

Subliminal temporal integration of linguistic information under discontinuous flash suppression

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Whether unconscious complex visual information integration occurs over time remains largely unknown and highly controversial. Previous studies have tended to use a combination of strong masking or suppression and a weak stimulus signal (e.g., low luminance), resulting in a low signal-to-noise ratio during unconscious stimulus presentation. To lengthen the stimulus exposure, we introduced intermittent presentation into interocular suppression. This discontinuous suppression allowed us to insert a word during each suppression period and deliver multiple words over time unconsciously. We found that, after participants received the subliminal context, they responded faster to a syntactically incongruent target word in a lexical decision task. We later replicated the finding in a separate experiment where participants exhibited chance performance on locating the subliminal context. These results confirmed that the sentential context was both subjectively and objectively subliminal. Critically, the effect disappeared when the context was disrupted by presenting only partial sentences or sentences with a reversed word order. These control experiments showed that the effect was not merely driven by word–word association but instead required integration over multiple words in the correct order. These findings support the possibility of unconscious high-level, complex information integration.

although it has been shown that single-word processing can occur subliminally, whether multi-word processing can occur subliminally remains highly controversial (e.g., for single-word subliminal semantic priming, see Costello, Jiang, Baartman, McGlennen, & He, 2009; Dehaene et al., 1998; Greenwald, Draine, & Abrams, 1996; for single-word syntactic priming, see Ansorge, Reynvoet, Hendl, Oetl, & Evert, 2012; Berkovitch & Dehaene, 2019; Iijima & Sakai, 2014; Sereno, 1991).

In the domain of temporal integration, Van Gaal, Naccache, Meuwese, van Loon, Leighton, Cohen, and Dehaene (2014) showed that sequential word-to-word priming occurred when a masked word preceded the target word. That is, when the meaning of a masked adjective was consistent with a subsequent target noun (e.g., good–peace), shorter reaction times and lower error rates were observed when participants were asked to judge the valence of the target (positive or negative). However, when another masked modifier was added, participants failed to integrate the third word with the adjective–noun combination. Similarly, Yang, Tien, Yang, & Yeh (2017) showed that a Chinese sentential context suppressed interocularly did not exert a priming effect on a subsequent congruent or incongruent target word. This is interpreted as a failure of subliminal sequential integration. On the other hand, with a dual-task paradigm, Batterink and Neville (2013) found an early syntactic event-related potential component (early left anterior negativity), indexing automatic detection of syntactic anomaly even when participants failed to detect the syntactic violation in a sentence. In a similar vein, our previous study showed that, after consciously perceiving a two-word sentential context, a syntactically incongruent word broke through interocular suppression and reached consciousness faster than the syntactically congruent counterpart (Hung & Hsieh, 2015). One simple explanation for these studies may be that the integration between conscious and unconscious information can

Introduction

To digest a stream of incoming information, it is expected that one needs to integrate multiple units seamlessly. The human mind's ability to integrate information enables us to associate independent words and form coherent expressions. Information integration requires connecting multiple visual items across space and time, rendering it a highly complex process. Thus,

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occur; yet, the unconscious process operates only at the single-word level (i.e., between one subliminal word and one supraliminal word/context). Taken together, previous studies have shown that temporal integration could occur between a single conscious unit and a single unconscious unit (Costello et al., 2009; Nakamura, Makuuchi, Oga, Mizuochi-Endo, Iwabuchi, Nakajima, & Dehaene, 2018). However, no previous studies have conclusively shown such integration across multiple unconscious units.

One possible reason why unconscious integration did not occur in previous studies could be insufficient subliminal signals. In most temporal masking paradigms, the presentation duration of a masked stimulus is tremendously limited, typically taking place at the millisecond level (for a review, see Kouider & Dehaene, 2007). Recent advances in interocular suppression thus offer an excellent chance to lengthen subliminal presentation duration, as the breakthrough of the initially suppressed stimulus takes place at the second level (e.g., continuous flash suppression) (Tsuchiya & Koch, 2005). In continuous flash suppression, one of the observer's eyes receives a stream of dynamically changing patterns (the suppressor) while the other eye receives a static target stimulus (the suppressed). Here, we took advantage of the lengthened subliminal duration of the interocular suppression and introduced an additional element: the *intermittent* presentation of the stimuli. We named this new variant *discontinuous flash suppression* (dCFS). The suppressor was created for three reasons. First, the intermittent presentation during binocular presentation was expected to stabilize the dominating percept during multistable vision (Leopold, Wilke, Maier, & Logothetis, 2002), which theoretically lengthens the duration of suppression. Second, an on-and-off presentation also allowed us to insert a new word during the on period, providing an opportunity for delivering multi-word contextual information. Third, in a recent study (Hung, Wu, & Shimojo, 2020), we adopted this paradigm to suppress a single word and found that this suppressed word elicited semantic priming to a subsequent conscious target word. This finding provided evidence that word-level information can be processed at a deep level (e.g., semantics).

