SD = 97$), producing a main effect of SOA, $F(2, 40) = 179.997$, $p < .0001$. This effect was present in all subsequent analyses that included SOA as a factor. It presumably reflects the well-known temporal warning effect (see, e.g., Niemi & Näätänen, 1981) and was not considered further either.

The two-way interaction Matching Condition × SOA approached significance, $F(2, 40) = 3.171$, $p = .053$, due to the fact that the advantage in RTs for matching over non-matching trials was slightly reduced at the 270-ms SOA (34 ms) and 400-ms SOA (39 ms) compared to the 120-ms SOA (57 ms).

A second and more important within-participants two-way ANOVA was conducted on mean correct RTs for non-matching trials only, with probe type (below product vs. neutral) and SOA (120, 270, and 400 ms) as factors. Consistent with our prediction about automatic activation, probes that were the nodes below the product of the two numbers of the cue were rejected more slowly ($M = 593$ ms, $SD = 111$) than were neutral probes ($M = 576$ ms, $SD = 106$), resulting in a highly significant main effect of probe type, $F(1, 20) = 19.216$, $p < .0001$ (see Table 1).

SOA again yielded a significant main effect, $F(2, 40) = 122.668$, $p < .0001$, with participants responding more quickly as SOA increased. The two-way Probe Type × SOA interaction, contrary to what we expected, was not significant ($F < 1$). This means that the interference effect, indexed by slower RTs for below-product probes that for neutral probes, was present at all SOAs (120-ms SOA: 18 ms; 270-ms SOA: 21 ms; 400-ms SOA: 13 ms; also see Table 2).

[1] Another possibility is that single-digit probes always require a "yes" response (we thank Wim Fias for suggesting this alternative account).

TABLE 1
Mean RTs[a] and % of correct responses for the nodes adjacent to the product trials and neutral trials in Experiments 1–6

	Probe type					
	Multiple		*Neutral*		*Interference*	
Experiment	*RT*	*% correct responses*	*RT*	*% correct responses*	*RT*	*% correct responses*
1	593	.93	576	.95	17*	.2
2	598	.95	580	.96	18*	.1
3	610	.94	600	.97	10	.3*
4	617	.97	601	.98	16*	.1
5	625	.94	619	.95	6	.1
6	608	.93	594	.94	14*	.1

Note: Probes in the multiple condition were the nodes below the product in Experiments 1 (related to the first number in the digit-cue) and 3 (related to the second number in the digit-cue), and the nodes above the product in Experiments 2 and 5 (related to the first number in the digit-cue), and 4 and 6 (related to the second number in the digit-cue). RT = reaction time.
[a] In ms.
* Significant interference effects.

The main effect of probe type is very important because it provides the first behavioural evidence that participants who are presented with two numbers automatically activate not only the product but also the number that is the node below the product in the multiplication table of the first number of the cue. This interference effect is said to be automatic on the grounds that arithmetic is completely task irrelevant in the number-matching task. It is also very important to remember that, differently from Thibodeau et al. (1996), whose study, to our knowledge, is the only one that investigated the multiplication network by using a non-arithmetic task, no multiplication symbol was shown in our experiment.

The magnitude of the interference did not significantly vary as a function of SOA. This result is different from that observed by Thibodeau et al. (1996) for the interference generated by product probes. In fact, even though in their study the two-way interaction between probe type and SOA only approached significance, pairwise comparisons showed that the interference effect was reliable only at the 100-ms and 120-ms SOAs. The presence of interference also at the intermediate and at the long SOAs might seem difficult to reconcile with the notion that automatic activation produced by the number-matching task is a short-lived phenomenon. LeFevre et al. (1988) claimed that the interference does not last for long because it is plausible that participants voluntarily suppress the unwanted activation, because it is detrimental for performing the task at hand. Alternatively, it is possible to hypothesize that activation simply decays with time. However, it should be noted that according to Neely (1991; Neely & Kahan, 2001) at least in the verbal domain active inhibition or spontaneous decay of irrelevant information does not take place before 400 ms, and possibly even later (see, e.g., Becker, Moscovitch, Behrmann, & Joordens, 1997; Deacon, Tae-Joon, Ritter, Hewitt, & Dynowska, 1999). As 400 ms was our longest SOA, we can reasonably assume that we were still in the time window of automatic activation.

TABLE 2
Mean RTs[a] for the nodes adjacent to the product trials and neutral trials in Experiments 1–6 as a function of SOA

		Probe type			
		Multiple		*Neutral*	
Experiment	*SOA*	*M*	*SD*	*M*	*SD*
1	120	652	95	634	102
	270	579	109	558	101
	400	549	106	536	95
2	120	657	120	642	117
	270	586	117	563	117
	400	551	114	536	116
3	120	670	119	659	126
	270	591	110	590	120
	400	566	104	553	114
4	120	689	98	677	106
	270	594	102	585	83
	400	568	96	541	85
5	120	692*	95	669*	94
	270	605	97	615	103
	400	577	103	573	111
6	120	667	74	663	80
	270	598	76	580	81
	400	560	72	541	68

Note: Probes in the multiple condition were the nodes below the product in Experiments 1 (related to the first number in the digit-cue) and 3 (related to the second number in the digit-cue), and the nodes above the product in Experiments 2 and 5 (related to the first number in the digit-cue), and 4 and 6 (related to the second number in the digit-cue). Note that the Probe Type × SOA interaction was significant in Experiment 5 only.
[a] In ms.
* Interference effect significant at 120-ms SOA only.

Accuracy data

In the present and all subsequent experiments, errors included misses (i.e., no response) and incorrect responses (i.e., wrong key presses).

A first ANOVA was conducted on percentage of correct responses, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors. There was a main effect for both matching condition, $F(1, 20) = 5.269$, $p < .04$, with participants showing higher accuracy for matching ($M = 0.94$, $SD = 0.08$) than for non-matching ($M = 0.92$, $SD = 0.06$) trials, and for SOA, $F(2, 40) = 5.837$, $p < .007$, with participants responding more accurately as the SOA increased (120-ms SOA: $M = 0.91$, $SD = 0.09$; 270-ms SOA: $M = 0.94$, $SD = 0.05$; 400-ms SOA: $M = 0.94$, $SD = 0.06$). The two-way interaction was not significant.

