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The limits of unconscious semantic priming

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Abstract
Semantic information can be accessed unconsciously, yet it remains unclear to what extent unconscious semantic information spreads across association networks. We compared conscious and unconscious semantic priming among different levels of semantic associations: direct, cross-form, and metaphoric associations. Chinese words associated with thermal qualities (cold or warm) were adopted as the primes, followed by a discrimination task regarding the target being associated with coldness or warmth. The targets were (1) words with thermal qualities, (2) illustrations representing thermal qualities, or (3) words describing personality traits that are metaphorically associated with thermal qualities. We first demonstrated the typical semantic priming effect in the three types of semantic associations when the prime was visible (Experiment 1). We then rendered the primes invisible using the continuous flash suppression paradigm and found a reversed semantic priming effect for the direct association and yet no priming effects for the cross-form and metaphoric associations (Experiment 2). These results suggested that unconscious semantic priming only occurs between directly associated stimuli while consciousness is necessary for higher-level associations and facilitatory interactions, delineating the contrast between unconscious and conscious semantic processing.

Keywords Semantic priming · Continuous flash suppression · Consciousness · Thermal quality

Introduction

Unconscious and conscious processing in the human brain are suggested to be dissociated to a certain level (Dehaene et al., 2006). On the one hand, information in the rapid feedforward stream is processed and represented unconsciously at multiple hierarchical levels (Hochstein & Ahissar, 2002). Specifically, unconscious processing stream includes not only low-level features such as orientations and shapes (Hesselmann et al., 2016; Kanai et al., 2006) but also higher-level complex and meaningful representations such as digits, eye-gaze directions, facial expressions, and natural scenes (Almeida et al., 2013; Bahrami et al., 2010; Chen & Yeh, 2012; Luo et al., 2016; Mudrik et al., 2011; Tan & Yeh, 2015; Yang et al., 2007; Yang & Yeh, 2018a, b). On the other hand, conscious experience regarding a given stimulus is formed when the associated representations exceed a certain threshold and gain priority over other stimuli (Driver & Vuilleumier, 2001). The global neuronal workspace theory (GNWT) states that conscious processing involves the short-term preservation of the attended information in a global neural loop (Dehaene et al., 2003; Sergent & Dehaene, 2004; Van Vugt et al., 2018). According to the GNWT, information that is processed unconsciously is fragmentary and local; on top of that, information that is processed consciously is dispersed across a vast neural network and becomes reportable.

Mudrik et al. (2014) proposed the idea of an "integration window" to further explain the distinction between unconscious and conscious processing. According to this

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concept, the information presented in close space and/or time can be associated unconsciously (i.e., in a small spatiotemporal integration window); otherwise, consciousness is required for associating information across a wide spatiotemporal integration window. This notion has further been extended to the semantic domain when it comes to associating meaningful stimuli or applying logical syntactic rules, called the *semantic processing integration window* (*SPIW*, Mudrik et al., 2014). Mudrik et al. proposed that the limits of unconscious semantic integration could be examined by adopting the priming paradigm and manipulating the level of semantic relation between the prime and target. They defined low-level semantic relations as the associations between pieces of knowledge belonging to the same category (e.g., a stop sign and a no-entry sign), and high-level semantic relations as associating conceptual and metaphoric knowledge (e.g., a street sign indicating multiple directions as a metaphor for difficulties in decision making). Associating low-level semantic relations can occur unconsciously, but associating high-level semantic relations requires consciousness. According to the SPIW, we expected that *visible* primes would modulate behavioral responses toward targets regardless of the level of semantic relations between the primes and targets; in contrast, *invisible* primes should only modulate behavioral responses toward targets when they have low- rather than high-level semantic relations.

Semantic priming typically refers to the facilitation of the processing of a target when it is preceded by a semantically related prime rather than an unrelated prime (e.g., Meyer and Schvaneveldt (1971). Semantic priming is closely related to the mechanism of language processing and memory because the prime-target relationship forms a time-evolving retrieval cue that facilitates semantic access to the target (Hutchison et al., 2013; McNamara, 2005). Semantic priming effect has been demonstrated between various prime and target such as word-word, picture-picture, word-picture, and picture-word pairs (Carr et al., 1982; Sperber et al., 1979), suggesting that words and pictures share a common semantic representation/network (Bajo, 1988). Nevertheless, stimuli having lower- and higher-level semantic relations seem to be dominantly processed at distinct neural networks. Previous studies suggest that low-level semantic relationships such as a related word-word pair (e.g., lion and tiger) are mainly processed in the left-lateralized semantic network while integrating indirectly related word pairs (e.g., lions and stripes; Sass et al., 2009), high-level semantic relationships (e.g., picture-word pairs; Kircher et al., 2009), and metaphorically associated word pairs (e.g., stinging and insult; Anaki et al., 1998), would further recruit the right hemisphere.

Here we aimed to empirically test the idea that low-level semantic associations occur at the levels of both unconscious and conscious processing, and high-level semantic associations only occur at the level of conscious processing. We compared one low-level and two types of high-level semantic associations between prime and target using visible or invisible primes. The low-level semantic association constituted two words both referring to thermal quality (cold or warm). The first type of high-level semantic association was cross-form pairings between words and illustrations that are associated with abstract thermal concepts. The second type of high-level semantic association consisted of metaphorically associated word pairs, one referring to thermal quality and the other as a personality trait metaphorically associated with thermal quality. Specifically, a warm person means he or she is friendly, kind, and helpful, whereas a cold person is considered heartless and hostile. Such metaphors between thermal qualities and personality traits are innately rooted in human cognition (Fiske et al., 2007).

