Reading and doing arithmetic nonconsciously

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The modal view in the cognitive and neural sciences holds that consciousness is necessary for abstract, symbolic, and rule-following computations. Hence, semantic processing of multiple-word expressions, and performing of abstract mathematical computations, are widely believed to require consciousness. We report a series of experiments in which we show that multiple-word verbal expressions can be processed outside conscious awareness and that multistep, effortful arithmetic equations can be solved unconsciously. All experiments used Continuous Flash Suppression to render stimuli invisible for relatively long durations (up to 2,000 ms). Where appropriate, unawareness was verified using both objective and subjective measures. The results show that novel word combinations, in the form of expressions that contain semantic violations, become conscious before expressions that do not contain semantic violations, that the more negative a verbal expression is, the more quickly it becomes conscious, and that subliminal arithmetic equations prime their results. These findings call for a significant update of our view of conscious and unconscious processes.

nonconscious processes | automaticity | CFS

The scientific investigation of consciousness and the human unconscious is an ongoing interdisciplinary effort that is central to our understanding of the human mind. The goal is simple: to map the functions performed by nonconscious processes and the functions that are performed consciously, and to understand how these two sets of functions are implemented in the brain. The modal view in cognitive sciences associates consciousness with capabilities that are uniquely (or largely) human. Two prime examples of capabilities of this kind, which are cataloged among the greatest achievements of human culture, are complex language and abstract mathematics. It is not surprising then that the modal view holds that the semantic processing of multiple-word expressions and performing of abstract mathematical computations require consciousness (1–4). In more general terms, sequential rule-following manipulations of abstract symbols are thought to lie outside the capabilities of the human unconscious.

This view has received extensive empirical support. Although numerous studies have documented processing of subliminally presented single units of meaning (e.g., a word or a number) (5–8) as well as unconscious retrieval of simple arithmetic facts (9–11), previous research has generally failed to document unconscious performance of functions that require multiple (and sequenced) rule-based operations on more than one abstract unit (12–14). [Recently, work by Ric and Muller (10) has shown that simple addition (adding two numbers with a sum that is not greater than six) can occur nonconsciously. Although addition of this sort does not require more than one operation, we find these data very encouraging in terms of the challenge that we propose here.]

The present study challenges this modal view of consciousness and the unconscious. Specifically, we argue that people can semantically process multiple-word expressions and that they can perform effortful arithmetic computations outside of conscious awareness. In all of our experiments, we use Continuous Flash Suppression (CFS) (15), a cutting edge masking technique that allows subliminal presentations that last seconds. CFS is a game changer in the study of the unconscious (16), because unlike all previous methods, it gives unconscious processes ample time to engage with and operate on subliminal stimuli. Indeed, in the present set of experiments, we show that humans can semantically process subliminal multiple-word expressions and that they can nonconsciously solve effortful arithmetic equations.

CFS consists of a presentation of a target stimulus to one eye and a simultaneous presentation of rapidly changing masks to the other eye. The rapidly changing masks dominate awareness until the target breaks into consciousness (Fig. 1) (17–19). Importantly, this suppression may last seconds (15). We used this technique in two different ways. In the first section, the critical dependent variable was the time that it took the stimuli to break suppression and pop into consciousness (popping time) (17). In the second section, we used masked expressions as primes and measured their influence on consequent judgments. Objective and subjective measures ensured unawareness of the primes.

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Results

Reading. In all of the experiments in this section, we monocularly presented verbal expressions (e.g., black eye) masked by a series of Mondrian-like colorful shapes that were presented to the other eye. The task demanded that participants press a key as soon as verbal stimuli (e.g., a letter, a phoneme, or a word) break suppression and pop into consciousness. Accordingly, participants were explicitly instructed to look for verbal stimuli (the targets) and indicate, as quickly as possible, whether they appeared above or below a fixation point (the expressions appeared with a probability of 0.5 above/below fixation). Thus, popping time served as our dependent variable in this first set of experiments.

