Conditional automaticity in retrieving multiplication facts: Evidence from Chinese*

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Abstract Adults automatically retrieve multiplication facts in a number matching task, in which participants judge whether the target number is one of the two cue digits presented previously. They are slower in rejecting the number which is the sum or the product of cues than a neutral number. The present study explored, with Chinese adult participants, whether such automaticity in retrieving multiplication facts can be affected by experiential and experimental factors such as learning experience and task set. We classified cue digits into two categories: small number first (the ascending order) and large number first (the descending order), according to whether the smaller or larger digit was presented on the left of the other. Experiment 1 found that product numbers were more difficult to reject than non-product numbers. Moreover, the order of cues played a role in modulating the magnitude of the interference effect, with ascending order conditions having larger interference than descending order conditions. Experiment 2 added a task-irrelevant addition or subtraction sign between the two cues and replicated the pattern of effects in Experiment 1, although the interference effects were significantly reduced. Experiment 3 instructed participants to judge whether the target number was the sum of the two cue digits. No interference effect was found for the target that was the product of cues. These findings suggest that the retrieval of multiplication facts, albeit automatic, can be influenced by learning experience (cue order effects in Experiments 1 & 2), the compatibility of the cuing context with the stored template information (reduced interference effects across Experiments 1 & 2), and task set (elimination of interference effects in Experiment 3). Retrieving multiplication facts is therefore conditionally automatic.

Keywords: automaticity, conditional automaticity, multiplication facts, number matching, interference effect.

Cognitive models of mental arithmetic[1-4] generally assume that in simple mental operations like single-digit addition and multiplication, people retrieve the arithmetic facts, i.e., the stored numerical representations, directly from long-term memory to solve problems such as addition $1+1=2$ and multiplication $3 \times 7 = 21$. Previous studies has provided evidence that these arithmetic facts can be retrieved obligatorily even when they are not required by the task[5-10]. However, there is no consensus on the extent to which these arithmetic facts, particularly multiplication, can be retrieved automatically, nor is it clear whether such automatic retrieval of multiplication facts can be accomplished upon a number of conditions, such as the availability of attentional resources and the contextual congruency with the stored template[11]. The main purpose of the present study is to investigate whether the automaticity in retrieving multiplication facts can be affected by experiential and experimental factors such as learning experience and task set, and to provide evidence for the conditional automaticity in mental processes by using a number matching task with Chinese adult participants.

The number matching task was initially developed by LeFevre et al.[6]. In the task, participants are presented horizontally with two cue digits (e.g., 3 and 7). After a short time delay, a third digit (e.g., 10 or 21) is presented as a probe and participants are asked to judge whether the third digit (the probe target) is one of the two cue numbers. The crucial manipulation is on the third number, which can be the sum or the product of the two cues or an unrelated or neutral number (e.g., 9 or 20). Interference effects for the sum or product numbers, compared with the matched neutral numbers, have been observed in several studies[6-8,12,13]. According to one view, the presentation of two cue digits activates their corresponding representations in an arithmetic network. This activation spreads automatically to associative number nodes, such as the sum or the multiplication product[2,5,14]. The associative activation in-

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terferes with the "no" judgment of the current matching task even though it is task-irrelevant. Thus the interference effect in the number matching task can be taken as an indication of the automaticity in retrieving arithmetic facts.

In many cases, the activation of arithmetic facts is so automatic that the interference effect occurs in the number matching task even when the operation sign is missing[5,6,11], when the target is a number word[6], when the probe target is a node adjacent to the product of the cue pair[5], or when participants are performing a working-memory consuming secondary task[11]. These findings fit the criteria of automaticity in mental processes, such as the obligatory activation[15,16], the intentionality and the capacity criteria[17]. There has been, however, evidence suggesting that this automaticity is conditional[18]. For instance, Rusconi et al.[11] found that when the cue numbers were presented at unusual locations relative to learning context (e.g., with one digit above and one below the fixation, rather than two digits on either the left or the right of the fixation), the interference effect for the product probe in number matching was greatly reduced or even eliminated. The authors suggested a contextual definition of automaticity for the retrieval of multiplication facts. According to the authors, during the process of automatization, people learn to encode location information along with numbers. This fixed spatial relation for operands constitutes part of the stored template information for multiplication facts. The environmental cues in presentation of the initial cue numbers would facilitate retrieval processes if congruent with the stored information. A change of the locations of cue numbers, however, leads to incongruence between the environmental cues and the stored template information, understanding memory retrieval.

To further explore the instances that the automaticity in retrieving multiplication facts can be influenced and to support the argument of conditional automaticity, in the present study we followed Rusconi et al.[11] and investigated two further conditions. The first condition is the matching between environmental triggering cues and the learning experience (learnt pattern) of such facts. Specifically we ask whether the two cue digits presented in the ascending or descending order, defined according to whether the smaller or larger digit is presented on the left of the other, play a role in retrieving multiplication facts. The triple-code model of number representation[19,20] explicitly assumes that multiplication facts are stored in memory with the verbal format learnt at school. Chinese school children and adults tend to learn the multiplication table[21,22] in the ascenting order, such as $4\times6=24$ rather than $6\times4=24$. When calculating 6×4, they employ a number-order reversion strategy before getting access to the long-term memory to retrieve the exact product of 4 and 6[23-26]. Such reversing strategy would probably increase the interference effect and the response time in the number matching task.