Using interocular suppression, we have previously found that, following a two-word conscious sentential context, a syntactically incongruent word broke through interocular suppression faster than the syntactically congruent counterpart (Hung & Hsieh, 2015). To further examine whether subliminal sentential context from multi-word integration could exert an effect, in the current study we interocularly suppressed the first two words of a sentence and measured how participants responded to the third conscious word, which was either syntactically congruent or incongruent to the syntactic structure provided by the first two words. Such a design

utilized the sentential context as an integral, subliminal prime and avoided using breakthrough speed to directly measure unconscious processing, as the latter could be interpreted as conscious access rather than unconscious processing (e.g., Gayet, Van der Stigchel, & Paffen, 2014). Based on our previous findings, we hypothesized that if subliminal temporal integration could occur over multiple words, participants would subsequently respond faster to a syntactically incongruent word compared with a syntactically congruent counterpart.

Methods

Participants

All participants (age range, 18–35 years) reported normal or corrected-to-normal vision. They gave written informed consent prior to the experiment and were reimbursed \$10 for participating in a 60-minute session. The language proficiency criterion for participating in Experiments 1a and 2a was using English as their most proficient language. The participants were mainly from the National University of Singapore community. Experiments 1b and 2b recruited volunteers from the California Institute of Technology community with the same criterion. These experiments were conducted in accordance with the tenets of the Declaration of Helsinki and were approved by the institutional review board of National University of Singapore (Experiments 1a and 2a) and California Institute of Technology (Experiments 1b and 2b). In Experiment 1a, three participants were removed from analyses and replaced because of outlier performance ($3 SD$ away from the group mean) on low mean accuracy on the lexical decision task ($n = 1$) or high false alarm rates on the blank trials (breakthrough in blank trials; $n = 2$); the tasks are described below. Twenty participants were included in the final analysis in each experiment. This number was a priori determined based on an 80% power calculation of our previous study (Hung & Hsieh, 2015). These criteria were later applied to all of the following experiments. In Experiments 1b, 2a, and 2b, the excluded participants ($3 SD$ away from the group mean) had low accuracy on the lexical decision task (1b, $n = 3$; 2a, $n = 0$; 2b, $n = 1$) or high false alarm rates on the blank trials (1b, $n = 0$; 2a, $n = 2$; 2b, $n = 0$).

General experimental apparatus

In all experiments, the visual stimuli were generated with MATLAB (The MathWorks, Inc., Natick, MA) and Psychtoolbox (Brainard, 1997; Pelli, 1997).

Participants viewed the dichoptic images through a mirror stereoscope mounted on a chin rest from a distance of 57 cm. In Experiments 1a and 2a, the stimuli were presented against a black background on a 22-inch Samsung 2233RZ (Suwon-si, South Korea) liquid-crystal display (LCD) monitor with a resolution of 1680×1050 pixels and a refresh rate of 60 Hz. In Experiments 1b and 2b, a 30-inch Apple M9179LL/A (Cupertino, CA) LCD monitor with a resolution of 2560×1600 pixels and a refresh rate of 60 Hz was used. Throughout the experiment, a white frame (subtending $3.9^\circ \times 3.9^\circ$) remained on-screen to facilitate proper fusion.

Experimental design: Experiment 1a

Forty three-word sentences from our previous study were selected (Hung & Hsieh, 2015). Each sentence followed a format of subject–verb–object syntactically congruent (CON) or subject–verb–verb syntactically incongruent (InCON). All verbs used in this experiment were transitive and derived from the top 500 most frequently used verbs (Brysbaert & New, 2009). For the syntactically incongruent condition, syntactic violation was created by substituting the object in the original subject–verb–object sentences with another verb. The two conditions thus had *identical subliminal sentential context* preceding the third target word (e.g., birds eat worms vs. birds eat drank). Each participant received both conditions of the sentence, allowing us to later measure the influence from an identical context to the syntactically congruent and incongruent target. The length and frequency of the third words were matched. For number of alphabets, objects = 6.35 (1.48) versus verbs = 6.33 (1.25); $t_{paired}(39) = 0.15$; $p = 0.88$. For frequency per million words (Brysbaert & New, 2009; Brysbaert, New, & Keuleers, 2012), objects = 57.36 (175.40) versus verbs = 47.54 (116.84); $t_{paired}(39) = 0.28$; $p = 0.78$. A complete stimuli list is included in the Supplementary Materials.