We adopted the continuous flash suppression (CFS) paradigm (Fang & He, 2005; Tsuchiya & Koch, 2005) to rigorously control the visual words to be invisible for a relatively long period than other techniques such as backward masking (Breitmeyer & Ogmen, 2000). CFS is a prolonged form of interocular suppression to prevent the target from reaching consciousness by presenting a rapid sequence of high-contrast Mondrian patterns to an observer's one eye (usually the dominant eye) that would intensively suppress the lower-contrast target stimulus presented to the other eye (i.e., the non-dominant eye). Both human behavioral and neural studies have demonstrated that semantic information of words can be unconsciously accessed under CFS (Costello et al., 2009; Eo et al., 2016; Sklar et al., 2012; Yang & Yeh, 2011; Yang et al., 2017; though see Moors et al., 2017). Hence, CFS is an ideal paradigm to study unconscious semantic processing of visual words (Breitmeyer, 2015; Yang et al., 2014).

We began by examining the semantic priming effects of the above three types of stimulus pairs when the prime was presented consciously (Experiment 1). We then examined semantic priming effects when the prime was presented unconsciously in Experiment 2 for thermal word pairs (Experiment 2 A), cross-form pairs (Experiment 2B), and `metaphorically associated pairs (Experiment 2 C). We posited that visible primes in Experiment 1 should result in semantic priming effects for all three types of stimulus pairs whereas invisible primes in Experiment 2 should result in semantic priming effects only between low-level semantic stimuli (i.e., the thermal word pairs), but not between high-level semantic stimuli (i.e., the cross-form and metaphorically associated pairs).

General method

Participants

Participants were recruited from National Taiwan University and they are native speakers and skilled readers of Mandarin Chinese. All participants had normal or corrected-to-normal vision, and no history of dyslexia, neurological problems, psychiatric disorders, or brain injury by self-report. They were naïve about the purpose of the experiment and were compensated with course credits or 75 NTD. The study was approved by the Research Ethics Committee at the National Taiwan University.

Apparatus

The stimuli were presented on a 19-inch CRT monitor (1024 × 768 resolution at 120-Hz refresh rate) and controlled by Matlab (the Math Works, Natick, USA) with Psychophysics Toolbox (Brainard, 1997; Pelli & Vision, 1997).

Stimuli

Full lists of stimuli and associated statistical tests of the stimuli are reported in Supplementary Materials.

Prime. Twelve Chinese two-character words referring to thermal qualities (six for coldness and six for warmth) were used as primes in Experiments 1 and 2 (see Table S1 in the Supplementary Materials). The warm words were rated as significantly higher in warmness than the cold words, while the warm and cold words had similar mean valence. Occurrence frequency and the number of strokes were matched between the warm and cold words. Thus, familiarity and perceptual complexity of the words would not be confounding factors in the experiments.

Target. Three types of targets were used in this study: (1) words related to thermal qualities; (2) illustrations representing thermal qualities, and (3) words referring to personality traits (Fig. 1A).

Words of thermal qualities. Another 20 Chinese two-character words (10 for coldness and 10 for warmth, Table S2), different from the primes, were used as targets in Experiments 1 and 2 A. Mean values of warmness were significantly higher for the warm words than the cold words. Valence, occurrence frequency and the number of strokes were all similar between the cold and warm words.

Illustrations. Ten grayscale illustrations representing coldness and 10 representing warmth adopted from Zhou et al. (2017) were used as targets in Experiments 1 and 2B (Figure S1). The rated warmness was significantly higher for the warm illustrations than the cold illustrations. Valence was similar between the cold and warm illustrations.

Words of personality traits. Twenty Chinese two-character words referring to personality traits that are metaphorically associated with the thermal concepts were used as targets in Experiments 1 and Experiment 2 C (10 associated with cold traits and 10 with warm traits, Table S3). The rated warmness was significantly higher for the warm words than the cold words. There were no differences in occurrence frequency and number of strokes between the warm and cold traits.

Semantic relatedness between the primes and the targets. We also checked the semantic relatedness between the primes and targets in Experiments 1 and 2 (Table S4). The statistical results demonstrated higher semantic relatedness for congruent pairs than incongruent pairs in three types of stimulus pairs, but the semantic association was higher in the word-word and cross-form pairs than in the metaphorically associated pairs.

CFS masks. The CFS masks were 16° ⊆ 16° Mondrian patterns with 10 Hz refresh rates. Each mask consisted of 6000 color rectangles. Participants viewed stimuli through shutter glasses (NVIDIA 3D Vision 2) which could present images to one eye while blocking the vision of the other eye. When two visual stimuli were presented alternately and synchronously with the frequency of the shutter glasses, each stimulus would be presented to only one eye (i.e., a dichoptic presentation). In Experiment 1, the prime was superimposed on the CFS masks and they were presented to both eyes of the participants, so the primes were visible. In Experiment 2, the CFS masks were presented to the dominant eye to make the primes presented to the non-dominant eye invisible. The dominant eye was determined by The Miles Test (Laby et al., 1998): The participants were asked to extend both of their arms with palms facing away, forming a small hole by crossing the thumbs and forefingers. Participants looked at a small object through the small hole with both eyes open, and then watched with each eye individually. If the object was still seen through the small hole when using the right eye, then his/her right eye was dominant; otherwise, his/her left eye was dominant.

Procedure

The main experiment consisted of a primed discrimination task followed by a subjective visibility check of the prime (Fig. 1B). In each trial, participants were instructed to fixate on the cross in the center of the display and press the space bar to initiate the trial. Then, a prime and a series of CFS masks were presented one to each eye dichoptically for 1000 ms. The contrast (Michelson contrast) of the primes was increased from 0 to 70% in 1000 ms in a linear fashion while the contrast of the Mondrian masks remained at 100%. Participants were asked to pay attention to the masks.