The second condition that may undermine the notion of automaticity in retrieving multiplication facts is task set. There have been abundant evidences showing one kind of mental arithmetic process (e.g. addition) can be impaired by another (e.g. multiplication facts retrieval) when people are only engaging one or switching between the two[10,11,27,28]. Winkelman and Schmidt's classic study[27] showed that when participants were performing a verification task with simple additions or multiplications, they were very slow in rejecting false equations whose results were correct for the other operations. This effect is usually called "associative confusion effect". Importantly, by using the verification task for problems, Zbrodoff and Logan[10] went further to demonstrate that the magnitude of this associative confusion effect can be modulated by the task set. The confusion effect was larger when multiplication and addition equations were mixed (i.e., participants switched between tasks) than only one type of arithmetic operation was task-relevant. Additionally, Rusconi et al.[11] also found that a secondary arithmetic task such as backward subtraction could reduce the confusion effect in the verification task, but not the interference effect in the number matching task. These studies together may imply that the automatic retrieval of multiplication facts could be eliminated, at least influenced, by another arithmetic process (e.g., addition).

Experiment 1 was conducted to replicate, with Chinese adult participants, the interference effect in the number matching task in the absence of multiplication signs. Moreover, this experiment would examine whether the order of cue digits, as a manipulation of the environmental cue, could modulate the interference effect. Given the learning experience in Chinese (learning problems in ascending order), we a priori hypothesized that the interference effects in descending order conditions would be smaller, if not be eliminated, than those in ascending order conditions. Experiment 2 was similar to Experiment 1, except that the task-irrelevant addition or subtraction sign was added between the two cue digits. Changing the cueing context in Experiment 1 by adding non-multiplication signs can lead to a mismatch with the stored template information (" + " or " − " instead of " × "). We investigated whether the incompatibility of the cueing context with the stored template information would be salient enough to affect the automatically retrieving process. In Experiment 3, participants were asked to judge whether the target number was the sum of the two cue digits. Addition was the explicit task set. Different from Rusconi et al.[11] and Winkelman and Schmidt[27], we used a number matching task setting for addition operation rather than verification setting. So the impact of task set on the automaticity of the activation of multiplication facts could be examined in the number matching setting. We hypothesized that different task sets can have a strong impact on the automatic retrieval of multiplication facts, leading to elimination of interference effects.

1 Experiment 1

Experiment 1 followed closely the designs in Galfano et al.[5] and Rusconi et al.[11] but divided the cue digits into two categories according to whether the smaller number appeared on the left or on the right in the horizontal presentation. Moreover, the time interval between the onset of the cue pair and the onset of the probe target (stimulus onset asynchrony or SOA) was manipulated. Previous studies[6,13] have shown that SOA is critical to automatic retrieval of arithmetic facts. The automatic activation of multiplication facts may interfere less with the current number matching task over time as a result of deactivation. The interference effect in the number matching task, as shown by a number of studies[5], disappears in a long SOA (>270 ms).

1.1 Method

1.1.1 Participant

Twenty students (10 male, 10 female) at Peking University, aged between 18 and 27 years, participated in the experiment. They were all right-handed, with normal or corrected-to-normal vision. All of them gave their informed consent to participate in the experiment although they were naïve to the exact purpose of the study. They were paid for their participation.

1.1.2 Design and materials

The trials in this experiment fell into two classes: matching conditions where the probe matched one of the cues and non-matching conditions where the probe matched neither of the cues. The non-matching conditions were consisted of three within-subject factors, with SOA (120 ms, 270 ms, and 400 ms), cue number order (ascending and descending), and probe type (product and neutral) forming a 3×2×2 factorial design. Participants were supposed to respond with "no" to probe targets in these conditions. To prevent participants from using response strategies based on whether both cue numbers were single-digit, filler cue pairs were created by replacing one single-digit number in a cue pair with a double-digit number (see Appendix 1). The selection of filler conditions followed the same principles for the non-filler ones (see below for details).

The matching conditions, which required "yes" responses to probe targets, were designed to balance responses, making half of them associated with "yes" and the other half "no". To prevent participants from using response strategies based on the occurrence of the cues and probes in the nonmatching conditions, these numbers were also used in the matching conditions. In the matching-ascending-cue-balancing condition and the matching-descending-cue-balance condition, the same cues used in the nonmatching-ascending or nonmatching-descending conditions were also used here. In the matching-probe-balancing conditions, one number of the cue pair and their product used in a nonmatching condition were used as cues. Filler conditions included cue pairs in which one cue was double-digit (see Appendix 1).

In selecting cue numbers and their products, the following restrictions were applied:

(1) Ties were excluded to avoid tie effect (response is faster to tied than non-tied operands).

