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Role of visual awareness on semantic integration of sequentially presented words: An fMRI study

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ABSTRACT

Reading comprehension requires the semantic integration of words across space and time. However, it remains unclear whether comprehension requires visual awareness for such semantic integration. Compared to earlier studies that investigated semantic integration indirectly from its priming effect, we used functional magnetic resonance imaging (fMRI) to directly examine the processes of semantic integration with or without visual awareness. Specifically, we manipulated participants' visual awareness by continuous flash suppression (CFS) while they viewed a meaningful sequence of four Chinese words (i.e., an idiom) or its meaningless counterpart (i.e., a random sequence). Behaviorally, participants had better recognition memory for idioms than random sequences only when their visual awareness was interfered rather than blocked by CFS. Neurally, semantics-processing areas, such as the superior temporal gyrus and inferior frontal gyrus, were significantly activated only when participants were aware of word sequences, be they meaningful or meaningless. By contrast, orthography-processing areas, such as the fusiform gyrus and inferior occipital gyrus, were significantly activated regardless of visual awareness or word sequence. Taken together, these results suggest that visual awareness modules the functioning of the semantic neural network in the brain and facilitates reading comprehension.

1. Introduction

Reading is necessary for learning and communication. To comprehend the meaning of a sentence, we must extract the meanings of individual words and integrate the meanings of multiple words across space and time (Cohen et al., 2000). The semantic processing of a single word can be extracted without visual awareness (Yeh, He, & Cavanagh, 2012; Zhou, Lee, & Yeh, 2016; Zhou et al., 2016; for review, see Naccache, 2008). It is unknown, nevertheless, if multiple words (such as phrases or sentences) may do the same thing. In this study, we looked into a contentious topic in our study: the role of visual awareness in the temporal integration of semantic information.

To investigate whether the temporal presentation of multiple words can be integrated without visual awareness, we presented words sequentially for some time under the paradigm of continuous flash suppression (CFS; Fang & He, 2005; Tsuchiya & Koch, 2005), which has been developed as a tool to probe unconscious processing of this nature. In this paradigm, a critical stimulus is presented to one eye while a constantly changing high-contrast mask is presented to the other eye. As a result of interocular suppression, observers cannot perceive the critical stimulus for up to several seconds, a significantly longer duration compared to other paradigms such as masking and attentional blink (Kim and Blake, 2005). This advantage enables manipulating word sequences for long periods while visual awareness remains blocked.

Previous studies using the CFS paradigm have shown that language information can be processed unconsciously at different levels, including morphology (Costello, Jiang, Baartman, McGlennen, & He, 2009), orthography (Jiang, Costello, & He, 2007; Yang & Yeh, 2011), lexical (Yang, Zhou, et al., 2017), syntax (Hung & Hsieh, 2015), and semantic integration (Sklar et al., 2012; Tu et al., 2019). When suppression time was measured, Jiang et al. (2007) were the first to show that recognizable words could break interocular suppression faster than

Abbreviations: fMRI, functional magnetic resonance imaging; CFS, continuous flash suppression.

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unrecognizable ones. Furthermore, Costello et al. (2009) found that a semantically related preceding prime word could help detect a CFS-suppressed target word more quickly than its semantically unrelated counterpart. Even without a preceding visible prime word to activate the brain semantic network before the presentation of the target word, negative emotion words were shown to require a longer time to be released from CFS than neutral words, suggesting that the CFS-suppressed words *per se* could be processed up to the semantic level (Prioli & Kahan, 2015; Yang & Yeh, 2011).

In addition to the unconscious processing of a single word, several research looked at whether the meanings of multiple words could be integrated when they were presented concurrently under CFS (Karpinski, Briggs, & Yale, 2018; Sklar et al., 2012; Tu et al., 2019; van Gaal et al., 2014 but see Rabagliati et al., 2018). For example, Sklar et al. (2012) presented a three-word sentence on a screen. They discovered that semantically incongruent sentences (e.g., "I ironed coffee") were released from interocular suppression faster than semantically congruent ones (e.g., "I ironed clothes"). While some studies (Rothkirch & Hesselmann, 2017; Shanks, 2017) claimed that the findings of Sklar et al. (2012) were based on post hoc data selection, other studies replicated the results of semantic integration when seeing arithmetic equations (Karpinski et al., 2018) or Chinese idioms (Tu et al., 2019). These results suggest that when multiple words are presented simultaneously, their meanings can be spatially integrated to some degree without awareness.

However, when multiple words are presented sequentially rather than simultaneously, previous research indicated that visual awareness is required for semantic integration over time. For example, Yang, Tien, Yang, and Yeh (2017) presented a series of four-character Chinese idioms, where the first three characters served as the prime, either with or without CFS masks, and the target was the fourth visible character. The N400 components of the incongruent prime-target pairs were significantly more negative than the congruent pairs when the prime was visible (without the CFS masks) but not when it was invisible (with the CFS masks). Similarly, Mongelli, Meijs, van Gaal, and Hagoort (2019) primed a picture target with either a single word or a three-word sentence, with the preceding prime having either a congruent or incongruent meaning with the picture target. By adopting a masking paradigm to manipulate visual awareness of the prime words, they discovered that the incongruent single words and incongruent three-word sentences evoked a higher N400 component than their congruent counterparts in the unmasked condition. However, only the single word, but not the three-word sentence, with a short prime-target stimulus onset asynchrony (SOA) evoked a stronger N400 component in the incongruent than congruent conditions in the masked condition. The authors concluded that long-range feedback from the inferior frontal lobe was required for sentence temporal integration when visual awareness was blocked by the masks.

Only one study, to our knowledge, has demonstrated that sequentially presented words can elicit greater brain activation than nonword phrases under CFS (Axelrod, Bar, Rees, & Yovel, 2014). They used fMRI to investigate subliminal language processing by presenting six-word sentences made up of real words or nonword strings with CFS to participants. The superior temporal sulcus and the middle frontal gyrus both revealed distinct activation levels in response to six-word sentences versus nonwords. The authors concluded that the activation of the frontal lobe was involved in unconscious language processing. Despite this, it was insufficient to trigger visual awareness based on objective and subjective responses. Note, however, that because their experimental baseline used nonword strings to contrast with real word sentences, it remains unclear which levels of language processing were involved (e.g., orthography, semantic at the single word level, or semantic integration over several words).

We investigated this issue in the current study by presenting four Chinese words sequentially, either forming a meaningful idiom or a meaningless random sequence, to see if sequential semantic integration under CFS is feasible. This manipulation allows fair comparisons that isolate the semantic integration of multiple words from the related processes concerning the orthography and/or the meaning of single words. In this design, any further semantic integration processing, if it exists, will be indicated by discrepancies between the idiom and random sequence conditions.

