Psychon Bull Rev (2013) 20:581–585
DOI 10.3758/s13423-012-0364-1

BRIEF REPORT

Suppressed semantic information accelerates analytic problem solving

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Published online: 19 December 2012

Abstract The present study investigated the limits of semantic processing without awareness, during continuous flash suppression (CFS). We used compound remote associate word problems, in which three seemingly unrelated words (e.g., *pine*, *crab*, *sauce*) form a common compound with a single solution word (e.g., *apple*). During the first 3 s of each trial, the three problem words or three irrelevant words (control condition) were suppressed from awareness, using CFS. The words then became visible, and participants attempted to solve the word problem. Once the participants solved the problem, they indicated whether they had solved it by insight or analytically. Overall, the compound remote associate word problems were solved significantly faster after the problem words, as compared with irrelevant words, were presented during the suppression period. However this facilitation occurred only when people solved with analysis, not with insight. These results demonstrate that semantic processing, but not necessarily semantic integration, may occur without awareness.

Keywords Awareness · Continuous flash suppression · Semantic processing · Semantic integration · Binocular rivalry · Problem solving

Our mental functions can be influenced by events of which we are unaware (Kouider & Dehaene, 2007; Maier, 1931; Schunn & Dunbar, 1996). One way to present information below awareness is to present visual information under continuous flash suppression (CFS). CFS uses a dichoptic presentation in which participants view critical stimuli with the nondominant eye, while viewing a dynamic mask presented to the dominant eye. When people view information under CFS, even for extended presentation periods, they rarely report suppressed information; yet some processing occurs. For instance, meaningful stimuli, such as upright faces or words in a native language, are processed differently than are meaningless stimuli (Jiang, Costello, & He, 2007), and fearful expressions emerge from suppression faster than their matched controls (Yang, Zald, & Blake, 2007). CFS is an effective and reliable technique for suppressing even highly salient images throughout a relatively long viewing period—at least 3 min (Lin & He, 2009). It is now widely used to suppress visual stimuli from awareness (Jiang et al., 2007; Pasley, Mayes, & Schultz, 2004; Tsuchiya & Koch, 2005; Yang et al., 2007).

Outside of awareness, the mind may not only code individual features, but also temporarily bind distributed features to give rise to coherent cortical representations (Lin & He, 2009). When people view complex scenes under CFS, they more quickly become aware of scenes that contain an incongruent object, as compared with scenes containing a congruent object (Mudrik, Breska, Lamy, & Deouell, 2011). Thus, the coherence, or incoherence, of the entire scene is processed without awareness, at least to some degree.

Here, we were interested in whether people engage semantic processing when viewing words that are suppressed via CFS and, if so, what the limits are of that processing. In other masking paradigms, when people view words for a few milliseconds, they show some evidence of semantic processing. For instance, semantic priming from masked words has been demonstrated in a variety of tasks, including lexical decision tasks, naming, and semantic categorization (McNamara, 2005). Also, masked words, but not masked nonwords, activate left-hemisphere language areas (Diaz & McCarthy, 2007; but see Abrams, Klinger, & Greenwald, 2002).

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Only a few studies have used CFS to investigate semantic processing. When people view words suppressed from awareness by CFS, semantically related words and words that share subword fragments break from suppression more quickly than unrelated words, suggesting that words, even when suppressed from awareness, can benefit from semantic and subword priming (Costello, Jiang, Baartman, McGlennen, & He, 2009). However, there may be limits to how much semantic processing occurs under CFS. For instance, the N400 event-related potential, an index of semantic mismatch between a stimulus and the context in which it is presented, is attenuated with increasing suppression of unrelated stimulus words following clearly visible context words and is completely absent when unrelated stimulus words are presented under full suppression (Kang, Blake, & Woodman, 2001).

It remains unknown how well any semantic processing that occurs under CFS can be used in higher-level tasks, such as to help solve problems. That is, can the semantic processing during CFS be used for anything, or does it simply bias semantic priming? Here, we employed compound remote associate word problems (Bowden & Jung-Beeman, 2003) to investigate semantic processing and, specifically, semantic integration under CFS. In the compound remote associate problems, three seemingly unrelated words (e.g., *pine*, *crab*, *sauce*) form a common compound with a solution word (e.g., *apple*). We used CFS to suppress problem words (or irrelevant words) for 3 s, then fully revealed the word triads. If people solve word problems more quickly following suppressed problem words than following suppressed irrelevant words, this would indicate that the suppressed problem words were semantically processed.

In addition, we investigated the limits of semantic processing under suppression by examining whether the processing of suppressed words is particularly conducive for analytic solving or insight solving. Because insight solving is relatively more dependent on semantic integration (Jung-Beeman et al., 2004), an improvement in insight solving would demonstrate that semantic integration of multiple words can occur under CFS. Conversely, if people improve (following suppressed problem words) only when solving problems analytically, this would demonstrate that some semantic processing can occur, but without semantic integration across multiple words.