In each trial, the first two words were suppressed by dCFS. In the temporal domain, each word was sandwiched by flashing colored Mondrian patterns (10 Hz) for 400 ms. The word appeared slightly later and ended slightly earlier (two frames gap on each end on a 60-Hz monitor, ~ 66.67 ms) to prevent sudden breakthrough into consciousness (Figure 1). Therefore, each word was presented for approximately 333 ms in each on period and repeated five times. In each presentation, only a single word was shown. The third target word could be either congruent or incongruent, with or without a precedent context, leading to a 2 (congruence) \times 2 (context presence) \times 40 (number of sentences) design, resulting in 160 trials. Eighty pseudowords were generated using Wuggy, a pseudoword generator (Keuleers & Brysbaert, 2010).

Identical to the real-word conditions, each pseudoword was either preceded by two real words or not, leading to another 160 trials. These pseudowords served to balance the ratio of real words to pseudowords and were not relevant to our main research question. In addition, 20 visible fillers were added with words other than the original 40 sentential contexts. In these filler trials, the words were superimposed on the Mondrians to simulate the breakthrough trials. Participants were expected to detect these trials with near perfect performance (for the design tree, see Figure 2). Participants were instructed to respond if any part of the stimulus became visible during the suppression period to end the trial immediately. If nothing was detected during the suppression period, participants proceeded to perform a lexical decision task on the visible word (i.e., the third target word). In a lexical decision task, the participants were instructed to judge whether a word was a real word or a pseudoword. Participants were explicitly instructed to respond as quickly and as accurately as possible. The trial sequence and design tree are shown in Figure 1 and Figure 2, respectively.

Prior to the main experiment, a 40-trial thresholding session was performed to gauge the breakthrough thresholds of the first two words. The procedure was identical to the main experiment with the goal to familiarize the participants with the trial sequence with a different list of words. The contrast of each word was adjusted with a three-up/one-down procedure, known as the Bruceton test (Dixon & Mood, 1948). That is, the contrast was increased after three consecutive non-breaking trials but was decreased right after a breaking trial. The step size was 2.5% of full alpha value. This adaptive thresholding procedure continued in the main experiment to ensure consistent breaking rates.

Results: Experiment 1a

All the statistical analyses reported were performed on MATLAB with customized scripts. All numbers are reported in the format of mean (*SEM*). To objectively establish that the participants could perform the tasks well, we first examined their responses on visible fillers and trials that had no context (blanks) to gauge their ability to catch fillers and to determine false breaking rates. The mean accuracy to catch visible fillers was 99.5% (2.24%), and the mean false breaking rate was 0.69% (0.7%), indicating that the participants responded with high accuracy and consistency. The overall breaking rates were 35.13% (0.62%) with the contrast thresholds of word 1 and word 2 at 10.09% (1.58%) and 10.45% (1.88%), respectively.

A paired *t*-test was performed to compare the accuracy (ACC) and reaction times (RTs) of the target