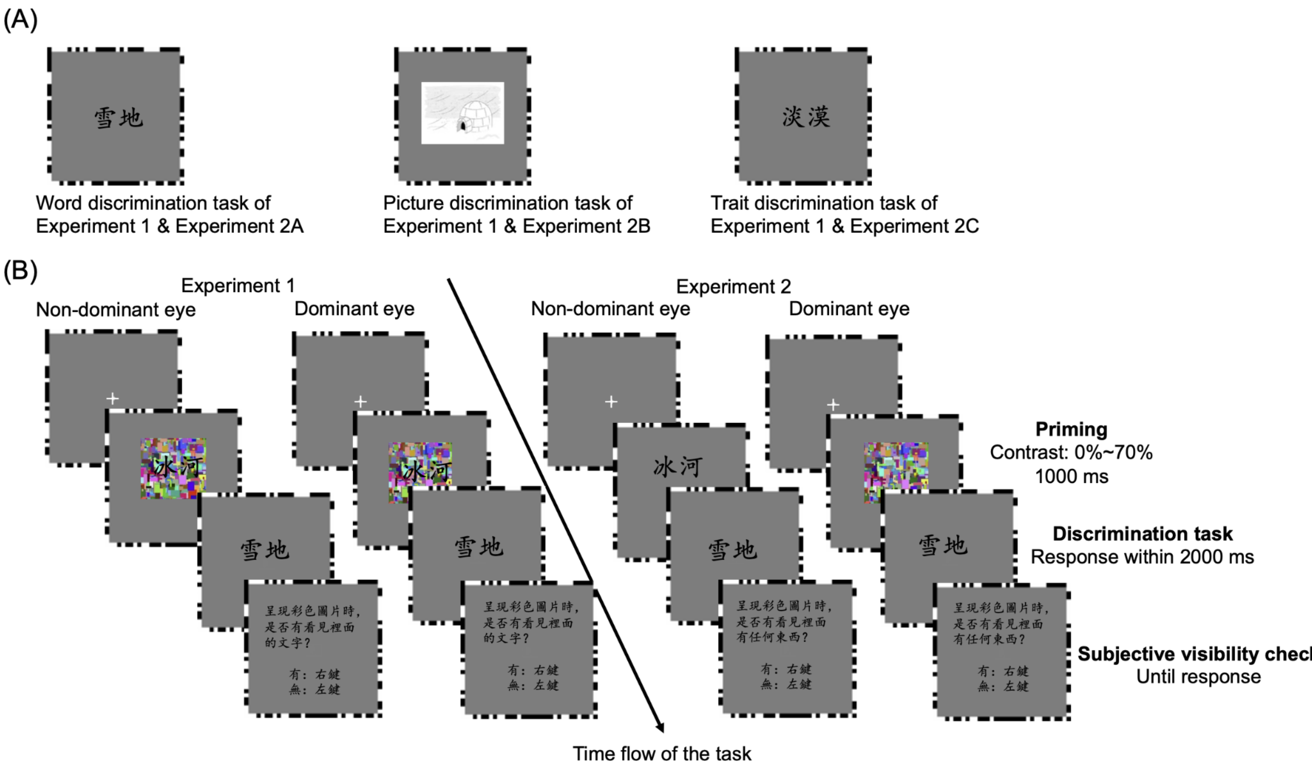

Fig. 1 (A) Examples of three types of targets used in the present study. The left panel shows an example word related to thermal qualities used in the word discrimination task in Experiments 1 and 2 A. The meaning of the word shown here "雪地" is "snowy ground". The middle panel shows an example illustration used in the picture discrimination task in Experiments 1 and 2B. The right panel shows an example word of personality traits used in the trait discrimination task in Experiments 1 and 2 C. The meaning of the word shown here "淡漠" is "impassive". (B) The CFS presentation was followed by the word discrimination task and subjective visibility check. In the word discrimination task, the prime was presented for 1000 ms. Participants were asked to discriminate the following target as either cold or warm. Then, participants completed a subjective visibility check of the visibility of the prime at the end of each trial. In Experiment 1, the prime was superimposed on the CSF masks and presented to both eyes; hence, the prime was visible. In Experiment 2, the prime was presented to the non-dominant eye while the CFS masks were presented to the dominant eye; hence, the prime was rendered invisible. The prime "冰河" used in Fig. 1B means "glacier"

Then, a target with 100% contrast was presented to both eyes. Participants were required to discriminate the meaning of the target associated with either coldness or warmth by pressing 'A' or 'L' on the keyboard using their left or right index fingers, respectively. They were asked to respond as accurately and rapidly as possible. The assignment of response correspondent keys was counterbalanced between participants. The trial would be terminated automatically if the participant did not respond in two seconds after the onset of the target, and this trial would be excluded from further analysis.

After the primed discrimination task, participants performed the subjective visibility check of the prime. In Experiment 1, the participants were required to report whether there was a two-character word in the trial they just conducted given that the prime should be visible. In Experiment 2, the participants were inquired whether there was anything superimposed on the CFS masks given that the prime should be invisible. In Experiment 2, if the participant reported that they had seen something on the masks in a given trial, the highest contrast of the prime in the next trial would be decreased by 2.5% to reduce the possibility that the participant would see the prime again. After the main experiment in Experiment 2, an additional objective visibility check session was performed to confirm that the contrast of the prime was below the participants' conscious threshold under CFS.

Data analysis

In Experiment 1 where the supraliminal primes were presented, all participants were included for further analysis; however, if the participants reported that they did not see the prime in the subjective visibility task in a given trial, the trial was removed from further analysis to ensure that the primes were all *visible* to the participants in the remaining trials.

In Experiment 2 where the subliminal primes were presented, to ensure that the participants were not aware of the presentation of the primes, exclusion criteria at both the participant and the trial levels were employed: If the accuracy of the objective visibility check (see details in Experiment 2) of a given participant was significantly higher than chance level (i.e., 50%) in terms of the binomial test, then the data of this participant would be excluded from further analysis. In the remaining participants, if they reported that they had seen something superimposed on the masks in the subjective visibility check in a given trial, then the trial would be excluded from further analysis. With these two exclusion criteria, we ensured that the trials included for analysis were all *invisible* to the participants.

