High-Level Semantic Visual Information Can Be Processed Unconsciously: Meta-Analytic Evidence from the Continuous Flash Suppression Paradigm

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Abstract

Whether high-level semantic information can be unconsciously perceived and processed has been a widely discussed and controversial issue in the field of psychology. This study investigated the processing of high-level semantic information within the continuous flash suppression paradigm (CFS), a novel method introduced by Tsuchiya in 2004 for studying subliminal processing, and compared two variants of this paradigm: priming effects under CFS and breaking continuous flash suppression (b-CFS). The results revealed that, regarding the CFS paradigm, semantic processing occurs in unconscious contexts, a finding consistent with the meta-analysis results of Van den Bussche et al. (2009). However, the meta-analysis results for the priming paradigm under CFS were not consistent with previous research. We speculate that this is because, although CFS prolongs the duration of unconscious processing, it actually disrupts normal unconscious processing, resulting in weaker effects compared to the priming paradigm.

Full Text

High-Level Semantic Visual Information Can Be Processed Unconsciously: Meta-Analytic Evidence from the Continuous Flash Suppression Paradigm

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Abstract

Whether high-level semantic information can be perceived and processed unconsciously has been a widely discussed and controversial issue in psychology. This study focused on the continuous flash suppression (CFS) paradigm, a novel method for investigating subliminal processing proposed by Tsuchiya in 2004, to examine the processing of high-level semantic information within this framework and compared two variants of the paradigm: priming under CFS and breaking continuous flash suppression (b-CFS). The results revealed that, for the CFS paradigm overall, semantic processing occurs in unconscious contexts, consistent with the meta-analytic findings of Van den Bussche et al. (2009). However, the meta-analytic results for priming under CFS did not align with previous research. We speculate that although CFS extends the duration of unconscious processing, it may actually interfere with normal unconscious processing mechanisms, resulting in weaker effects compared to traditional priming paradigms.

Keywords: unconscious processing; continuous flash suppression; meta-analysis

Numerous studies have demonstrated that semantic information can be perceived and processed under conscious conditions, but can it also be processed unconsciously? As early as 1983, Marcel investigated unconscious semantic priming effects. In his experiments, participants were presented with either visible (conscious) or masked invisible (unconscious) prime words followed by target stimuli, and were required to judge whether the target was a word or non-word. The results showed that under unconscious conditions, participants' reaction times were faster when the prime and target were semantically related compared to when they were unrelated. This finding was considered important evidence that prime stimuli could be unconsciously categorized and semantically processed. Dehaene et al. (1998) obtained similar conclusions using number words as primes, with consistent results across behavioral, EEG, and fMRI experiments.

While substantial empirical research supports the existence of semantic processing under unconscious conditions, some studies have reported contradictory findings (e.g., Greenwald & Liu, 1985; Zimba & Blake, 1983). To reconcile these conflicting results and investigate whether semantic processing truly occurs unconsciously, Van den Bussche, Van den Noortgate, and Reynvoet (2009) employed meta-analytic methods. They examined three tasks in subliminal priming paradigms: semantic categorization (judging targets as positive or negative), lexical decision (judging targets as words or non-words), and naming tasks (reading targets aloud). Their meta-analysis yielded mean effect sizes of 0.80 (95% CI: 0.60, 1.00) and 0.47 (95% CI: 0.36, 0.59), demonstrating the existence of semantic processing in subliminal priming paradigms. However, this meta-analysis only investigated priming effects.

In 2004, Tsuchiya proposed the continuous flash suppression (CFS) paradigm based on binocular rivalry, providing a new method for studying high-level cognitive processing in unconscious contexts. CFS is built upon binocular rivalry technology but is not entirely equivalent to it. The paradigm presents rapidly flashing images to the dominant eye while simultaneously presenting static stimuli to the other eye. The static stimuli are suppressed by the flashing images, thereby extending the duration of unconscious visual stimulation from tens of milliseconds to several seconds (Tsuchiya & Koch, 2005). Compared to binocular rivalry, CFS provides more stable suppression for longer periods. Under such prolonged and stable suppression, visual information is believed to be processed more deeply and completely rather than merely partially perceived. Numerous researchers have found that high-level information can indeed be processed under CFS-induced unconscious conditions, including object categorization (Almeida, Mahon, Nakayama & Caramazza, 2008), numerical processing (Bahrami et al., 2010), and emotional facial expression processing (Yang, Zald & Blake, 2007).