Previous studies (e.g., Mongelli et al., 2019; Yang et al., 2017) may have been unable to observe the semantic priming effect indicative of semantic integration of multiple words across time under CFS because these effects are the end products of a potentially incomplete semantic processing; that is, semantic information may have been processed but not sufficiently maintained to influence the response to the target. After all, Faivre and Koch (2014) demonstrated that the unconscious temporal integration of both apparent motion and biological motion could only be observed over a short length of time (100 ms) but not over a more extended period (1000 ms). Thus, it is plausible that the semantic information of successively presented invisible words was integrated, but it decayed too quickly to be observed in these prior studies. This potential was therefore explored in the current study using fMRI, which can show brain activation and processing of semantic integration online without relying on the consequence of semantic priming.

2. Methods

2.1. Participants

The sample size was determined using G*Power 3.1.9.3 (Faul, Erdfelder, Lang, & Buchner, 2007), and the effect size was calculated by an fMRI study testing object-scene integration with and without visual awareness (Faivre, Dubois, Schwartz, & Mudrik, 2019). Based on the median effect size of Cohen's $d = 1.06$ from the imaging data (Table 1 in Faivre et al., 2019) and type I error probability of 0.05, 12 participants were required to achieve a power of 0.9 (two-tailed *t*-test with matched pairs). To be conservative, we recruited 27 participants but removed three participants who did not pass the quality control throughout all imaging analyses (see Section 3.2). All participants were native Mandarin Chinese speakers with normal or corrected-to-normal vision and gave informed consent before the experiment. The Research Ethics Committee at National Taiwan University approved this study (REC: 201408HM005).

2.2. Stimuli, materials, and apparatus

This experiment was programmed with the Psychtoolbox-3 (Brainard, 1997; Kleiner, 2010; Pelli, 1997) in Matlab (The Math Works, Natick, USA). A goggle display system (Resonance Technology Inc., Northridge, USA) with 800 × 600 pixels at 60 Hz was used to show visual stimuli. Throughout the experiment, each eye was shown a gray background frame ([128, 128, 128] on the RGB scale) with a black and white random segmented outline square (9° × 9°, 0.3° thickness) to aid steady fusion of the two eyes.

We used an idiom recognition task with two types of stimuli: *CFS (masked)* and *superimposed* presentations (Fig. 1). In the CFS presentation, participants viewed traditional Chinese words dichoptically with CFS masks; multiple words (2° × 2°) were presented consecutively at the center of the display and projected to the participant's non-dominant eye. At a 10 Hz flashing frequency, CFS masks (6° × 6°) with random colors (from 0 to 255 on the RGB scale) and random rectangles widths (from 0.02° to 1.07°) were displayed to the dominant eye (Tsuchiya & Koch, 2005), which was determined using a hole-in-card test (Porac & Coren, 1978) before the experiment began. In the superimposed presentation, words were superimposed on the CFS masks, and both eyes received the same superimposed stimuli binocularly. Additionally, a functional localizer task was carried out in which words without the CFS masks were presented to both eyes.

Preceding the idiom recognition task, the Weber contrast of black-

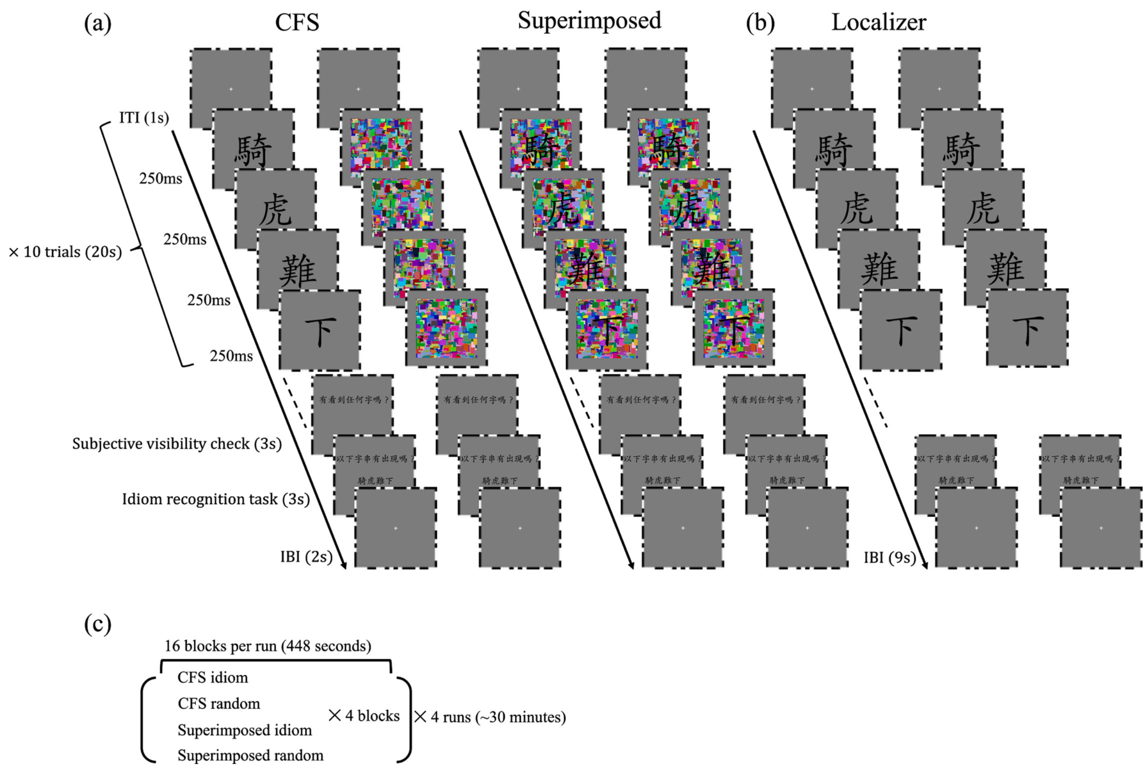

Fig. 1. (a) Experimental procedure of the idiom recognition task: The visual stimuli were either masked under CFS or superimposed on the masks. Participants were asked a subjective visibility question ("Did you see any character?"), followed by an idiom recognition question ("Had this four-character sequence appeared? [An idiom]") after each block of 10 trials. (b) Experimental procedure of the localizer task: visual stimuli were presented without masks and without subjective visibility questions to serve as a functional localizer. (c) The experimental protocol: The idiom recognition task had 16 blocks per run for four runs. The illustration is not drawn to scale.

inked words ($M = 30.06$ %, $SD = 23.29$ %), relative to the gray background, were adjusted individually by a four-up-one-down staircase procedure (see Section 2.3.1). For each participant, the same contrast of words was used in both CFS and superimposed presentations based on the staircase procedure, whereas the contrast in the localizer task was fixed at 50 %. Among the 320 Chinese four-character idioms used in this study, 160 idioms were used for the staircase procedure, and 160 idioms taken from our previous studies (Yang, Tien, et al., 2017) were used for the idiom recognition task to ensure no repetition of idioms were used for the contrast calibration in the staircase procedure and the idiom recognition task.