In Experiments 1 and 2, participants were presented with semantically coherent vs. semantically incoherent multiple-word expressions. Experiments 3a–3d are control experiments. In Experiments 4a and 4b ,participants were presented with verbal phrases that varied in affectivity. Previous literature suggests that incongruent and negative stimuli break suppression faster than their controls (18, 20). Hence, we predicted that semantically incoherent expressions would become conscious more quickly than semantically coherent ones (Experiments 1 and 2), and that the more negative a phrase is, the more quickly it would become conscious (Experiments 4a and 4b).

In the first experiment, participants were presented with different types of three-word expressions. Expressions in the incoherent condition described actions with improper objects (e.g., I ironed coffee). Control (coherent) expressions included object-appropriate actions (e.g., I made coffee) and action-appropriate objects (e.g., I ironed clothes) (Table S1). These expressions and other filler trials were presented in a random order.

As argued above, we hypothesized that semantically incoherent expressions would appear in consciousness before the (semantically coherent) control expressions. The results supported our prediction. Semantically incoherent expressions broke suppression

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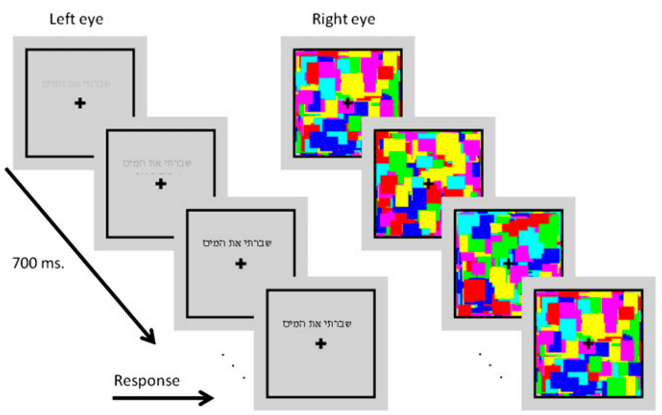

Fig. 1. Schematic representation of the experimental paradigm used in experiments 1 and 2. The target sentence was presented to participants' left eyes. It competed with a dynamic (10 Hz) mask pattern presented to participants' right eyes. The target sentence was gradually ramped up in contrast during the first 700 ms of presentation.

before semantically coherent ones [mean = 939.44, SD = 195.47 vs. mean = 958.79, SD = 197.15, respectively; $t(30) = 2.63$, $P = 0.013$]. Experiment 2 replicated Experiment 1 using different expressions, in which inanimate objects perform actions (e.g., the bench ate a zebra). Control expressions were as similar as possible in terms of structure (Table S2). Once again, semantically incoherent expressions became conscious (mean = 1,059.25, SD = 317.57) before semantically correct expressions [mean = 1,108.36, SD = 346.05; $t(20) = 2.92$, $P = 0.009$].

Because coherence in Experiments 1 and 2 is a property of the expressions but not their parts (e.g., there is no incoherence in "I," "ironed," or "coffee"), the documented differences in popping times indicate that the multiple-word expressions can be semantically processed.

To test the possibility that the stimuli in the different conditions broke suppression at the same time but conscious decision processes speeded up the responses to semantically incoherent ones, we conducted four control experiments. The stimuli in these experiments were not masked, and in the first two experiments, participants engaged in the exact same task: to indicate, as quickly as possible, whether the stimuli appeared above or below fixation. Experiment 3a used the stimuli of Experiment 1, and Experiment 3b used the materials of Experiment 2. Reaction times were practically identical (the average difference between incoherent and coherent expressions was −2.25 ms in Experiment 3a and 1.94 ms in Experiment 3b; both P values > 0.54; Tables S3 and S4). Because the nature of Experiments 3a and 3b might be more perceptual than the nature of Experiments 1 and 2, Experiments 3c (with the materials of Experiment 1) and 3d (with the materials of Experiment 2) used a more semantic task. Participants were asked to indicate to what extent the expressions make sense (on a scale of one to seven). There were marked differences between coherent and incoherent expressions in terms of their perceived coherency (P values < 0.001) (Table S5). Importantly, rating the incoherent expressions (that broke suppression earlier in Experiments 1 and 2) took much longer (P values < 0.05). Together, the results of these four control experiments show that conscious decision processes do not yield the same patterns as those processes documented in Experiments 1 and 2, thereby strongly implying that conscious decision processes do not account for the findings of the first two experiments.