We then calculated mean RTs to represent participants' performance in the primed discrimination task. Trials with (1) incorrect responses and (2) RTs higher or lower than three standard deviations (SDs) from the mean RT of each participant were excluded from the analysis. Individual mean RTs were submitted to an analysis of variance (ANOVA) on the factors of Task (word, picture, and trait discrimination task), Prime (cold or warm), and Target (cold or warm), and the interaction between Prime and Target would suggest a congruency effect between them. We estimated the semantic congruency effect by calculating the mean RTs in the congruent (both prime and target belong to the cold or warm category) and incongruent conditions (the prime and target belong to different categories). The typical semantic congruency effect would be manifested by a shorter RT in the congruent than the incongruent condition.

Experiment 1: visible primes

In Experiment 1, we examined the semantic priming effect induced by visible primes on three types of targets. The experimental paradigm was similar to the CFS-priming experiments used before (Yang et al., 2017) except that the primes were presented binocularly and superimposed on the CFS masks. There were three tasks in Experiment 1: First, in the word discrimination task (word-word pairs), the prime-target pairs were semantically congruent (e.g., Glacier-Chill) or incongruent (e.g., Freeze-Fire). Second, in the picture discrimination task (cross-form pairs), the primes were semantically congruent or incongruent with the targets which were illustrations. Third, in the trait discrimination task (metaphorically associated pairs), the primes were metaphorically congruent (Freeze-Heartless) or incongruent (Freeze-Sanguine) with the target words which refer to personality traits. Because the preceding prime was visible in this experiment, RTs were expected to be shorter in the congruent than in the incongruent condition regardless of the task.

Method

Twelve participants (6 males, age range: 18–35 years) participated in Experiment 1. The number of participants was determined based on an 80% power calculation of Experiment 1 in Kouider and Dupoux (2004)'s study investigating conscious semantic priming (required $N=8$, we added four more participants to be more conservative). The design of the primed discrimination task adopted a 2 (Prime: cold or warm) × 2 (Target: cold or warm) × 3 (Task: word, picture, or trait) within-participant design. There were three blocks in Experiment 1, one for each task. The order of the blocks was counterbalanced across participants.

For each task, there were 240 trials (12 cold/warm primes × 20 cold/warm targets) which were presented in a pseudorandom order, resulting in a total of 720 trials. Participants completed 16 trials for practice before the experiment. Stimuli in the practice trials were not used in the main experiment.

Results

There were 10.04% of trials removed, including 3.95% of trials due to incorrect responses (4.37%, 3.99%, and 3.49% in the word, picture, and trait discrimination tasks, respectively), 5.67% of trials where the prime was not perceived consciously, and 0.42% of trials due to RTs exceeding 3 SDs.

Individual mean RTs were submitted to a three-way repeated-measures ANOVA on the factors of Prime, Target, and Task (Fig. 2). The main effect of Target was significant ($F(1,11)=5.50$, $p=.04$; $\eta_p^2=0.33$; $BF_{10}=0.20$), but not the main effect of Prime ($F(1,11)=0.51$, $p=.49$; $\eta_p^2=0.04$; $BF_{10}=0.19$). The main effect of Task was marginally significant ($F(1,11)=3.21$, $p=.06$; $\eta_p^2=0.23$; $BF_{10}=3991.09$); however, post-hoc tests demonstrated no significant difference between the three tasks (all $t(11)<2.21$, $ps>0.14$ with *Bonferroni correction*, Cohen's $d<0.65$; all $BF_{10}<0.99$). Critically, the two-way interaction between Prime and Target was significant ($F(1,11)=28.60$, $p<.001$; $\eta_p^2=0.72$; $BF_{10}=20.61$). That is, we found a semantic congruency effect that RT was shorter in the congruent than in the incongruent condition regardless of the task (word discrimination task: 622 vs. 654 ms, $t(11)=3.25$, $p=.024$, Cohen's $d=0.94$; $BF_{10}=7.32$; picture discrimination task: 580 vs. 620 ms, $t(11)=5.15$, $p=.001$, Cohen's $d=1.49$; $BF_{10}=106.50$; trait discrimination task: 653 vs. 679 ms, $t(11)=2.93$, $p=.042$, Cohen's $d=0.84$; $BF_{10}=4.57$; p-values were adjusted with Bonferroni correction). In addition to significant differences revealed by t-tests, the values of Cohen's d and Bayesian

