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No Influence of Masked Priming on the Multiplication Fact Retrieval in a Result Verification Task

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Supplementary Materials: Data, Materials [see Index of Supplementary Materials]

Abstract

In three experiments, we used a masked prime in a verification task to investigate the processing stages occurring during multiplication fact retrieval. We aimed to investigate the retrieval process by overlapping its execution with the processing of a masked prime consisting of a number. Participants evaluated the correctness of multiplication equations, where the result was preceded by a masked prime (presented for 30 ms, with different stimulus onset asynchrony between the operands and the prime). Decade consistency and relatedness of the prime were manipulated. For example, given the equation 4 x 7 = 28, the prime could be: a neighbor either decade consistent (24) or inconsistent (32), or an unrelated number either decade consistent (23) or inconsistent (31). We expected that the feature of the prime (relatedness or decade consistency) that generates interference depends on the processing stage reached when the prime is processed. Although Experiment 1 showed promising results, Experiments 2 and 3 suggest that the pattern found in Experiment 1 was a false positive. Overall, the paradigm used in this study (i.e., masked prime with a verification ask) does not seem to produce a stable interference during the retrieval process.

Keywords

decade consistency, multiplication fact retrieval, masked prime, interacting neighbors model

Multiplication facts are thought to be stored in a dedicated memory system (De Visscher & Noël, 2013; De Visscher, Noël, & De Smedt, 2016; Galfano et al., 2003, 2004, 2009; McCloskey, Harley, & Sokol, 1991; Niedeggen & Rösler, 1999), which is conceptualized as an associative network (see, for example, Campbell, 1995; Galfano et al., 2009; Verguts & Fias, 2005a). Evidence suggests that when a pair of operands is presented (e.g., 7 × 3), both the product (e.g., 21) and the neighbors (the set of results adjacent to the product; e.g., 14 and 28 for the operand 7, and 18 and 24 for the operand 3) are activated due to activation spreading within this associative network (Galfano et al., 2003, 2004, 2009; Niedeggen & Rösler, 1999). This activation spreading is assumed to drive the retrieval process, which terminates when one of the result nodes exceeds a decision threshold (if retrieval is successful then the product will have the highest activation level).

Multiplication fact retrieval has been implemented in the *interacting neighbors model* (Verguts & Fias, 2005a). Four main components characterize the model architecture: input field (representation of the operands), semantic field (representation of the arithmetic facts), decomposition field (representation of the decades and units of the products), and response field (holistic representation of the products). The processing stream proceeds through these main components from the input to the response field. In this manuscript, we will consider these components as sequential processing stages of the multiplication retrieval process.

The existence of a semantic stage is supported by the relatedness effect: close neighbors create more interference compared to unrelated numbers, even if the numerical distance is similar (Bahnmueller et al., 2020; Didino, Knops, Vespignani, & Kornpetpanee, 2015; Domahs et al., 2007; Niedeggen & Rösler, 1999). For example, given the operands 3 and 7, it is more difficult to reject the probe 24 (neighbor) compared to the probe 23 (unrelated number). During the semantic stage, the nodes coding the arithmetic facts are activated, either as phonological (Dehaene & Cohen, 1997) or abstract amodal representations (Whalen, McCloskey, Lindemann, & Bouton, 2002). When two operands are encoded, the activation level of the arithmetic fact nodes is a function of the association strength between these instances of the model. The stronger the association, the greater the activation level. For example, given the operands 3 and 7, the peak of activation is at the node *{3 × 7 = 21}*, but the neighbors (*{3 × 6 = 18}*, *{3 × 8 = 24}*, *{2 × 7 = 14}* and *{4 × 7 = 28}*) are also active, even though to a lesser extent.

The semantic nodes in turn spread activation to the decomposition field. Based on evidence suggesting that multi-symbol numbers are represented in a componential fashion (Bahnmueller, Nuerk, & Moeller, 2018; Huber, Nuerk, Willmes, & Moeller, 2016; Nuerk, Weger, & Willmes, 2001; Nuerk & Willmes, 2005; Verguts & De Moor, 2005; Wood, Nuerk, & Willmes, 2006), in the decomposition field results are componentially represented following the place-value structure of the Hindu–Arabic number system. Namely, decade and unit digits are represented by two separate fields. For example, given the operands 3 and 7, in the decomposition field the result 21 is represented by the co-activation of the node 2 in the decade field and the node 1 in the unit field. An important feature of the interacting neighbors model is that the neighbors can cooperate or compete with the product. Cooperation occurs when consistent neighbors activate the same decade or unit, whereas competition occurs when inconsistent neighbors activate a different decade or unit. Therefore, the retrieval process is facilitated by consistent neighbors and inhibited by inconsistent neighbors. For example, given the operands 3 and 7, the neighbor node *{4 × 7 = 28}* is decade consistent and thus cooperates with the product node *{3 × 7 = 21}* to activate the decade 2 (i.e., the decade digit of both 28 and 21, respectively); whereas the neighbor node *{2 × 7 = 14}* is decade inconsistent and thus competes with the product node by activating the decade 1 (i.e., the decade digit of 14).

The decade consistency effect is in line with the assumption that a componential representation underpins a core processing stage of multiplication fact retrieval. However, only few studies provided evidence that decade consistency can influence result production (Domahs, Delazer, & Nuerk, 2006; Verguts & Fias, 2005b), result verification (Bahnmueller et al., 2020; Domahs et al., 2007) or artificial arithmetic problems (Campbell et al., 2011). For example, Domahs and colleagues (2006) found that decade consistent errors (e.g., 7 × 4 = 21) were significantly more likely than decade inconsistent errors (e.g., 7 × 4 = 35). In an EEG study with a verification task, Domahs and colleagues (2007) used short and long stimulus onset asynchronies (SOAs) between operands and probe (i.e., the result to evaluate). Participants were slower to reject decade consistent probes compared to inconsistent ones and this consistency effect was stronger for the long SOA than for the short SOA. Moreover, probe consistency modulated the electrophysiological response (i.e., N400 effect) only in the long SOA condition. Domahs and colleagues' study also showed that the consistency effect arises later than the relatedness effect. In line with the architecture of the interacting neighbors model, this result suggests that the semantic stage precedes the activation of componential representations. Bahnmueller and colleagues (2020) also found a consistency effect (more errors with decade consistent probes than inconsistent ones) and an interaction between consistency and relatedness (decade consistency effect emerged only for neighbor probes). However, the consistency effect did not interact with SOA and was not significant in the response latency analysis.

To the best of our knowledge, no previous study used a masked prime to investigate the consistency effect. However, it has been shown that the relatedness of a visible prime can affect the retrieval process. In a result production task with a visible prime presented for 200 ms, Campbell (1991) found an interaction between prime type and problem difficulty. Faster reaction times (RTs) and a lower error rate (ER) were observed for a product prime (i.e., the prime was the product of the operands) compared with a neutral prime ("##"), and this advantage was larger for difficult than for easy problems. Moreover, neighbor primes produced more interference (slower RTs and a higher ER) than unrelated primes, and again this difference was greater for difficult problems (for a similar effect in a verification task see Ashcraft et al., 1992, as cited in Jackson & Coney, 2005). Within the framework of the interacting neighbor model, these results can be interpreted by assuming that neighbor primes provide additional activation to neighbor nodes at the semantic stage and thus the product node encounters more competition (a similar interpretation applies also to the network interference model, Campbell, 1995). Meagher and Campbell (1995) also found faster RTs for the product prime and slower RTs for neighbor and unrelated primes, compared to a neutral prime. However, the relatedness effect was modulated by the inter-stimulus interval (ISI) between prime and problem. In fact, while the interference from unrelated prime was constant, the interference from neighbor primes was largest for an ISI of 0 ms and decreased proportionally with increasing ISI. Moreover, neighbor primes were associated with longer RTs and higher ER compared to unrelated primes for the 0 ms ISI, but not for longer ISIs. This result is consistent with Domahs and colleagues' (2007) study, inasmuch as both suggest that the semantic stage (the one responsible for the relatedness effect) is activated very early in the retrieval process. The semantic relationship between a visible prime (multiplications presented for 100 ms) and a target number also affected number naming tasks. In fact, compared to a neutral condition (e.g., prime: "X × Y"), operand pairs facilitated the naming of the product (e.g., prime: "7 × 3", target: 21) and inhibited the naming of unrelated numbers (e.g., prime: "7 × 3", target: 48) (García-Orza, Damas-Lopez, Matas, & Rodriguez, 2009; Jackson & Coney, 2005, 2007a, 2007b).

In the current study, we used a masked prime in a verification task to investigate the processing stages occurring during multiplication fact retrieval. To the best of our knowledge, no other studies used this methodology to investigate the retrieval process. The advantage of this paradigm lies in the possibility to overlap the processing of a masked digit prime with the concurrent retrieval process without overtly interrupting the participant's stream of thought. We hypothesized that the interference of a prime on the retrieval process should depend on its relatedness (neighbor vs. unrelated prime) and on the decade consistency between prime and probe.

We conducted three experiments. Experiment 1 aimed to investigate whether a prime could interfere with the retrieval process. From its results we derived a model that describes the relationship between prime and retrieval process. The predictions of this model were then tested in Experiments 2 and 3. To evaluate these predictions, we varied the SOA between operands and prime. Experiments 2 and 3 also included a prime detection task to evaluate whether or not the prime was consciously perceived by the participants.