A second two-way repeated measures ANOVA was conducted on percentage of correct responses for non-matching trials only, with probe type and SOA as factors. The main effect of probe type approached significance, $F(1, 20) = 3.395$, $p = .08$, due to the tendency for participants to respond more accurately to neutral probes ($M = 0.95$, $SD = 0.08$) than to below-product probes ($M = 0.93$, $SD = 0.11$). Clearly no speed–accuracy tradeoff influenced the data. Likely interference affected accuracy as well as RTs (see Table 1). The main effect of SOA was significant, $F(2, 40) = 6.770$, $p < .004$, performance being more accurate as SOA increased. The two-way interaction was not significant ($F < 1$).

EXPERIMENT 2

In Experiment 2 we tested the hypothesis that when the probe was the node above the product related to the first number of the initial number pair, it would be rejected more slowly than items that were unrelated to the initial pair. We used the same SOAs as those employed in Experiment 1.

Method

Participants

A total of 21 undergraduates (7 males and 14 females) from the University of Padua, all right-handed, volunteered to take part in this experiment. Their age ranged from 20 to 28 years. All participants had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. None had participated in Experiment 1.

Materials

A new list of stimuli for each of the six probe conditions was created, with the same constraints as in Experiment 1 (see Appendix B). Crucial stimuli here were those items in the non-matching condition for which the probe was the node above the product related to the first number of the initial pair.

For the present experiment, we prepared a list with six stimuli for each type, so that we had a list of 36 stimuli in total (see Appendix B). The SOA between cue and probe was 120, 270, or 400 ms. We repeated each list three times for each level of SOA, for a total of 324 stimuli per participant.

Apparatus, procedure, and design

All aspects of this experiment were identical to those of Experiment 1. Three within-participants factors, matching condition (2 levels: matching and non-matching), probe type (3 levels: above product, neutral, and filler), and SOA (3 levels: 120, 270, and 400 ms) were considered. Each participant performed a single experimental session, which consisted of three blocks of 108 trials each.

Results and discussion

RT data

The application of the outliers-trimming algorithm resulted in the removal of approximately 1.4% of all observations in the present experiment. A two-way repeated measures ANOVA, with the main terms of matching condition (matching vs. non-matching) and

SOA (120, 270, and 400 ms), was performed on mean correct RTs. Participants responded faster to matching trials (*M* = 557 ms, *SD* = 112) than to non-matching trials (*M* = 602 ms, *SD* = 124), producing a main effect of matching condition, $F(1, 20) = 55.235$, $p < .0001$. Participants were faster in responding as the SOA increased (120-ms SOA: *M* = 637 ms, *SD* = 121; 270-ms SOA: *M* = 565 ms, *SD* = 110; 400-ms SOA: *M* = 538 ms, *SD* = 109), which resulted in a main effect of SOA, $F(2, 40) = 117.786$, $p < .0001$. Also, the two-way interaction was significant, $F(2, 40) = 4.616$, $p < .02$, due to the fact that the advantage in RTs for matching over non-matching trials decreased as the SOA increased (60 ms at the 120-ms SOA, 43 ms at the 270-ms SOA, and 33 ms at the 400-ms SOA). This pattern is the same as the one observed in the previous experiment.

A second and more interesting two-way repeated measures ANOVA was performed on mean correct RTs for non-matching trials only, with probe type (above product vs. neutral) and SOA (120, 270, and 400 ms) as factors. Critical to our hypothesis, there was a main effect of probe type, $F(1, 20) = 5.784$, $p < .027$, with participants responding slower to above-product probes (*M* = 598 ms, *SD* = 123) than to neutral probes (*M* = 580 ms, *SD* = 124; also see Table 1). This result clearly shows that above-product multiples related to the first operand are able to produce an automatic activation that interferes with performance in the number-matching task. The main effect of SOA was again significant, $F(2, 40) = 58.822$, $p < .0001$. Also, as in Experiment 1, the two-way Probe Type × SOA interaction was not significant ($F < 1$). This pattern of results shows that the interference effect produced by the above product probes was very similar to that produced by the below-product probes, being reliably present at all SOAs (120-ms SOA: 14 ms; 270-ms SOA: 23 ms, 400-ms SOA: 15 ms; also see Table 2). Apparently, both multiples related to the leftmost number in the initial pair received an involuntary activation, with a very similar time course, resulting from the previous presentation of the digit cue. We interpret this finding as evidence that, in the multiplication network, activation spreads directly from the product node to adjacent nodes, either up or down, via associative connections in the table related to the leftmost digit in the number cue.

Accuracy data

An ANOVA was performed on percentage of correct responses, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors.

A main effect emerged for both matching condition, $F(1, 20) = 6.192$, $p < .023$, with participants showing higher accuracy for matching (*M* = 0.95, *SD* = 0.06) than for non-matching (*M* = 0.92, *SD* = 0.08), and SOA, $F(2, 40) = 9.785$, $p < .001$, with participants responding more accurately as the SOA increased (120-ms SOA: *M* = 0.91, *SD* = 0.08; 270-ms SOA: *M* = 0.94, *SD* = 0.07; 400-ms SOA: *M* = 0.95, *SD* = 0.06). The two-way interaction was not significant.

A second two-way repeated measures ANOVA was conducted on percentage of correct responses for non-matching trials only, with probe type and SOA as factors. The main effect of probe type was not significant ($F < 1$). The main effect of SOA was significant, $F(2, 40) = 6.345$, $p < .004$, because performance improved as SOA increased. The two-way interaction was not significant. In conclusion, even if no evidence for the interference effect emerged in accuracy data, the observed pattern of error rates across experimental conditions makes any speed–accuracy tradeoffs unlikely.

EXPERIMENT 3

In Experiments 1 and 2 the nodes adjacent, either above or below the product node of the multiplication table of the first number in the initial pair, received an automatic activation. That was indexed by an interference effect that impaired performance in the number-matching task. The present experiment was aimed at exploring whether probes that were the node below the product of the second number of the initial pair were also activated automatically. The same SOAs as those in Experiments 1 and 2 were employed.

Method

Participants

A total of 30 undergraduates (8 males and 22 females) from the University of Padua, all right-handed, volunteered to take part in this experiment. Their age ranged from 19 to 27 years. All participants had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. None had participated in the previous experiments.