The next experiments use affectivity to examine nonconscious processing of verbal expressions. In Experiment 4a, we manipulated the affective meaning of verbal expressions (e.g., black eye or sand box) (Table S6). The expressions were carefully pretested such that their affective meaning did not stem from the individual words (e.g., neither black nor eye is extremely negative, but a black eye is negative). Participants' task was to indicate, as quickly as possible, whether stimuli appeared above or below fixation. Based on previous findings, we hypothesized that negativity would lead to faster popping times (18, 21). A linear regression (which allows us to capitalize on the availability of a continuous variable – the affective ratings of the expressions) supported this prediction. The more negative a verbal expression was, the faster it became conscious [$\beta = 0.356$, $t(44) = 2.523$, $P = 0.015$]. A replication of this experiment (Experiment 4b) was run with a new set of participants, and it obtained very similar results [$\beta = 0.318$, $t(44) = 2.229$, $P = 0.031$].[†] Because the extraction of the affective tone of an expression requires semantic processing, these results indicate that participants nonconsciously processed multiple-word expressions.

To examine whether differences in popping times may have reflected differences in conscious decision criteria, we ran Experiment 5, a replication of Experiments 4a and 4b, in which the stimuli were not masked (a similar logic was used in Experiments 3a and 3b). If the differences in popping times reflect conscious decision processes, then they should appear in Experiment 5 as well. The results, however, were qualitatively different: affectivity did not predict decision times when the stimuli were consciously perceived [$\beta = 0.003$, $t(44) = 0.017$, $P = 0.987$].

The results of Experiments 4a and 4b suggest that semantic processing of multiple-word phrases can be accomplished by nonconscious processes. They extend the results of Experiments 1 and 2 in two important ways. First, they use another factor, namely affective meaning, to examine nonconscious processing of verbal expressions (18, 21). Second, although in Experiments 1 and 2, the incoherent verbal expressions consisted of novel combinations (e.g., I ironed coffee), whereas those combinations in the control conditions were more familiar (I ironed clothes), there were no systematic differences in novelty in Experiments 4a and 4b.

In the next section, we examine another uniquely human, abstract, symbolic, rule-following system, namely arithmetic. To allow for generalization beyond a specific methodology, we move from a breaking-into-consciousness design to a priming design. We examine the effects of subliminal stimuli on conscious stimuli that follow them. We used both subjective and objective measures (22–24) to verify the subliminality of the primes.

Arithmetic. A conscious pilot compared solution times to addition and subtraction of equations that contain two and three digits (e.g., 9 − 3 vs. 9 − 3 − 4). The pilot showed that equations with three digits took much longer to solve [$t(20) = 17.43$, $P < 0.001$], thereby suggesting that they are more difficult and require more steps to solution. We begin our exploration of nonconscious arithmetic computations with these more difficult equations.

Each trial in this set of experiments contained a CFS-masked equation (henceforth, a prime). After the prime (e.g., 9 − 3 − 4 =), participants were presented with a visible target stimulus, to which they were asked to respond. All experiments had two basic conditions. In the compatible condition, the result of the primed

[†]To control for the effects of the single words on popping times, we conducted a regression with expressions' affective value, the mean affective value of the individual words, and the length (number of letters) of the expression. The model was marginally significant [$F(3,42) = 2.804$, $P = 0.051$]. Word affectivity and length did not predict popping times ($P > 0.3$). The expression's affective value, however, remained a significant predictor [$\beta = 0.377$, $t(42) = 2.627$, $P = 0.012$]. The same analysis for Experiment 4b yielded similar results: a significant model [$F(3,42) = 8.666$, $P < 0.001$] and a significant effect of the expressions' affective value [$\beta = 0.353$, $t(42) = 2.856$, $P = 0.007$]. The valence of the single words and their length also predicted popping times [$\beta = -0.294$, $t(42) = -2.380$, $P = 0.022$ and $\beta = -0.441$, $t(42) = -3.634$, $P = 0.001$]. Importantly, these analyses show that the affective value of multiple-word expressions predicts popping time, even when the effects of the single words are statistically controlled.

equation was the target stimulus (10). In the incompatible condition, it was not (11). We expected to find an advantage in the compatible conditions. Such an advantage would indicate that the result of the primed equation was mentally accessed (9–11) (that is, that the equation had been solved).