2.3. Design and procedure

This study included three phases: A staircase procedure, the idiom recognition task, and the localizer task. The maximal contrast of CFS had to be measured individually for successful interocular suppression (Blake, Goodman, Tomarken, & Kim, 2019). We employed an adaptive staircase procedure to obtain the maximum luminance contrast of stimuli suppressible by CFS for each participant to reach sufficient stimulus strength for unconscious processing at the beginning of the experiment. In the idiom recognition task, we presented idiom and random sequences in the CFS and superimposed presentations to the goggle that the participant wore as the participant's head was scanned using fMRI. After that, the localizer task was then conducted to localize the functional regions of interest (ROIs) by comparing the idiom and random sequence conditions.

2.3.1. Staircase procedure

This initial phase was utilized to determine the appropriate contrast for each participant's CFS presentation individually. Under CFS, each trial provided a sequence of four Chinese words (one at a time for 250 ms). Following that, participants were asked if they had detected any part of the sequence other than the masks; this response was used to adjust the luminance contrast of words presented. The initial contrast was set at 50 % Weber contrast; it was increased by 2 % if the individuals did not detect the stimuli under CFS for four consecutive trials and dropped by 2 % if the participants did. This staircase procedure ended with 12 reverse points, and the mean contrast of the last six reversals was used for the idiom recognition task. According to the equality $\{1-[1-p(x)]^4 \cong .5\}$from Levitt (1971), the probability of visibility $[p(x)]$ at the end of this four-up-one-down staircase procedure would be 15.9 %.

2.3.2. Idiom recognition task

This second phase used a within-subject blocked design with an orthogonal manipulation of two factors: presentation (CFS, superimposed) and sequence (idiom, random) to form four conditions. There were four runs, each with 16 blocks and an equal probability of the four conditions (four blocks each, Fig. 1c). We first divided 160 idioms into four sets by random assignment to ensure that the four conditions had the same 160 idioms. Each set (i.e., 40 idioms) was assigned to the four conditions in a run. Each condition's 40 idioms were randomly assigned to four blocks within a run, with each block containing 10 idioms. The sequences of 10 idioms were randomly assigned in a block for the idiom trials. We shuffled the 10 idioms into 40 words for the random trials and then randomly assigned the sequences of words in a block. To support that all random sequences are meaningless phases, none of the blocks had more than two words in the same sequence as the idioms used.

A fixation frame was presented for one second as an inter-trial interval (ITI) before each trial, as shown in Fig. 1a. Four Chinese words were shown for 250 ms each in a trial, forming either a four-word idiom or a random sequence. A 20-second stimulus presentation was created by interleaving 10 fixation frames and 10 trials. After that, a three-second subjective visibility check was presented. Participants were asked if they had detected any parts of the characters during the block. A four-character sequence was presented on the screen for three seconds after this question. Participants were asked to determine whether or not this four-character sequence had been presented during the block. Half of the probe idioms or random sequences were introduced in the block (i.e., the answer should be "yes"), whereas the other half were presented in the preceding staircase task (i.e., the answer should be "no"). To investigate perceptual rather than memory processes during idiom recognition, we randomly selected the idioms or random sequences that had been presented from either the first or the last trial of a block to take advantage of the primacy and recency effects in memory (Miller & Campbell, 1959), respectively. We can define unconscious processing in terms of a subjective and an objective criterion, respectively, by using the subjective visibility check and the idiom recognition task. A fixation was presented for two seconds to serve as an inter-block interval (IBI) baseline. Each run lasted 448 s (16 blocks of 28 s).

2.3.3. Localizer task

This final phase was undertaken with a single run after the idiom recognition task to localize brain areas for idiom processing. Both eyes were shown all of the Chinese words without masks (Fig. 1b). There were eight blocks of idiom sequence and eight blocks of random sequence. Each block lasted for 20-seconds, interleaving 10 trials and 10 fixation ITIs. The procedure was the same as the idiom recognition task, except for the following differences: there was no subjective visibility question because the words were visible without masks, and after the idiom recognition task, a fixation was presented for 9 s to serve as a baseline. This task lasted for 512 s (16 blocks of 32 s).

2.4. Image acquisition and analysis

The experiment was conducted in a 3-Tesla Magnetom Prisma scanner (Siemens, Erlangen, Germany) with a 20-channel birdcage head coil at National Taiwan University. Whole-brain functional images were recorded using gradient echo-planar imaging (EPI) [35 slices, matrix size = 64 × 64, flip angle = 90°, repetition time (TR) = 2000 ms, echo time (TE) = 30 ms, field of view (FOV) = 192 × 192 mm^2, voxel size = 3 mm isotropic]. We conducted four runs of 224 volumes each in the idiom recognition task and one run of 256 volumes in the localizer task. We employed a T1-weighted MPRAGE sequence (192 slices, matrix size = 256 × 256, FA = 8°, TR = 2000 ms, TE = 2.3 ms, FOV = 240 × 240 mm^2, voxel size = 0.93 mm isotropic) to acquire anatomical images. With a standard pre-processing pipeline, SPM12 was utilized (Wellcome Department of Imaging Neuroscience, London, UK) to analyze fMRI data from our idiom recognition and localizer tasks. The *EPI* volumes were realigned, co-registered, segmented, normalized, and smoothed with Gaussian filters for single participants (6 mm) and group (12 mm) analysis.

The statistical analyses included the analysis of the whole brain and region of interest (ROI). For the whole-brain analysis, we fitted the fMRI data with a general linear model in the localizer task using the idiom and random sequences as regressors of interest together with one response period (i.e., idiom recognition task for three seconds) and six motion-correction (x, y, z, pitch, roll, yaw) parameters as nuisance regressors. In the individual-level analysis, we investigated the effect of idiom, random sequence, and idiom versus random sequence. After that, the individual comparisons were further submitted to one-sample two-tailed t-tests for group-level analyses. The analysis for the idiom recognition task was similar to that for the localizer task above, but the regressors of interest were the four (CFS-idiom, CFS-random, superimposed-idiom, and superimposed-random) conditions. The nuisance regressors were the responses period (i.e., the subjective visibility check and the idiom recognition task for six seconds) and six motion parameters. The xjView toolbox (https://www.alivelearn.net/xjview) was used to define brain regions.