While this new paradigm has introduced new vitality to the field, it has also generated contradictory results. Costello et al. (2009) combined CFS with priming paradigms to stably suppress prime stimuli and observed unconscious semantic priming effects. However, Kang, Blake, and Woodman (2011) failed to find ERP evidence supporting this conclusion using identical experimental procedures. Sklar et al. (2012) employed the breaking continuous flash suppression (b-CFS) paradigm to investigate unconscious sentence processing. In their experiments, stimuli masked by CFS were presented to participants, who pressed a button as soon as they detected the stimulus (i.e., when it broke through suppression into consciousness). The duration from stimulus onset to button press served as an index of unconscious processing depth, with longer durations indicating more extensive unconscious processing. The results showed that ungrammatical sentences produced significantly longer breakthrough times than grammatical sentences, suggesting unconscious processing of complex sentence meaning. However, subsequent replication studies with larger sample sizes failed to reproduce these findings (Rabagliati, Robertson & Carmel, 2018).

The substantial CFS literature provides conflicting evidence regarding unconscious semantic processing. Synthesizing results across different studies may yield more unified conclusions, and meta-analysis offers a quantitative research design for systematically evaluating past studies. By combining independent studies, meta-analysis provides comprehensive and quantitative review of large, complex, and contradictory literatures, offering more precise estimates of effect sizes. This approach is well-suited for integrating previous research on unconscious semantic processing under CFS and providing more accurate estimates of semantic processing in subliminal contexts. The present study employs meta-analytic methods to examine the effect of semantic processing under unconscious conditions and to identify variables that moderate these effects.

2.1 Different Paradigms Under CFS

Yang et al. (2014) categorized CFS paradigms into three types: (1) adaptation aftereffects under CFS; (2) priming effects under CFS; and (3) breaking continuous flash suppression (b-CFS). Adaptation aftereffects are relatively rare in behavioral experiments, so this study does not discuss this method. In the CFS priming paradigm, CFS is used to mask prime stimuli, allowing them to be presented stably for longer durations in an unconscious state, followed by presentation of target stimuli for response. The stronger the association between prime and target, the faster and more accurate participants' responses to the target. In the b-CFS method, only a single masked stimulus is presented until it breaks through CFS suppression into consciousness. The duration from stimulus onset to breakthrough serves as participants' threshold in the CFS context, with complex or unfamiliar stimuli requiring longer times to break through suppression.

2.2 Level of Consciousness

In unconsciousness research, regardless of paradigm or statistical method employed, whether participants can visually perceive stimulus presence is a crucial variable. Therefore, clearly delineating the boundary between conscious and unconscious perception is a critical step in experiments. Conscious states are classified according to subjective or objective thresholds. When using subjective thresholds, participants report their perception of prime stimuli, choosing between visible or invisible. If a stimulus is physically present but participants report seeing nothing, that trial is considered to involve unconscious information processing. Objective thresholds incorporate participants' confidence in their judgments. Considering uncertainty—when participants are unsure whether they perceived a stimulus—researchers using objective thresholds typically do not use single-trial responses as consciousness indicators but instead employ signal detection theory to assess consciousness levels across the entire experiment (Doyen, Klein, Simons & Cleeremans, 2014).

In b-CFS paradigms, different response tasks also raise issues regarding consciousness levels (Yang et al., 2014). The process of stimulus breakthrough exists in a gray area of uncertainty, making it difficult to definitively distinguish conscious from unconscious states. Numerous studies indicate that regardless of method used to investigate consciousness, visual awareness of complex stimuli varies across different levels (e.g., Kang et al., 2011; Kouider & Dupoux, 2004; Overgaard et al., 2006; Sandberg et al., 2010). Mudrik et al. (2013) found that results for judging whether faces were familiar differed when using color identification versus location judgment accuracy as thresholds. Therefore, whether participants respond to stimulus presence, location, or other features may influence final experimental results.