Participants' lack of awareness was confirmed by two strict criteria. First, they completed an objective test block, in which they repeatedly made two-alternative forced-choice judgments regarding the primes (22, 23). Second, participants completed a subjective measure that consisted of direct questions about the nature of the stimuli and the tasks (24). We used the binomial distribution to determine whether each participant performed better than chance on the objective block and excluded from analyses all those participants who did. Also excluded were participants who reported any form of subjective awareness of the stimuli. Where we do not discuss it further, group analyses showed that the performance of the groups was not significantly better than chance (P values > 0.75).

In Experiment 6, participants were presented with CFS-masked three single-digit equations (e.g., 9 − 3 − 4 =) (Table S7). After the prime, a visible number (e.g., the number 2) appeared on the screen, and participants were asked to pronounce it. Because the time course of a nonconscious solution of equations was unknown, the equations were either presented for 1,700 or 2,000 ms (between participants). Whether the equations were composed of addition or subtraction operands was a within-participants factor.

In the subtraction condition, reaction times (RTs) to correct responses showed a significant effect of priming ($F_{1,15}$ = 16.79, P = 0.001) (Fig. 2*A*) and no interaction of priming and the prime presentation duration (P > 0.16).[‡] Surprisingly, there was no effect of priming in the addition condition (P > 0.33). One possible explanation for this finding is that, because addition is easier and solved faster,[§] the solutions of the addition equations had already decayed when the targets appeared on screen. To examine this possibility, Experiment 7 (Table S8) examined nonconscious arithmetic with shorter presentation times (1,000 and 1,300 ms; between participants). Replicating Experiment 6, the results showed significant priming effects for subtraction (F_{28} = 5.41, P = 0.027) with no interaction with presentation duration (P > 0.86)[¶] (Fig. 2*B*). Again, there was no effect in the addition condition (P values > 0.25).[‖]

The results so far show that subtraction equations are solved nonconsciously and hence, are sufficient to confirm our hypothesis that complex arithmetic can be performed unconsciously. However, why did not we find evidence for nonconscious solution of the easier-to-solve addition equations? Motivated by recent research on numerical cognition, we introduced two changes and examined unconscious addition once again. The first change is anchored in research which indicated that, when confronted with easy numerical comparisons (but not with difficult ones), unconscious processes make many parallel computations, even if those computations are not necessary for the focal task (26). This finding raises the possibility that participants may have been less strategic in the addition (vs. subtraction) equations, a fact that may have masked priming effects (a test of this idea with conscious arithmetic is Experiment 8). To minimize participants' ability to conduct such unnecessary computations, Experiment 9 used two single-digit equations (e.g., 8 + 7 =) (Table S9). The second change consisted of using a new task, in which subjects judged whether arithmetic statements were correct. Thus, for example, after having been subliminally primed with 8 + 7 =, participants were supraliminally exposed to 9 + 6 = 15, and they were asked to indicate, using a key press, whether the latter was correct or incorrect. This modification made solving math equations a conscious task goal, and thus, it may have increased participants' incentive to engage in solving addition equations.

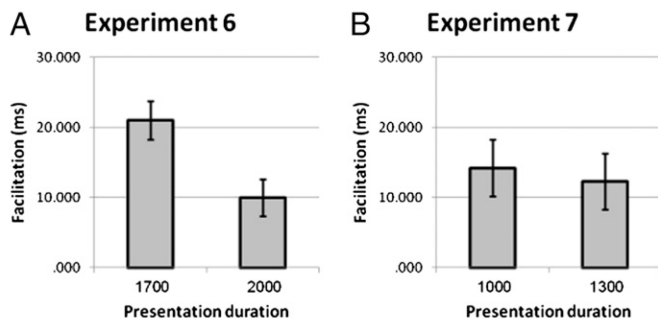

Fig. 2. Facilitation effect [(average RT in the priming condition) − (average RT in the control condition)] for Experiments 6 (*A*) and 7 (*B*). Error bars denote SEM.