In the ROI analysis, 3 mm isotropic voxels smoothing was used for each participant to avoid excessive smoothing that blurred the signal (Stelzer et al., 2014). We used the idiom, random, and the contrast of idiom and random sequences in the localizer task to define individual-level functional ROIs (p <.001, uncorrected) with the MarsBaR region of interest toolbox (Matthew et al., 2002). Because the individual-level functional ROIs varied across individual participants, we combined the group-level results (see Section 3.2.1) from the whole-brain analysis in the localizer task with individual-level functional ROIs to refine conjunction ROIs individually. We concentrated on ROIs in the left hemisphere of the semantic neural network (Cohen et al., 2000; Davey et al., 2016; Liu et al., 2013; Vandenberghe et al., 1996), including inferior occipital gyrus (IOG), fusiform gyrus (FG), superior temporal gyrus (STG), and inferior frontal gyrus (IFG). In each ROI, we extracted the beta estimates (percentage of signal change) from the four conditions (CFS-idiom, CFS-random, superimposed-idiom, and superimposed-random) in the idiom recognition task and performed group-level repeated-measured ANOVA. We also conducted one-sample two-tailed t-tests to examine whether the percent signal changes (relative to the fixation baseline) of the four conditions were significantly different from zero.

3. Results

3.1. Behavior results

3.1.1. Localizer task.

The performance in this task showed that idioms (M = 91.67 %, SD = 8.3 %) had higher accuracy than random sequences (M = 82.87 %, SD = 12.33 %), two-tailed t(26) = 3.215, SD = 0.142, p =.0035, indicating that idioms were easier to remember than random sequences when the words were well perceived.

3.1.2. Idiom recognition task.

To examine the brain activations with and without awareness in the CFS presentation, we sorted the participants into an *objectively-defined* unawareness (OU) group and a *subjectively-defined* unawareness (SU) group (Merikle, Smilek, & Eastwood, 2001; Seth et al., 2008) for the analyses below. The OU group was defined by a perceptual capacity to recognize the word sequences, whereas the SU group was characterized by an introspective experience of perceiving a single word. While previous studies on unconscious processing using either objective or subjective criteria showed highly correlated results (e.g., Del Cul, Dehaene, & Leboyer, 2006), these two definitions may probe different aspects of visual awareness. In the OU group, all participants showed chance-level performance in the idiom recognition task (i.e., within the box of a purple dashed line in Fig. 2). In the SU group, all participants had lower than 50 % visibility in the subjective visibility check (i.e., within the box of an orange dashed line in Fig. 2).

3.1.2.1. Accuracy in the OU group. Three participants (s7, s9, and s15) were excluded because their accuracies (M = 72.92 %, SD = 12.63 %) were higher than chance (50 %) in the CFS presentation based on chi-square goodness of fit tests. The remaining participants (n = 24) were sorted into the OU group, and the individual accuracies of each participant were not significantly higher than 50 % ($x^2 < 2, p > .157$ for all participants). Their accuracies were further submitted to a 2 (presentation: CFS, superimposed) by 2 (sequence: idiom, random) repeated measure analysis of variance (ANOVA), and two-tailed t-tests were conducted throughout the text to compare idiom and random sequences.

There was a main effect of presentation [$F(1,23) = 298.05, p < .0001, \eta_p{}^2 = 0.93$]; the superimposed presentation (M = 82.73 %, SD = 8.96 %) showed higher accuracy than the CFS presentation (M = 48.74 %, SD = 4.37 %). There was also a main effect of sequence ($F(1,23) = 16.87$, $p < .001$, $\eta_p{}^2 = 0.43$); idioms (M = 68.58 %, SD = 9.05 %) had higher

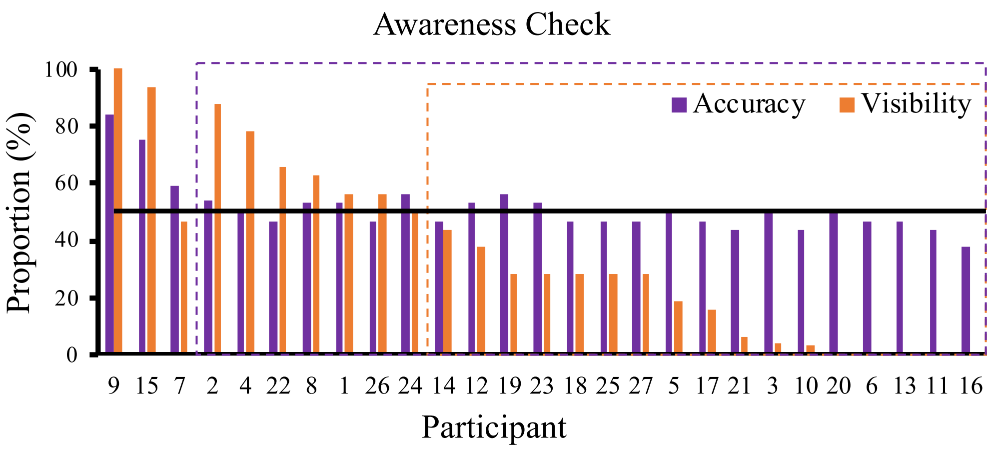

Fig. 2. The accuracy (purple bars) and visibility (orange bars) in the CFS presentation from each participant. The vertical axis indicates the proportion of accuracy and visibility in the idiom recognition task, while the horizontal axis represents participant ID. Participants in the objectively-defined unawareness (OU) group and subjectively-defined unawareness (SU) group are shown with the purple and orange dashed lines, respectively. The solid black horizontal line reflects the 50% chance level performance in the idiom recognition task. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

accuracy than random sequences (*M* = 62.89 %, *SD* = 7.35 %). Importantly, the interaction between presentation and sequence was significant ($F(1,23) = 13.51$, $p = .001$, $\eta_p{}^2 = 0.37$). The accuracy of idioms (*M* = 88.19 %, *SD* = 11.42 %) was higher ($t(23) = 5.12$, $p < .001$) than random sequences (*M* = 77.26 %, *SD* = 9.08 %) in the superimposed presentation. In the CFS presentation, however, there was no simple main effect of sequence ($t(23) = 0.24$, $p = .81$). These findings imply that when participants were aware of word sequences, they could recognize idioms more accurately than random sequences, but not when they were not. Additionally, accuracy for both idioms [*M* = 48.95 %, *SD* = 6.67 %, $t(23) = -0.74$, $p = .46$] and random sequences [*M* = 48.52 %, *SD* = 5.63, $t(23) = -1.26$, $p = .22$] did not differ from chance-level performance in the CFS presentation, indicating that word sequences were invisible in the CFS presentation (Fig. 3a). These results support that our participant-by-participant staircase procedure created a suitable contrast to render stimuli subliminal at both individual and group levels (Shanks, 2017).

3.1.2.2. Visibility in the SU group. While the OU group's chance-level performance in the CFS presentation shows that participants were unaware of the idioms, it is also possible that they were aware of parts of the words and used that knowledge to infer or guess what the idioms were. We thus analyzed the participants' answers to the first question about the visibility of the words presented and excluded 10 participants whose visibility percentages were >50 % (s1, s2, s4, s7, s8, s9, s15, s22, s24, and s26). The rest of the participants made up the SU group (n = 17). We assumed that the SU group had more stringent criteria for what constitutes unawareness. It was possible that a participant would have reported "visible" even if they just saw a fragment of the word because the subjective visibility was evaluated by asking participants if they had identified any portions of the characters during a block. They might only access a portion of the idiom; therefore, their performance was only chance-level.