2.3 Other Moderating Variables

Both Rabagliati et al. (2018) and Karpinski et al. (2018) used larger sample sizes than original studies in their replication attempts and obtained conclusions inconsistent with the original findings. If publication bias exists, meta-analytic results will tend to overestimate effect sizes from small-sample studies, which may show larger effects than large-sample studies (Begg & Berlin, 1998). Therefore, this study examines the moderating effect of sample size. Different stimulus materials also introduce variations in processing difficulty, with more complex stimuli being more difficult to process. Consequently, stimulus materials are also examined as a moderating variable. Additionally, the duration of suppressed stimulation may relate to the depth of visual processing inhibition under CFS (see Moors & Hesselmann, 2018), so priming stimulus duration is examined as a separate moderating variable specifically for the CFS priming paradigm.

3.1 Literature Search

This study obtained empirical research primarily by searching Chinese and English literature databases. The time range was limited to between 2004 (when Tsuchiya published the first CFS paper) and March 2020. The literature search followed these steps: (1) Using English keywords "continuous flash suppression" and "semantic" and Chinese keywords "连续闪烁抑制" and "语义" to search Web of Science, Pubmed, and PsycINFO for published English articles, PsychArxiv for unpublished English articles, and CNKI and Wanfang databases for published Chinese articles and dissertations. (2) Conducting separate searches in journals that publish numerous CFS-related articles, such as *Consciousness and Cognition* and *Frontiers in Psychology*. (3) Employing backward citation searching through reference lists of empirical studies and review articles. (4) Contacting corresponding authors via email when full articles could not be accessed through databases.

3.2 Literature Inclusion and Exclusion

This study applied the following criteria to include or exclude searched literature: (1) Articles must be complete, standard psychological empirical studies; non-psychological studies, reviews, or incomplete articles were excluded. (2) Articles must provide behavioral experimental statistics; studies providing only EEG or fMRI results were excluded. (3) Articles must employ CFS paradigm methods; studies using priming or binocular rivalry paradigms were excluded. (4) Articles must investigate semantic processing in the visual domain. In CFS priming paradigms, primes and targets must have direct semantic relationships (e.g., autumn-harvest). In b-CFS paradigm studies, content must involve semantic-level processing (e.g., differences in breakthrough times between emotional words). Studies investigating other sensory modalities such as audition or touch were excluded. (5) Articles must investigate subliminal contexts; studies where prime stimuli exceeded 100ms duration without masking were excluded. (6) Articles must investigate healthy participants; case studies and clinical samples were excluded. (7) Studies must provide statistical information (e.g., sample size, means, standard deviations, t-values, F-values) for effect size calculation. When statistical information was incomplete, authors were contacted via email to request necessary data. Studies were only excluded if authors did not respond or declined to provide information.

The literature inclusion and exclusion process is illustrated in the figure. After removing duplicates, 86 articles were collected. Following application of inclusion criteria, 25 effect sizes from 7 articles were included in the meta-analysis.

[Figure 1: see original paper] Literature inclusion process

3.3 Literature Coding

Table 1 presents the variables to be coded, coding content, and operational definitions for each variable. Two researchers independently coded the 7 eligible articles according to the coding rules in the table. To demonstrate coding validity and reliability, the researchers compared their coding results and found no significant discrepancies.

Table 1. Literature Coding

Variable	Coding Content	Operational Definition
Sample size	Continuous variable	Represents the sample size in each study, with specific data based on reported results
Language	1=English, 2=Chinese, 3=German, 4=Hebrew	Represents the language type used in experiments, not indicating participants' native language
Method	1=CFS priming paradigm, 2=b-CFS paradigm	Represents which method was employed in the experiment
Stimulus material	1=Word, 2=Phrase or sentence, 3=Other	Represents the type of priming stimulus materials used
Number of trials	Continuous variable	Represents the total number of trials each participant completed
Priming stimulus duration	Continuous variable	Represents the presentation duration of priming stimuli; this variable appears only in CFS priming paradigms
Consciousness level test	1=Yes, 0=No	Represents whether any method was used to test participants' consciousness state. In b-CFS paradigms, consciousness level is assumed to be tested, so all studies are coded as 1.
Consciousness test method (a)	1=Subjective threshold test, 2=Objective threshold test	Represents which consciousness test method was used; only coded for CFS priming paradigm experiments.