Experiment 1

In this experiment, the prime could be the product (identity prime), a pair of letters (neutral prime), a neighbor number, or an unrelated number that is either decade consistent or inconsistent with the product. Based on the interacting neighbors model (Verguts & Fias, 2005a) and on the findings reported above, we made the following predictions for an arithmetic verification task in which a masked prime precedes the presentation of the to-be-evaluated result. We will refer to *facilitation* when a condition elicits RTs faster than the neutral prime (i.e., letters) and to *interference* when RTs are slower. First, we expected a decade consistency effect. A decade consistent prime (i.e., prime and product share the decade) should facilitate the retrieval process by providing additional activation to the correct decade. On the other hand, a decade inconsistent prime (i.e., prime and product do not share the decade) should activate a competing decade that interferes with the retrieval of the product. Second, we also expected a relatedness effect. A neighbor prime should generate more interference compared to an unrelated prime. Only neighbor primes can activate nodes that are semantically related with the operands and thus interfere with the product retrieval. Moreover, since unrelated primes are not associated with any multiplication fact, the consistency effect could be weaker in these primes. Third, identity primes should facilitate the retrieval process by contributing to the activation of the product and/or to the encoding of the probe. Finally, we also evaluated how these effects were influenced by problem size (a very important variable in mental arithmetic, see Verguts & Fias, 2005a; Zbrodoff & Logan, 2005).

Method

Participants

Thirty German-speaking participants took part in the study. The data of two participants were excluded from the analysis for having poor accuracy in one block (42%) and slow response times (mean RTs = 1276 ms; sample mean RTs ranging from 447 to 871 ms), respectively. The participant selection procedure is reported in the Supplementary Materials. Therefore, we analyzed the data of twenty-eight participants (20 female, 7 male, 1 reported being not represented by these two categories; mean age (*SD*) = 25.1 (4.6), range = 19–32). All participants had normal or corrected-to-normal vision and gave informed consent to participate for course credits or 8€. The study was approved by the Ethics Committee at the Department of Psychology of Humboldt-Universität zu Berlin (Nr. 2019-42).

Stimuli and Design

Stimuli were the operand pairs from 3 × 3 to 8 × 8 (thirty-six multiplications). The operands 2 and 9 were excluded because their neighbor problems include 1 × N and 10 × N, respectively, which are probably solved by means of rules instead than by retrieval. Each operand pair was presented 16 times: 8 times in a correct equation (the probe was the product of the operands, e.g., 3 × 7 = 21) and 8 times with an incorrect equation (3 × 7 = 24). Therefore, the total number of trials was 576 (36 problems x 16 equations). The stimuli set is reported in the Appendix (Table A1).

Correct equation trials (e.g., 3 × 7 = 21) included six prime conditions: neutral (i.e., two letters), identity (e.g., 21), neigh-con (decade consistent neighbor; e.g., 24), neigh-inc (decade inconsistent neighbor; 18), unrel-con (decade consistent unrelated; 23) and unrel-inc (decade inconsistent unrelated; 19). Neutral primes consisted of two capital letters, which were randomly selected in each trial from a subset (A, E, F, H, K, M, N, R, U, W) created to have low visual similarity between Hindu-Arabic numbers and capital letter forms. To balance the correctness of the probe, for each operand pair, the identity and the neutral primes were presented twice each (i.e., 6 primes + 2 repetitions = 8 correct equations).

All neighbor and unrelated primes were also presented as a probe in incorrect equations: decade consistent neighbor (e.g., 3 × 7 = 24), decade inconsistent neighbor (3 × 7 = 18), decade consistent unrelated (3 × 7 = 23), decade inconsistent unrelated (3 × 7 = 19). Each incorrect equation was presented once with an identity prime and once with a neutral prime.

Analysis was performed only on correct equations in which an operand pair could have both a decade consistent and a decade inconsistent neighbor (see Table A1). The other operand pairs were considered as fillers and were presented so that all neighbor primes included in the analysis were also presented as probes in correct equations.

Procedure

Participants sat at about 60 cm from the monitor (refresh rate 100 Hz). Stimulus presentation and response collection were implemented in Matlab, using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). The experiment started with ten practice trials in which one of the operands was either 2 or 9. Stimuli were sequentially presented at the center of the monitor. Each trial started with a fixation point (‘‘#’’) presented for 1000 ms, followed by the first operand, the sign (‘‘X’’) and the second operand, presented for 300 ms each. The second operand was followed by a forward mask (“##”) for 170 ms, the prime for 30 ms, a backward mask (“##”) for 100 ms, and then the probe remained on the screen until the participant answered or for 2000 ms. This stimulus onset asynchrony (SOA_{170}) between the forward mask and the prime has been used as reference in Experiments 2 and 3 (see Table A3). The onset of all stimuli was synchronized with the refresh cycle of the screen. To reduce the visual physical overlap between prime and probe, the digits of the prime stimulus (1.6 cm high and 1.2 cm wide, visual angle 1.5° × 1.1°) were smaller than the other digits/symbols (3 cm high and 2.2 cm wide, visual angle 2.9° × 2.1°). In the experimental trials, if no key was pressed within the 2000 ms response window, a speed feedback asking for faster performance appeared on the screen. In the practice trials, both accuracy and speed feedback were provided. The duration of the intertrial interval was 1000 ms. Participants responded by pressing the “X” and “M” keys on the keyboard. The response key assignment to “correct” and “incorrect” was counterbalanced across participants. Participants were not informed of the prime and were asked to judge the correctness of the probe as fast and accurately as possible. The order in which problems and conditions were presented varied randomly for each participant. Participants performed 8 blocks (72 trials each) and could take short breaks between them. An experimental session lasted between 40 and 60 minutes (average duration: 50 minutes).

Results

Analysis was performed in R (R Core Team, 2021) and RStudio (RStudio Team, 2021), using the following open source packages: BayesFactor (Morey & Rouder, 2018), ggpubr (Kassambara, 2020), ggridges (Wilke, 2021), here (Müller, 2020), janitor (Firke, 2021), knitr (Xie, 2014, 2015, 2021), kableExtra (Zhu, 2021), plotly (Sievert, 2020), tidyverse (Wickham et al., 2019). The raincloud plots were generated with the code from Allen et al. (2021). Analyses were performed only on correct equation trials and non-filler trials (see Table A1).

Trials with incorrect (311 trials, 5.78%) or omitted responses (22 trials, 0.41%), RTs faster than 200 ms (1 trial, 0.02%), or wrong timing (1 trial, 0.02%, i.e., trials in which the onset of the stimulus on the screen was not correct) were excluded from the analysis. For each participant (only considering correct equation trials), trials with RTs more than 2.5 SD from the mean were considered outliers and excluded from the analysis (166 trials, 3.3%). Effect sizes are reported following the recommendation of Lakens (2013). The data and the R code used for the analysis are available at the Open Science Framework (see Supplementary Materials). For each participant, mean RTs were calculated across the factors prime and problem size. There were six prime conditions (neutral, identity, neigh-con, neigh-inc, unrel-con and unrel-inc) and two problem size conditions (small, product ≤ 30, and large, product > 30). The neutral prime was used as a baseline to test the effect of the other prime conditions, separately for small and large problems. Mean RTs are reported in Table 1 and Figure 1.

Table 1

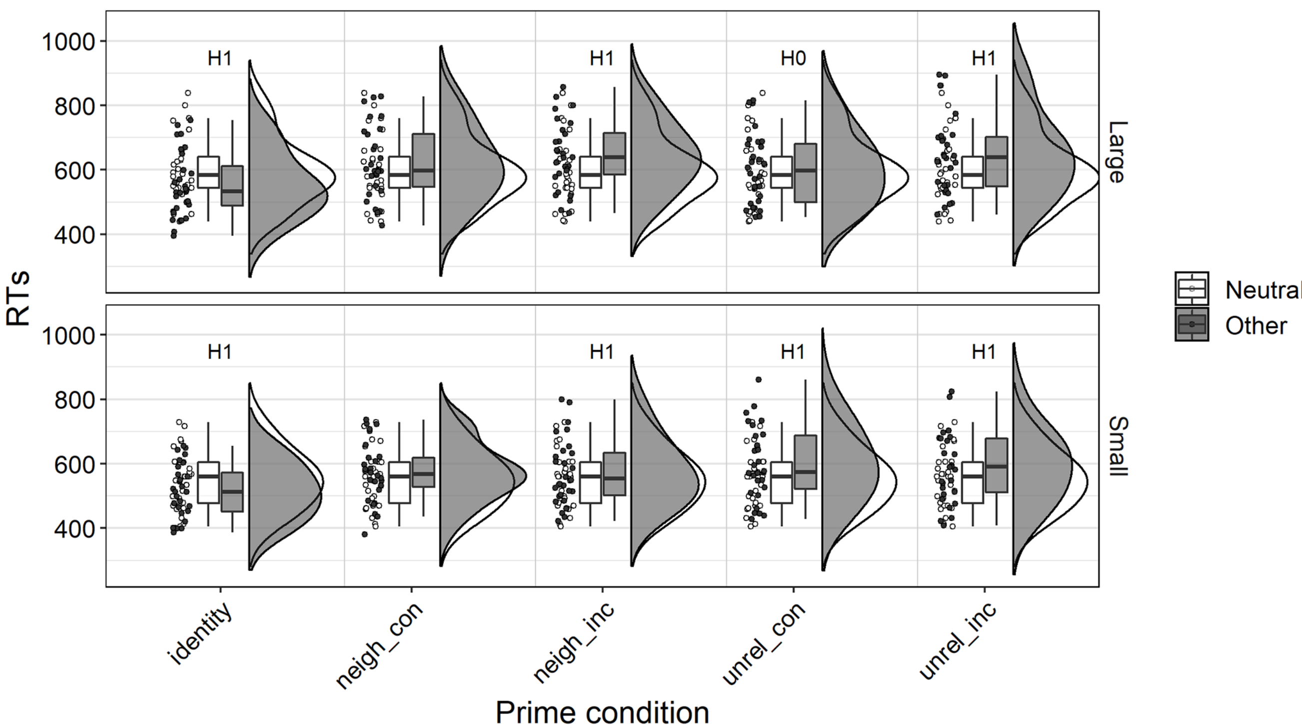
Mean RTs and Bayes Factors for Each Prime and Problem Size Combination