The SU group's visibility data were analyzed using a 2 (presentation: CFS, superimposed) by 2 (sequence: idiom, random) repeated measure ANOVA (Fig. 3b). There was a significant main effect of presentation [$F(1,16) = 529.01$, $p < .0001$, $\eta_p{}^2 = 0.97$]: the superimposed presentation (*M* = 97.86 %, *SD* = 2.64 %) had higher visibility than the CFS presentation (*M* = 15.87 %, *SD* = 14.66 %). There was a significant main effect of sequence [$F(1,16) = 11.6$, $p = .004$, $\eta_p{}^2 = 0.42$]: idioms (*M* = 58.82 %, *SD* = 8.32 %) had higher visibility than random sequences (*M* = 54.90 %, *SD* = 7.87 %). An interaction between presentation and sequence was also found [$F(1,16) = 5.88$, $p = .028$, $\eta_p{}^2 = 0.27$]. In both the superimposed presentation [idiom: 99.14 % (*SD* = 2.38 %) versus random: 96.57 % (*SD* = 3.91 %), $t(16) = 2.75$, $p = .014$] and the CFS presentation [idiom: 18.51 % (*SD* = 15.74 %) versus random: 13.24 % (*SD* = 14.20 %), $t(16) = 3.40$, $p = .004$], idioms were more visible than random sequences. The fact that the higher visibility for idioms than random sequences in the CFS presentation implies that meaningful sequences broke interocular suppression more easily when the words were

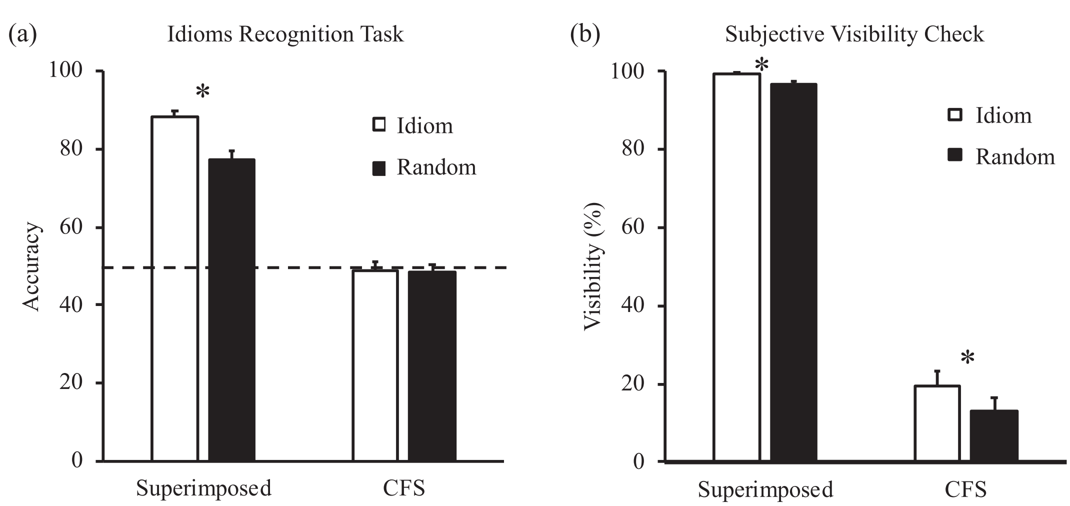

Fig. 3. Behavior results of the idiom recognition task. In the idiom recognition task, the accuracy of idioms was higher than that of random sequences only in the superimposed presentation but not in the CFS presentation. The chance level performance was found only in the CFS presentation. The subjective visibility check for idioms revealed higher visibility than random sequences in the superimposed and CFS presentations.

near-threshold.

3.2. Whole-brain analysis of imaging data

Three participants (s7, s13, and s19) were excluded from the full fMRI analysis because their brain activity failed to pass the quality control of imaging: Their primary visual cortex showed no activation, despite the fact that it should have been active due to the high-contrast masks presented in the CFS and superimposed presentations. The Appendix included an explanation of how to remove participants from each activity in detail.

3.2.1. Localizer task

The analyses included 24 participants. The idiom sequence induced significant activations (p <.05, FWE correction) in the right medial temporal gyrus (MTG), bilateral FG, left precentral gyrus (PreCG), left thalamus, and left STG. The random sequence triggered significant activations (p <.05, FWE correction) in the bilateral IOG, left PreCG, left IFG, and left STG. Additionally, we compared idioms with random sequences and found significant activations (p <.001, uncorrected) in the bilateral STG (see Fig. 4a and Appendix Table 1a).

3.2.2. Idiom recognition task

The idiom recognition task included superimposed and CFS presentations. We sorted the participants into the OU and the SU groups in the CFS presentation to examine the brain activations with and without awareness, as mentioned in Section 3.1.2.

3.2.2.1. Superimposed presentation. The analysis included 24 participants. The idiom sequence induced significant activations (p <.001, uncorrected) in the right FG, left PreCG, left STG and left postcentral gyrus (PostCG). Similar patterns were found in the random sequence, as significant activations were seen (p <.001, uncorrected) in the right FG, left IFG, left STG, left anterior cingulate cortex (ACC), and left PostCG (Fig. 4b and Appendix Table 1b). These results indicate that the neural activations of the semantic neural network expanded up to high-level regions when word sequences were visible. Nevertheless, there was no significant activation when idioms were contrasted with random sequences.

3.2.2.2. CFS presentation (the OU group). The analysis included 22 participants who performed at the chance level on the idiom recognition task during the CFS presentation (see Section 3.1.1).

The idiom sequence significantly activated (p <.001, uncorrected) the bilateral FG, left PreCG, left IFG, bilateral ACC, and right insula. The random sequence revealed significant activations (p <.001, uncorrected) in the bilateral FG, left middle frontal gyrus (MFG), left ACC, and left IFG (see Fig. 5a and Appendix Table 2a). These findings imply that the long-range feedforward loops in cortices associated with high-level processes occurred even when participants were unable to recognize the word sequences presented. When the idiom and random sequences were compared, there was no significant difference in activation.

3.2.2.3. CFS presentation (the SU group). The analysis included 15 participants whose mean visibility in the CFS presentation was lower than 50 %. In addition, because the CFS presentation still had 15.87 % of blocks visible in the SU group (see Section 3.1.2.2 and Fig. 3), we eliminated blocks where participants reported any word visible during a block. In other words, for imaging analyses, only the entirely invisible blocks without any visible words were sorted into the SU group.