(2) No numbers in cue pairs included digit 0 or 1, because they tend to elicit the retrieval of rules

rather than the retrieval of results. For instance, the product of 0 and N (any number) must be 0, whereas the product of 1 and N must be N.

(3) No probe number in a set of stimuli was the sum of the two cue numbers. This was to prevent the potential confounding of the product interference effect from the "associative confusions"[27].

(4) No digits were used twice in a set of stimuli in order to avoid partial matching between a cue and the target.

(5) A neutral probe, although it was not the product of the current cue pair, was the product of other two numbers (mostly two single-digit numbers).

(6) Neutral probes were close to the products of cue pairs in magnitude, such that half of the neutral targets were slightly larger than the products and another half were slightly smaller than the products. This restriction could prevent the contamination of data by the distance effect[29].

Each experimental condition contained 24 sets of stimuli, with the same set used twice (see Appendix). Over the three SOA conditions, the same set of stimuli was then presented six times to a participant. The selection of SOAs followed the parameters used in previous studies[5,6].

1.1.3 Procedure

Stimulus sets from different conditions were mixed and presented in random orders to participants. The sequence of events for each trial is shown in Fig. 1. On a screen of a monitor with refresh rate at 80 Hz per second, the stimuli appeared in white on the black background. Each trial began with a hash mark as the fixation sign at the center of the screen for 400 ms. A pair of digits (the cues) were then presented for 63 ms, with a distance of 3° of visual angle between them. The cue pair was then masked for 33 ms by a line of hash marks. After a variable ISI (23, 173, or 303 ms), which resulted in the SOA of 120 ms, 270 ms, or 400 ms, the probe number was presented and remained visible until the participant's response or until 2500 ms elapsed. A blank screen of 500 ms was presented before the beginning of the next trial. Participants were instructed to respond "yes" if the probe was the same as one of the cue numbers and to respond "no" if the probe was not in the cue pair. They were asked to respond as quickly and as accurately as possible by pressing the left or right key on a joystick with their left or right index finger. The assignment of "yes" or "no" response to the response hand was counterbalanced over participants.

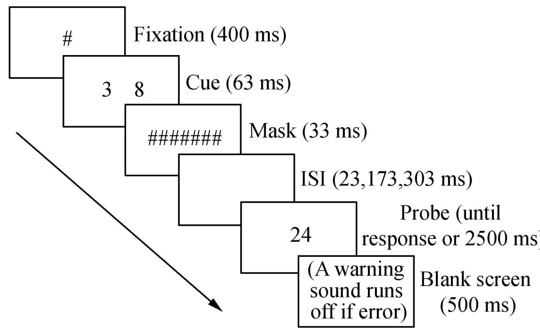

Fig. 1. Sequence of events on single trial in Experiment 1.

The Presentation software (http://nbs.neurobs.com/) was used to present stimuli and record responses. At the end of each trial, if a participant responded incorrectly or did not respond within 2500 ms, he/she would be given a 500-Hz tone, lasting 100 ms, as auditory feedback. Before the formal test, participants received 100 practice trials. The formal stimuli were divided into three blocks, with each block having 288 trials. For each participant, complete randomization for trials was conducted before the division of test blocks, with the restriction of no more than three consecutively presented trials requiring the same responses. Enough time was given to participants for rest between blocks.

1.2 Result

The accuracy of one participant in making judgments was unacceptably low (below 70%). His data was excluded from analyses. For the remaining data of 19 participants, the overall accuracy was 93.7%. RTs faster or slower than 2.5 standard deviations above or below the mean of each experimental condition were considered as outliers and were removed from data analyses. This resulted in the removal of approximately 2.2% of observations for all the 19 participants. Mean RTs for experimental conditions, together with the interference effects for the product probes, are listed in Table 1. Only data from nonmatching trials would be analyzed as the data from matching trials were irrelevant to our purpose. This principle was also applied to the following two experiments.

Table 1. Mean RTs (ms) and error percentages for non-matching trials in Experiments 1—3

Exp	SOA	Order	Product			Neutral			Interference	
			RT	SD	%Err	RT	SD	%Err	RT	%Err
1	120	Ascending	602	85	12.5	559	73	5.9	43	6.6
		Descending	590	94	14.5	568	82	6.4	22	8.1
	270	Ascending	527	84	5.9	504	82	2.6	23	3.3
		Descending	528	80	3.9	503	78	2.4	25	1.5
	400	Ascending	493	82	5.0	467	77	2.9	26	2.1
		Descending	496	108	7.5	481	97	3.5	15	4.0
2	120	Ascending	529	72	10.0	509	56	4.4	20	5.6
		Descending	537	71	8.7	524	84	4.6	13	4.1
	270	Ascending	471	61	6.5	446	66	2.9	25	3.6
		Descending	461	63	4.6	454	67	2.9	7	1.7
	400	Ascending	440	66	4.8	422	58	2.9	18	1.9
		Descending	435	70	5.6	420	57	3.1	15	2.5
3	150	Ascending	515	47	5.9	515	50	6.6	0	−0.5
		Descending	517	44	6.1	518	52	6.5	−1	−0.4
	300	Ascending	452	48	3.5	449	53	3.3	3	0.2
		Descending	445	41	3.9	440	50	4.4	5	−0.5