Variable	Coding Content	Operational Definition
Consciousness test method (b)	1=Respond to stimulus, 2=Respond to stimulus location	Represents which consciousness level was reached in each trial; only coded for b-CFS paradigm experiments.

Note: Since all experiments in the actual coding tested consciousness level, this item is not presented. Since all experiments in the actual coding used subjective threshold tests, this item is not presented.

3.4 Effect Size

All eligible studies in this meta-analysis employed single-sample within-subjects designs where all participants experienced all experimental conditions. Since most studies only provided sample sizes, t-values, or F-values, this study adopted Rosenthal' s (1991) calculation method to compute Cohen' s d effect sizes from t-values or F-values. Additionally, we estimated sampling error (SE) following Morris and DeShon' s (2002) calculation method.

Table 2 presents the coding results, sample sizes, and sampling errors for each study.

Table 2. Coding Results

Study	Language	Method	d	se
Kido et al., 2014 exp 3	1	1	0.23	0.20
Lei et al., 2017	2	1	0.27	0.13
Rabagliati, Robertson & Carmel, 2018 exp 1	1	2	0.05	0.13
Rabagliati, Robertson & Carmel, 2018 exp 2	1	2	0.03	0.13
Rabagliati, Robertson & Carmel, 2018 exp 3	1	2	0.01	0.13
Rabagliati, Robertson & Carmel, 2018 exp 4	1	2	0.09	0.13
Rabagliati, Robertson & Carmel, 2018 exp 5	1	2	0.08	0.13
Rabagliati, Robertson & Carmel, 2018 exp 6	1	2	0.13	0.13
Rabagliati, Robertson & Carmel, 2018 exp 7	1	2	0.04	0.13
Rabagliati, Robertson & Carmel, 2018 exp 8	1	2	0.11	0.13
Rabagliati, Robertson & Carmel, 2018 exp 9	1	2	0.06	0.13
Rabagliati, Robertson & Carmel, 2018 exp 10a	1	2	0.01	0.13
Sklar et al., 2012 exp 1	1	2	0.31	0.13
Sklar et al., 2012 exp 2	1	2	0.29	0.13
Sklar et al., 2012 exp 4a	1	2	0.49	0.13
Sklar et al., 2012 exp 4b	1	2	0.49	0.13
Yang et al., 2017 exp 1a	2	1	0.09	0.20
Yang et al., 2017 exp 1b	2	1	0.09	0.20
Yang et al., 2017 exp 2b	2	1	0.09	0.20
Yang et al., 2017 exp 4a	2	1	0.09	0.20

Study	Language	Method	d	se
Yang et al., 2017 exp 4b	2	1	0.09	0.20
Yang & Yeh, 2011 exp 1	2	1	0.09	0.20
Yang & Yeh, 2011 exp 2	2	1	0.09	0.20
Zabelina et al., 2013 a	1	1	0.09	0.20
Zabelina et al., 2013 b	1	1	0.09	0.20

Note: d and se values are presented with two decimal places in the table, but calculations retained as many decimal places as possible.

3.5 Software and Models

All data analyses were implemented using R language in RStudio software (R Core Team, 2019; RStudio Team, 2016). The rma.uni() function in the metafor package was used for the main meta-analysis procedures (Viechtbauer, 2010). Given that included studies differed in sample size, participants' native language, stimulus materials, number of trials, and other variables, this study assumed all studies in the meta-analysis were random samples and treated methodological variables as moderators to explain study heterogeneity. Therefore, this study employed a random-effects model and restricted maximum-likelihood estimation to estimate effect sizes and test moderating variables.

4.1 Main Effect Test

The main effect of semantic processing was tested to determine whether high-level semantic processing occurs in subliminal contexts. As shown in Figure 1, the random-effects model revealed an average semantic effect size of 0.16 (95% CI: 0.02, 0.30). This result indicates a significant main effect of semantic processing ($z = 2.25$, $p = 0.024$), demonstrating that high-level semantic information can be processed unconsciously. Separate main effect tests for semantic processing in the CFS priming paradigm and b-CFS paradigm showed that in the CFS priming paradigm, the average semantic effect size was -0.06 (95% CI: -0.24, 0.12), with a non-significant main effect ($z = -0.66$, $p > 0.1$). In contrast, in the b-CFS paradigm, the average semantic effect size was 0.28 (95% CI: 0.10, 0.45), with a significant main effect ($z = 3.12$, $p < 0.01$).