In the GLM adopted, invisible CFS-idiom and invisible CFS-random blocks were used as regressors of interest. Visible CFS-idiom blocks, visible CFS-random blocks, superimposed-idiom blocks, superimposed-random blocks, the response period, and six motion parameters were the regressors of no interest.

The idiom sequence showed significant activations in the bilateral FG, right middle occipital gyrus (MOG), and left postCG. The random sequence showed significant activations in the bilateral lingual gyrus (LG), bilateral MOG, left FG, and left PostCG (see Fig. 5b and Appendix Table 2b). These results suggest that when CFS blocked subjective

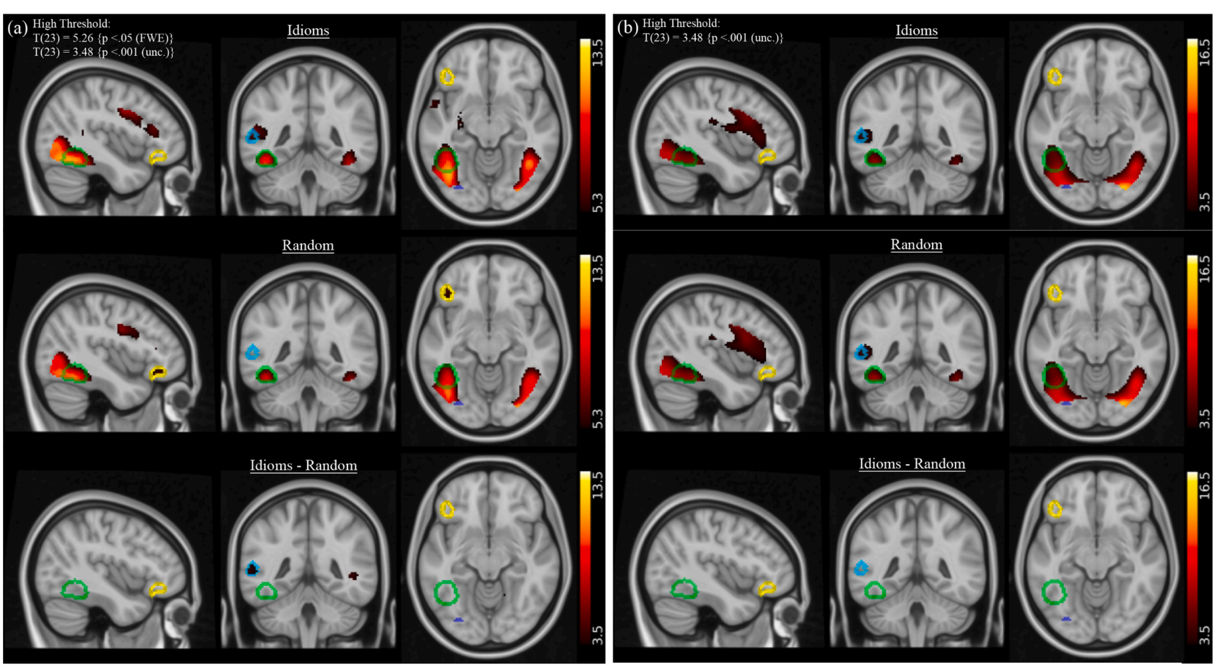

Fig. 4. Brain activations during (a) the localizer task and (b) the superimposed presentation. In each panel, from top to bottom, the three panels of figures show the effects of idiom, random, and idiom versus random, respectively. In both conditions, idiom and random sequences activated the left IOG, bilateral FG, left STG, and left IFG. In the localizer task, activations in the bilateral STG were detected in the comparison between idiom versus random sequences (See Appendix Table 1 for the details). The color outlines indicate the regions for the ROI analysis: IOG (blue), FG (green), STG (cyan), and IFG (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

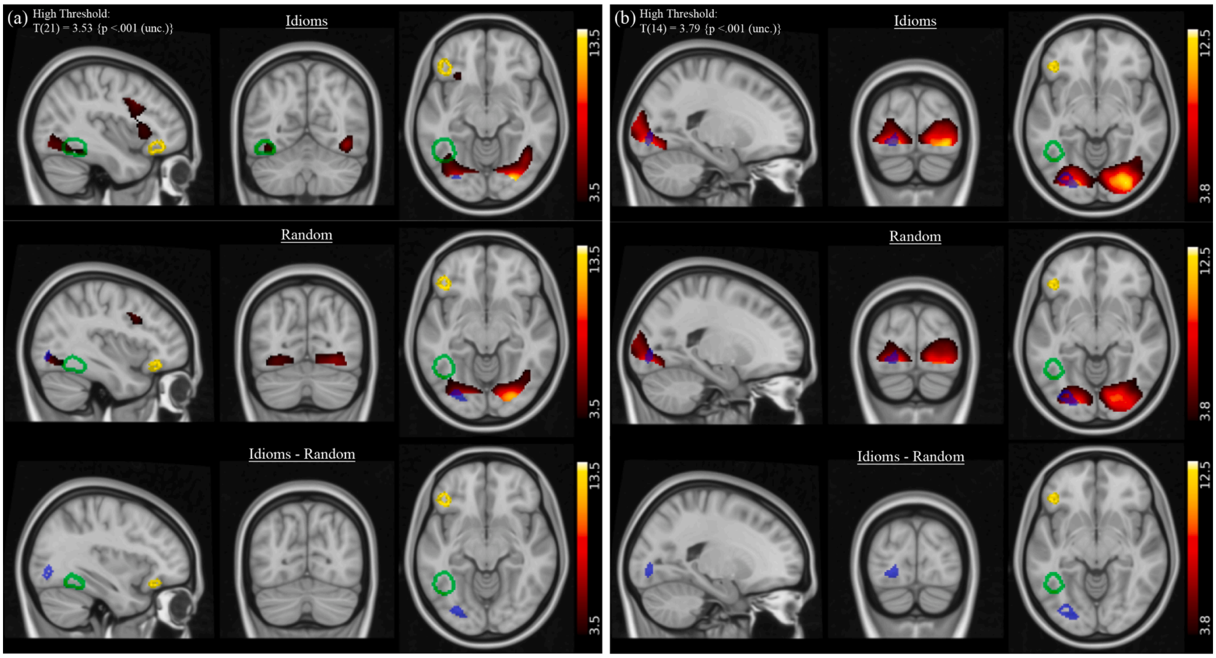

Fig. 5. Brain activations in (a) the CFS-OU group and (b) the CFS-SU group. In each panel, from top to bottom, figures show the effect of idiom, random, and idiom versus random, respectively. In the CFS-OU group, both idiom and random sequence activated the bilateral FG, left ACC, and left IFG. In the CFS-SU group, both the idiom and random sequence activated the left FG and left PostCG. However, when idioms were compared to random sequences, there was no significant activation in both the objectively-defined unawareness group and subjectively-defined unawareness group (See Appendix Table 2 for details). The color outlines indicate the regions for the ROI analysis: IOG (blue), FG (green), STG (cyan), and IFG (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

experiences of word sequences, the processing of visual stimuli was primarily constrained in the visual cortex. There was no significant difference in activation when the idiom and random sequences were compared.