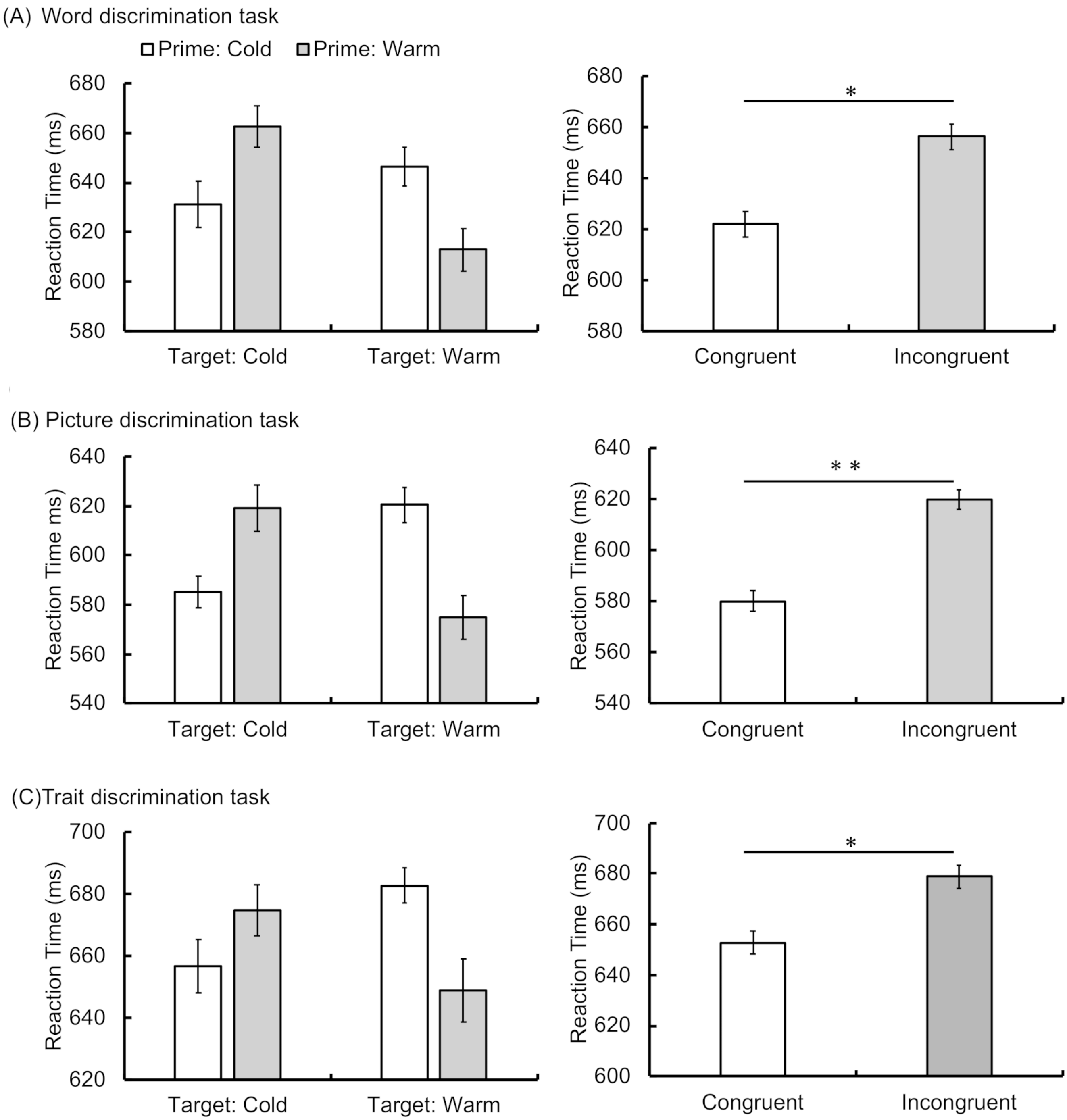

Fig. 2 The results of Experiment 1 for (A) word discrimination task, (B) picture discrimination task, and (C) trait discrimination task. Mean RTs in each condition of a factorial design (Prime x Target) are shown in the left panels, and the congruency effects between the prime and target are shown in the right panels. The congruency effect is calculated by subtracting the mean RTs in the congruent (both prime and target belong to the cold or warm category) from that in the incongruent condition (the prime and target belong to different categories). Error bars represent +/-1 within-participant SEMs (Cousineau, 2005; Loftus & Masson, 1994) of the mean. * and ** denote $p < .05$ and $p < .01$, respectively

factor suggest that there were strong congruency effects on three types of prime-target pairs.

Discussion

In Experiment 1, we examined the semantic congruency effects of the three types of prime-target pairs used in the