Analysis of variance (ANOVA) was carried out on RTs to non-matching trials, with cue number order (ascending vs. descending), probe type (product vs. neutral) and SOA (120 ms vs. 270 ms vs. 400 ms) as three within-participant factors. There was a main effect of SOA, $F(2,36)=173.38$, $p<0.001$, with responses to targets slowest at the shortest SOA (582 ms), fastest at the longest SOA (485 ms), and in the middle at the SOA of 270 ms (516 ms), indicating that responses were faster when more time for preparation was given. This was attributed to a preparation effect and we would not discuss this any further. The main effect of cue number order was not significant, $F(1,18)<1$. This indicated that participants generally made responses as quickly in ascending order conditions as in descending order conditions.

Importantly, the main effect of probe type was significant, $F(1,18)=62.24$, $p<0.001$, with responses slower to the product targets (541 ms) than to neutral targets (515 ms). There was a trend towards significance for the interaction between this effect and cue number order, $F(1,18)=3.57$, $0.05<p<0.1$. With a priori hypothesis, we considered this trend a significant effect, with the overall interference effect larger for the ascending trials (30 ms) than for the descending trials (22 ms). The two-way interaction between probe type and SOA was not significant, $F(2,36)=2.27$, $p>0.1$, indicating that the interference effect did not differ over three SOA, nor the three-way interaction between probe type, cue number order and SOA, $F(2,36)=1.16$, $p>0.1$. The interference effects for different cue number order and different SOA are shown in Fig. 2.

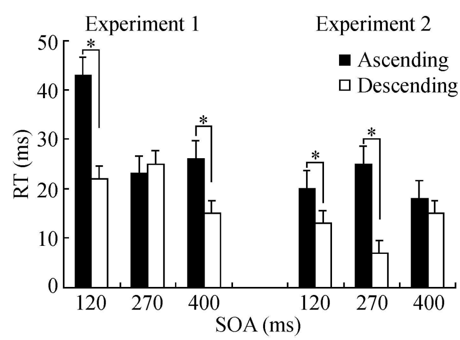

Fig. 2. Interference effect in Experiments 1 and 2.

Similar analyses were conducted for error percentages in non-match trials. The main effect of SOA was significant, $F(2,36)=15.05$, $p<0.001$, with participants responding with less errors as SOA increased (9.8%, 3.7%, and 4.7% respectively). The main effect of cue number order was not significant, $F(1,18)=1.00$, $p>0.1$, mirroring the findings in RTs. However, the main effect of probe type was significant, $F(1,18)=23.90$, $p<0.001$, indicating that participants made more errors when probes were the products of cues (8.2%) than when probes were unrelated to the cues (3.9%). No other effects reached significance.

1.3 Discussion

The main findings were that there were interference effects for the products of cue numbers in the number matching task; these interference effects appeared in all three SOA conditions tested and were larger when the cue numbers were in ascending order than in descending order.

The overall interference effects for the product numbers replicated previous studies[5,11] and provided evidence that even when two cue numbers are presented without a multiplication sign, the representation of their product is automatically activated, causing the interference. In addition, this activation can last a relatively long time as the interference effect appeared at the longest SOA tested. This is possible because the Chinese people take more excises of multiplication during learning[25]. Their higher numerical skills increase the automaticity in activating representations of product numbers, making them more resistant to decay over time.

An interesting pattern (cue order effect or operand order effect) was observed as interference effects were larger for ascending conditions than for descending conditions. This cue order effect is probably contingent upon learning experience, implying that the automaticity can be affected by experiential factors. When learning the multiplication table, the Chinese are taught to recite an operation in the ascending way. Naturally, the Chinese have more exposure to multiplication problems with smaller operand first. This learning experience may help to strengthen to a larger extent the automaticity in retrieving the product of two operands presented in ascending order than that for the descending one. However, problems with descending order numbers have also been practiced frequently enough to generate a strong, though less, automaticity in retrieving the product. The smaller but significant interference effects for descending order condition provided evidence for this. Our findings are in line with Siegler's distribution-of-association model[30], which claimed that variability in associative strength across problems arises from differences in presentation frequency (e.g., exposure frequency) and selection of procedures over the development of an arithmetic ability. In particular, the operands order effect is attributed to the stronger associations between solutions and operands in ascending order.