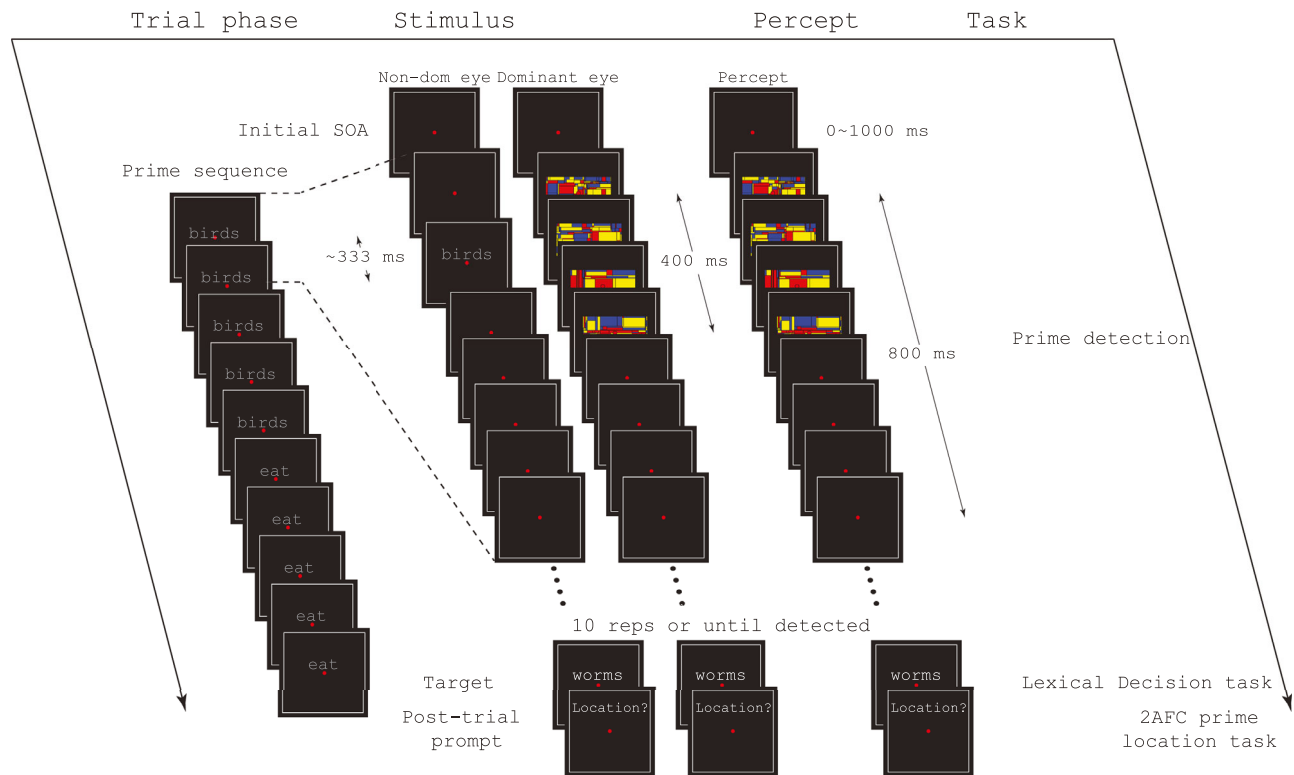


Figure 1. Trial sequence. The trial began with a randomized period ranging from 0~1000 ms, after which the dominant eye was presented with colored Mondrian patterns flashing at 10 Hz. The non-dominant eye was presented with a single prime word above or below the fixation. The prime word began 2 frames after and ended 2 frames before the Mondrians to prevent sudden breakthrough. Each cycle consisted of a 400-ms on and a 400-ms off period. Each word was repeated for five cycles, for a total of 10 cycles, or until breakthrough was detected. Participants were instructed to report when any part of the prime word was detected during the 10 cycles. The trial ended immediately when prime visibility was indicated. If the prime was not detected, participants were instructed to make a lexical decision on the subsequent target word. In Experiments 1b and 2b, a two-alternative forced-choice location task prompted the participants to report the hidden word location, serving as an objective measure of prime awareness. On the left, a prime sequence schematic is shown. SOA = stimulus onset asynchrony.

words between congruent and incongruent conditions. The results reported here were normalized against the baseline condition in which no sentence context was present; that is, the gain or loss of having a preceding subliminal sentence context was calculated for each condition. This procedure was adopted to prevent the possibility that the intrinsic differences between the two conditions (e.g., different syntactic categories) could drive any effect. In the results, $CON_{\text{without context}}$ and $InCON_{\text{without context}}$ simply refer to identical target words used in the congruent and incongruent conditions without a preceding subliminal context.

The comparison on ACC yielded no difference, $t(19) = 0.69$, $p = 0.50$, Bayes factor = 0.17, possibly due to ceiling performance. The mean ACC of the target word in each condition was as follows: $CON_{\text{with context}}$, 97.36%; $CON_{\text{without context}}$, 95.82%; $InCON_{\text{with context}}$, 97.24%; $InCON_{\text{without context}}$, 96.7%. For RTs, we normalized the relative change of each condition

(e.g., between $CON_{\text{with context}}$ and $CON_{\text{without context}}$) by dividing the response times by the mean response of the two conditions (e.g., $CON_{\text{with context}}$ and $CON_{\text{without context}}$). This normalization allowed us to discount the baseline response time differences of the two conditions (i.e., response time difference between nouns and verbs without a preceding context) and focused on the difference driven by the congruence. The results were significant, $t(19) = 2.80$, $p = 0.01$, Bayes factor = 14.94 (Figure 3, left panel), showing that reaction times to *incongruent* target words were faster when preceded by a suppressed sentential context. We also performed the same analysis on unnormalized data and found a similar result, $t(19) = 2.51$, $p = 0.02$, Bayes factor = 7.92. Please note that the Bayes factors (Dienes, 2011; Dienes & Mclatchie, 2017) were estimated based on the effect size we obtained in our prior study with a one-tail directional prediction (faster responses to syntactically incongruent targets) (Hung & Hsieh, 2015).