A significant effect of priming ($F_{1,32}$ = 4.52, P = 0.041) indicated that participants made fewer mistakes in the compatible (mean = 3.2%, SD = 3.3%) vs. the incompatible (mean = 4.4%, SD = 2.49%) condition.[**] These results indicate that addition equations can also be performed unconsciously (similar results with the digits one through five are given in ref. 10). What the specific conditions are under which addition and subtraction equations are nonconsciously solved turns out to be a complex issue that must be left for future investigations.

Discussion

Data from multiple experiments show that we can semantically process multiple-word expressions and solve effortful arithmetic equations nonconsciously. These findings emerged in two very different paradigms—breaking into consciousness and priming—in subliminal presentation durations that ranged from 800 to 2,000 ms and across a large variety of stimuli. Unawareness of the stimuli was verified by using either breaking suppression as the dependent measure (Experiments 1, 2, 4a, and 4b) or strict objective and subjective criteria (Experiments 6, 7, and 9).

As far as verbal abilities are concerned, the present results show that we can semantically process a number of words and their relations, even when the words are presented subliminally. One possible interpretation of these results is that incoherent verbal stimuli break suppression faster, because the words are only weakly associated. Compare the sentences "The window got mad at her" with "The gentleman got mad at her" (Experiment 2).

‡To further examine awareness, we regressed subtraction facilitation scores (RTs for incongruent minus congruent trials) on objective block scores (centered so that a score of zero indicated chance level) (39). The results showed significant facilitation when accuracy in the objective block is at chance [$\beta_{intercept}$ = 14.78, $t(15)$ = 3.91, P = 0.001] and insignificant slope [β = 86.85, $t(15)$ = 1.47, P = 0.161].

§This explanation was verified in the pilot described. The results showed that addition equations were, indeed, solved faster than subtraction equations [mean = 1,795.01 ms, SD = 274.36 and mean = 2,167.78 ms, SD = 494.33, respectively; $t(20)$ = 3.69, P = 0.001].

¶As a group, participants fared better than chance on the objective block (P < 0.01). However, there was a significant negative correlation between facilitation scores and objective block scores (r = −0.39, P = 0.032). Awareness of the equations, then, reduced facilitation, thereby working against the hypothesized effect. Another way of verifying that subtle awareness is not producing the effects is to use the regression method described above. This analysis showed significant facilitation, even when accuracy in the objective block was at chance [$\beta_{intercept}$ = 20.32, $t(29)$ = 3.33, P = 0.002].

‖One other possible difference between addition and subtraction is that magnitude matters. The solutions to addition equations were larger than the solutions for subtraction equations and hence, more difficult to compute. The data, however, show no differences between addition equations that yielded high vs. low solutions (all P values > 0.17). These results suggest that magnitude does not play a crucial role here.

**There was a marginal effect on RTs (P = 0.08), raising the possibility that participants were also slower on incompatible trials. This result may suggest that the presentation of nonconscious equations results in strategic changes in processing. Because this effect was not hypothesized, we do not wish to make much of it.

The proposed explanation holds that, because of the weaker semantic association between windows (vs. gentleman) and getting mad, the first expression breaks suppression faster. Another explanation, one that we naturally prefer, is that the sentences were fully read and comprehended, and because the former scenario is more surprising than the latter (think about that shouting window), it broke suppression faster. Future studies should disentangle these alternative explanations.

Importantly, there is little doubt that the expressions used in Experiments 4a and 4b were understood, despite the fact that they were comprised of multiple words.

As far as mathematical ability is concerned, we provided data for the solution of effortful arithmetic equations that require multiple steps to solution. These data show that unconscious processes can perform sequential rule-following manipulations of abstract symbols—an ability that, to date, was thought to belong to the realm of conscious processing. The limits of nonconscious arithmetic (and mathematical and logical abilities more largely) remain unclear. Some of us (27, 28) have argued that unconscious processes can perform every fundamental, basic-level function that conscious processes can perform. Because our conscious arithmetic abilities vary considerably, this view suggests that there should be vast individual differences in these nonconscious abilities. Future research should explore the boundary conditions of nonconscious mathematics.