Materials

A total of 15 new stimuli for each of the six probe conditions were created so that we had a list of 90 stimuli for each SOA (see Appendix C). Crucial stimuli were those items in the non-matching condition for which the probe was the node below the product of the second number of the initial pair. As in previous experiments, we used neutral probes that in most cases were nodes belonging to multiplication tables different from those of the operands in the initial number pair.

Apparatus, procedure, and design

These were the same as those in previous experiments. Each participant performed a single experimental session, consisting of 270 trials.

Results and discussion

RT data

Approximately 2.8% of all observations were removed as a consequence of the application of the trimming procedure. A two-way repeated measures ANOVA, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as within-participants factors, was performed on mean correct RTs. Participants were faster in responding to matching trials (M = 565 ms, SD = 112) than to non-matching trials (M = 609 ms, SD = 116), producing a main effect of matching condition, $F(1, 29) = 28.829$, $p < .0001$. Participants produced faster responses as the SOA increased (120-ms SOA: M = 638 ms, SD = 117; 270-ms SOA: M = 575 ms, SD = 109; 400-ms SOA: M = 548 ms, SD = 105), which resulted in a main effect of SOA, $F(2, 58) = 192.883$, $p < .0001$. The two-way interaction was also significant, $F(2, 58) = 3.443$, $p < .04$. The advantage in RTs for matching over non-matching trials decreased as SOA increased (55 ms at the 120-ms SOA, 40 ms at the 270-ms SOA, and 36 ms at the 400-ms SOA). This pattern is consistent with those observed in the previous experiments.

More important for the purpose of the present experiment, a two-way repeated measures ANOVA was performed on mean correct RTs for non-matching trials only, with probe type (below product vs. neutral) and SOA (120, 270, and 400 ms) as factors. The main effect of probe type failed to reach significance $F(1, 29) = 1.731$, $p = .199$ (below product node: $M = 610$ ms, $SD = 119$; neutral probe: $M = 600$ ms, $SD = 127$; see Table 1). The main effect of SOA was significant, $F(2, 58) = 122.009$, $p < .0001$, whereas the two-way Probe Type × SOA interaction was not ($F < 1$; see Table 2). These results seem to show that below-product multiples related to the second operand of the initial pair are not activated automatically. However, before accepting the null hypothesis for the main effect of probe type, at least another possibility should be considered. It might well be that the SOAs that we employed were not long enough for the activation to spread along the multiplication network for the second operand. Another possibility is that the stimuli that we selected were, for unknown reasons, less than ideal for triggering an automatic activation.

Accuracy data

An ANOVA was conducted on percentage of correct responses, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors.

A significant main effect emerged for both matching condition, $F(1, 29) = 10.778$, $p < .004$, with participants showing a higher percentage of correct responses for matching ($M = 0.96$, $SD = 0.05$) than for non-matching ($M = 0.92$, $SD = 0.07$), and SOA, $F(2, 58) = 8.352$, $p < .002$, with participants responding more accurately as the SOA increased (120-ms SOA: $M = 0.92$, $SD = 0.07$; 270-ms SOA: $M = 0.95$, $SD = 0.06$; 400-ms SOA: $M = 0.95$, $SD = 0.05$). The two-way interaction was not significant.

A more important two-way repeated measures ANOVA was performed on percentage of correct responses for non-matching trials only, with probe type and SOA as factors. Crucially, the main effect of probe type was significant, $F(1, 29) = 9.910$, $p < .005$, with participants responding more accurately to neutral probes ($M = 0.97$, $SD = 0.07$) than to below-product nodes ($M = 0.94$, $SD = 0.07$; see Table 1). As in the previous experiments, the main effect of SOA was significant, $F(2, 58) = 8.519$, $p < .002$, testifying that participants became more accurate as SOA increased. The two-way interaction was not significant ($F < 1$).

Accuracy data showed that the probes being the node below the product of the two numbers in the digit pair were rejected less accurately than probes that were neutral with respect to the numbers in the digit pair. The presence of the interference effect in at least one of the two dependent variables of interest does speak in favour of an involuntary activation of arithmetic facts in the multiplication network. Moreover, it should be noticed that the non-significant RT difference was in the direction predicted by the interference effect. Thus, no evidence for speed–accuracy tradeoff emerged in the present experiment either.

EXPERIMENT 4

Experiment 4 was devoted to investigating whether probes that were the node above the product related to the second number of the initial pair were activated automatically. The same SOAs as those in the previous experiments were used.

Method

Participants

A total of 20 undergraduates (13 males and 7 females) from the University of Padua, all right-handed, volunteered to take part in this experiment. Their age ranged from 19 to 25 years. All participants had normal or corrected-to-normal vision, and were naive as to the purpose of the experiment. None had participated in the previous experiments.

Materials

A total of 11 new stimuli for each of the six probe conditions were created so that we had a list of 72 stimuli for each SOA (see Appendix D). Crucial stimuli were those items in the non-matching condition for which the probe was the node above the product related to the second number of the initial pair.

Apparatus, procedure, and design

The apparatus and procedure were exactly the same as those used in previous experiments. Each participant performed a single experimental session, which consisted of 216 trials.

Results and discussion

RT data

The application of the outliers-trimming algorithm resulted in the removal of approximately 2.2% of all observations. A two-way repeated measures ANOVA, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors, was performed on mean correct RTs. Participants responded faster to matching trials (M = 585 ms, SD = 107) than to non-matching trials (M = 618 ms, SD = 101), producing a main effect of matching condition, $F(1, 19) = 12.682$, $p < .003$. Participants were faster in responding as the SOA increased (120-ms SOA: M = 662 ms, SD = 101; 270-ms SOA: M = 588 ms, SD = 94; 400-ms SOA: M = 555 ms, SD = 92), which resulted in a main effect of SOA, $F(2, 38) = 256.914$, $p < .0001$. Also, the two-way interaction was significant, $F(2, 38) = 7.720$, $p < .003$, due to the fact that the advantage in RTs for matching over non-matching trials decreased as SOA increased (54 ms at the 120-ms SOA, 28 ms at the 270-ms SOA, and 19 ms at the 400-ms SOA). This pattern is the same as the one that had emerged in the previous experiments.