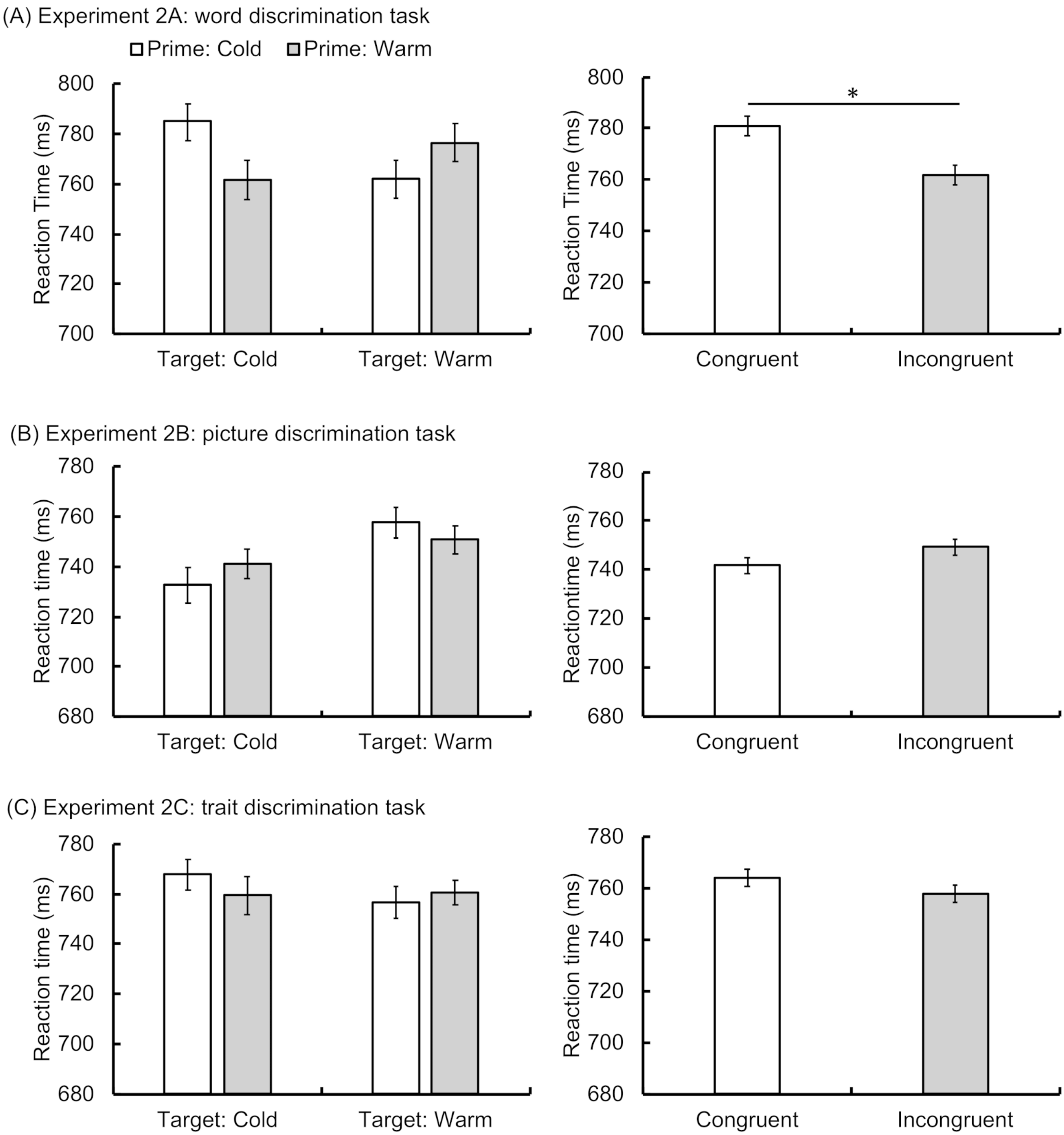

Fig. 3 The results of Experiment 2. Left panels depict the mean RTs in each condition in the Prime x Target factorial design, and the right panels depict the congruency effect of Experiments 2 A, 2B, and 2 C. Error bars represent +/-1 within-participant SEMs (Cousineau, 2005; Loftus & Masson, 1994). * denotes $p < .05$

current study: word-word pairs, cross-form pairs, and metaphorically associated pairs. Results showed that when the primes were visible, RTs of target discrimination were reliably shorter in the congruent than in the incongruent condition for three types of prime-target pairings regardless of their levels of semantic associations.

Experiment 2: invisible primes

We separately examined the semantic priming effect of the word-word pairs (Experiment 2 A), cross-form pairs (Experiment 2B), and metaphorically associated pairs (Experiment 2 C) when the prime was subliminally presented. The same stimuli as in Experiment 1 were used here, and the only difference was that the primes were rendered invisible using CFS. If the meaning of a word can be accessed unconsciously, we should observe the semantic priming effect as in Experiment 1.

Methods

There were 35, 41, and 36 participants (13, 10, 16 males) in Experiments 2 A, 2B, and 2 C, respectively (age range: 18–35 years); however, 11, 17, and 12 participants in Experiment 2 A, 2B, and 2 C were excluded from further analysis respectively, because their accuracy in the objective visibility check exceeded chance level (50%). Hence, 24 participants remained in the final analyses of each experiment. The number of participants in the final analyses was a priori determined based on an 80% power calculation of Experiment 1 in Almeida et al. (2008), which demonstrated an unconscious priming effect under CFS.

The meaning of the primes (cold or warm) and the target (cold or warm) were manipulated in a 2×2 within-participants design. The prime-target pairs used in Experiments 2 A, 2B, and 2 C were word-word, cross-form, and metaphorically associated pairs, respectively. The procedure was the same as Experiment 1 except that the primes were invisible using the dichoptic presentation of the CFS paradigm.

An additional objective visibility check session was performed after the main experiment which consisted of 48 trials (12 primes × 4 repetitions) presented in a pseudorandom order to confirm that the contrast of the prime was below the participants' conscious threshold under CFS. Each trial began with a presentation of prime and CFS masks using the same dichoptic procedure as in the main experiment. The contrast of the prime increased from 0 to 70% in 1000 ms in each trial, the same as (or higher than) in the main experiment. Participants were asked to discriminate the meaning of words as either coldness or warmth regardless of the visibility of the prime. Other details were the same as the main experiment.

Results

There were 17.77%, 16.85%, and 17.95% trials discarded in Experiments 2 A, 2B, and 2 C, respectively: The error rates in the discrimination task were 4.72%, 5.12%, and 5.57%, additional 10.71%, 9.98%, and 10.33% of trials were discarded because participants reported detection of objects superimposed on the CSF, and finally, 2.34%, 1.75%, and 2.05% of trials were excluded due to RTs exceeding 3 SDs in Experiments 2 A, 2B, and 2 C, respectively.

The RTs data of Experiments 2 A, 2B, and 2 C were submitted to a three-way mixed ANOVA. The types of Prime (cold or warm) and Target (cold or warm) were treated as the within-participant factor, whereas Task as the between-participant factor. As in Experiment 1, if the significant interaction between Prime and Target was observed, we then estimated the congruency effect by calculating the difference of mean RTs between the congruent and incongruent conditions.

The results of the three-way mixed ANOVA showed that none of the main effect was significant: Task ($F(2, 69) = 0.314$ $p = .73$, $\eta_p^2 = 0.009$; $BF_{10} = 0.443$), Prime ($F(1, 69) = 0.38$, $p = .54$, $\eta_p^2 = 0.005$; $BF_{10} = 0.14$), and Target ($F(1, 69) = 0.23$, $p = .64$, $\eta_p^2 = 0.003$; $BF_{10} = 0.16$). No two-way interactions were significant, either: Task and Prime ($F(2, 69) = 0.23$, $p = .80$, $\eta_p^2 = 0.007$; $BF_{10} = 0.07$), Task and Target ($F(2, 69) = 1.64$, $p = .20$, $\eta_p^2 = 0.045$; $BF_{10} = 0.72$), and Prime and Target ($F(1, 69) = 2.30$, $p = .13$, $\eta_p^2 = 0.032$; $BF_{10} = 0.38$). Critically, however, the three-way interaction was significant ($F(2, 69) = 3.89$, $p = .02$, $\eta_p^2 = 0.101$; $BF_{10} = 1.31$), suggesting that the Prime x Target interaction differed among the three tasks. Hence, we performed separated two-way repeated-measures ANOVAs of RTs on the factors of Prime and Target in Experiments 2 A, 2B, and 2 C.