To conclude, research conducted in recent decades has taught us that many of the high-level functions that were traditionally associated with consciousness can occur nonconsciously [reviews are in refs. 5, 25, 26, 29, and 30; for example, learning (31, 32), forming intuitions that determine our decisions (2, 3), executive functions (33, 34), and goal pursuit (35, 36)]. Here, we showed that uniquely human cultural products, such as semantically processing a number of words and solving arithmetic equations, do not require consciousness. These results suggest that the modal view of consciousness and the unconscious, a view that ties together (our unique) consciousness with (humanly unique) capacities, should be significantly updated.

Materials and Methods

Participants. Three hundred seventy-two Hebrew University students (256 female, mean age = 23.8 y) participated in 13 experiments for payment or course credit: 32 participants (18 female, mean age = 23.4 y) in Experiment 1; 21 participants (12 female, mean age = 25.1 y) in Experiment 2; 16 participants (10 female, mean age = 23.2 y) in Experiments 3a and 3c; 18 participants (9 female, mean age = 24.3 y) in Experiments 3b and 3d; 30 participants (18 female, mean age = 25.6 y) in Experiment 4a; 28 participants (14 female, mean age = 24.4 y) in Experiment 4b; 28 participants (18 female, mean age = 23.7 y) in Experiment 5; 42 participants (36 female, mean age = 21.9 y) in Experiment 6; 65 participants (51 female, mean age = 23.1 y) in Experiment 7; 36 participants (27 female, mean age = 24.3 y) in Experiment 8; and 56 participants (43 female, mean age = 23.1 y) in Experiment 9. Participants in Experiments 1–5 were all native Hebrew speakers.

Apparatus. In all experiments except for Experiment 8, stimuli were presented on a CRT monitor controlled by either DirectRT experimental software (Experiments 1, 2, 3a, 3b, 3c, 3d, 7, 8, and 10) or psychtoolbox (37) extension for MATLAB (Experiments 4a, 4b, and 5). In Experiments 1, 2, 4a, 4b, 5, 6, 7, and 9, the CRT monitor was fitted with a mirror stereoscope to allow stimuli to be presented monocularly.

Stimuli. ***Experiments 1–3.*** The stimuli were three-word sentences in Hebrew consisting of a subject, a verb, and an object. One-fourth (31) of the sentences were semantically incorrect (violations). In Experiments 1, 3a, and 3c, these violations were sentences in which actors performed impossible actions (e.g., John ironed the coffee), and each matched with two types of control sentences. In one control condition, sentences contained the original object and a possible action (e.g., John made coffee; one-fourth of the sentences). Another control condition contained the original action with a proper object (e.g., John ironed the clothes; one-fourth of the sentences). One-fourth of the sentences were semantically correct fillers. Experiments 3a and 3c included 40 additional filler sentences (10 violations and 30 semantically correct). The control sentences as well as the fillers were of the same length as the experimental sentences, and they were as similar as possible in terms of structure and meaning.

In Experiments 2, 3b, and 3d, violations were sentences in which inanimate objects performed actions (e.g., The bench ate a zebra). Each violation was paired with a control sentence in which an animate subject performed the action (e.g., The lion ate a zebra). One-half of the sentences were semantically correct fillers (meeting the requirements mentioned above). Experiments 3b and 3d included 24 additional filler sentences (6 violations and 18 semantically correct).

A full list of stimuli is presented in Tables S1, Experiments 3a and 3c, and S2, Experiments 2, 3b, and 3d.

Experiments 4a, 4b, and 5. These experiments used forty-six two-word expressions in Hebrew, with varying affective valance (Table S6). All of the expressions were composed of affectively neutral words (Table S6). Stimuli were chosen based on two pilots. In the first study, 20 participants (16 females, mean age = 25.6 y) from the Hebrew University rated 76 expressions on an affective scale (−5, most negative; +5, most positive). In the second study, 20 participants (15 females, mean age = 24.6 y) from the Hebrew University rated all of the single words comprising the expressions on the same scale. In both pilots, presentation order was random. The affective value of the 46 verbal expressions chosen for the experiment ranged from −4.7 to 2.05. The valance of each individual word was not significantly different from zero.