An alternative explanation for the reduced interference effect in descending order is that participants reverse the order of cue numbers[24,26,27] before the automatic retrieval of multiplication facts is accomplished. The reversing strategy is common for Chinese adults. For instance, LeFevre and Liu[27] asked Chinese participants to produce orally the product of two operands. They found that participants were slower in response when the operands were in descending order than in ascending order. Such order effect, however, did not appear in Canadian participants who had learnt a full multiplication table (in both orders). The reversing strategy is only taken when the order of operands entering into multiplication are incongruent with the learnt pattern of multiplication facts. Verguts and Fias[31] have recently developed a uniform connectionist model of retrieval in multiplication that takes the reversing strategy into account. They assume in the "semantic field" where connections of operands and products are represented, only half of all problems in multiplication are stored in memory, either with ascending-order-operands or descending-order-operands problems. Given such an organization, when a problem is presented in the reverse order, the operands are first reversed into a compatible order with those represented in the semantic field. This reversing operation takes some time[27], leading to prolonged RTs. Although little is known about how operands are mentally reversed, our findings support Verguts and Fias's model.

2 Experiment 2

In Experiment 2 we put non-multiplication operation (e.g., addition or subtraction) signs between the cue numbers. This manipulation was to examine whether the interference effects are affected when the environmental cues severely violate the stored template information. The addition or subtraction signs could induce other task-irrelevant cognitive processes, such as attentional distraction or addition facts retrieval. In the current study, we were not interested in what kind of mental processes were induced. The pivot of this manipulation was to investigate the extent to which the retrieval of multiplication facts is automatic. If the interference effects and cue order effects were again significant, it might provide evidence for the ubiquitous automaticity. But if such effects were reduced or eliminated, it might suggest that the automaticity in retrieving multiplication facts is conditional.

2.1 Method

2.1.1 Participant

Twenty students (6 male, 14 female) at Peking University, between 18 and 27 years old, were paid to participate in the experiment. All of these 20 volunteers were right handed and had normal or corrected-to-normal vision. They gave their informed consent to participate in the experiment but they were naïve to the exact purpose of the experiment.

2.1.2 Stimuli and procedure

The design, stimuli and procedure were similar to Experiment 1. There were, however, three important changes in the design and procedure. The first change was that an addition ("+") or subtraction sign ("−") was presented together with a cue pair. The addition sign was added between a cue pair in ascending order, whereas the subtraction sigh was put between the cue numbers in descending order. Participants were asked to ignore the arithmetic symbols (addition or subtraction signs) between the cues. The second and third changes were that the fixation sign was now a dot instead of a hash mark and that a 200 ms blank screen was inserted between the presentation of fixation and the presentation of the cue numbers. The purpose of these changes was to make the subsequently presented addition or subtraction sign at this location perceptually more salient and easier to identify.

2.2 Result

The overall accuracy of responses in Experiment 2 was 95.3%. RTs faster or slower than 2.5 standard deviations above or below the mean in each experimental condition were taken as outliers and were removed from the data before further analyses. This resulted in the removal of approximately 2.3% of observations over the 20 participants. Mean RTs, response error percentages and the interference effects are reported in Table 1.

ANOVA on RTs to non-matching trials was conducted, with SOA (120, 270, 400 ms), cue number order (ascending, descending) and probe type (product, neutral) as three within-participant factors. Participants responded more rapidly as SOA increased (525 ms, 457 ms and 429 ms respectively), producing a main effect of SOA, $F(2,38)=142.17$, $p<0.001$. The main effect of cue number order was not significant, $F(1,19)=1.03$, $p>0.1$. The interference effects for different cue number order and different SOA are shown in Fig. 2.

Importantly, the main effect of probe type was significant, $F(1,19)=37.28$, $p<0.001$, with responses slower to product targets (478 ms) than to neutral targets (462 ms). The two-way interaction between probe type and SOA was not significant, $F(2,38)<1$, nor the three-way interaction probe type, SOA and cue number order, $F(2,38)<1$, indicating that SOA had no effect on other factors. However, the two-way interaction between probe type and cue number order was significant, $F(1,19)=4.42$, $p<0.05$, indicating that, across SOAs, the interference effect for product probes was larger when cues were in ascending order (20 ms) than in descending order (11 ms). The latter effect was significant by itself in a further test, $F(1,19)=10.16$, $p<0.01$.

For error percentages, the main effect of SOA was significant, $F(1,19)=11.02$, $p<0.001$, with fewer error committed as the SOA increased (6.2%, 4.2% and 4.1% respectively). There was also a main effect of probe type, $F(1,19)=9.78$, $p<0.01$, with more errors committed on product targets (6.7%) than neutral targets (3.5%). No other effects or interactions reached significance.

To compare the pattern of interference effects in Experiments 1 and 2, a global analysis on RTs was conducted with the experiment as a between-subject factor, and SOA, cue number order and probe type as three within-subject factors. Importantly, we found a significant interaction between probe type and experiment, $F(1,38)=5.99$, $p<0.05$, suggesting that the overall interference effect in Experiment 1 (26 ms) was significantly larger than the effect in Experiment 2 (16 ms). The interaction between probe type and cue number order was significant, $F(1,38)=7.96$, $p<0.01$, whereas the three-way interaction between probe type, cue number, and experiment was not, $F(1,38)<1$. This suggested that across the two experiments, the interference effect was consistently larger when the cues were in ascending order (25 ms) than when they were in descending order (17 ms).