3.3. *Region of interest (ROI) analysis of imaging data*

The ROIs analysis separated the participants into the OU and SU groups. As mentioned, the individual ROIs were refined from the conjunction between the group-level results in the localizer task and the individual-level functional ROIs. As shown by the color outlines regions in Figs. 4 and 5, the semantic neural network, including left IOG, FG, STG, and IFG, was selected for the ROIs analysis. The percentage of signal change in each ROI was submitted to a 2 (presentation: CFS and superimposed) by 2 (sequence: idiom and random) repeated measure ANOVA. General patterns showed that the percentages of signal changes decreased as the higher brain areas were involved. In addition, only the superimposed presentation (but not the CFS presentation) revealed significant signal changes in the left STG and left IFG.

3.3.1. *OU group*

We could not find individual conjunction ROIs from some participants; therefore, there were unequal sampling sizes among ROIs (left LOG: 22; left FG: 22; left STG: 17; left IFG:13) but equal sampling sizes among the four conditions. In general, there was a significant main effect of presentation in all ROIs ($Fs > 8.67$; $ps < 0.01$); the superimposed presentation revealed higher signal changes than the CFS presentation. Neither the main effect of sequence ($Fs < 2.92$, $ps > 0.11$) nor the interaction between presentation and sequence ($Fs < 2.64$, $ps > 0.12$) were found among all ROIs.

We also conducted a two-tailed one-sample *t*-test to further test if the percentages of signal changes of four conditions relative to the fixation baseline were significantly different from zero in each ROI region. The results showed that signal changes in the left IOG and left FG were significantly larger than zero ($ts > 3.72$, $ps < 0.001$) in all four conditions (i.e., superimposed-idiom, superimposed-random, CFS-idiom, and CFS-random). On the other hand, only the superimposed-idiom and superimposed-random conditions ($ts > 2.32$, $ps < 0.01$) had significant signal changes in the left-STG and left-IFG, but neither the CFS-idiom nor the CFS-random condition did ($ts < 1.97$, $ps > 0.067$; Fig. 6a and Appendix Table 3a).

3.3.2. *SU group*

The SU group had unequal sampling sizes across ROIs (left LOG: 15; left FG: 15; left STG: 11; left IFG: 9), but the overall patterns were similar to the OU group. There was a significant main effect of presentation across all ROIs ($Fs > 9.42$; $ps < 0.01$), and the superimposed presentation had larger signal changes than the CFS presentation. None of the ROIs had a significant main effect of sequence ($Fs < 0.09$, $ps > 0.77$) or the interaction between presentation and sequence ($Fs < 4.42$, $ps > 0.06$). In the left IOG and left FG, all four conditions had significantly higher percentages of signal change than zero ($ts > 2.94$, $ps < 0.02$). In contrast, only the superimposed-idiom condition ($ts > 2.24$, $ps < 0.05$) revealed significant signal changes in the left-STG and left-IFG (Fig. 6b and Appendix Table 3b).

4. General discussion

This study looked into whether semantic information could be integrated over time without visual awareness. We investigated how the relevance of word sequence impacts brain activations with and without visual awareness by presenting Chinese characters sequentially to generate either idioms or random sequences. According to behavioral data and brain activations of the semantic neural network, the results suggest that visual awareness modulates the processing of sequentially presented words.

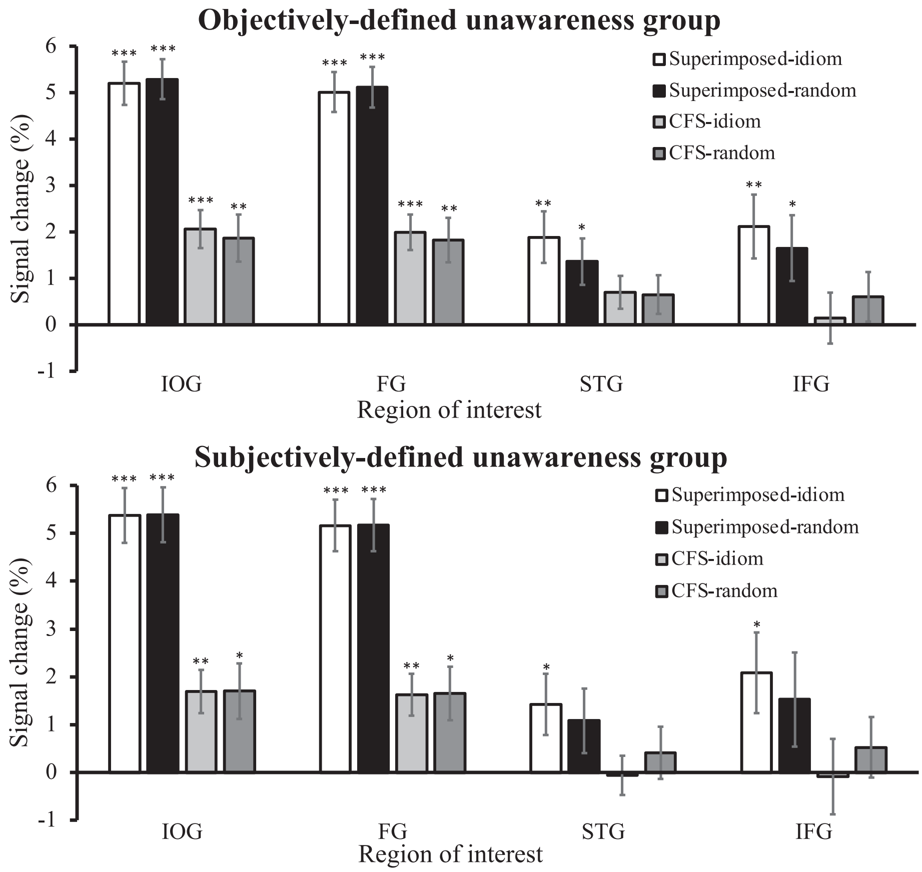

Fig. 6. ROI results in (a) the OU group and (b) the SU group. In each panel, from left to right, figures show the percentage of signal changes of four conditions in the left IOG, left FG, left STG, and left IFG. Results in both groups showed larger signal changes in the superimposed presentation than in the CFS presentation across all ROIs. IOG = inferior occipital gyrus, FG = fusiform gyrus, STG = superior temporal gyrus, IFG = inferior frontal gyrus. The star markers indicate that significant percentages of signal changes were higher than zero (***p <.001, **p <.01, *p <.05).