Experiment 2A. Neither the main effect of Prime ($F(1,23) = 0.70$, $p = .41$, $\eta_p^2 = 0.03$; $BF_{10} = .22$) nor that of Target ($F(1,23) = 0.13$, $p = .73$, $\eta_p^2 = 0.005$; $BF_{10} = .22$) was significant. However, their interaction was significant ($F(1,23) = 6.88$, $p = .02$, $\eta_p^2 = 0.23$; $BF_{10} = .31$). Interestingly, RT was *longer* in the congruent than in the incongruent condition (781 vs. 762 ms, $t(23) = 2.62$, $p = .02$, Cohen's $d = 0.71$; $BF_{10} = 3.40$), suggesting a negative semantic priming effect (Fig. 3A). Both the values of Cohen's d and the Bayesian factor suggest that the reversed congruency effect was moderate. Hence, the meaning of subliminal primes was accessed even when suppressed by the CFS masks; however, subliminal primes induced a reversed semantic congruency effect, contrasting to the typical semantic congruency effect induced by the visible primes in Experiment 1.

Experiment 2B. The results of the two-way repeated-measures ANOVA (Fig. 3B) showed that both main effects of Prime and Target were not significant (Prime: $F(1,23) = 0.02$, $p = .89$, $\eta_p^2 = 0.001$, $BF_{10} = 0.19$; Target: $F(1,23) = 3.72$, $p = .07$, $\eta_p^2 = 0.14$, $BF_{10} = 1.97$), nor was their interaction ($F(1,23) = 1.46$, $p = .24$, $\eta_p^2 = 0.06$,, $BF_{10} = 0.24$). Consistently, the mean RTs were not statistically different between the congruent and incongruent conditions (742 vs. 749 ms; $t(23) = 1.21$, $p = .24$, Cohen's $d = 0.25$, $BF_{10} = 0.41$). There was no evidence for the semantic congruency effect for the cross-from pairs when the primes were subliminally presented.

Experiment 2C. The results of the two-way repeated-measures ANOVA (Fig. 3C) showed that both main effects of Prime and Target were not significant (Prime: $F(1,23) = 0.15$, $p = .71$, $\eta_p^2 = .006$, $BF_{10} = 0.17$; Target: $F(1,23) = 0.32$, $p = .58$, $\eta_p^2 = .01$, $BF_{10} = 0.19$), nor was their interaction ($F(1,23) = 0.87$, $p = .36$, $\eta_p^2 = .04$, $BF_{10} = 0.06$). Consistently, mean RTs were not statistically different between the congruent and incongruent conditions (764 vs. 758 ms, $t(23) = 0.93$, $p = .36$, Cohen's $d = 0.19$, $BF_{10} = 0.32$). There was no evidence for the semantic congruency effect for metaphorically associated pairs when the primes were subliminally presented.

Discussion

In Experiment 2, we examined three types of prime-target pairings when the prime was rendered invisible. We observed a reversed congruency effect (i.e., longer RTs in the congruent than the incongruent condition) for word-word pairs in Experiment 2 A, and null priming effects for cross-form pairs and metaphorically associated pairs in Experiments 2B and 2 C. Compared to Experiment 1 in which the same prime-target pairs demonstrated a typical semantic congruency effect when the prime was visible, the results in Experiment 2 demonstrated that the meaning of unconscious words was accessed, but it could only influence closely related words (i.e., a low-level semantic association) but not cross-form illustrations and metaphorically associated words (i.e., high-level semantic associations). Note that this pattern of results cannot simply be explained by the level of semantic associations between the prime and target since it was rated similarly in the word-word and cross-form pairs, and both of them were higher than in the metaphorically associated pairs.

One might wonder that the reversed congruency effect in Experiment 2 A was attributed to the post hoc data selection because 11 participants were removed from the final analysis due to their higher-than-chance accuracy in the objective visibility check. Shanks (2017) suggested that such a post hoc data selection might inflate the probability of type I error in studying unconscious processing due to a statistical artifact called *regression to the mean*. Specifically, we only analyzed the data of participants whose accuracy in the objective visibility check was lower than the chance level in Experiment 2 A; namely, these included participants' mean accuracy was lower than the mean accuracy of the entire sample. Then, regression to the mean would imply that the included participants' true accuracies in the objective visibility check should be on average higher than their observed accuracies. That is, in the visibility check, some of the included participants might be able to perceive the stimuli, though their observed accuracies were lower than the chance level because their performance might vary in a certain range around the threshold, leaving the possibility that some included participants might have perceived primes in some trials in the main CSF experiment.

Sklar et al. (2021), however, suggest that the influence of the artifact of "regression to the mean" was generally overestimated. That is, the inflation of the observed performance with subliminal stimuli due to regression to the mean is not a major concern when (1) the objective awareness measure is reliable and (2) participants' objective awareness measure and their performances in the main experiment did not correlate with each other. Here we demonstrated that (1) the objective visibility check (i.e., the awareness measure) used in Experiment 2 A was reliable ($r = .67$, $t(33) = 5.20$, $p < .001$ in split-half reliability test) and (2) participants' performances in the objective visibility check did not correlate with the priming effect ($r = .14$, $t(33) = 0.82$, $p = .42$). Taken together, the results in Experiment 2 A cannot be simply explained by the regression to the mean due to post hoc data selection.

In Experiment 2, the contrast of the prime was decreased if participants detected something superimposed on the CFS masks in a given trial. This trial-by-trial adjustment was meant to keep the prime invisible to each participant because there were individual differences in the sensitivity of detecting stimuli under CFS masks. This subjective adjustment caused differences in contrast level of the prime across participants. However, in Experiment 2 A, the reversed congruency effect did not correlate with the final contrast of the prime of each participant ($r = .07$, $t(22) = 0.33$, $p = .74$), suggesting that the effect was not systematically influenced by the contrast level of the prime used for individual participant.