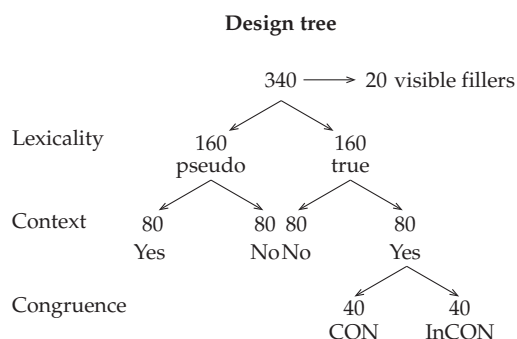


Figure 2. Design tree of the main experiments. The numbers denote the number of trials. Twenty of the overall trials were visible fillers to verify if participants indeed paid attention to the prime detection. In the remaining trials, lexicality denotes target lexicality. Half of the trials were pseudowords and the other half real words. In each half, half of the trials contained a sentential context. Furthermore, in the real-word condition with a context, half of the trials had a congruent syntactic relationship between the context and the target (context: subject + verb; target: object), and the other half had an incongruent syntactic relationship (context: subject + verb; target: verb).

Experimental design: Experiment 1b

To ensure that participants were truly unconscious of the subliminal sentential context, in Experiment 1b we further added in an *objective* measure of consciousness in every trial. In *non-breaking trials* where participants already subjectively indicated no visibility of the prime words, participants were further asked to perform a two-alternative, forced-choice (2AFC) task on guessing the location (below or above the fixation point) of the subliminal words. Chance performance on this task was used as an objective indicator of no visibility of the stimulus. All other procedures and stimuli remained identical as Experiment 1a.

Results: Experiment 1b

Similar to Experiment 1a, the mean accuracy to catch visible fillers was 98% (1.28%), and the mean false breaking rate was 4.75% (1.35%), indicating that participants responded with high accuracy and consistency. The overall breaking rate was 36.84% (1.02%) with the mean contrast thresholds of word 1 and word 2 at 11.16% (0.62%) and 10.86% (0.54%), respectively. Importantly, the 2AFC localization on the suppressed context yielded an overall performance of 50.02% (0.62%), which was not different from chance, $t(19) = 0.03$, $p = 0.98$, showing that the suppression

was successful and participants were objectively not conscious of the context. Furthermore, to examine if the faster responses to syntactically incongruent words was at least partially dependent on having conscious awareness of the context, a correlation analysis between the participants' accuracy on the 2AFC task and the main effect was performed. There was no significant correlation ($r = -0.02$, $p = 0.94$), indicating that better conscious localization of the context was not crucial for the subliminal effect to occur.

Similarly, we reported comparisons of the ACC and RT on the target words after normalizing to the baseline blank trials. The comparison on ACC yielded no difference, $t(19) = 0.95$, $p = 0.36$, Bayes factor = 0.29. The target word mean ACC in each condition was as follows: CON_{with context}, 98.71%; CON_{without context}, 98.11%; InCON_{with context}, 97.21%; InCON_{without context}, 98.28%. For RTs, the results successfully replicated those of Experiment 1a, showing that reaction times to *incongruent* target words were faster when preceded by a suppressed sentential context, $t(19) = 2.71$, $p = 0.01$, Bayes factor = 23.32 (Figure 3, right panel). A similar pattern was observed on unnormalized data (direct subtraction between conditions with and without context), $t(19) = 2.71$, $p = 0.01$, Bayes factor = 27.34.

$$RT_{normalized} = \frac{RT_{with\ context} - RT_{without\ context}}{(RT_{with\ context} + RT_{without\ context})/2}$$

Potential lexical category confound: Verbs versus nouns

In both Experiments 1a and 1b, the incongruent target words were always verbs and the congruent target words were always nouns. Although we normalized the RTs of both conditions against their corresponding target words without the invisible context, it is crucial to know whether pure lexical category differences could drive the RT differences we found in both experiments. We thus directly compared the raw RTs of the two conditions without a preceding invisible context. We found that the baseline RTs of the target words were *reversed* in both main experiments. For Experiment 1a, RT_INCON_{without context} = 0.970 s vs. RT_CON_{without context} = 0.938 s, $t(19) = 2.54$, $p = 0.02$. For Experiment 1b, RT_INCON_{without context} = 1.533 s vs. RT_CON_{without context} = 1.351 s, $t(19) = 3.29$, $p = 0.004$. These results show that when there was no invisible context participants indeed responded faster to the nouns than the verbs, indicating that our findings were not simply driven by lexical category differences. If anything, the contextual effect was entirely against the baseline reaction time differences between the two lexical categories.