[Figure 2: see original paper] Main effect results for semantic processing

4.2 Heterogeneity Test

Following Higgins and Thompson' s (2002) recommendations, H^2 and I^2 tests were used to estimate effect size heterogeneity. The I^2 test result, presented as I^2, reflects the proportion of observed total variation due to true heterogeneity. The H^2 test result, presented as H, reflects the ratio of observed total variation to sampling variation. Additionally, metafor provides the Q test (Cochran, 1954) as another heterogeneity indicator, testing whether observed variation exceeds estimated sampling variation. Significant differences indicate high heterogeneity.

Heterogeneity testing revealed an estimated true variance (^{2}) of 0.085 (SE = 0.035). The Q test was significant (Q = 70.79, df = 24, $p < .0001$), indicating significant heterogeneity in effect sizes. The I^2 value was 73.71, suggesting that 73.71% of observed total variation was due to true differences. According to the 75% rule, I^2 values above 75% indicate high heterogeneity, suggesting moderately high heterogeneity in our results. The H^2 test result was 1.949. According to Higgins and Thompson (2002), H values exceeding 1.5 indicate relatively high heterogeneity.

In the CFS priming paradigm, the estimated true variance (^{2}) was 0.026 (SE = 0.036). The Q test was marginally significant (Q = 13.88, df = 8, p = 0.085), suggesting relatively homogeneous effect sizes. The I^2 test indicated that 35.70% of observed variation was due to true differences, with an H^2 value of 1.25, indicating low heterogeneity. In the b-CFS paradigm, the estimated true variance (^{2}) was 0.090 (SE = 0.045). The Q test was significant (Q = 49.97, df = 15, $p < .0001$), indicating significant heterogeneity. The I^2 test showed that 78.06% of observed variation was due to true differences, with an H^2 value of 2.14, indicating high heterogeneity.

4.3 Moderating Effect Test

This study examined four variables as potential moderators of high-level semantic processing in unconscious contexts: sample size, method, stimulus material, and consciousness level. Since all CFS priming paradigm experiments collected in this study used subjective thresholds to measure consciousness level, no variation existed for this variable, so consciousness level moderation was only tested in the b-CFS paradigm. Additionally, we separately examined priming stimulus duration as a moderator specifically for the CFS priming paradigm. The QE test, a variant of the Q test that incorporates moderating variables, examines whether observed variation exceeds sampling variation when a moderator is considered. If significant differences remain, the moderator cannot adequately explain overall heterogeneity.

Results showed that neither sample size nor stimulus material had significant moderating effects: Q__sample(df = 1) = 2.00, p = 0.1571; Q__material(df = 2) = 5.03, p = 0.0809. Method demonstrated a significant moderating effect on high-level semantic processing in unconscious contexts, Q(df = 2) = 11.09, p = 0.0039.

In the CFS priming paradigm, neither sample size nor stimulus material showed significant moderating effects: Q__sample(df = 1) = 0.0037, p = 0.9; Q__material(df = 2) = 0.0194, p = 0.99. Priming stimulus duration showed a significant moderating effect, Q(df = 1) = 6.43, p = 0.0113, and the QE test indicated that priming stimulus duration adequately explained heterogeneity, QE(df = 7) = 7.46, p = 0.383.

In the b-CFS paradigm, stimulus material did not show a significant moderating effect, $Q(df = 2) = 1.4706$, $p = 0.4794$. Sample size demonstrated a significant moderating effect, $Q(df = 1) = 31.01$, $p < 0.0001$, and the QE test indicated that sample size substantially explained heterogeneity in this paradigm, $QE(df = 14) = 18.96$, $p = 0.167$. Consciousness level also showed a significant moderating effect, $Q(df = 2) = 15.58$, $p = 0.004$, but this variable did not adequately explain heterogeneity.