General discussion

The present study explored the limits of unconscious processing compared to conscious processing in the semantic domain using the CFS paradigm. We examined the semantic congruency effect of three types of stimulus pairs: word-word pairs, cross-form word-picture pairs, and metaphorically associated word-trait pairs. In Experiment 1, we confirmed that the typical semantic congruency effect (i.e., *shorter* RTs in the congruent than in the incongruent condition) for the three types of stimulus pairs was reliable when the primes were visible. In Experiment 2, we examined the semantic congruency effect using the same stimulus pairs while the primes were subliminal. Surprisingly, the semantically related word-word pairs now demonstrated a reversed semantic congruency effect (i.e., *longer* RTs in the congruent than in the incongruent condition); however, neither cross-form word-picture pairs nor metaphorically associated word-trait pairs demonstrated any semantic congruency effect. Our results, therefore, highlight the dissociation between conscious and unconscious processing by disclosing two limits of unconscious processing in the semantic domain.

The first limit lies in that, only low-level semantic associations (i.e., semantically related word-word pairs in Experiment 2 A) were observed in unconscious processing. In other words, consciousness is needed for the processing of high-level semantic associations (i.e., cross-form word-picture or metaphorically associated pairs in Experiments 2B and 2 C). This is consistent with Mudrik et al. (2014)'s hypothesis regarding the necessity of consciousness at different levels of information integration. Specifically, they proposed the SPIW to quantify the distance of semantic relatedness with which meaningful stimuli can be associated. Presumably, low-level semantic associations within a smaller SPIW can be achieved in unconscious processing. Conversely, hig-level, longer-distance, and more abstract associations correspond to a larger SPIW and require consciousness to integrate. Because the levels of semantic associations are presumably continuous, the implication of our results contrasts with the proposal of qualitatively discontinuous unconscious and conscious processing based on the GNWT (Dehaene et al., 2003; Sergent & Dehaene, 2004). According to the GNWT, conscious processing is dissociated from unconscious processing because the former recruits the parietal-frontal network which provides a top-down amplification and maintenance of long-distance functional connectivity and synchrony that enables sensory signals to become visible (Van Vugt et al., 2018).

The second limit is the contrasting semantic congruency effect for the low-level semantic association in conscious processing compared to unconscious processing. Specifically, the visible prime (e.g., Glacier) induced a *faster* response to a congruent target (e.g., Chill) than an incongruent one (e.g., Fire). However, the same prime when rendered invisible led to a *slower* response to a congruent than incongruent target. The contrasting effects of visible and invisible prime were consistently observed in an electrophysiological study: using the CFS paradigm, Yang et al. (2017) replicated a typical N400 effect (i.e., larger negativity for incongruent compared to congruent word-pairs) when the primes were visible; in contrast, N400 effect was reversed (i.e., larger negativity for congruent compared to incongruent word-pairs) when the primes were invisible. Note that the N400 component is not only associated with semantic congruency, but also with attentional selection (Almeida et al., 2008; Okita & Jibu, 1998).

It is therefore plausible that the reversed congruency effect induced by invisible primes could be explained by the attentional selection, which is analogous to the negative priming effect at the semantic level (Tipper, 1985). For example, when two objects were overlapped as primes (one was attended whereas the other was ignored), responses for the following target were slower when it was identical or categorically related to the previously ignored prime than when it was irrelevant. Along with this vein, in Experiment 2 A, the participant's attention was guided to the CFS masks (as instructed) and the invisible word was intensively inhibited. Thus, the processing of the target which was semantically related to the prime would also be impeded and demonstrate a negative priming effect at the semantic level. This explanation would also highlight the successful semantic access of the invisible primes which were two-character words though being masked by the CFS.

The contrasting semantic congruency effects induced by invisible and visible primes in the present study may represent the two sides of the role of attention: inhibitory and facilitatory processing driven by unattended and attended stimuli, respectively. Their contrast further emphasizes the role of consciousness in top-down attention and flexible controls (Kiefer, 2007) that are initiated from the parietal-frontal network (Baars et al., 2013; Dehaene et al., 2006). That is, the visible stimulus plausibly guided top-down attention and flexible controls to actively select semantically related information to establish an integrative and coherent representation, and consequently resulted in the positive priming effect.

Consistent with what we have found here, accumulating evidence has demonstrated that the meaning of complex visual objects, faces, and symbols can be extracted even when suppressed at the unconscious level using the CFS paradigm (Almeida et al., 2013; Bahrami et al., 2010; Costello et al., 2009; Eo et al., 2016; Luo et al., 2016; Mudrik et al., 2011; Sklar et al., 2012; Yang et al., 2007, 2017; Yang & Yeh, 2011). However, some opposing arguments state that subliminal presentation in CFS relies on interocular suppression that occurs in early monocular channels where visual information is fragmental, and the associated meaning has not yet been accessed (Moors et al., 2017). It should be noted that in the CFS paradigm, the suppressed stimulus is typically presented for a few seconds and the stimulus intensity gradually increases (see our procedure). Hence, the representations of the suppressed stimulus along the visual hierarchy may build up over time, though remaining invisible. In addition, our results in Experiment 2 demonstrate that the semantic congruency effect induced by the suppressed stimulus is highly susceptible to the type of the target, suggesting that adopting appropriate stimulus-probe relationships plays a crucial role in revealing the unconscious processing of the stimuli. These are critical considerations for future studies aiming to further investigate unconscious semantic processing.

Conclusion

In summary, our results demonstrate critical dissociations between conscious and unconscious processing. High-level semantic associations such as cross-form and metaphoric associations require consciousness; in contrast, low-level semantic associations occur in both conscious and unconscious processing, though the stimulus suppressed into the unconscious level may inevitably interfere with the following semantically related items and lead to a negative priming effect. Hence, consciousness plays an important role in associating complex information. Future studies can investigate whether unconscious and conscious processing are continuous or discriminately dissociated given certain conditions.

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Data Availability The data and materials for all experiments can be found at https://osf.io/trf6g.

Declarations

Competing interests The authors declare that they have no conflict of interest to disclosure.

Ethics approval This study was conducted following the 1964 Helsinki Declaration and its later amendments and approved by the Research Ethics Committee at the National Taiwan University.

Consent to participate Informed written consents were obtained from all participants in the present study.

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