Problem size / Prime	*M*	*SD*	*SE*	Diff	BF_{10}	BF_{01}
Large						
identity	555	100	19	-43	129	0.01
neigh-con	622	113	21	25	2.93	0.34
neigh-inc	645	106	20	47	2388.08	< 0.01
neutral	597	106	20	–	–	–
unrel-con	603	110	21	5	0.23	4.43
unrel-inc	645	125	24	48	70.51	0.01
Small						
identity	513	84	16	-37	203.26	< 0.01
neigh-con	573	92	17	23	1.43	0.70
neigh-inc	575	103	19	24	5.03	0.20
neutral	551	88	17	–	–	–
unrel-con	600	114	22	50	334.14	< 0.01
unrel-inc	590	109	21	40	83.18	0.01

Note. SD = standard deviation; *SE* = standard error; Diff: difference between non-neutral primes and neutral prime; BF_{10}: evidence in favor of the alternative hypothesis; BF_{01}: evidence in favor of the null hypothesis.

Figure 1

RTs Distributions Across the Prime Conditions as a Function of Problem Size



Note. For each prime condition, RTs are presented as boxplot and raincloud plot (points represent participants RTs jittered along the x axis). Separately for small and large problems, the neutral prime condition is replicated next to the other conditions to facilitate the comparison. “H0” and “H1” indicate the conditions with B_{01} and B_{10} larger than 3, respectively. Neutral: neutral prime condition; Other: other prime conditions.

The effect of the prime was tested with Bayes factors (Table 1; see Supplementary Materials for frequentist analysis). For each non-neutral prime condition, we tested the null hypothesis that there was no difference compared to the neutral condition (H_0: $\delta = 0$). The alternative hypothesis was two-sided, H_1: $\delta \neq 0$. The prior distribution for δ was specified as a Cauchy distribution with scale r = 0.707. The Bayes factors were computed with the BayesFactor package (Morey & Rouder, 2018).

For small problems, we found strong evidence that unrelated primes (unrel-con and unrel-inc) produced interference, whereas there was moderate (neigh-inc) or inconclusive (neigh-con) evidence for the interference of neighbor primes. This pattern was interpreted as a reverse relatedness effect, inasmuch only unrelated primes produced strong interference. For large problems, we found strong evidence that decade inconsistent primes (neigh-inc and unrel-inc) produced interference, whereas decade consistent primes showed inconclusive evidence (neigh-con) or moderate evidence of a lack of interference (unrel-con). This pattern was interpreted as a decade consistency effect, inasmuch as only decade inconsistent primes produced strong interference. Identity primes showed the same pattern in both small and large problems and produced facilitation.

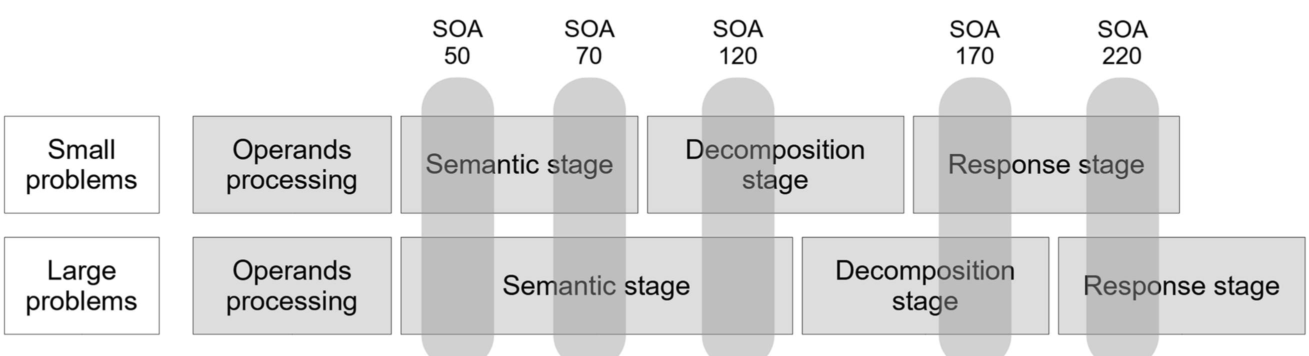
Conclusions

Experiment 1 aimed to evaluate whether a masked prime can be used to influence the retrieval process in mental multiplication. Overall, identity primes generated facilitation and the other primes generated interference (Figure 1 and Table 1). This result is in line with previous studies (Ashcraft et al., 1992; Campbell, 1991; García-Orza et al., 2009; Jackson & Coney, 2005, 2007a, 2007b; Meagher & Campbell, 1995). Unexpectedly, the effect of the prime was modulated by problem size. We observed a reverse relatedness effect in small problems and a decade consistency effect in large problems. We interpreted these results as suggesting that the effect of the prime is modulated by the temporal overlapping between the processing of the prime itself and the processing stage reached in the retrieval process.

To explain these results, we developed a theoretical framework (graphically summarized in Figure 2) that aimed to describe how a prime can affect the processing stages underlying the retrieval process. We assumed that the feature of the prime that generates interference depends on the processing stage reached when the prime processing starts. The processing stages are based on the interacting neighbors model (Verguts & Fias, 2005a) and are assumed to take place sequentially during the retrieval process. During the semantic stage, arithmetic facts are accessed and activated, and thus neighbor primes should generate more interference compared to unrelated primes (*relatedness effect*). During the decomposition stage, in which decades and units are represented in a componential fashion, decade inconsistent primes should create more interference compared to consistent ones (*consistency effect*). During the response stage, that is, when a number (i.e., the product if the retrieval process was successful) is available in working memory to perform task-related decisions, primes with a defined stimulus-response (S-R) mapping should generate more interference than primes without a defined link (*S-R association effect*). A defined S-R link emerges when there is a univocal relationship between a stimulus and a motor response (Abrams & Greenwald, 2000; Damian, 2001; Greenwald, Abrams, Naccache, & Dehaene, 2003; Kunde, Kiesel, & Hoffmann, 2003). In our experiment, stimuli used as unrelated prime (e.g., 23) were presented as a probe only in incorrect equations (e.g., 3 × 7 = 23). The univocal association between unrelated probe (23) and motor response (i.e., "incorrect" button press) could have created a direct mapping between them. Therefore, when presented as a prime, unrelated numbers could automatically trigger a motor response (i.e., "incorrect") because they had a defined (univocal) S-R link. On the contrary, neighbor primes (e.g., 24) were presented as a probe in both correct (e.g., 3 × 8 = 24) and incorrect equations (e.g., 3 × 7 = 24), and thus they were not associated with a univocal motor response and their S-R link was undefined.

Figure 2

A Prime Is Supposed to Affect Different Stages Depending on Problem Size (Small vs. Large) and SOA (Experiment 1: SOA_{170}; Experiment 2: SOA_{070}, SOA_{120}, SOA_{170}; Experiment 3: SOA_{050}, SOA_{170}, SOA_{220})



Note. The vertical bars indicate which processing stage (gray boxes) is affected by a prime with a specific SOA. The length of the boxes and the position of the vertical bars illustrate the conceptual framework and approximately describe the hypotheses on the temporal dynamic of the retrieval process.

Another aspect to take into account is that the retrieval process takes longer in large problems compared to small ones (Zbrodoff & Logan, 2005). Therefore, given a constant SOA between operands and prime, the prime processing overlaps with a later stage in small problems (faster retrieval) compared to large problems (slower retrieval). In other words, small and large problems are affected by different features of the prime.

In large problems, decade inconsistent primes generated interference while no effect emerged for decade consistent primes (Figure 1). This consistency effect can be explained by the overlapping between the prime processing and the decomposition stage. In fact, during this stage, the feature of the prime that creates interference should be decade consistency. Decade inconsistent primes should increase the activation of an incorrect decade representation during the decomposition stage and thus slow down the retrieval process.

In small problems, unrelated primes generated more interference than neighbor primes (Figure 1). Since this pattern is reversed compared to a standard relatedness effect (Bahnmueller et al., 2020; Campbell, 1991, 1995; Didino et al., 2015; Domahs et al., 2007; Meagher & Campbell, 1995; Niedeggen & Rösler, 1999; Verguts & Fias, 2005a), we interpreted it as an S-R association effect. In fact, following our hypothesis, in small problems, the prime processing occurred during the response stage. In our experiment, unrelated primes were presented as a probe only in incorrect equations (e.g., 6 × 8 = 41). Therefore, the response required by a correct equation (i.e., "correct") and that activated by the S-R link (i.e., "incorrect") of unrelated primes were inconsistent and produced longer RTs. Neighbor primes generated less interference because they did not have a defined S-R link.