A second and more interesting two-way repeated measures ANOVA was performed on mean correct RTs for non-matching trials only, with probe type (above product vs. neutral) and SOA (120, 270, and 400 ms) as factors. The main effect of probe type was significant, $F(1, 19) = 12.157$, $p < .003$, with participants responding slower to above-product probes (M = 617 ms, SD = 110) than to neutral probes (M = 601 ms, SD = 107; see Table 1). This finding shows that above-product multiples related to the rightmost number in the digit cue were also activated. As in all the previous experiments, SOA yielded a significant effect, $F(2, 38) = 140.406$, $p < .0001$, whereas the two-way Probe Type × SOA interaction was not significant ($F < 1$).

Data showed that presentation of the digit pair caused above-product multiples of the second number in the cue to be automatically activated. As in previous experiments for other multiples, the pattern did not seem to vary as SOA increased (see Table 2), as shown by the lack of significance of the two-way interaction.

Accuracy data

An ANOVA was performed on percentage of correct responses, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors.

The main effect of matching condition was significant, $F(1, 19) = 13.011$, $p < .003$, with participants showing a higher percentage of correct responses for matching ($M = 0.97$, $SD = 0.04$) than for non-matching ($M = 0.94$, $SD = 0.06$). Neither the main effect of SOA, nor the two-way interaction was significant.

A two-way repeated measures ANOVA was performed on percentage of correct responses for non-matching trials only, with probe type and SOA as factors. The main effect of probe type was not significant ($F < 1$). The lack of significance might be the result of a ceiling effect. In fact, accuracy levels for both probes were very high (above product: $M = 0.98$, $SD = 0.05$; neutral: $M = 0.98$, $SD = 0.04$; see Table 1). The main effect of SOA was significant, $F(2, 38) = 4.208$, $p < .03$, with participants becoming more accurate as SOA increased. The two-way interaction was not significant ($F < 1$).

So far, we have interpreted our results as attributable to an involuntary activation of the multiples adjacent to the product of the digits present in the cue. This activation would be triggered by the mere presentation of the digits in the cue. However, because of the limited number of stimuli in the neutral and below/above product conditions, some subtle probe-specific factors, rather than the cue–probe relation, might have produced the pattern of results we observed. More specifically, two possible confounds might have occurred. First, magnitude of the probe was in most cases (see Appendices A, B, C, and D) smaller in the below/above-product condition than in the neutral condition. Thus, the interference effect we observed was perhaps due to this bias. In fact, the slower RTs for the above/below-product conditions might have resulted from the distance effect in number comparison, which was shown to occur even when numbers were to be physically compared (e.g., Dehaene & Akhavein, 1995). In the number-matching task, the mere presentation of numbers might have triggered an automatic magnitude-related comparison. Note that this alternative account, based on magnitude comparison, would shed some light on the lack of significance for the interaction between interference and SOA in all our experiments. A second possible confound might have originated from the fact that we did not control for the differences between the crucial probes (below/above-product and neutral) and the actual product of the numbers in the cue. Splits between a stated result and the correct answer are known to affect performance in arithmetic verification tasks (e.g., Ashcraft & Battaglia, 1978): Larger splits tend to yield faster RTs. That would perhaps account for the faster RTs observed for neutral probes compared to nodes adjacent to the product probes. In order to rule out these alternative accounts, we carried out two additional experiments, in which the effects of the magnitude comparison and of the split from the product were taken into consideration and kept to a minimum.

EXPERIMENT 5

In Experiment 5 we tried to replicate the results of Experiment 2 by avoiding the confounds possibly caused by the stimulus set used in the previous experiments. As in Experiment 2, we were interested in elucidating whether probes that were the node above the product of the first number of the initial pair were activated automatically. The same SOAs as those used in the previous experiments were employed.

Method

Participants

A total of 19 undergraduates (9 males and 10 females) from the University of Padua, all right-handed, volunteered to take part in this experiment. Their age ranged from 19 to 25 years. All participants had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. None had participated in the previous experiments.

Materials

A total of 7 new stimuli for each of the six probe conditions were created so that we had a list of 42 stimuli for each SOA (see Appendix E). Additional criteria were used to create the stimulus set, besides those used in the previous experiments. First, the average numerical magnitude of the above-product probes was always larger than the magnitude of the neutral probes. Under these conditions, if the advantage in performance observed for the neutral probes was caused by their magnitude, it should disappear in the present experiment and possibly reverse. Second, the split between the actual product of the numbers in the cue and the neutral probes was now always smaller than the split between the actual product and the above-product probes. Again, if the advantage in performance of the neutral probes was due to their larger split from the actual product, then such an effect should vanish in the present experiment and possibly reverse. Third, digit probes in the crucial conditions did not include 5 or multiples of 5, as 5-times problems are relatively easy compared to other problems (e.g., Campbell & Graham, 1985). Note that the presence of multiples of 5 in the previous experiments also might have affected the results, speeding up RTs in the neutral condition and thus apparently increasing the interference effect.

Because the criteria illustrated here are very strict, in order to have a reasonable number of stimuli we had to partially modify some of the criteria adopted in the previous experiments. First, we included also stimuli in which the single-digit numbers in the cues matched either number in the double-digit probes. Therefore two stimuli out of seven had partial matches between one of the numbers in the cue and the probe. However, this was true for every probe condition, with two partial matches for the above-product probes, two for the neutral probes, and two for the fillers (see Appendix E). Matching fillers were the same probes as those used for the non-matching neutral trials, so that the crucial probes (either above product or neutral) occurred in both the matching and non-matching conditions. Crucial stimuli in the present experiment were those items in the non-matching condition for which the probe was the node above the product related to the second number of the initial pair. As in previous experiments, we used neutral probes that in most cases were nodes belonging to multiplication tables different from those of the operands in the initial number pair. For each cue, neutral and above-product probes were congruent for parity. This means that if, for instance, the above product probe was an odd number, then the neutral probe was also an odd number. Finally, in contrast to previous experiments, the hash sign ("#") was used as fixation point and for masking the cue instead of the asterisk. This was done because in some mathematical contexts the asterisk is used as the multiplication sign. The presence of the asterisk as a fixation point might have activated multiplication, and this, in turn, might have caused a strategic component to be involved in the interference effect (note that Thibodeau et al., 1996, used the asterisk). Given that the lexicon for arithmetic facts, compared to word lexicon, consists of a considerably lower number of units, we did not have much choice for stimuli selection. Therefore, we believe that the stimuli that we employed in the present experiment and in Experiment 6 were the best controls possible respecting the constraints discussed earlier. That is, neutral probes were not divisible by either number in the cue, but belonged in most cases to some other multiplication table; their numerical magnitude was larger than the magnitude of the multiple probes; their split from the product of the numbers in the cue was smaller than the split of the multiple probes; and probes in the crucial trials (multiple and neutral) did not include either 5, multiples of five, or ties.