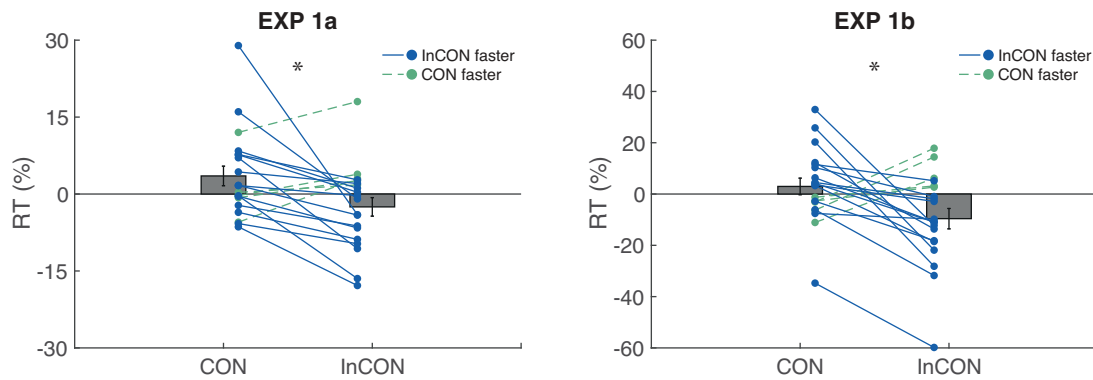


Figure 3. Individual and group data on normalized reaction time percentage differences between congruent and incongruent target words (left, Experiment 1a; right, Experiment 1b). Both experiments showed faster response time to the incongruent target words. The response time in each condition was first contrasted with the baseline response time (i.e., the response time to a target without a precedent context) and further divided by the mean response time. Individual data are shown as dots, and the group data are shown as bars. Blue dots indicate individuals who showed faster response in the incongruent condition, and green dots indicate individuals who showed faster response in the congruent condition. The data for the same participant in the two conditions are connected by a solid (InCON faster) or a dashed (CON faster) line. Error bars denote standard errors. * $p < 0.05$ at the group level.

Experimental design: Experiment 2a

The purpose of Experiment 2a was to examine whether the subliminal effect observed in Experiments 1a and 1b was driven by the contextual effect generated from the integration of the first two suppressed words or was merely a word–word association between the second and third words (e.g., eat–worms vs. eat–drank). In this control experiment, we removed the first words of the sentences and only presented the second words under suppression, which resulted in a total of five cycles. The rest of the procedure remained identical. If the findings in Experiments 1a and 1b were indeed caused by (in)congruence between the subliminal sentential context and the supraliminal target, we would expect the effect to disappear.

Results: Experiment 2a

The mean accuracy to catch visible fillers was 100%, and the mean false breaking rate was 0.25% (0.37%), indicating that participants performed the experiment with high accuracy and consistency. The overall breaking rates were 27.56% (2.08%) with the mean contrast level of the suppressed word at 9.51% (0.72%). Similarly, the comparison of ACC yielded no difference, $t(19) = -0.31$, $p = 0.76$, Bayes factor = 0.08: CON_{with context}, 97.51%; CON_{without context}, 96.58%; InCON_{with context}, 98.23%; InCON_{without context}, 99.1%. Critically, the comparison of CON versus InCON RTs yielded no difference either before normalization, $t(19) = -0.68$ $p = 0.50$, Bayes factor = 0.28, or after

normalization, $t(19) = -0.66$, $P = 0.52$, Bayes factor = 0.28 (Figure 4, left panel). The results here suggest that what we found in Experiments 1a and 1b was driven by the temporal integration of the suppressed sentential context and its sentence-level association to the target word, rather than a word–word association between the second and third words.

Experimental design: Experiment 2b

In Experiment 2b, we made two changes to Experiment 1a to ensure that the participants were truly unconscious of the subliminal text, as well as to rule out one more alternative explanation of our main finding in Experiments 1a and 1b. Similar to Experiment 1b, we added in a 2AFC location task as an objective measure of consciousness. The findings in Experiment 2a suggested that word–word association between the second (subliminal) and third (supraliminal) words did not drive the effect in Experiments 1a and 1b; however, one could still argue that the word–word association between the first and third words might have driven the effect (e.g., birds–worms vs. birds–drank). In order to address this possibility, in Experiment 2b, we flipped the first two words to deconstruct the sentence. If our effect was merely driven by word–word association between the first and the third words, we would expect to replicate the findings in Experiments 1a and 1b. Otherwise, if the effect was indeed due to the subliminal integration of two prime words in the correct order, we would expect the effect to disappear after a destruction of sentential context.