The hypothesis that different effects emerge based on the overlapping between the prime processing and the processing stages of the retrieval process, can be evaluated by varying the onset of the prime. In Experiment 1, the SOA between prime and probe was constant. The following experiments will use different SOAs to test the predictions of our theoretical framework. How different SOAs are expected to influence the retrieval process is graphically presented in Figure 2. Since no previous studies used a masked prime in a verification task, no data was available to select the SOAs. The SOAs used in Experiments 2 and 3 aimed to explore how the interference of the prime changes as a function of the SOA. Therefore, our predictions only approximately described the hypotheses on the temporal dynamic of the retrieval process and we aimed to refine them empirically with the results of Experiments 2 and 3.

Experiment 2

Experiment 2 aimed to replicate the results obtained in Experiment 1 and to test our assumptions about the overlapping between the processing of the prime and the processing stages underlying the retrieval process. Three SOAs between the operands and the prime were included: SOA_{070}, SOA_{120}, and SOA_{170} (see Table A3). The predictions for these SOAs are graphically represented in Figure 2.

The prime processing should overlap with the semantic stage in the SOA_{070} condition for both small and large problems, and in the SOA_{120} condition for large problems. This should generate a relatedness effect (i.e., a neighbor prime should create more interference compared to an unrelated prime). The prime processing should overlap with the decomposition stage in the SOA_{120} condition for small problems. This should generate a consistency effect (i.e., a decade inconsistent prime should create more interference compared to a decade consistent prime). The SOA_{170} condition should generate the same effects found in Experiment 1. Namely, a consistency effect in large problems and an S-R association effect in small problems (more interference by an unrelated prime compared to a related prime).

A forced-choice prime detection task was also included to evaluate the visibility of the prime (e.g., García-Orza et al., 2009; Hesselmann, Darcy, Sterzer, & Knops, 2015; Naccache & Dehaene, 2001; Ratinckx, Brysbaert, & Fias, 2005).

Method

Participants

Thirty-four German-speaking participants took part in the study. The data of six participants were excluded from the analysis for having poor accuracy in one block (see Supplementary Materials). Therefore, we analyzed the data of twenty-eight participants (17 female, 11 male; mean age (*SD*) = 30.6 (6.2), range = 21–40). All participants had normal or corrected-to-normal vision and gave informed consent to participate for course credits or 8€. The study was approved by the Ethics Committee at the Department of Psychology of Humboldt-Universität zu Berlin (Nr. 2019-42)

Stimuli and Design

Since the use of three SOAs increased the number of trials, we re-designed the stimulus set to reduce the number of trials to the minimum. The new stimulus set is reported in the Appendix (Table A2). Fifteen operand pairs were presented 10 times in a correct equation (e.g., 3 × 7 = 21) and 10 times in an incorrect equation (e.g., 3 × 7 = 24).

Correct equation trials (e.g., 3 × 7 = 21) included five prime conditions: neutral (i.e., two letters; same letters as in Experiment 1), neigh-con (decade consistent neighbor; e.g., 24), neigh-inc (decade inconsistent neighbor; 18), unrel-con (decade consistent unrelated; 23) and unrel-inc (decade inconsistent unrelated; 19). Each prime condition was presented twice (i.e., 5 primes × 2 presentations = 10 correct equations).

All neighbors and unrelated primes were also presented as a probe in incorrect equations: decade consistent neighbor (e.g., 3 × 7 = 24), decade inconsistent neighbor (3 × 7 = 18), decade consistent unrelated (3 × 7 = 23), decade inconsistent unrelated (3 × 7 = 19). Each incorrect equation was presented once with an identity prime and once with a neutral prime. To balance the correctness of the probe, two additional incorrect equations (one with a neighbor probe and one with an unrelated probe) were randomly selected for each participant (i.e., [4 probes × 2 presentations] + 2 randomly selected = 10 incorrect equations). Therefore, the total number of non-filler stimuli was 300 (15 problems × [10 correct + 10 incorrect equations]). The numbers used as unrelated primes were presented as probes only in incorrect equations. Five filler problems were chosen to have all neighbor primes presented as probes in both correct and incorrect equations. For example, the filler equation 2 × 5 = 10 was chosen to have the number 10 associated with both response keys (i.e, "correct" in equation 2 × 5 = 10 and "incorrect" in equation 3 × 5 = 10). Each filler was presented both as a correct equation (e.g., 2 × 5 = 10) and as an incorrect equation (e.g., 2 × 5 = 12), and always with a neutral prime. There were in total ten filler stimuli (5 fillers × 2 presentations). The stimulus set (300 non-filler trials + 10 filler trials) was presented three times, once with each SOA. Therefore, the total number of trials was 930 (310 trials × 3 SOAs).

Procedure

Experiment 2 was identical to Experiment 1 with the following exceptions. In Experiment 2, we varied the SOA duration between the forward mask and the prime. Three SOAs were used: 70 ms (SOA_{070}), 120 ms (SOA_{120}), and 170 ms (SOA_{170}; used also in Experiment 1). Like in Experiment 1, in all SOAs, the sum of the duration of the forward mask, prime, and backward mask was 300 ms, and the prime was always presented for 30 ms (see Table A3 in the Appendix). The order in which conditions and SOAs were presented varied randomly for each participant. Participants performed 10 blocks (93 trials each) and could take short breaks between them. The experiment started with ten practice trials in which one of the operands was either 2 or 9. An experimental session lasted between 60 and 90 minutes (average duration: 70 minutes).

Forced-Choice Prime Detection Task

After the verification task, the participant was informed of the presence of the prime and asked to perform a forced-choice prime detection task. In this task, the participant was asked to classify the prime. The fifteen non-filler operand pairs used in the verification task were also used in the prime detection task (see Table A2). Each operand pair was presented with two probes (correct vs. incorrect equation), 2 primes (neutral vs. number), and 3 SOAs (SOA_{070}, SOA_{120}, and SOA_{170}). Incorrect probes and primes were selected at random independently for each participant from the same set used in the verification task. Therefore, the total number of trials was 180 (15 problems × 2 probes × 2 primes × 3 SOAs).

The procedure was the same as in the verification task, with the following exceptions. Participants had to evaluate whether the prime was a number or a letter. Participants responded by pressing the "X" and "M" keys of the keyboard. The response key assignment to "letter" and "number" was counterbalanced across participants. Participants were asked to respond as fast and accurately as possible. The order in which conditions and SOAs were presented varied randomly for each participant. Participants performed two blocks (90 trials each) and could take a short break between them.

Results

Result Verification Task

Analyses were performed only on correct equation trials and non-filler trials (see Table A2). Trials with incorrect (863 trials, 6.85%), omitted responses (49 trials, 0.39%), RTs faster than 200 ms (4 trials, 0.03%), or wrong timing (5 trials, 0.04%) were excluded from the analysis. For each participant (only considering correct equation trials), trials with RTs more than 2.5 *SD* from the mean were considered outliers and excluded from the analysis (391 trials, 3.3%). The data and the R code used for the analysis are available at the Open Science Framework (see Supplementary Materials).

For each participant, mean RTs were calculated across the factors prime (neutral, neigh-con, neigh-inc, unrel-con, and unrel-inc), problem size (small and large), and SOA (SOA_{070}, SOA_{170}, and SOA_{120}). The neutral prime was used as the baseline to test the effect of the other prime conditions, separately for each combination of problem size and SOA. Mean RTs are reported in Table 2 and Figure 3.