Apparatus, procedure, and design

They were the same as those in previous experiments. Each participant performed a single experimental session, consisting of three blocks of 126 trials each. Participants were clearly informed that there were possible partial matching stimuli and were instructed to respond "yes" only when the match was full.

Results and discussion

RT data

Approximately 3% of all observations were removed as a consequence of the application of the trimming procedure. A two-way repeated measures ANOVA, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as within-participants factors, was performed on mean correct RTs. Participants were faster in responding to matching trials (M = 560 ms, SD = 96) than to non-matching trials (M = 620 ms, SD = 105), as shown by a significant main effect of matching condition, $F(1, 18) = 36.175$, $p < .0001$. Participants produced faster responses as the SOA increased (120-ms SOA: M = 646 ms, SD = 91; 270-ms SOA: M = 576 ms, SD = 96; 400-ms SOA: M = 548 ms, SD = 104), which resulted in a main effect of SOA, $F(2, 36) = 195.777$, $p < .0001$. The two-way interaction was not significant ($F < 1$).

A two-way repeated measures ANOVA was performed on mean correct RTs for non-matching trials only, with probe type (above product vs. neutral) and SOA (120, 270, and 400 ms) as factors. The main effect of probe type failed to reach significance $F(1, 18) = 1.253$, $p = .28$ (above-product node: M = 625 ms, SD = 109; neutral probe: M = 619 ms, SD = 109). The main effect of SOA was significant, $F(2, 36) = 129.824$, $p < .0001$. Contrary to all previous experiments, the two-way Probe Type × SOA interaction was also significant, $F(2, 36) = 3.571$, $p < .04$. Pairwise comparisons (t tests) showed that there was a significant interference effect at the 120-ms SOA ($p < .02$), due to the fact that RTs were significantly slower in the above-product trials than in the neutral trials (see Table 2). The interference effect, however, was not significant ($F < 1$) at either the 270-ms SOA or the 400-ms SOA. These results show that above-product multiples related to the first operand of the initial pair were indeed automatically activated.

The alternative accounts stating that the results in the previous experiments were produced by a bias caused by the size of the split from the product and the average magnitude of the crucial probes can be reasonably discarded. In fact, in the present experiment we used probes that should have produced the opposite pattern. However, even if the main effect of probe type was not reliable, the interaction showed that RTs were significantly longer for the above-product trials than for the neutral trials, at least at the shortest SOA. That argues against the alternative accounts and is clear evidence that the above-product nodes were automatically activated by the mere presentation of the digit cue. The fact that the interference effect was not significant at the longer SOA shows that the effect tended to fade away when participants were given enough time before probe presentation, and it is in line with the study of Thibodeau et al. (1996).

Accuracy data

A first ANOVA was conducted on percentage of correct responses, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors.

The main effect of matching condition was not significant ($p = .182$), whereas SOA yielded a significant effect, $F(2, 36) = 6.599$, $p < .005$, with participants responding more accurately as SOA increased (120-ms SOA: $M = 0.93$, $SD = 0.06$; 270-ms SOA: $M = 0.95$, $SD = 0.06$; 400-ms SOA: $M = 0.95$, $SD = 0.07$). The two-way interaction was also significant, $F(2, 36) = 7.152$, $p < .003$, with participants being more accurate on matching trials, but only at the 120-ms SOA.

A second two-way repeated measures ANOVA was performed on percentage of correct responses for non-matching trials only, with probe type and SOA as factors. The main effect of probe type was not significant ($F < 1$). As in the previous experiments, the main effect of SOA was significant, $F(2, 36) = 9.605$, $p < .001$, showing that participants were more accurate as SOA increased. The two-way interaction was not significant ($F < 1$). No evidence for speed–accuracy tradeoff emerged in the present experiment.

EXPERIMENT 6

This experiment was aimed at replicating the results of Experiment 4 without the possible confounds mentioned earlier. As in Experiment 4, we were interested in investigating whether probes that were the node above the product related to the second number of the initial pair were automatically activated. The same SOAs as those in the previous experiments were used.

Method

Participants

A total of 20 undergraduates (12 males and 8 females) from the University of Padua, all right-handed, volunteered to take part in this experiment. Their age ranged from 19 to 26 years. All participants had normal or corrected-to-normal vision, and were naive as to the purpose of the experiment. None had participated in the previous experiments.

Materials

A total of 8 new stimuli for each of the six probe conditions were created so that we had a list of 48 stimuli for each SOA (see Appendix F). The criteria used for selecting stimuli were the same as those adopted in Experiment 5. Crucial stimuli were those items in the non-matching condition for which the probe was the node above the product related to the second number of the initial pair.

Apparatus, procedure, and design

The apparatus and procedure were exactly the same as those used in the previous experiments. Each participant performed a single experimental session, consisting of 288 trials.

Results and discussion

RT data

The application of the outliers-trimming algorithm resulted in the removal of approximately 2.8% of all observations. A two-way repeated measures ANOVA, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors, was performed on mean correct RTs. Participants responded faster to matching trials (M = 537 ms, SD = 79) than to non-matching trials (M = 601 ms, SD = 84), resulting in a main effect of matching condition, $F(1, 19) = 62.249$, $p < .0001$. Participants were faster in responding as the SOA increased (120-ms SOA: M = 629 ms, SD = 81; 270-ms SOA: M = 555 ms, SD = 75; 400-ms SOA: M = 522 ms, SD = 70), which resulted in a main effect of SOA, $F(2, 38) = 255.474$, $p < .0001$. The two-way interaction was not significant ($F < 1$).