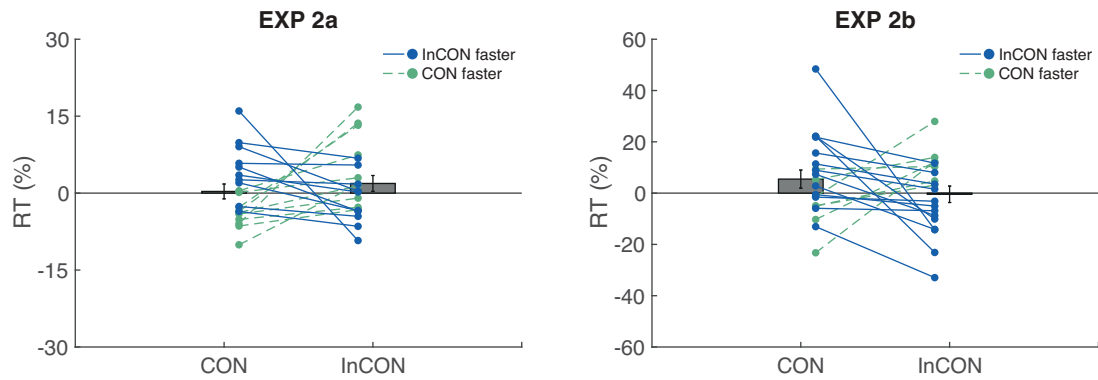


Figure 4. Individual and group data on normalized reaction time percentage differences between congruent and incongruent target words (left, Experiment 2a; right, Experiment 2b). The calculation was identical to the previous experiments. Individual data are shown as dots, and the group data are shown as bars. Blue dots indicate individuals who showed faster response in the incongruent condition, and green dots indicate individuals who showed faster response in the congruent condition. The data for the same participant in the two conditions are connected by a solid (InCON faster) or a dashed (CON faster) line. Error bars denote standard errors.

Results: Experiment 2b

The mean accuracy to catch visible fillers was 99.25% (0.41%), and the mean false breaking rate was 3.16% (1.06%), indicating that participants performed the experiment with high accuracy and consistency. The overall breaking rate were 35.5% (0.51%) with the mean contrast levels of suppressed word 1 and word 2 at 11.13% (0.58%) and 10.42% (0.45%), respectively. The 2AFC localization on the suppressed context yielded an overall performance of 51.89% (0.79%), which was higher than chance, $t(19) = 2.38$, $p = 0.03$. However, further analysis showed that the (in)congruence effect was not correlated with localization performance ($r = 0.21$, $p = 0.38$). Similarly, the comparison on ACC yielded no difference, $t(19) = 0.34$, $p = 0.74$, Bayes factor = 0.15: CON_{with context}, 98.41%; CON_{without context}, 97.58%; InCON_{with context}, 96.96%; InCON_{without context}, 96.74%. Critically, the comparison on RTs yielded no difference both before normalization, $t(19) = 1.19$, $p = 0.25$, Bayes factor = 1.79, or after normalization, $t(19) = 1.13$, $p = 0.27$, Bayes factor = 1.15 (Figure 4, right panel). The results here further ruled out the possibility that word–word association between words 1 and 3 drove the effect in Experiments 1a and 1b.

General discussion

Information integration over and beyond several units is critical for coping with the massive information flow that occurs moment by moment. This complex processing typically requires holding and assembling

information across different items in space or in time. Due to the complexity and flexibility required to perform such a task, consciousness is typically believed or argued to be a prerequisite. However, previous studies have relied on null findings to affirm the role of consciousness on complex information processing. That is, once consciousness is depleted with a particular method (e.g., crowding, masking, interocular suppression), if an effect that could be found with conscious perception disappears, it is then concluded that consciousness is a prerequisite for such an effect (Axelrod & Rees, 2014; van Gaal et al., 2014; Yang et al., 2017). We argue that such a conclusion is unwarranted because it remains elusive whether the subliminal stimulus strength was strong enough in these studies. Previous studies have tended to optimize the *luminance* of a subliminal stimulus with a thresholding procedure; however, the *duration* of its presentation was rarely manipulated. Here, we introduced a novel form of interocular suppression, named discontinuous flash suppression (dCFS), and utilized dCFS to examine temporal integration of subliminal linguistic information. Our results showed faster response times to syntactically incongruent target words when those target words were preceded by a subliminal sentential context. This finding challenges previous findings on the importance of consciousness in information integration.