Table 2

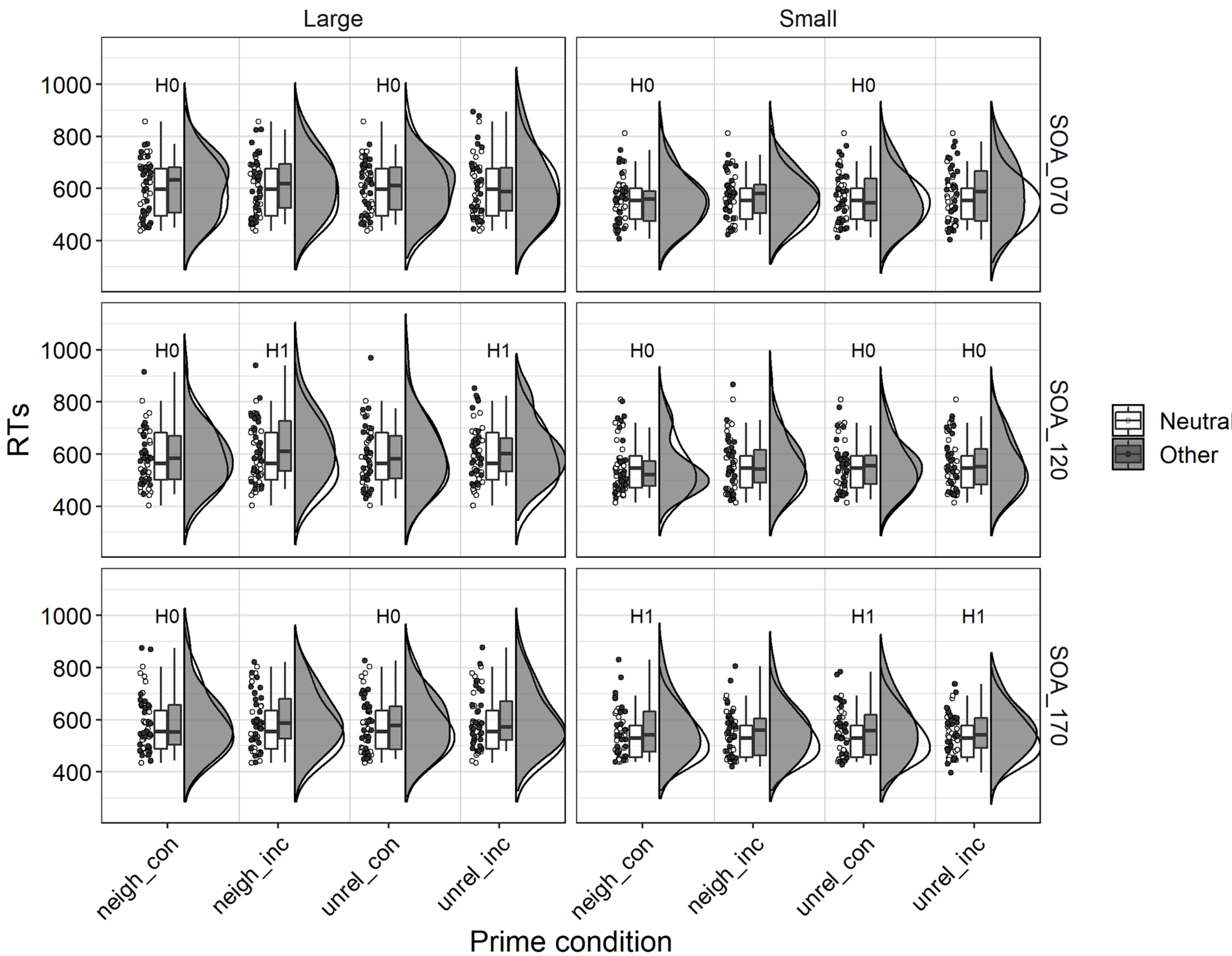
Mean RTs and Bayes Factors for Each Prime, Problem Size and SOA Combination

Problem size / Prime	*M*	*SD*	*SE*	Diff	BF_{10}	BF_{01}
SOA_{070}						
Large						
neigh-con	605	105	20	11	0.29	3.44
neigh-inc	618	111	21	23	0.98	1.02
neutral	594	107	20	–	–	–
unrel-con	600	92	17	5	0.23	4.31
unrel-inc	611	125	24	17	0.34	2.90
Small						
neigh-con	553	93	18	-1	0.20	4.93
neigh-inc	571	86	16	17	0.73	1.36
neutral	554	88	17	–	–	–
unrel-con	563	99	19	8	0.27	3.65
unrel-inc	578	112	21	24	1.03	0.97
SOA_{120}						
Large						
neigh-con	592	105	20	10	0.29	3.43
neigh-inc	630	119	22	48	191.02	0.01
neutral	582	108	20	–	–	–
unrel-con	595	126	24	13	0.36	2.79
unrel-inc	617	112	21	36	9.05	0.11
Small						
neigh-con	552	103	20	-2	0.20	4.89
neigh-inc	562	102	19	8	0.36	2.81
neutral	554	102	19	–	–	–
unrel-con	552	88	17	-2	0.20	4.91
unrel-inc	564	96	18	10	0.27	3.66
SOA_{170}						
Large						
neigh-con	589	110	21	13	0.28	3.57
neigh-inc	601	103	19	25	1.50	0.67
neutral	576	106	20	–	–	–
unrel-con	582	102	19	5	0.22	4.63
unrel-inc	605	108	20	29	1.73	0.58
Small						
neigh-con	562	101	19	32	10.72	0.09
neigh-inc	555	96	18	25	2.69	0.37
neutral	531	77	15	–	–	–
unrel-con	559	103	19	28	4.20	0.24
unrel-inc	556	87	17	25	5.60	0.18

Note. SD = standard deviation; *SE* = standard error; Diff = difference between non-neutral primes and neutral prime; BF_{10}: evidence in favor of the alternative hypothesis; BF_{01}: evidence in favor of the null hypothesis.

Figure 3

RTs Distributions Across the Prime Conditions as a Function of Problem Size and SOA



Note. For each prime condition, RTs are presented as boxplot and raincloud plot (points represent participants RTs jittered along the x axis). Separately for problem size and SOA, the neutral prime condition is replicated next to the other conditions to facilitate the comparison. “H0” and “H1” indicate the conditions with B_{01} and B_{10} larger than 3, respectively. Neutral: neutral prime condition; Other: other prime conditions.

The effect of the prime was tested with Bayes factors (Table 2; see Supplementary Materials for frequentist analysis). For each non-neutral prime condition, we tested the null hypothesis that there was no difference compared to the neutral condition (H_0: $\delta = 0$). The alternative hypothesis was two-sided, H_1: $\delta \neq 0$. The prior distribution for δ was specified as a Cauchy distribution with scale r = 0.707.

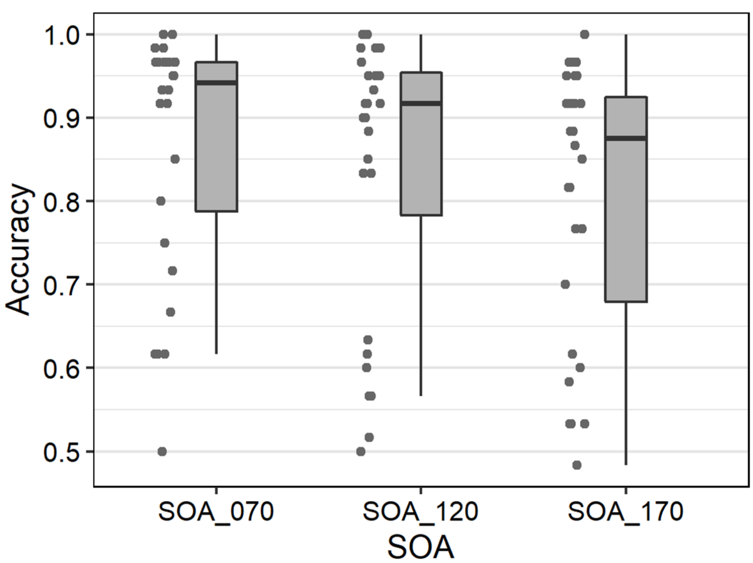
For SOA_{170} and small problems, we found moderate evidence for a generic priming effect independently of the prime condition. Except for decade inconsistent neighbor primes (neigh-inc), all other prime conditions produced interference. For SOA_{120} and large problems, we found moderate/strong evidence for a decade consistency effect. Decade inconsistent primes (neigh-inc and unrel-inc) produced interference, whereas decade consistent primes showed inconclusive evidence (unrel-con) or moderate evidence in favor of a lack of interference (neigh-con). The other prime, problem size, and SOA conditions showed inconclusive evidence for either H_1 or H_0, or evidence of a lack of interference.

Forced-Choice Prime Detection Task

There were 809 trials (16% of the total) with incorrect responses, 2 (0.04%) with omitted responses and 158 (3.13%) with RTs faster than 200 ms. For each participant, mean accuracy was calculated across SOA conditions (SOA_{070}, SOA_{120}, and SOA_{170}). Mean accuracies are reported in Figure 4. Accuracy was analyzed with Bayes factors. For each SOA condition, we considered the null hypothesis that the mean accuracy was 0.5 (H_0: $\delta = 0.5$), since a random classification of the prime as a letter or a number would lead to an accuracy of approximately 0.5. The alternative hypothesis was two-sided, H_1: $\delta \neq 0.5$. The prior distribution for δ was specified as a Cauchy distribution with scale r = 0.707. Mean accuracies were 0.87 (*SD* = 0.15) for SOA_{070}, 0.84 (*SD* = 0.17) for SOA_{120}, 0.81 (*SD* = 0.16) for SOA_{170}. For all SOA conditions, we found decisive evidence for H_1 (BF_{10} > 1000), showing that participants were able to reliably perform the task.

Figure 4

Accuracy Across the SOA Conditions



Note. Each data point represents a participant.

Conclusions

Experiment 2 aimed to replicate the results of Experiment 1 (SOA_{170}), to test the predictions for the other SOA conditions (SOA_{070} and SOA_{120}), and to evaluate the visibility of the prime. We expected a relatedness effect for SOA_{070} (both problem sizes) and for SOA_{120} in large problems, a consistency effect for SOA_{120} in small problems and for SOA_{170} in large problems, and an S-R association effect for SOA_{170} in small problems (Figure 2).

Results showed a consistency effect for SOA_{120} in large problems (only decade inconsistent primes generated interference) and a generic interference for SOA_{170} in small problems (except for the decade inconsistent neighbor prime, all other prime conditions generated interference). Therefore, these results do not provide evidence in favor of our theoretical framework and fail to replicate the results of Experiment 1. Overall the effect of the prime conditions does not show a clear pattern.

The results of the prime detection task clearly show that participants were able to perform this task. For all SOAs, the mean accuracy was above 80%. This indicates that the mask stimulus (i.e., "##") and the short duration (30 ms) were not sufficient to mask the prime. Since the prime detection task and the verification task shared the same trial structure, we can conclude that the prime may not have remained below the consciousness threshold in the verification task either. The lack of evidence in favor of our model could, at least partially, be attributed to the visibility of the prime. Therefore, in the following experiment, we modified the mask stimulus to reduce the visibility of the prime and further evaluate the proposed model.