A second two-way repeated measures ANOVA was performed on mean correct RTs for non-matching trials only, with probe type (above product vs. neutral) and SOA (120, 270, and 400 ms) as factors. The main effect of probe type was significant, $F(1, 19) = 9.948$, $p < .004$, with participants responding slower to above product probes (M = 608 ms; SD = 85) than to neutral probes (M = 594 ms, SD = 91; see Table 1). This finding confirms the results of Experiment 4, showing that above-product multiples related to the rightmost number in the cue were involuntary activated. Apparently, the magnitude of the probes and their split from the product did not play any important role in the previous experiments. SOA yielded a significant effect, $F(2, 38) = 137.991$, $p < .0001$, whereas the two-way interaction was not significant ($p = .329$). The lack of significance of the interaction shows that the interference effect did not vary in magnitude as a function of SOA (see Table 2). This finding is consistent with the pattern of results of Experiment 4. At least for the above-product node related to the second number in the cue; the lack of significance of the interaction was not due to the fact that the average magnitude and the split from the product of the probes were not balanced.

Accuracy data

An ANOVA was performed on percentage of correct responses, with matching condition (matching vs. non-matching) and SOA (120, 270, and 400 ms) as factors.

The main effect of matching condition was not significant ($p = .1$). SOA yielded a significant main effect, $F(2, 38) = 9.005$, $p < .002$, with participants being more accurate as the SOA increased. The two-way interaction was not significant ($F < 1$).

A two-way repeated measures ANOVA was performed on percentage of correct responses for non-matching trials only, with probe type and SOA as factors. The main effect of probe type was not significant ($F < 1$). The main effect of SOA was significant, $F(2, 38) = 5.375$, $p < .009$, with participants becoming more accurate as SOA increased (120-ms

SOA: $M = 0.91$, $SD = 0.08$; 270-ms SOA: $M = 0.94$, $SD = 0.09$; 400-ms SOA: $M = 0.95$, $SD = 0.07$). The two-way interaction was not significant ($F < 1$). As in the previous experiments, there was no evidence for speed–accuracy tradeoff.

GENERAL DISCUSSION

The experiments presented here demonstrated that, in adults, there was an automatic activation of multiples that were not relevant to the task. The number-matching paradigm devised by LeFevre and colleagues (1988) was used in all the experiments. The participants' task was to verify whether a probe number was present or not in a previously presented pair of numbers. This task does not require any arithmetic skill or knowledge, because it simply relies on numerical comprehension processes (Campbell, 1994). In contrast, other paradigms that were used to address automaticity in arithmetic, as indexed by cross-operation interference (e.g., Winkelman & Schmidt, 1974; Zbrodoff & Logan, 1986) or within-operation interference (e.g., Campbell, 1987, 1991; Koshmider & Ashcraft, 1991; Stazyk et al., 1982), are based on tasks in which participants are explicitly required to make use of arithmetic knowledge.

In the number-matching task, automatic activation of arithmetic is indexed by participants being slower in rejecting probes that have some arithmetic relation with the initial digit pair than in rejecting unrelated probes. This within-operation interference effect emerges from activation of both the sum (e.g., LeFevre & Kulak, 1994; LeFevre et al., 1988; Lemaire et al., 1994) and the product of the digit pair (e.g., Thibodeau et al., 1996). However, automatic activation of addition facts was questioned on the grounds that these results might be attributed to an automatically activated counting procedure, rather than to automatic access to addition facts in long-term memory (Baroody, 1994). Although there are arguments against this non-retrieval interpretation (see Thibodeau et al., 1996), it is clear that the same criticism does not hold for multiplication. This is because it would seem highly implausible that adults solve multiplication problems by means of a counting-on procedure similar to that postulated by Groen and Parkman (1972) for addition (also see Miller et al., 1984; Parkman, 1972).

Thibodeau et al. (1996) provided evidence that the product of the digit pair produces an interference effect that slows performance in the number-matching task. However, in their study, the multiplication sign was shown between the numbers in the cue. Although LeFevre et al. (1988) demonstrated that the presence of the operation sign is not necessary for activation to occur in the case of addition, one might claim that the presence of the sign renders the activation less "automatic".

The present experiments were devised to test the hypothesis that not only the product of the two digits is automatically activated upon presentation of the digit cue. In accord with the hypothesis, multiples corresponding to nodes adjacent to the product in the multiplication table of the first (Experiments 1 and 2) and second number (Experiments 3 and 4) of the digit cue also proved to be automatically activated. No multiplication symbol was presented between the two numbers in the cue, and thus a strategic component was unlikely to be involved in the interference effect. Moreover, selection of stimuli in the present experiments was based on stricter criteria than those in Thibodeau et al.'s (1996) study.

In order to exclude alternative accounts based on the way stimuli were selected, two additional experiments were conducted. The procedure of the previous experiments was exactly replicated, except that the stimuli were now selected so as to minimize any effects of numerical magnitude and of the split from the product. In fact, one might argue that the pattern of results that we interpreted as due to an automatic activation resulting in interference are attributable to the fact that, in the first experiments, neutral probes were often larger than below/above-product probes. That would have caused faster RTs to neutral probes simply because of a distance effect (see, e.g., Dehaene & Akhavein, 1995). In typical number-comparison tasks, participants are presented with two numbers and are requested to press one of two keys depending on whether the number on the left or right is the larger. The classic pattern of results is that RTs are an inverse function of the numerical difference between the two numbers. In the number-matching paradigm, this phenomenon would predict that RTs to the probe increase as the numerical distance between the numbers in the cue and the probe declines. Because our neutral probes were often larger than the below/above-product probes, the same pattern of results is predicted both by interference due to automatic activation of multiples and by numerical distance. The same pattern would also be predicted by an alternative account based on the split effect (e.g., Ashcraft & Battaglia, 1978). The split effect consists of the observation that in an arithmetic verification task RTs to false problems are faster if the incorrect answer is far from the correct one. Based on that, one might interpret the faster RTs to the neutral probe as the consequence of the fact that neutral probes in our experiments often had a larger split from the actual product of the cue digits than had the below/above-product probes. In order to prove that the distance effect and the split effect played no role in our experiments, Experiments 5 and 6 were performed, in which the influence of these effects on the data was reasonably minimized. This was achieved by selecting new stimuli for which both the numerical magnitude and the split between the product of the cue digits of the neutral probes was always smaller than the magnitude and the split of the crucial probes. As a result of these manipulations, if the alternative accounts really had an impact on our previous experiments, we should have now expected longer RTs for the neutral probes than for the crucial probes. Because of these criteria, we could only test the above-product condition. In fact, no neutral stimuli meet both constraints if the crucial probes are the nodes below the product. Results from the control experiments ruled out the alternative accounts and confirmed that both the nodes above the product related to either the first (Experiment 5) or the second (Experiment 6) number in the initial pair were involuntary activated. In fact, the pattern of results was consistent with that observed in the previous experiments and did not reverse as predicted by the alternative explanations based on the distance effect and the split effect. Because the effects of distance and split proved to be negligible in the control experiments investigating the nodes above the product, there is no reason to believe that they affected the data in the experiments examining the nodes below the product.