2.3 Discussion

Although the overall interference effects for product probes were reduced from 26 ms in Experiment 1 to the present 16 ms, the general pattern of these effects did not change. Similar interference effects and cue order effects were observed across Experiment 1 & 2. Interference effects were observed for stimuli with cue numbers in either ascending or descending order and across all SOAs. This suggested that the presentation of two cue numbers with non-multiplication operation signs in between still activated automatically the representation for their product even though the environmental triggering cues violated the learnt pattern of these facts. This automaticity was quite resilient since such manipulation of cueing context would perhaps induce other task-irrelevant competing processes such as distracting attention or simple addition/subtraction, interfering with the automatic retrieval of multiplication facts. The reduction of the interference effects in Experiment 2 may suggest that the automatic retrieval of multiplication facts was undermined to some extent by the manipulation of cueing context.

Across Experiments 1 and 2, we observed significant interference from automatic retrieval of multiplication facts. However, as the automaticity of this mental process can be affected by the experiential factors including the learning experience and the contextual compatibility with the stored template information, we propose that this automaticity is conditional.

3 Experiment 3

To investigate whether the automatic retrieval process can be influenced by task set, we introduced an explicit arithmetic task (simple addition) to Experiment 3 while preserving the task setting in the form of number matching. It has been reported that Chinese adults use retrieval strategy to solve simple addition problems[32]. By presenting probes as products of two operands, we investigated whether a secondary task-irrelevant arithmetic process, retrieval of multiplication facts, is automatically engaged to interfere with the primary one.

3.1 Method

3.1.1 Participant

Twenty students (5 male, 15 female) from Peking University participated in the experiment. They were not tested for Experiment 1 or 2 and were paid for their participation. They were right-handed, aging from 18 to 27. All participants had normal or corrected-to-normal vision and were naïve to the exact purpose of the experiment.

3.1.2 Stimuli and procedure

The critical stimuli associated with "no" responses in this experiment had three within-participant factors: SOA (150 ms, 300 ms), cue number order (ascending, descending), and probe type (product, neutral). Two SOAs were used in this experiment because we found that SOA did not participate in any interactions with the interference effects in the previous experiments.

For all the critical non-matching conditions, the probe was not the sum of the two previously presented cue numbers. The whole sets of stimuli are shown in Appendix 2. Principles used in Experiment 1 to constrain the selection of stimuli were also applied here except the third and the fourth. In addition, in each set of stimuli, the sum of the two cue numbers was smaller than their product by at least 5, but no more than 35. Both product probe and the matched neutral probe could be odd or even to prevent participants from using a strategy based on the odd-even rule (e.g. the sum of one odd and one even number must be odd). All the cue numbers used in the ascending order conditions were also used in the descending order conditions. Cue numbers for matching conditions were the same as used in the non-matching conditions.

Experimental procedures were similar to those in Experiment 2. The whole experiment had 640 trials, with the non-matching stimuli set repeatedly presented 4 times and the matching stimuli set 8 times. Trials from different conditions were randomly mixed and were divided into 4 blocks. Participants received 100 practice trials before the formal test.

3.2 Results

The overall accuracy of participants' responses was 98%. Error responses and outliers that were faster or slower than 2.5 standard deviations above the mean in each experimental condition were removed from the data before further analyses. The removed outliers took approximately 3% of observations for the 20 participants. Mean RTs and error percentages are reported in Table 1.

ANOVA on RTs to non-matching trials was conducted, with SOA (150 ms, 300 ms), cue number order (ascending, descending) and probe type (product, neutral) as three within-participant factors. Participants responded more speedily when SOA increased (517 ms vs. 447 ms), producing a main effect of SOA, $F(1,19) = 399.23$, $p < 0.001$. The main effect of cue number order was not significant, $F(1,19) < 1$.

Importantly, the main effect of probe type was not significant, $F(1,19) < 1$, indicating that there was no interference effect. Responses to product probes (482 ms) were as fast as responses to neutral probes (481 ms). The two-way interaction between probe type and SOA was significant, $F(1,19) = 5.15$, $p < 0.05$. It is clear from Table 1 that this interaction was mainly due to the slower responses (by 4 ms) to product probes than to neutral probes at the SOA of 300 ms. However, the effect at 300 ms did not reach significance by itself, $F(1,19) = 1.85$, $p > 0.1$. No other interactions reached significance.

For error rates, the main effect of SOA was significant, $F(1,19) = 11.74$, $p < 0.01$, with fewer error committed at the long SOA (6.3%) than at the short SOA (3.8%). No other effects or interactions reached significance.

3.3 Discussion

The interference effect, as indexed by slower RTs to product numbers than to neutral numbers, was eliminated in Experiment 3. This pattern was very different from what were obtained in the last two experiments. The primary task set, retrieval of addition facts, was not suffered from interference from the potential automatic retrieval of multiplication facts. The finding suggested that automatic retrieval of multiplication facts depends on the availability of cognitive resources, which had been used on the primary task. If true, it may be inconsistent with a traditional view on automaticity, assuming that the automatic process is free from the restrain of processing resources[15−17,33]. Rusconi et al.[11] found that interference effect from product probe in number matching was still observable even with a secondary task of random spatial tapping, backward subtraction, or articulatory suppression. Result in the present study went beyond Rusconi's data to suggest that the automaticity in retrieving multiplication facts can be eliminated when another arithmetic process becomes predominant. The task set can have a strong impact on the task-irrelevant automatic retrieval process.