Experiment 3

Experiment 3 aimed to replicate the results from Experiment 1 and to test our assumptions. Three SOAs were included: SOA_{050}, SOA_{170}, and SOA_{220} (see Table A3). The predictions for these SOAs are graphically represented in Figure 2. The prime processing should overlap with the semantic stage in the SOA_{050} condition for both small and large problems. This should generate a relatedness effect. The SOA_{170} condition should generate the same effects found in Experiment 1. Namely, a consistency effect in large problems and an S-R association effect in small problems. The prime processing should overlap with the response stage in the SOA_{220} condition for both small and large problems. This should generate an S-R association effect. This experiment also aimed to reduce the visibility of the prime by using a different mask stimulus (i.e., a sequence of four letters) and to evaluate how the new mask influences the effect of the prime.

Method

Participants

Thirty German-speaking participants took part in the study. The data of one participant was excluded from the analysis for having poor accuracy in one block (see Supplementary Materials). Therefore, we analyzed the data of twenty-nine participants (18 female, 11 male; mean age (*SD*) = 27.6 (6.3), range = 18–39). All participants had normal or corrected-to-normal vision and gave informed consent to participate for course credits or 8€. The study was approved by the Ethics Committee at the Department of Psychology of Humboldt-Universität zu Berlin (Nr. 2019-42)

Stimuli, Design, and Procedure

Experiment 3 used the same stimuli and design as Experiment 2 (see Table A2). The procedure was identical to Experiment 2 with the following exceptions. The SOA conditions were 50 ms (SOA_{050}), 170 ms (SOA_{170}; used also in Experiments 1 and 2), and 220 ms (SOA_{220}). The duration of forward mask, prime, and backward mask used in the three SOA conditions are reported in Table A3 in the Appendix. The forward and backward masks were a sequence of four letters. On each trial, four letters were randomly chosen from the same set used for the neutral prime, separately for the forward and backward masks.

Forced-Choice Prime Detection Task

The prime detection task was identical to Experiment 2 with the following exceptions. The SOA conditions were 50 ms (SOA_{050}), 170 ms (SOA_{170}), and 220 ms (SOA_{220}). The forward and backward masks were a sequence of four letters.

Results

Results Verification Task

Analyses were performed only on correct equation trials and non-filler trials (see Table A2). Trials with incorrect (728 trials, 5.58%), omitted responses (80 trials, 0.61%), RTs faster than 200 ms (11 trials, 0.08%), or wrong timing (3 trials, 0.02%) were excluded from the analysis. For each participant (only considering correct equation trials), trials with RTs more than 2.5 *SD* from the mean were considered outliers and excluded from the analysis (399 trials, 3.2%). The data and the R code used for the analysis are available at the Open Science Framework (see Supplementary Materials). For each participant, mean RTs were calculated across the factors prime (neutral, neigh-con, neigh-inc, unrel-con, and unrel-inc), problem size (small and large), and SOA (SOA_{050}, SOA_{170}, and SOA_{220}). The neutral prime was used as the baseline to test the effect of the other prime conditions, separately for each combination of the factors problem size and SOA. Mean RTs are reported in Table 3 and Figure 5.

Table 3

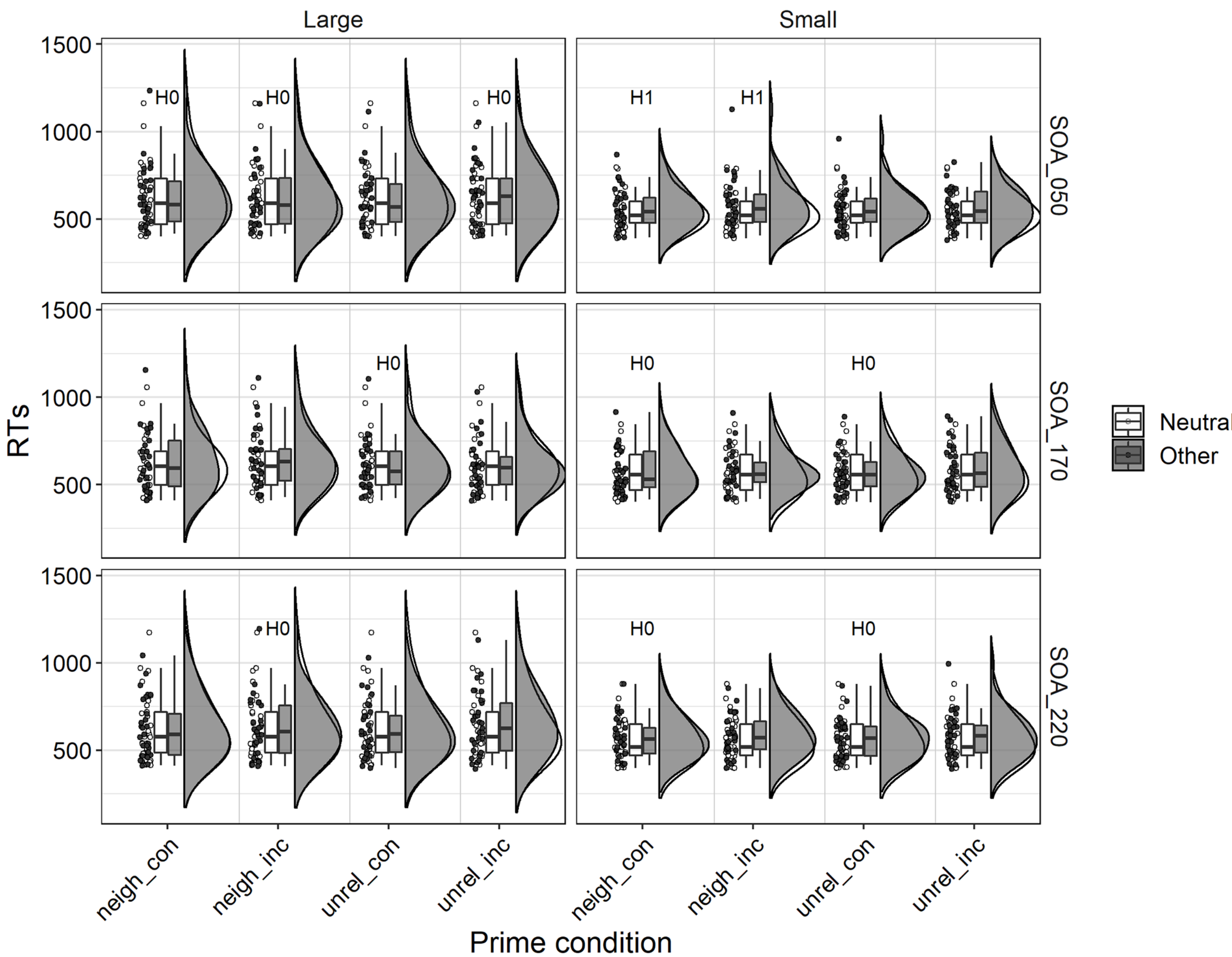
Mean RTs and Bayes Factors for Each Prime, Problem Size and SOA Combination

Problem size / Prime	*M*	*SD*	*SE*	Diff	BF_{10}	BF_{01}
			SOA_{050}			
Large						
neigh-con	623	176	33	-8	0.23	4.30
neigh-inc	616	174	32	-15	0.32	3.13
neutral	631	186	34	–	–	–
unrel-con	614	162	30	-16	0.38	2.62
unrel-inc	632	169	31	1	0.20	5.05
Small						
neigh-con	566	115	21	22	4.04	0.25
neigh-inc	590	152	28	46	8.35	0.12
neutral	544	106	20	–	–	–
unrel-con	556	120	22	12	0.35	2.89
unrel-inc	561	110	20	17	0.51	1.95
			SOA_{170}			
Large						
neigh-con	634	173	32	16	0.35	2.88
neigh-inc	644	165	31	26	2.56	0.39
neutral	618	155	29	–	–	–
unrel-con	606	145	27	-12	0.30	3.37
unrel-inc	600	143	27	-18	0.63	1.59
Small						
neigh-con	572	123	23	6	0.23	4.26
neigh-inc	576	116	21	10	0.38	2.64
neutral	566	122	23	–	–	–
unrel-con	565	110	20	-1	0.20	5.04
unrel-inc	590	136	25	24	0.77	1.30
			SOA_{220}			
Large						
neigh-con	620	169	31	-13	0.37	2.72
neigh-inc	625	173	32	-9	0.23	4.39
neutral	634	188	35	–	–	–
unrel-con	613	155	29	-20	0.52	1.91
unrel-inc	648	180	33	15	0.34	2.93
Small						
neigh-con	569	114	21	8	0.25	4.04
neigh-inc	586	117	22	26	1.13	0.89
neutral	560	125	23	–	–	–
unrel-con	566	110	20	6	0.25	4.02
unrel-inc	582	128	24	21	1.28	0.78

Note. SD = standard deviation; *SE* = standard error; Diff: difference between non-neutral primes and neutral prime; BF_{10}: evidence in favor of the alternative hypothesis; BF_{01}: evidence in favor of the null hypothesis.

Figure 5

RTs Distributions Across the Prime Conditions as a Function of Problem Size and SOA



Note. For each prime condition, RTs are presented as boxplot and raincloud plot (points represent participants RTs jittered along the x axis). Separately for problem size and SOA, the neutral prime condition is replicated next to the other conditions to facilitate the comparison. "H0" and "H1" indicate the conditions with B_{01} and B_{10} larger than 3, respectively. Neutral: neutral prime condition; Other: other prime conditions.