Our main finding that response times were significantly shorter for a syntactically incongruent target word preceded by an invisible sentential context replicated our previous study. We showed that subsequent to a two-word conscious sentential context, syntactically incongruent words reached consciousness faster under interocular suppression (Hung & Hsieh,

2005). These findings may first appear inconsistent with the literature. For example, studies have documented that, subsequent to a visible congruent linguistic context, people responded faster to the target word (O’Seaghdha, 1989; Seidenberg, Waters, Sanders, & Langer, 1984; Simpson, Peterson, Casteel, & Burgess, 1989). However, we offer several reasons to provide a theoretical background for our findings. First of all, unconscious processing may be tuned to detect inconsistency, saliency, or anomaly in the stimulus, which is evident in unconscious saliency processing (Hsieh, Colas, & Kanwisher, 2011; Zhaoping, 2008). Second, although shorter response times have been observed when responding to a word semantically or syntactically related and temporally close to another invisible, undetected, or unrecognized word (e.g., for subliminal semantic priming, see Costello et al., 2009; Dehaene et al., 1998; Yeh, He, & Cavanagh, 2012); for subliminal syntactic priming, see Berkovitch & Dehaene, 2019; Iijima & Sakai, 2014), this word-level unconscious priming effect was less clear when it came to the sentence or phrase level. For example, it was reported that semantically incongruent sentences broke through suppression faster than congruent sentences (Sklar, Levy, Goldstein, Mandel, Maril, & Hassin, 2012; but see a recent failure on replication, Rabagliati, Robertson, & Carmel, 2018). One determining factor could be stimulus-driven attention—that is, stimuli that attract attention most (e.g., associated words and inconsistent context) enjoy a reduction of response time or better performance (e.g., for facial attractiveness, see Hung, Nieh, & Hsieh, 2016; Nakamura & Kawabata, 2018; for erotic body, see Jiang, Costello, Fang, Huang, & He, 2006). A systematic study on what exactly attracts our attention unconsciously is required to reach a conclusion. Finally, our results are compatible with other recent empirical findings. For example, online temporal integration of a subliminal syntactic structure can be explained by the early occipital sensitivity to syntactic incongruence (Dikker, Rabagliati, Farmer, & Pylkkänen, 2010). Meanwhile, it has been shown that readers were less likely to skip syntactically incongruent words while reading (Brothers & Traxler, 2016). This finding suggests that pre-target-word syntactic context forms grammatical constraints that guide attention during sentence comprehension, which in turn makes syntactic inconsistency salient. Nevertheless, the exact mechanism underlying the early breakthrough or response of incongruency in the current paradigm requires further research.

Our finding on subliminal temporal integration can be attributed to the enhanced subliminal strength under dCFS. In fact, in bistable perception, intermittent presentation has been shown to stabilize the salient stimulus while keeping the other stimulus suppressed and invisible. Leopold et al. (2002) showed that intermittent presentation stabilized the dominating

percept in bistable perception, both with intermittent presentation of the visual stimulus and with eye blinking at the second level (e.g., stimulus on/eyes open for 2 seconds and stimulus off/eyes closed for 5 seconds). The study also showed that the decrease of reversals in bistable perception during intermittent presentation cannot be explained by the sheer loss of stimulus exposure, as the stabilization effect was significantly stronger than what shortened exposure predicted. In our study, introducing the intermittent presentation to interocular suppression allowed repetitive presentation of the prime words. Because the optimal subliminal strength to elicit an effect remains unknown, in both the temporal domain (i.e., stimulus duration) and the spatial domain (i.e., stimulus contrast), dCFS serves as a potential tool for studying our capability to process and utilize unconscious information.

Because the brain receives a massive amount of information at all times, one central issue in psychology and neuroscience remains: When and how do we form a coherent pattern by integrating information from different sources? Visual statistical learning has shed light on the answer. For example, in the third experiment of Turk-Browne, Jungé, and Scholl (2005), even when participants had no explicit knowledge and awareness of visual triplet sequences during the learning phase, responding to the later elements of the sequence had a reaction time advantage in the test phase. Such results indicate that we could continuously track sequences in the environment implicitly. Our study, however, approached this possibility with a very different question by asking: *Can people extract a well-learned sequence when the visual information does not enter our consciousness at all?* Our results gave an affirmative answer.

The unconscious operating system can be regarded as the frontline of our interaction with the environment or as a seemingly automatic process that is mostly present in the background. This system has often been described as being fleeting, as the information decays quickly, and complex information integration fails to occur (Dehaene & Changeux, 2011). However, based on our findings that temporal information integration across multiple units could occur without the stimulus entering our conscious awareness, we argue that the complexity of information integration may not be an accurate divider of our conscious and unconscious worlds. As we by definition do not have conscious access to our unconscious processing system, it is considered a rigid system that lacks the ability to integrate information, scientifically or intuitively. This notion is challenged by our findings that a sentential context, albeit suppressed and invisible, could still influence the lexical decision on a subsequent word.

Keywords: syntax, semantics, consciousness, continuous flash suppression, unconscious processing

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