Critics may argue that the lack of the biphasic pattern in which automatic activation is present at short SOAs and disappears at long SOAs is difficult to reconcile with the claim that interference is an automatically triggered phenomenon (this criticism applies to all the experiments except Experiment 5). However, one must consider that the longest SOA used in our experiments (400 ms), is long enough for automatic activation to fade away only for addition facts (see LeFevre et al., 1988). In Thibodeau et al.'s (1996) study, the longest SOA was 350 ms, and still there was a (nonsignificant) difference in the direction predicted by the interference effect (13 ms), and the Probe Type × SOA interaction was only close to significance. In addition, the interference produced by the activation of nodes adjacent to the product may still be present at the 400-ms SOA, without disproving the automaticity of the effect. Neely

(1991) argued that semantic priming effects last for at least 400 ms. If one assumes that arithmetic processing is similar to language processing (see Ashcraft, 1992), then we should expect voluntary inhibition of automatically activated nodes to follow a similar time course as that in the verbal lexicon. Therefore, we would expect interference from adjacent nodes to disappear if SOAs longer than 400 ms are used. As we indicated earlier, the results of Experiment 5 differ from those of the other experiments for the Probe Type × SOA interaction. The reasons for this discrepancy are not clear. One possibility is that the distance effect and/or the split effect affected the time course of the pattern we observed. Perhaps the pattern observed in Experiment 2, with a consistent disadvantage in RTs for the above-product probes related to the first number of the initial pair, was in part due to the co-occurrence of interference with the effects of distance and split. The contribution of these last phenomena, however, is assumed to have been very small, considering that Experiments 5 and 6 showed that, unlike interference, the effects of distance and split were negligible. One may even speculate that the Probe Type × SOA interaction was not significant because of a difference in the time course of activation spreading from the first and the second number of the initial pair.

Our conclusion that the neighbour nodes of the product are also activated upon presentation of two digits fits well with the results of several other studies (e.g., Campbell, 1987; Campbell & Graham, 1985; Miller et al., 1984), which showed that most errors committed by adults performing multiplications in a production task are table related. In other words, adults reliably tend to produce answers that are multiples of the problems' operands. Very important, there seems to be a sort of distance effect, because adults tend to produce close neighbours of the product more often than far neighbours. A consistently similar pattern of results was obtained in neuropsychological patients (e.g., Cohen & Dehaene, 1994; McCloskey, 1992). Also, Stazyk et al. (1982) showed that participants performing a verification task on multiplication problems were slower in rejecting multiples of the correct solution than nonassociative lures (within-operation interference). This evidence converges in support of the view that multiplication facts are organized in a highly interrelated structure.

The results of the present study can be accounted for by two integrated models that were proposed in the cognitive arithmetic literature: Ashcraft's (1987, 1992) network retrieval model, and Campbell's (1994) network interference model. The network retrieval model assumes that each operand node is connected directly to the answer node for each problem involving that operand. According to Ashcraft's model, involuntary activation of the multiples adjacent to the product would result from a local spread of activation among operand nodes in a network where adjacent nodes are more strongly interlinked to the product than are more distant nodes. Therefore, activation in the network would spread from the product directly to the closest neighbours (adjacent nodes of both operands). The old version of the network retrieval model (i.e., the table-search model; Ashcraft & Battaglia, 1978) would not be able to account for our findings. In fact, this old model assumes that operand nodes are connected only indirectly to answer nodes, and that activation spreads from the operands to the product passing through all the intermediate nodes in the table. According to the table-search model, we should have expected a different pattern of activation for the below- and above-product nodes. More specifically, the model would predict activation to be present for the below-product nodes at short SOAs and then to dissipate, and to be present for the above-product nodes only at long SOAs. Our data seem to speak against these predictions. However, it must be noted that the model was abandoned because of its low explanatory power as regards to other important phenomena in cognitive arithmetic, such as the problem-size effect (Ashcraft, 1987).

Campbell's (1994) network interference model would also be able to account for our data because one of the central assumptions of the model is that each operand has stored links to many possible answers, correct and incorrect, the latter being mostly table related to both operands (e.g., Campbell & Graham, 1985). In the network postulated by Campbell, activation would spread from operands to the entire set of answers associated with them, thus including multiples from each operand. Among the multiples, the level of activation will be higher the closer neighbours are to the product, because of the stronger association resulting from past experience.

In conclusion, the results reported here are of particular relevance in that they show that the mere visual presentation of two numbers is able to activate the multiples adjacent to the product related to both numbers in the initial pair. Activation of adjacent nodes is automatic and stimulus driven because arithmetic is task irrelevant, and no operation sign is interposed between the numbers in the initial pair.