Experiments 6 and 7. Each priming equation was matched with one congruent and one incongruent target number, and it was presented only one time to each participant (counterbalanced between participants). Stimuli in Experiment 6 were selected such that (*i*) the target number could not be identical to any of the numbers comprising the equations, (*ii*) the target number could not constitute a partial solution of the equations, and (*iii*) the average distance between the digits and the target in each equation was the same for congruent and incongruent conditions. These constraints resulted in uneven number of stimuli (80 addition equations and 74 subtraction equations) (Table S7). We used one additional criterion in Experiment 7. The numeric distance between the correct solution for the equations and their targets ranged from zero to four. These constraints resulted in 64 addition equations and 48 subtraction equations (Table S8).

Experiment 8. Forty three-digit addition and subtraction equations (20 of each) were randomly chosen from those equations used as primes in Experiment 7.

Experiment 9. Twenty-four two-digit addition equations were used. Each equation was presented two times with a congruent target equation and two times with an incongruent equation (Table S9).

Procedure. ***Experiments 1, 2, 4a, and 4b.*** During each trial, a fixation cross was presented binocularly at the center of each eye's visual field. Lexical stimuli were presented monocularly in 12-pt David font (Experiments 1 and 2) or 15-pt Ariel font (Experiments 4a and 4b) and gradually ramped up in contrast (from 0% to 50%) during the first 700 (Experiments 1 and 2) or 900 ms (Experiments 4a and 4b) of presentation. The masks were patterns of randomly assigned colored squares, changing randomly at a rate of 10 Hz. (Fig. 1). Lexical stimuli appeared either below or above fixation (probability = 0.5). Participants' task was to indicate whether the sentences (or any part of them—a word, letter, or feature) appeared above or below fixation by pressing the appropriate key. They were instructed to respond as quickly as they could. In Experiments 1 and 2, the mask was always presented to the left eye, and the sentence was presented to the right eye. In Experiments 4a and 4b, the mask was randomly presented to one eye, and the expression was presented to the other eye. Experiment 4b was conducted in a session with several other experiments, and it always followed another task in which subjects were presented with masked verbal stimuli.

Experiments 3a and 3b. The procedure of Experiments 1 and 2 were followed with the following exception. Participants viewed the screen naturally and not through a stereoscope. Accordingly, verbal stimuli were presented in 44-pt Arial font, and no masks were presented. Participants' task and instructions were the same as in Experiments 1 and 2.

Experiments 3c and 3d. Experiments 3c and 3d followed the procedure of Experiments 3a and 3b with the exception that the participants' task was to rate to what extent the expressions make sense (on a scale of one to seven). Experiments 3c and 3d were performed in the same session and on the same subjects as Experiments 3a and 3b, respectively.

Experiment 5. The procedures of Experiments 4a and 4b were followed with two changes: The verbal stimuli in Experiment 5 were presented binocularly, and no masks were presented. Participants' task and instructions were the same as in Experiments 4a and 4b.

Experiments 6 and 7. Participants were told that they take part in a "numbers and equations task". Each experimental block was preceded by a practice phase of 15 supraliminal equations. Each experimental trial began with the monocular presentation of a prime equation, presented in 12-pt Arial font, to the participants' nondominant eye. Visual masks, comprised of three rows of randomly chosen Hebrew letters presented in 13-pt Arial font, were presented monocularly to the contralateral eye, changing at a rate of 10 Hz. The primes were presented for either 1,700 or 2,000 ms (between participants) in Experiment 6 and either 1,000 or 1,300 ms (between participants) in Experiment 7. All primes were followed by the binocular presentation of a fixation (500 ms). Finally, a target number was binocularly presented until the microphone registered a voice response.

Immediately after the completion of the experimental block, a forced-choice objective test was administered (22, 23). The objective block was comprised of 64 trials, in which the presentation parameters were identical to the experimental trials. Participants were informed about the existence of primes. In Experiment 6, the participants' task was to report the parity of the first digit in the masked equations. In Experiment 7, one-half of the equations presented in the objective test were identical to those equations used in the experiment, and the other one-half were comprised of three random Latin letters (e.g., A − B − C =). Participants' task was to indicate whether the presented equation was comprised of letters or numbers. On completion of the objective test, participants were debriefed and directly asked whether they had seen the primes during the experimental blocks.