Method

Participants

Twenty-one undergraduate students (13 females and 8 males) from Northwestern University (age 18–21 years, $M = 21$ years) were paid $10 for their participation. All participants had normal or corrected-to-normal vision, were right-handed native English speakers, and were tested individually in a dimly lit room. The experiment was approved by the university Institutional Review Board, and informed consent was obtained from all participants prior to their participation.

Apparatus

Stimuli were displayed on a 21-in. color CRT monitor (85 Hz, 1,400 × 1,050 resolution) at a viewing distance of 110 cm. The experiment was controlled with an Apple MacBook running OS X 10.6.8 and using Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) for MATLAB. A stereoscope with four front-surface mirrors (with an integrated forehead rest) was used to present stimuli to separate eyes.

Stimuli

Participants attempted to solve 80 compound remote associate problems. These word problems were divided into two sets and assigned to two conditions (counterbalanced across participants): In the experimental condition, 40 word problems were preceded by the actual problem words, presented under CFS, whereas in the control condition, the 40 word problems were preceded by 40 new irrelevant triplets of words (no relation to the compound remote associate problems or to one another), also presented under CFS. The experimental and control conditions were randomly intermixed across trials. All stimuli were displayed within a binocularly presented frame (5.19° × 5.30°, luminance = 1.98 cd/m^2) defined by 1.30°-thick checkerboard borders consisting of 0.78° × 0.78° colored red squares (luminance = 14.4 cd/ m^2) presented against a light white background (luminance = 80 cd/m^2). The binocularly presented frame remained on the screen throughout each trial to promote stable binocular fusion.

Procedure

The experiment took approximately 1 h. At the beginning of each session, eye dominance was evaluated for each participant. Participants started each trial by pressing a key on the keyboard. During the first 3 s of each trial, the word triplet was suppressed from awareness using CFS—that is, by presenting the triplet to the nondominant eye and a dynamic mask to the dominant eye. The mask consisted of a colorful high-contrast pattern of colors —black (2.03 cd/m^2, CIE [0.354, 0.342]), pink (21.1 cd/m^2, CIE [0.288, 0.153]), red (18.1 cd/m^2, CIE [0.559, 0.365]), green (53.5 cd/m^2, CIE [0.315, 0.554]), cyan (58.8 cd/m^2, CIE [0.232, 0.309]), blue (1.06 cd/m^2, CIE [0.169, 0.007]), white (73.9 cd/ m^2, CIE [0.291, 0.316]), and yellow (67.6 cd/m^2, CIE [0.394, 0.496])—that continually changed every 100 ms.

After 3 s, the same word triplet (in the same word order) was presented to both eyes. Importantly, the words presented during suppression were either the same as or different from the

subsequently presented compound remote associate words. The problem remained on the screen until participants indicated that they had the solution by pressing the Enter key on the keyboard, up to a 12-s time limit. After pressing the key, participants verbalized their solution. Participants then indicated whether they had reached the solution by insight (by pressing the "I" key) or by analysis (by pressing the "A" key). Insight solutions were described to participants as follows: "An answer suddenly appears, even though you are somewhat unable to articulate how you reached the solution. Sometimes this is called the Aha! moment." Solutions by analysis were described as "deliberate and conscious solving, such as testing out different words until you find the solution; you are relatively able to report the steps that you used to reach the solution." It was emphasized that no solution type is better or worse than the other and that there are no right or wrong answers in reporting the insight or analytic way of solving the problem. After each trial, participants indicated whether they saw any words during the dynamic mask.

Ensuring suppression worked

To ensure that the word triplets were actually suppressed during CFS, we included 20 randomly intermixed catch trials, on which we simulated words breaking through the suppressing mask. On these trials, a word was faded in and out above the mask at a random time during the initial 3-s period. Because all participants reported the words on 100 % of the catch trials and the two types of trials appeared similar to the participants, we were confident that they would report words that broke through CFS. However, it remained possible that suppression would not be complete on every trial; for instance, some participants might detect letter features on some trials. Debates on the unconscious perception can be found elsewhere in the literature (see Pratte & Rouder, 2009; Snodgrass, Bernat, & Shevrin, 2004; Yang & Blake, 2012). A total of 100 trials were presented: 40 problem word trials, 40 irrelevant word control trials, and 20 catch trials (all catch trials were excluded from the analysis).

Any trials on which participants reported that they saw anything during the suppression period (*breakthrough* trials; $M = 6.45$ %, $SD = 6.23$) or on which participants produced incorrect solutions ($M = 4.40$ %, $SD = 6.34$) were removed from analyses. The number of breakthrough trials and incorrect solution trials did not differ significantly between the problem word and irrelevant word conditions.