[Figure 3: see original paper] Funnel plot for CFS paradigms

3.4 Publication Bias

This study employed three methods to assess publication bias: funnel plots, Egger' s linear regression test, and the trim-and-fill method. Funnel plots help judge heterogeneity existence and identify specific forms of publication bias, with observed effect sizes on the x-axis and corresponding standard errors on the y-axis. The vertical line represents the model-based estimated effect size. The funnel plot for CFS paradigms is shown in Figure 2. Egger' s linear regression test examines publication bias by calculating the correlation between observed results and their standard errors, with larger correlations indicating smaller bias. The trim-and-fill method estimates the number of missing studies on one side of the funnel plot and imputes data to create a more symmetric plot. However, it is important to note that the trim-and-fill method cannot produce more precise estimates through data imputation but serves only as a publication bias detection method (Duval & Tweedie, 2000), so imputed data should be considered only as a reference.

Given the high heterogeneity in effect sizes, this study used Egger' s linear regression test with random- or mixed-effects model regression to control for potential moderating factors when testing publication bias (Sterne & Egger, 2005). Results indicated significant publication bias in the overall analysis ($z = 2.50$, $p = 0.012$), no substantial publication bias in the CFS priming paradigm ($z = -0.68$, $p = 0.497$), and substantial publication bias in the b-CFS paradigm ($z = 6.02$, $p < .0001$). The moderating effect of sample size supported these conclusions.

Trim-and-fill results indicated that neither the overall CFS paradigm nor the CFS priming paradigm required additional imputed data. However, for the b-CFS paradigm, imputing one data point on the left side of the funnel plot was recommended. After imputation, the average semantic effect size in this paradigm was 0.25 (95% CI: 0.07, 0.43), with the main effect remaining significant ($z = 2.80$, $p < 0.01$).

This study investigated whether high-level semantic processing occurs under unconscious conditions. Regarding the CFS paradigm overall, semantic processing exists in unconscious contexts, consistent with Van den Bussche et al.' s (2009) meta-analytic results. However, the meta-analytic results for the CFS priming paradigm did not align with previous research.

The CFS priming paradigm is highly similar to traditional priming paradigms, differing only in that prime stimuli are masked by CFS rather than being unmasked or masked only before and after presentation. Based on the assumption that visual information can be more deeply and completely processed under CFS, the CFS priming paradigm should allow longer unconscious processing times, stronger processing intensity, and larger effects. However, meta-analytic results do not fully support this hypothesis. In the CFS priming paradigm, priming stimulus duration showed a significant moderating effect and adequately explained heterogeneity, indicating that information under CFS masking is indeed continuously processed over time, with longer processing durations producing stronger effects. Contrary to hypotheses, however, traditional priming paradigms showed stronger effects and demonstrated the existence of unconscious semantic processing. This discrepancy may arise because CFS disrupts unconscious processing mechanisms, thereby inhibiting the transition from unconscious to conscious states and consequently prolonging unconscious processing duration. In other words, although CFS extends unconscious processing time, it may actually interfere with normal unconscious processing, resulting in weaker effects compared to traditional priming paradigms. Izatt et al. (2014) found that with equivalent priming durations, both repetition priming and identity priming showed stronger effects under masked priming conditions than under CFS conditions, suggesting that CFS masking may interfere with unconscious stimulus processing and supporting our speculation.

This study has several limitations. Constrained by the research question, number of published studies, and inclusion criteria, the number of experiments included was relatively small, potentially limiting generalizability. Additionally, some effect sizes originated from the same studies, which may create substantial interdependence among effect sizes. Furthermore, the b-CFS paradigm showed substantial publication bias, so results from this paradigm should be interpreted cautiously.

Given the discrepancy between meta-analytic results for CFS priming and traditional priming paradigms, future research could directly compare CFS and priming paradigms using experimental methods or alternative statistical approaches to test whether CFS masking truly enhances unconscious processing effects. Subsequent studies could also employ fMRI technology to compare brain activity between CFS and non-CFS masking conditions, investigating how CFS masking influences visual processing and further elucidating its mechanisms.

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Note: Figure translations are in progress. See original paper for figures.