Zbrodoff and Logan[11] asked participants to verify whether a given equation (e.g., $4 + 6 = 10$) could stand. A wrong solution to the present operation could be right for another, competing operation. For instance, in $4 + 6 = 24$, 24 was the correct solution for multiplication. The authors found that participants were slower to reject such wrong solutions. A conclusion drawn from this study could be that engaging one operation does not completely inhibit another automatic arithmetic process. The difference between Zbrodoff and Logan's paradigm and the present number matching paradigm is whether the "wrong" solution (e.g., 24) is explicitly given in the problem. Simultaneously presenting both operands and the "wrong solution" could lead to an associative confusion effect. A recent study by Rusconi et al.[9] proposed that cueing with the product could also activate the multiplication network and spread the activation backward to its two operands. In the number matching paradigm, if 21 was presented as a cue, the probes of 3 and 7 were more difficult to reject than 2 and 8. They suggested that there are bidirectional links and spread of activation in the network of multiplication facts. This might be an alternative explanation of why the verification task could lead to associative confusions and why this task was not a good candidate for investigating the influence of the task set. The number matching setting precludes the appearance of automatic retrieval of multiplication facts from confounding effects driven by associative confusions.

4 General discussion

A previous study[11] suggested that the automatic retrieval of arithmetic facts may be a conditional process. Following this argument, we asked the question when and to what extent this automatic process is conditional. The present study attempted to answer this question by investigating whether the interference effect from automatic retrieval of products in the number matching task can be modulated either by the experiential factors such as learning experience, or the experimental factors including cueing context and task set. In Experiment 1, we observed strong interference effects for both cue number order conditions across three SOAs. The magnitude of interference effect was larger when the cue numbers were in ascending order than in descending order. Experiment 2 replicated these findings when a task-irrelevant addition or subtraction sign was put between the two cue numbers. The magnitudes of interference effects for both ascending and descending order conditions were reduced compared with the effects in Experiment 1. When simple addition became a predominant task-relevant task in Experiment 3 where participants were asked to judge whether the probe target was the sum of the two cue numbers, there was no interference for the product probe. The impact of experimental manipulations on the pattern of interference effects across three experiments together contribute to a better understanding of how and to what extent the retrieving process of multiplication facts is automatic.

It is widely acknowledged that the automaticity of a cognitive process has the following characteristics[15—17,33]: (1) obligatory activation, even if it is task-irrelevant; (2) load insensitivity, requiring no processing resources; (3) intentionality, triggered by presentation of the relevant information and resistant to suppression or expectation. The interference effects in our findings demonstrated that the retrieval of multiplication facts can be obligatorily achieved when it is task-irrelevant (Experiments 1 & 2), when other cognitive processes that consume the attention resources are induced by the cuing environment (Experiment 2) and when the relevant information is presented as cues (Experiments 1 & 2). The task-irrelevant retrieval process suffices the criteria of automaticity.

However, our findings revealed that such automaticity is conditional, depending on experiential and experimental factors. We extended Rusiconi et al.'s arguments[11] by providing evidence that such automaticity implicated by the interference effect can be modulated by the learnt pattern (effects of the cue number order in Experiments 1 & 2), the contextual compatibility with the stored template information (reduced interference effect in Experiment 2) and the task set for another mental arithmetic process (elimination of interference effect in Experiment 3). Therefore, we suggest that the retrieval of task-irrelevant multiplication facts, albeit automatic, is conditional upon a wealth of conditions including learning experience and task set.

The conditions affecting the automaticity we investigated in the present study have not been envisaged by many models of multiplication arithmetic. The Table Search Model[32], the Network Retrieval Model[34], the Mathnet Model[14] and the Network Inference Model[3] provide no insight into why in our study there were differential interference effects for cue numbers with different horizontal orders. In contrast, the Distribution-of-Association Model[30] and the new Connectionist Model[31] could accommodate this cue number order effect. Siegler[30] claimed that associative strength between operands and their products is developed over time by different exposure frequency for each problem. The problems with more exposure frequency for Chinese adults (operands in ascending order, 3×7) should have stronger associative strength with their product (21) than do the problems with less exposure frequency (operands in descending order, 7×3). Verguts and Fias's model[31] proposed that multiplication facts are stored with only one half of the problems (i.e., $3\times7=21$ or $7\times3=21$), following the "commutative principle" that assumes 3×7 equals 7×3 in memory. When retrieving the other half of multiplication facts, a reversing strategy has to be employed, giving rise to delayed RTs. The cue number order effects in Experiments 1 & 2 provie evidence for the above two models. However, a general pitfall of these two models is that they have no assumption on how the automatic retrieving process emerges. Future studies of automatic processing in arithmetic facts retrieval are needed.