Experiment 8. Participants were approached while seated in a public area in the campus and asked to fill a questionnaire. The questionnaire included 20 subtraction and 20 addition equations presented in separate blocks (order counterbalanced between participants). Participants were asked to solve each equation and write down the steps used to arrive at the solution (they were also given the option of marking no steps if they arrived at the solution without any intermediate steps).

Experiment 9. Participants completed 192 experimental trials. In 96 (50%) of the trials, the explicit target was correct (e.g., $3 + 4 = 7$), and in the remaining trials, it was incorrect (e.g., $4 + 6 = 13$); the data of the latter trials were not analyzed. Participants were asked to indicate the target's correctness by pressing one of two keys on the keyboard. Each target was preceded by a prime equation presented for 800 ms and a fixation cross, which was presented for 200 ms. The result of the primed equation was either identical to the result of the explicit target (50%) or not. At the end of the experiment, participants completed an objective test block (48 trials), which was identical to the test block of Experiment 6 with one modification. Participants were asked to judge the parity of the last digit in the equation instead of the parity of the first one.

Data Preparation. ***Reaction times and accuracy.*** In experiments for which reaction times were the dependent measure, trials in which participants did not respond correctly (1.05%, 1.47%, 2.73%, 3.83%, 2.02%, 5.2%, 2%, 0.11%, and 0.06% in Experiments 1, 2, 3a, 3b, 4, 5, 6, and 7, respectively) and had responses that were more than 3 SDs from each participant's mean (1.68%, 1.71%, 1.74%, 1.64%, 2.1% 2.08% 0.05%, 6.7%, 1.7%, 0.67%, and 3.96% in Experiments 1–7, respectively) were excluded from analysis. In the verbal experiments, reaction times that were longer than 10 s or shorter than 200 ms (0.85%, 0.9%, 1.53% 1.35% 1.01%, and 0.01% in Experiments 3a, 3b, 3c, 3d, 4a, and 4b) were also excluded from analysis. Also excluded were participants who did not respond correctly on more than 10% of the trials and participants with mean RTs that were 3 SDs slower than the group's mean (one participant in each of Experiments 1, 3a, and 5 and three participants in Experiment 3b). In Experiments 1–3d, reaction times that were more than 3 SDs from the general mean for each condition (incoherent or control) were excluded from analysis (1.76%, 2.06%, 1.26%, 0.5%, 2.02%, and 1.63% in Experiments 1, 2, 3a, 3b, 3c, and 3d, respectively). In Experiments 6 and 7, trials in which recording malfunctions occurred (2.56% and 1.58% in Experiments 6 and 7, respectively) were excluded from analysis.

Awareness tests. In Experiments 6, 7, and 9, we used the binomial distribution to determine whether each participant performed better than chance on the objective block and excluded from analyses all those participants who did (21, 30, and 7 participants in Experiments 6, 7, and 9, respectively). Note that, although the number of excluded participants may seem high, they fall within the normal range of long-duration CFS priming, in which successful suppression is strongly affected by individual differences (38). We additionally excluded participants who reported any subjective awareness of the primes (four, five, and three participants in Experiments 6, 7, and 9, respectively).

Experiment 8. Participants' responses were coded based on their solution strategy (that is, the order of steps used in solving the equations). The most frequent strategy for each type of equation (addition or subtraction) was identified as the participant's dominant strategy. The percentage of trials in which participants used their dominant strategy served as one dependent variable. Additionally, we computed proportion of strategy shifts (that is, cases in which equation N was solved by one strategy and equation N + 1 was solved by another strategy). This measure was used as a second dependent measure.

Experiment 9. Only trials in which the correct solution to the equation was presented were used in the analysis; 12 participants who did not make any mistakes in the incongruent condition (i.e., they were at ceiling) and therefore, could not have improved in the congruent condition were excluded from analyses. Also excluded was one participant who did not follow the experimental instructions.

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