The effect of prime was tested with Bayes factors (Table 3; see Supplementary Materials for frequentist analysis). For each non-neutral prime condition, we tested the null hypothesis that there was no difference compared to the neutral condition (H_0: $\delta = 0$). The alternative hypothesis was two-sided, H_1: $\delta \neq 0$. The prior distribution for δ was specified as a Cauchy distribution with scale r = 0.707.

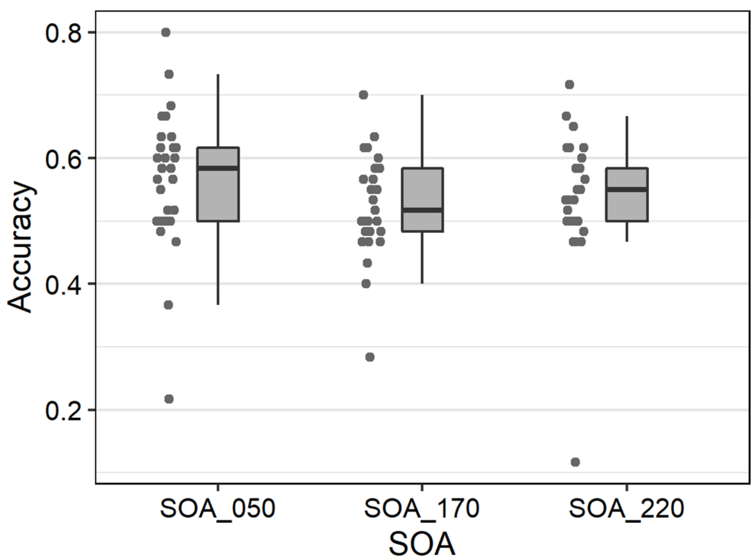
For SOA_{050} and small problems, we found moderate evidence for a relatedness effect. Neighbor primes (neigh-con and neigh-inc) produced interference, whereas unrelated primes (unrel-con and unrel-inc) showed inconclusive evidence. All the other conditions showed inconclusive evidence for either H_1 or H_0, or evidence of a lack of interference.

Forced-Choice Prime Detection Task

There were 2383 trials (45.7% of the total) with incorrect responses, 66 (1.3%) with omitted responses, 388 (7.4%) with RTs faster than 200 ms, and zero with wrong timing. For each participant, mean accuracy was calculated across conditions (SOA_{050}, SOA_{170}, and SOA_{220}). Mean accuracies are reported in Figure 6. Accuracy was analyzed with Bayes factors. For each SOA condition, we considered the null hypothesis that the mean accuracy was 0.5 (H_0: δ = 0.5). In fact, a random classification of the prime as a letter or a number would lead to an accuracy of 0.5. The alternative hypothesis was two-sided, H_1: δ ≠ 0.5. The prior distribution for δ was specified as a Cauchy distribution with scale r = 0.707. Mean accuracies were 0.56 (*SD* = 0.11) for SOA_{050}, 0.53 (*SD* = 0.08) for SOA_{170}, and 0.54 (*SD* = 0.1) for SOA_{220}. For SOA_{050}, we found moderate evidence for H_1 (BF_{10} = 10), showing that participants were able to perceive the prime. On the other hand, we found inconclusive evidence for either H_1 or H_0 for both SOA_{170} (BF_{10} = 0.7; BF_{01} = 1.4) and SOA_{220} (BF_{10} = 1).

Figure 6

Accuracy Across the SOA Conditions



Note. Each data point represents a participant.

Conclusions

Experiment 3 aimed to replicate the results of Experiment 1 (SOA_{170}), to test the predictions for the other SOA conditions (SOA_{050} and SOA_{220}), and to evaluate the visibility of the prime. We expected a relatedness effect for SOA_{050} (both problem sizes), a consistency effect for SOA_{170} in large problems, and an S-R association effect for SOA_{170} in small problems and for SOA_{220} in both problem sizes (Figure 2).

Results only showed a relatedness effect for SOA_{050} in small problems (only neighbor primes generated interference). No other prime condition generated interference and, in various conditions, there was evidence of a lack of interference (i.e., no difference to the neutral condition). Therefore, Experiment 3 also does not provide evidence in favor of our theoretical framework and failed to replicate the results of Experiment 1. Overall the effect of the prime condition does not reflect a clear interpretable pattern.

The results of the prime detection task show that many participants could perform the task also when the mask stimulus was a sequence of four letters. The visibility of the prime was reduced for SOA_{170} and SOA_{220}. However, many participants were still able to perform the prime detection task, suggesting that they could see the prime. The reduced visibility of the prime in SOA_{170} and SOA_{220} was associated with the absence of a priming effect. Therefore, the lack of effect cannot be ascribed to the prime visibility but rather to the fact that contrary to what we expected this paradigm cannot influence the retrieval process.

General Discussion

In this study, we conducted three experiments using a masked prime in a result verification task. We aimed to investigate whether the multiplication retrieval process could be affected by a prime. In line with previous studies (Ashcraft et al., 1992; Campbell, 1991; García-Orza et al., 2009; Jackson & Coney, 2005, 2007a, 2007b; Meagher & Campbell, 1995), an identity prime generated facilitation whereas the other primes generated interference in Experiment 1 (Figure 1). We found that decade inconsistent primes created more interference in large problems, whereas unrelated primes created more interference in small problems. These results were interpreted as evidence that the effect of a prime was modulated by the temporal overlapping between the processing of the prime itself and the processing stage reached in the retrieval process. Based on the interacting neighbors model (Verguts & Fias, 2005a), we developed a theoretical framework that aimed to explain the interaction between the prime and the processing stages (semantic stage, decomposition stage, and response stage). Experiments 2 and 3 tested this idea by varying the SOA between the operands and the prime. Figure 2 shows which processing stage was supposed to be affected by the various SOAs and problem sizes. Experiments 2 and 3 neither replicated the results of Experiment 1 nor provided support for our predictions. In Experiment 2, a consistency effect was observed for SOA_{120} in large problems (decade inconsistent primes produced interference), whereas a generic congruency effect was observed for SOA_{170} in small problems. In Experiment 3, a relatedness effect was observed for SOA_{050} in small problems (neighbor primes produced interference). Moreover, the results of the prime detection task in Experiments 2 and 3 suggest that participants were able to perceive the prime despite the masking and the short presentation time (30 ms).

Although Experiment 1 showed promising results, Experiments 2 and 3 suggest that the pattern found in Experiment 1 was a false positive. Overall, the paradigm used in this study (verification task with masked prime) does not seem to be able to reliably produce an interference during the retrieval process. In fact, the prime did not produce a stable interpretable pattern in the three experiments. A more parsimonious interpretation is that the results are probably false-positives. Moreover, the decade consistency effect can be explained by a pure peripheral interpretation. Namely, stronger interference can be expected by a decade inconsistent prime (compared to a decade consistent one) because the perceptual overlapping between the decade of the prime and the probe influence the encoding of the probe.

The fact that the prime did not generate any stable relatedness effect also suggests that the processing of the prime did not interfere with the retrieval process. In fact, a very large amount of evidence indicates that the retrieval process in multiplication is extremely sensitive to the relatedness factor, independent from the design, the procedure, or the stimuli used in an experiment (Bahnmueller et al., 2020; Campbell, 1991; Campbell, 1995; Didino et al., 2015; Domahs et al., 2007; Galfano et al., 2003, 2004, 2009; Meagher & Campbell, 1995; Niedeggen & Rösler, 1999; Verguts & Fias, 2005a). Therefore, one would expect the relatedness of the prime to affect the retrieval process. Previous studies reported a relatedness effect for visible primes (presented for 200 ms) and an interaction of this effect with problem size (e.g., Campbell, 1991; Meagher & Campbell, 1995). Domahs and colleagues (2007) showed that the relatedness effect temporally emerges before the decade consistency effect. In the interacting neighbors model, the processing stream also proceeds from the semantic stage to the decade competition stage (Verguts & Fias, 2005a). However, although we used various relatively short SOAs (SOA_{050}, SOA_{070}, and SOA_{120}) to elicit the relatedness effect, only the SOA_{050} in small problems produced a weak relatedness effect ($BF_{10} < 10$, see Table 3 and Figure 5). This weak evidence for a relatedness effect is not in line with the previous studies and further suggests that primes in the context of our paradigm cannot adequately influence the retrieval process.