Results

Overall, participants solved 43 % ($SD = 12$) of the remote associates problems within the 12-s limit, with an average solving time of 5.77 s ($SD = 1.29$).

Solving time

Reaction times were analyzed in an analysis of variance with type of words during suppression (problem words vs. irrelevant words) and type of solution (insight vs. analytic) as within-subjects factors. As was predicted, participants solved compound remote associate word problems following suppressed problem words significantly more quickly ($M = 5.46$ s, $SD = 0.26$) than they solved problems following suppressed irrelevant words ($M = 6.08$ s, $SD = 0.30$), $F(20, 1) = 6.38$, $p = .02$. Thus, even when a dynamic mask rendered the suppressed triplets unreportable, participants still processed the suppressed words, decreasing subsequent solution times for the compound remote associate word problems.

There was also a main effect for the type of solution: Participants solved word problems by insight faster ($M = 4.56$ s, $SD = 0.27$) than by analysis ($M = 6.97$ s, $SD = 0.27$), $F(20, 1) = 79.42$, $p < .001$, consistent with some past results (e.g., Subramaniam, Kounios, Parrish, & Jung-Beeman, 2009).

Interestingly, there was an interaction between the type of words presented during suppression and the type of solution, $F(20, 1) = 5.77$, $p = .03$. Specifically, participants solved word problems by analysis significantly more quickly following suppressed problem words ($M = 6.48$, $SD = 1.56$) than following irrelevant words ($M = 7.46$, $SD = 1.36$), $t(20) = -3.89$, $p = .001$. However, solving time for problems solved with insight did not differ following suppressed problem words ($M = 4.43$, $SD = 1.31$) and suppressed irrelevant words ($M = 4.69$, $SD = 1.58$), $t(20) = -.82$, $p = .42$ (see Fig. 1). Thus, suppressed presentation of the problem words selectively facilitated the speed of analytic solving.

Ensuring effective suppression

As was noted, we excluded from analyses all trials on which participants reported that the suppressed words broke into awareness. For the remaining trials, the fact that only one

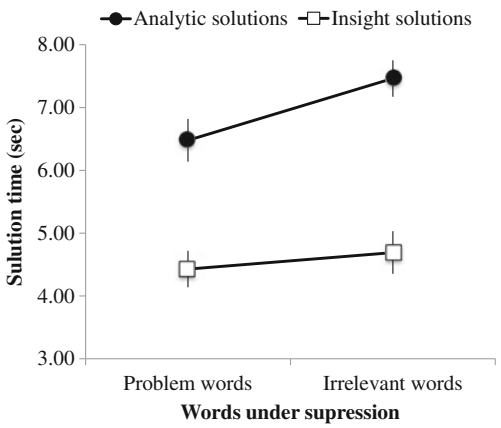

Fig. 1 Subliminal exposure to problem words speeds solution times, with the facilitation specific to the analytic, but not insight, solutions

type of solving was facilitated demonstrates that suppressed words did not break through suppression, which should have facilitated all solutions. For further control, we excluded data from 7 participants who reported breakthroughs on more than 15 % of trials. The remaining participants reported breakthroughs on only 3.3 % of trials (while still correctly reporting "breakthroughs" on 100 % of catch trials). For this subset of participants, the aforementioned pattern of results was even more robust: Participants solved word problems following suppressed problem words significantly more quickly (M = 5.28 s, SD = 0.33) than problems following suppressed irrelevant words (M = 6.15 s, SD = 0.36), $F(13, 1) = 8.36$, $p = .01$. The critical interaction became more pronounced, $F(13, 1) = 9.66$, $p < .01$. Again, only when solving by analysis did participants solve problems more quickly following suppressed problem words (M = 6.20 s, SD = 1.74) than following irrelevant words (M = 7.51 s, SD = 1.37), $t(13) = -4.03$, $p = .001$. Solving time when solving with insight did not differ following suppressed problem words (M = 4.36 s, SD = 1.20) versus suppressed irrelevant words (M = 4.79 s, SD = 1.51), $t(13) = -1.26$, $p = .23$.

Solution rates

Similar analyses were performed for solution rates (percent correctly solved out of total trials presented). Participants solved just as many problems following suppressed problem words (M = 43 %, SD = 12) as following suppressed irrelevant words (M = 42 %, SD = 12), $F(20, 1) = 0.29$, $p = .60$. There was also no main effect for the type of solution: Participants solved with insight (M = 45 %, SD = 20) only slightly (and nonsignificantly) more often than they solved with analysis (M = 41 %, SD = 19), $F(20, 1) = 0.32$, $p = .58$. Finally, type of words presented during suppression and solution type did not interact, $F(20, 1) = 1.49$, $p = .24$. Thus, it is not plausible that the problem words suppressed by CFS merely changed how participants reported solving. If this were the case, it should have led to a change in the proportion of problems reportedly solved by insight versus analysis; neither the number of problems nor the proportion solved by each type of process changed when suppressed problem words were presented.