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APPENDIX A

Problem set used in Experiment 1

Non-matching stimuli	Below-product trials	Cue	3 5	4 9	6 9	7 6	8 3	9 8	7 3
		Probe	12	32	48	35	16	63	14
	Neutral trials	Cue	3 5	4 9	6 9	7 6	8 3	9 8	7 3
		Probe	28	38	58	45	26	52	25
	Fillers	Cue	43 7	64 3	27 5	5 78	8 13	2 75	9 68
		Probe	29	87	34	62	46	94	73
Matching stimuli	Probe-balancing trials	Cue	12 5	32 9	48 7	6 35	9 16	2 63	8 14
		Probe	3	32	48	35	16	63	14
	Cue-balancing trials	Cue	3 5	4 9	6 9	7 6	8 3	9 8	7 3
		Probe	3	9	9	7	8	8	3
	Fillers	Cue	56 3	69 5	78 6	9 86	2 48	4 93	7 38
		Probe	3	5	6	9	2	4	7

APPENDIX B

Problem set used in Experiment 2

Non-matching stimuli	Above-product trials	Cue	6 3	7 4	3 4	4 8	6 7	7 8
		Probe	24	35	15	36	48	63
	Neutral trials	Cue	6 3	7 4	3 4	4 8	6 7	7 8
		Probe	45	81	72	27	25	54
	Fillers	Cue	4 81	3 68	8 27	42 5	28 6	56 2
		Probe	57	29	34	61	43	73
Matching stimuli	Probe-balancing trials	Cue	24 5	35 9	15 6	7 36	4 63	3 48
		Probe	24	35	15	36	63	48
	Cue-balancing trials	Cue	6 3	7 4	3 4	4 8	6 7	7 8
		Probe	6	4	3	8	7	8
	Fillers	Cue	4 73	6 47	5 84	72 3	89 2	54 7
		Probe	4	6	5	3	2	7

APPENDIX C

Problem set used in Experiment 3

Non-matching stimuli	Below-product trials	Cue	5 2	8 2	6 3	9 2	6 4	8 3	9 3	4 9	5 7	9 4	6 7	5 9	8 6	9 7	8 9
		Probe	8	14	15	16	18	21	24	27	28	32	35	36	42	56	63
	Neutral trials	Cue	5 2	8 2	6 3	9 2	6 4	8 3	9 3	4 9	5 7	9 4	6 7	5 9	8 6	9 7	8 9
		Probe	9	39	72	65	38	54	52	58	34	25	81	64	49	62	26
	Fillers	Cue	2 75	2 47	3 87	4 31	6 57	8 46	19 7	43 9	51 7	37 4	61 2	79 4	93 6	74 3	86 5
		Probe	94	85	41	67	23	53	82	71	83	59	89	58	84	69	91
Matching stimuli	Probe-balancing trials	Cue	31 8	14 5	15 2	16 9	18 4	21 4	24 9	6 27	3 28	5 32	8 35	8 36	9 42	7 56	2 63
		Probe	8	14	15	16	18	21	24	27	28	32	35	36	42	56	63
	Cue-balancing trials	Cue	5 2	8 2	6 3	9 2	6 4	8 3	9 3	4 9	5 7	9 4	6 7	5 9	8 6	9 7	8 9
		Probe	2	2	6	9	4	8	3	9	5	4	6	5	8	7	9
	Fillers	Cue	2 75	2 47	3 87	4 31	6 57	8 46	19 7	43 9	51 7	37 4	61 2	79 4	93 6	74 3	86 5
		Probe	2	2	3	4	6	8	7	9	7	4	2	4	6	3	5

APPENDIX D

Problem set used in Experiment 4

Non-matching stimuli	Above-product trials	Cue	2 6	4 7	7 2	7 8	6 3	6 4	8 3	2 3	5 7	3 7	8 6
		Probe	18	35	16	64	21	28	27	9	42	28	54
	Neutral trials	Cue	2 6	4 7	7 2	7 8	6 3	6 4	8 3	2 3	5 7	3 7	8 6
		Probe	9	26	45	39	72	38	54	65	34	25	49
	Fillers	Cue	2 75	9 68	3 87	4 31	6 57	8 46	19 7	43 9	37 4	61 2	74 3
		Probe	94	73	41	67	23	53	82	71	59	89	69
Matching stimuli	Probe-balancing trials	Cue	7 18	4 35	5 16	3 64	6 21	9 28	27 8	9 15	42 5	28 3	54 8
		Probe	18	35	16	64	21	28	27	9	42	28	54
	Cue-balancing trials	Cue	2 6	4 7	7 2	7 8	6 3	6 4	8 3	2 3	5 7	3 7	8 6
		Probe	2	4	7	8	6	4	3	2	5	7	6
	Fillers	Cue	2 75	9 68	3 87	4 31	6 57	8 46	19 7	43 9	37 4	61 2	74 3
		Probe	2	68	3	31	6	46	19	9	37	2	3

APPENDIX E

Problem set used in Experiment 5

Non-matching stimuli	Above-product trials	Cue	3 6	6 8	7 8	7 3	9 3	6 3	8 6
		Probe	21	54	63	28	36[a]	24	56[a]
	Neutral trials	Cue	3 6	6 8	7 8	7 3	9 3	6 3	8 6
		Probe	19	52	61	26	34[a]	14	46[a]
	Fillers	Cue	7 51	8 42	3 62	37 9	68 2	53 4	48 3
		Probe	82	29[a]	79	86	31	72	73[a]
Matching stimuli	Probe-balancing trials	Cue	21 6	54 7	63 2	3 28	8 36	7 24	9 56
		Probe	21	54	63	28	36	24	56
	Cue-balancing trials	Cue	3 6	6 8	7 8	7 3	9 3	6 3	8 6
		Probe	6	6	8	3	9	3	8
	Fillers	Cue	19 4	52 9	61 2	8 26	6 34	3 14	7 46
		Probe	19	52	61	26	34	14	46

[a]Trials with partial matching between the cue and the probe (either in teens or in units).

APPENDIX F

Problem set used in Experiment 6

Non-matching stimuli	Below-product trials	Cue	3 7	6 3	8 6	8 7	3 6	3 9	7 6	8 8
		Probe	28	21	54	63	24	36[a]	48	56[a]
	Neutral trials	Cue	3 7	6 3	8 6	8 7	3 6	3 9	7 6	6 8
		Probe	26	19	52	61	14	34	38	46[a]
	Fillers	Cue	7 51	8 42	6 27	3 62	37 9	68 2	53 4	41 3
		Probe	82	29[a]	58	79	86	31	72	73[a]
Matching stimuli	Probe-balancing trials	Cue	28 6	21 9	54 7	63 2	7 24	8 36	3 48	9 56
		Probe	28	21	54	62	24	36	48	56
	Cue-balancing trials	Cue	3 7	6 3	8 6	8 7	3 6	3 9	7 6	6 8
		Probe	3	6	8	7	3	9	6	8
	Fillers	Cue	26 8	19 7	52 9	61 2	3 14	6 34	4 38	7 46
		Probe	26	19	52	61	14	34	38	46

[a]Trials with partial matching between the cue and the probe (either in teens or in units).