Appendix 1

Stimuli sets used in Experiments 1 and 2

Non-matching	Ascending order product	Cue	2 8	2 9	3 7	3 8	4 7	4 8	4 9	6 7	6 9	7 8	7 9	8 9
		Probe	16	18	21	24	28	32	36	42	54	56	63	72
	Ascending order neutral	Cue	2 8	2 9	3 7	3 8	4 7	4 8	4 9	6 7	6 9	7 8	7 9	8 9
		Probe	15	38	26	14	39	27	75	34	51	62	86	46
	Ascending order fillers	Cue	2 43	3 64	4 27	5 78	6 17	7 54	8 35	9 82	2 39	3 52	4 19	5 23
		Probe	78	29	65	23	52	36	47	13	64	49	83	17
	Descending order product	Cue	8 2	9 2	7 3	8 3	7 4	8 4	9 4	7 6	9 6	8 7	9 7	9 8
		Probe	16	18	21	24	28	32	36	42	54	56	63	72
	Descending order neutral	Cue	8 2	9 2	7 3	8 3	7 4	8 4	9 4	7 6	9 6	8 7	9 7	9 8
		Probe	15	38	26	14	39	27	75	34	51	62	86	46
	Descending order Fillers	Cue	59 2	46 3	38 4	61 5	43 6	19 7	26 8	62 9	75 2	87 3	21 4	32 5
		Probe	78	29	65	23	52	36	47	13	64	49	83	17
Matching	Ascending order cue balancing	Cue	2 8	2 9	3 7	3 8	4 7	4 8	4 9	6 7	6 9	7 8	7 9	8 9
		Probe	2	2	3	3	4	4	4	6	6	7	7	8
	Ascending order probe balancing	Cue	8 16	9 18	7 21	8 24	7 28	8 32	9 36	7 42	9 54	8 56	9 63	9 72
		Probe	16	18	21	24	28	32	36	42	54	56	63	72
	Ascending Fillers	Cue	2 75	3 21	4 87	6 32	5 38	5 26	7 19	9 43	2 61	3 62	4 59	5 46
		Probe	2	3	4	6	5	5	7	9	2	3	4	5
	Descending order cue balancing	Cue	8 2	9 2	7 3	8 3	7 4	8 4	9 4	7 6	9 6	8 7	9 7	9 8
		Probe	8	9	7	8	7	8	9	7	9	8	9	9
	Descending order probe balancing	Cue	16 2	18 2	21 3	24 3	28 4	32 4	36 4	42 6	54 6	56 7	63 7	72 8
		Probe	16	18	21	24	28	32	36	42	54	56	63	72
	Descending order fillers	Cue	64 2	19 3	52 4	39 6	82 5	35 6	54 8	17 5	78 2	27 3	23 6	43 5
		Probe	2	3	4	6	5	6	8	5	2	3	6	5

Appendix 2

Stimuli sets used in Experiment 3

Non-matching	Ascending	Product	2 7	2 8	2 9	3 4	3 5	3 6	3 7	3 8	3 9	4 5
			14	16	18	12	15	18	21	24	27	20
			4 6	4 7	4 8	4 9	5 6	5 7	5 8	5 9	6 7	6 8
			24	28	32	36	30	35	40	45	42	48
		Neutral	2 7	2 8	2 9	3 4	3 5	3 6	3 7	3 8	3 9	4 5
			12	18	14	16	11	14	25	26	17	23
			4 6	4 7	4 8	4 9	5 6	5 7	5 8	5 9	6 7	6 8
			18	20	38	22	38	39	25	53	28	52
	Descending	Product	7 2	8 2	9 2	4 3	5 3	6 3	7 3	8 3	9 3	5 4
			14	16	18	12	15	18	21	24	27	20
			6 4	7 4	8 4	9 4	6 5	7 5	8 5	9 5	7 6	8 6
			24	28	32	36	30	35	40	45	42	48
		Neutral	7 2	8 2	9 2	4 3	5 3	6 3	7 3	8 3	9 3	5 4
			12	18	14	16	11	14	25	26	17	23
			6 4	7 4	8 4	9 4	6 5	7 5	8 5	9 5	7 6	8 6
			18	20	38	22	38	39	25	53	28	52

To be continued

Continued

Matching	Ascending	Addition	2 7	2 8	2 9	3 4	3 5	3 6	3 7	3 8	3 9	4 5
			9	10	11	7	8	9	10	11	12	9
			4 6	4 7	4 8	4 9	5 6	5 7	5 8	5 9	6 7	6 8
			10	11	12	13	11	12	13	14	13	14
	Descending	Addition	7 2	8 2	9 2	4 3	5 3	6 3	7 3	8 3	9 3	5 4
			9	10	11	7	8	9	10	11	12	9
			6 4	7 4	8 4	9 4	6 5	7 5	8 5	9 5	7 6	8 6
			10	11	12	13	11	12	13	14	13	14

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