The paradigm we implemented in this study aimed to use a masked prime to elicit unconscious processing. We aimed to test whether a prime can directly access the semantic representations of multiplication facts and influence the processing stages of the retrieval process. This could have allowed developing a new method to study how arithmetic knowledge is stored and retrieved. In our study, the prime was presented between forward and backward masks (two hashes "##" in Experiments 1 and 2, and four letters in Experiment 3) for a duration of 30 ms. This procedure was similar to that used in previous studies (e.g, Dehaene et al., 1998; Greenwald et al., 2003; Naccache & Dehaene, 2001; Reynvoet, Gevers, & Caessens, 2005) which aimed to investigate how numbers are represented and processed. Although four letters provided better masking compared to two hashes, the prime detection task suggests that the prime was consciously perceived. Various differences between our paradigm and the studies cited above could have increased the visibility of the prime in our experiments. For example, the prime was presented as an Arabic numeral (e.g., "24") rather than as a number world (e.g, "twenty-four"), trials consisted of a long sequence of stimuli (the elements of the equation were sequentially presented), and our task required to perform multiplications rather than evaluating parity or other semantic feature of a number. Changing these aspects could improve our paradigm and properly mask the prime. In our study, although the prime was irrelevant to the verification task (i.e., the correctness of the probe was not correlated with the prime condition), it could have been automatically processed. In fact, previous studies showed that a visible (task-irrelevant) prime can generate a relatedness effect (Campbell, 1991; Meagher and Campbell, 1995) and influence number naming (García-Orza et al., 2009; Jackson & Coney, 2005, 2007a, 2007b). Although the prime was not unconsciously processed, our model still predicts that its features (i.e., relatedness and decade consistency) should interfere with the retrieval process. Therefore, the lack of an interference from the prime on the retrieval process cannot be simply ascribed to the visibility of the prime. However, the visibility of the prime could have influenced the results differently. In the prime detection task, participants were asked to classify the prime as a letter or a number. Although the results indicate that participants could correctly identify the primes as numbers, this does not imply that they could also recognize *which* number was presented. Participants may have not been able to systematically identify the two-digit numbers. Namely, they could have been able to extract important perceptual features of the prime (e.g., one "close-circle" in 36), which would have allowed them to recognize the stimulus as a number, but still being unable to correctly assign these features (e.g., the "close-circle" feature is consistent with 36, 63, 39, etc.). This failed feature assignment may have led to the unsystematic pattern of results since the prime could not univocally activate the representation of a number and its features (relatedness and decade consistency).

Despite the lack of results, the current study provides some insights on how to investigate the retrieval process in multiplication. To the best of our knowledge, this is the first study using a masked prime in a verification task. We aimed to use unconscious processing as a tool to influence and thus to investigate the processing stages occurring during arithmetic fact retrieval. Being able to manipulate the features of a prime to generate interference on specific processing stages could have helped to disentangle how arithmetic facts are stored and retrieved. This study shows that this paradigm does not allow to influence the retrieval process and thus future studies should adopt a different strategy to investigate the retrieval process. This data can also be a useful starting point for future studies aiming to investigate mental arithmetic using a masked prime. In fact, this study indicates that the procedure we used (i.e., masking stimuli, prime duration, operands sequentially presented, etc.) is not effective, as in general, it provides an unstable and weak priming effect. Finally, since in the neutral condition the retrieval process is not affected by a digit prime, our data can be used in future studies for meta-analysis. All experiments and SOA conditions included a neutral prime (i.e., two letters), and about ninety participants took part in it. All raw data are included as Supplementary Materials.

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Acknowledgments: The authors have no support to report.

Competing Interests: André Knops is Editor-in-Chief of the *Journal of Numerical Cognition* but played no editorial role in this particular article or intervened in any form in the peer review process.

Data Availability: For this article, a data set is freely available (Didino, Brandtner, & Knops, 2021).

Supplementary Materials

The raw and processed data and the R code used for the analysis are freely accessible at the Open Science Framework (for access see Index of Supplementary Materials below).

Index of Supplementary Materials

Didino, D., Brandtner, M., & Knops, A. (2021). *Supplementary materials to "No influence of masked priming on the multiplication fact retrieval in a result verification task"* [Research data and code]. OSF. https://osf.io/4fvwe/

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Appendix

Table A1

List of Problems Used in Experiment 1

Operands	Product	Neighbor		Unrelated		Size
		Decade consistent	Decade inconsistent	Decade consistent	Decade inconsistent	
3 × 6	**18**	**15**	**21**	**14**	**22**	**Small**
3 × 7	**21**	**24**	**18**	**23**	**19**	**Small**
4 × 4	**16**	**12**	**20**	**13**	**22**	**Small**
4 × 5	**20**	**24**	**16**	**23**	**17**	**Small**
4 × 7	**28**	**24**	**32**	**23**	**31**	**Small**
4 × 8	**32**	**36**	**28**	**37**	**29**	**Large**
5 × 5	**25**	**20**	**30**	**22**	**31**	**Small**
5 × 6	**30**	**35**	**25**	**34**	**23**	**Small**
5 × 7	**35**	**30**	**40**	**31**	**41**	**Large**
5 × 8	**40**	**45**	**35**	**44**	**37**	**Large**
6 × 6	**36**	**30**	**42**	**31**	**41**	**Large**
6 × 7	**42**	**48**	**36**	**47**	**37**	**Large**
6 × 8	**48**	**42**	**54**	**41**	**53**	**Large**
7 × 7	**49**	**42**	**56**	**43**	**55**	**Large**
3 × 3	*9*	*6*	*12*	*7*	*11*	*Filler*
3 × 4	*12*	*15*	*9*	*17*	*7*	*Filler*
3 × 5	*15*	*12*	*18*	*13*	*19*	*Filler*
3 × 8	*24*	*21*	*27*	*22*	*26*	*Filler*
4 × 6	*24*	*20*	*28*	*22*	*29*	*Filler*
7 × 8	*56*	*49*	*63*	*47*	*62*	*Filler*
8 × 8	*64*	*56*	*72*	*57*	*71*	*Filler*
Mean value		30.5	32.4	30.4	32.7	
Mean difference		4.8	4.8	4.3	4.6	

Note. In correct equations, the probe was the product and the prime could be any of the neighbor and unrelated values, an identity prime (i.e., the product itself), or a neutral prime. In incorrect equations, the probe could be any of the neighbor and unrelated values and the prime could be an identity prime (i.e., the probe itself) or a neutral prime. In both correct and incorrect equations, capital letters (A, E, F, H, K, M, N, R, U, W) served as prime in the neutral prime condition. The analyses focused on the stimuli in bold (fillers were not analyzed). Mean value and mean difference (i.e., mean absolute difference between product and prime/proposed result) were calculated excluding the filler stimuli.

Table A2

List of Problems Used in Experiments 2 and 3

		Neighbor		Unrelated		
Operands	**Product**	**Decade consistent**	**Decade inconsistent**	**Decade consistent**	**Decade inconsistent**	**Size**
3 × 5	**15**	**10**	**20**	**11**	**23**	**Small**
3 × 6	**18**	**15**	**21**	**17**	**23**	**Small**
3 × 7	**21**	**24**	**18**	**23**	**19**	**Small**
4 × 4	**16**	**12**	**20**	**13**	**23**	**Small**
4 × 5	**20**	**24**	**16**	**23**	**17**	**Small**
4 × 7	**28**	**24**	**32**	**26**	**34**	**Small**
4 × 8	**32**	**36**	**28**	**37**	**29**	**Large**
5 × 5	**25**	**20**	**30**	**22**	**34**	**Small**
5 × 6	**30**	**36**	**24**	**38**	**22**	**Small**
5 × 7	**35**	**30**	**40**	**31**	**41**	**Large**
5 × 8	**40**	**48**	**32**	**47**	**33**	**Large**
6 × 6	**36**	**30**	**42**	**31**	**41**	**Large**
6 × 7	**42**	**48**	**36**	**47**	**37**	**Large**
6 × 8	**48**	**42**	**54**	**43**	**53**	**Large**
7 × 7	**49**	**42**	**56**	**46**	**52**	**Large**
2 × 5	*10*	*12*	-	-	-	*Filler*
3 × 4	*12*	*15*	-	-	-	*Filler*
3 × 8	*24*	*27*	-	-	-	*Filler*
6 × 9	*54*	*63*	-	-	-	*Filler*
7 × 8	*56*	*48*	-	-	-	*Filler*
Mean value		29.4	31.3	30.3	32.1	
Mean difference		5.1	5.1	4.0	5.5	

Note. In correct equations, the probe was the product and the prime could be any of the neighbor and unrelated values or a neutral prime. In incorrect equations, the probe could be any of the neighbor and unrelated values and the prime could be an identity prime (i.e., the probe itself) or a neutral prime. In both correct and incorrect equations, capital letters (A, E, F, H, K, M, N, R, U, W) served as prime in the neutral prime condition. In filler trials, the prime was always a neutral prime and the probe was the product or the decade-consistent neighbor value reported in the table. The analyses focused on the stimuli in bold (fillers were not analyzed). Mean value and mean difference (i.e., mean absolute difference between product and prime) were calculated excluding the filler stimuli.

Table A3

Procedure Used in the Experiments

	Stimuli duration																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Experiment 1																														
SOA_{170}									*FM (170)*										***prime***						*BM (100)*					
Experiment 2																														
SOA_{070}				*FM (70)*					***prime***											*BM (200)*										
SOA_{120}						*FM (120)*								***prime***									*BM (150)*							
SOA_{170}									*FM (170)*										***prime***						*BM (100)*					
Experiment 3																														
SOA_{050}			*FM (50)*				***prime***												*BM (220)*											
SOA_{170}									*FM (170)*										***prime***						*BM (100)*					
SOA_{220}											*FM (220)*													***prime***				*BM (50)*		

Note. The duration of the prime was always 30 ms. The total duration of forward mask (FM), prime, and backward mask (BM) was 300 ms. The numbers 1 to 30 are tens of milliseconds, and the numbers in parenthesis reflect the forward and backward masks duration in the various SOA conditions. The forward and backward masks were two hashes ("##") in Experiments 1 and 2; and four letters (from the same set used for the neutral prime, i.e., A, E, F, H, K, M, N, R, U, W) in Experiment 3.

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