Discussion

When people viewed problem words under CFS, they were unaware of the suppressed words, yet they still processed them enough to speed subsequent solving of remote associate problems. Importantly, people solved the problems faster only when they reported solving analytically, rather than by insight. The selective nature of this result (along with the 100 % performance on catch trials) argues against the suggestion that participants solved more quickly because suppressed words broke through into awareness, simply giving people more time to solve the word problems. Moreover, the selective nature helps to specify what type of semantic processing occurs when words are suppressed below awareness.

Analytic and insight problem solving

In the compound remote associate word problems, correct solutions require people to converge on the word that is common to all three words in the problem. Solutions reached by insight or by analysis involve different types of processing (for a review, see Kounios & Beeman, 2009). By definition, following insight solutions, participants are not able to report how they reached the solution. Thus, at least some critical processing supporting insight solutions occurs below the level of awareness. In contrast, participants are able to report most of the steps they took in reaching analytic solutions. Thus, the processing responsible for analytic solutions is conscious and deliberate. Insight and analytic processing also are associated with distinct patterns of neural activity. For instance, just prior to insight solutions, there is an increased fMRI signal in the right anterior temporal lobe and a burst of high-frequency (40-Hertz gamma-band) EEG activity over the same area, as compared with just prior to analytic solutions (Jung-Beeman et al., 2004). Because this area of the right temporal lobe is involved in semantic integration across distant relations (St. George, Kutas, Martinez, & Sereno, 1999; for a review, see Jung-Beeman, 2005), this indicates that insight solving depends on semantic integration more than does analytic solving.

In the present experiment, participants showed facilitation only for analytic solving. If semantic integration occurred during suppression, we would have expected to see facilitation for insight, as well as analytic solutions. Therefore, we conclude that CFS does not permit or promote semantic integration. This fits with prior reports that stimulus words presented under CFS attenuate the amplitude of the N400 (Kang et al., 2001). Some prior work with CFS suggests that partial perceptual information can break through CFS (Yang & Blake, 2012). Thus, it is conceivable that on some trials, letter features were visible to participants; however, the question remains why such partial perception would facilitate only analytic solving.

Hypothetically speaking, it is possible that insight solutions were at the ceiling for solution rates; thus, only analytic solutions were facilitated. However, there is no a priori reason to assume that 4.56 s is the ceiling solution time for insight solutions.

How did CFS facilitate analytic solutions? It is possible that beginning a trial with problem words under flash suppression allowed for some semantic processing without the narrowing of semantic processing that typically occurs when people process words with awareness. Such semantic narrowing can cause people to fixate on more common associations that may not be helpful for solving compound remote associate word problems. Thus, during the CFS

presentation, participants could have been able to process the problem words without awareness, without being misled by strong associations to any one word. It is thus possible that processing of the problem words without awareness does not produce semantic integration to facilitate insight but that it produces enough semantic priming to nudge semantic processing toward the correct associations (or away from the dominant/incorrect one), so that once the word problem was revealed, participants could more efficiently solve the word problems analytically. Alternatively, the CFS preexposure gave the distant associations a boost, strengthening their activation, whereas the close associations got strong activation with or without the preexposure. Thus, the CFS preexposure may even out the associative space, akin to producing a flatter associative space described as helpful for creative problem solving by Martindale (1999).

Prior work suggests that unconscious thinking can improve complex, but not simple, decisions (see also Dijksterhuis, Bos, Nordgren, & van Baaren, 2006). CFS may be a useful tool for sidestepping the potential pitfalls of analytic thinking—namely, getting initially fixated on the wrong thought or idea while problem solving or making complex decisions. We believe that in the present study, CFS allowed unconscious processing, which discouraged incorrect fixation. Because of this initial unconscious processing, the subsequent conscious processing proceeded more smoothly, but still in an analytic fashion.

Conclusion

Limited semantic processing can occur without awareness and facilitate subsequent problem solving. Problem words, but not irrelevant words, presented under CFS facilitate consequent solving speed of the compound remote associate word problems. However, awareness may be necessary for semantic integration, since only analytic solutions, not insight solutions, were aided.

Author Note The research described in this article was supported by grants from the National Science Foundation Graduate Research Fellowship to D.L.Z., the National Institutes of Health (NIH R01 EY021184) to S.S., and the John Templeton Foundation (24467) to M.B.

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