4.1. The contributions of visual awareness to temporal semantic integration of words in the behavioral performance

The lack of difference in accuracy between idioms and random sequences under the CFS presentation suggests that participants did not benefit from the meaning of the semantic context provided in a sequence when awareness of the stimuli was blocked. Note that the inability to recognize idioms and random sequences under CFS should not be attributable to the insensitivity of the idiom recognition task we used here for the following reason. In the idiom recognition task, the "yes" responses were selected based on the primacy and recency effects (Miller & Campbell, 1959); thus, participants should remember them better than if the answers were selected from the middle of the block. Indeed, the localizer task and the superimposed presentation demonstrated high accuracy and a significant difference between idioms and random sequences, implying that participants could recall what they saw if visual awareness was preserved. These behavioral results indicate that interocular suppression prevented not only visual awareness of word sequences but also their semantic integration.

4.2. Brain activation of temporal integration with and without visual awareness

Regarding the brain activations of idioms and random sequences, respectively, when words were visible in both the localizer task and superimposed presentation, significant neural activations throughout the semantic neural network were found, including areas in the bilateral IOG, bilateral FG, left STG, and left IFG. These areas are highly related to language processing. The bilateral FG, for example, is a well-established brain area associated with visual word form processing (Cohen et al., 2000; Liu et al., 2008). Bilateral occipital-temporal activation was revealed to be involved in the orthographic processing of Chinese characters (Liu et al., 2013; Zhang, He, & Weng, 2018). More specifically, the left STG was found to be involved in semantic comprehension (Davey et al., 2016; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996), while the left IFG was implicated in the retrieval of semantic information (Fiez, 1997; Gabrieli, Poldrack, & Desmond, 1998; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Vandenberghe et al., 1996). These results imply that processing idioms and random sequences involved similar semantic neural networks at the single word level when the word sequences were visible.

However, the difference in brain activations between idioms and random sequences was only seen in the localizer task, not in the superimposed presentation, which can be explained further down. In the localizer task, the word sequences were visible without any masks, and activations of the bilateral STG were found, which are known to be activated when accessing word meanings (Davey et al., 2016; Nakamura, Dehaene, Jobert, Bihan, & Kouider, 2005; Vandenberghe et al., 1996) and comprehending idioms (Lauro, Tettamanti, Cappa, & Papagno, 2008). On the contrary, we found no significant difference in brain activations between idioms and random sequences in the superimposed presentation. The difference in results could be due to the difference in task demands and perceptual processing between the localizer task and superimposed presentation. For example, unlike the localizer task, the superimposed presentation included a visibility check, which raised additional task demand for visual memory (Bogousslavsky, Miklossy, Deruaz, Assal, & Regli, 1987) and word association (Ghosh et al., 2010). Moreover, the superimposed condition contained high contrast binocular masks and low contrast word sequences. There was a need for extra low-level processing to segregate word sequences from masks. Consequently, when words were superimposed on the binocular mask, there might be only shallow processing of semantic integration, as evidenced by the lower accuracy in the superimposed condition (M = 82.73 %) than in the localizer task (M = 87.27 %). While the contrast between idioms and random sequences activated the bilateral STG that was only observed in the localizer task and not in the superimposed presentation, the behavioral results suggest that when the viewers were aware of word sequences in both the localizer task and the superimposed presentation, they could recognize idioms better than random sequences.

The results were quite different when CFS blocked the participants' awareness of the word sequences. Participants included in the OU group whose objective-defined visibility was no higher than chance level (50 %) showed brain activation of the bilateral FG for both idioms and random sequences, reflecting unconscious processing of visual word forms (Cohen et al., 2000; Liu et al., 2008). The activation of the left IFG suggests that lexical retrieval (Axelrod et al., 2014; Gabrieli et al., 1998) may still take place unconsciously at the single word level. In contrast to the localizer task or superimposed presentation, the CFS presentation showed no activation in the left STG and neither significant result in the idiom recognition task, suggesting that comprehension of the meanings of words was substantially shallower when participants were unaware of the words than when they were aware of the words.

Participants included in the SU group whose subjective report was <50 % and the visible blocks were eliminated showed brain activation of the left FG for both idioms and random sequences; this shows that visual word forms of the stimuli were nonetheless processed even under a stringent criterion of unawareness. Notably, the increased activity of the occipital lobes (e.g., right MOG) in the SU group may imply that processing was more confined to the perceptual level. We also found activation in the left PostCG for both idioms and random sequences, which indicates that perceptual inputs triggered a feedforward activity that propagated to the parietal lobe without consciousness. Nevertheless, the activation was insufficient to generate visual awareness. There were no significant differences in activations between idioms and random sequences for the SU group, which is consistent with the results of the OU group, reflecting that semantic information cannot be temporally integrated without visual awareness in both subjectively defined or objectively defined criteria of unawareness to include the participants for analyses.

The ROIs analysis, like the whole-brain study, presents a consistent story. The superimposed presentation had a larger proportion of signal change than the CFS presentation in both the OU and SU groups. This finding is based on the fact that the superimposed and CFS presentations had the same number of participants in each ROI, allowing for a fairer comparison between the two presentations. Furthermore, while both CFS and superimposed revealed substantial signal changes in the lower-level areas like left IOG and left FG, only the superimposed presentation exhibited significant signal changes in the higher-level area like left STG and left IFG. These findings suggest that visual awareness indeed modulates neural activation along with the semantic neural network in a hierarchical manner.

4.3. Unconscious semantic integration in space and time

Some may argue that the null result in the CFS presentation we obtained here was due to the words being presented at the same fixation location, masking each other and preventing their potentially semantic integration. However, a recent finding revealed that spatial overlapping is not a critical factor influencing semantic integration (Tu et al., 2019). Their study used a backward masking paradigm to examine if multiple words can be integrated unconsciously to induce a semantic priming effect. Critically, they presented three spatially nonoverlapping Chinese characters to serve as an unconscious prime, which were presented either simultaneously (Experiment 1) or sequentially from left to right (Experiment 2). The semantic priming effect occurred only when the characters were displayed simultaneously rather than sequentially. That is, the main obstacle to unconscious semantic integration is temporal integration, not spatial overlapping.

4.4. Implication of the theories of consciousness

In the localizer task and the superimposed presentation, we found brain activations associated with higher-level processing (mostly in the left hemisphere's semantic networks), which is consistent with established theories of consciousness (Dehaene & Changeux, 2011; Dehaene, Changeux, Naccache, & Sergent, 2006; Lamme, 2006). The visual cortex was more activated in the SU group than in the OU group, which had modest activation in the left frontal lobes and left ACC. These disparate patterns suggest that perceptual capacity and subjective experience failures might stimulate various components of unconscious processing. On the other hand, whether or not participants were aware of the multiple words, the activation of the joint region (e.g., bilateral FG) was discovered, implying that visual word form processing merely relies on a local connection of the feedforward loop. By contrast, both idiom and random sequence triggered reliable activations of the frontal lobe only in the localizer task and superimposed presentation, but not the CFS presentation, suggesting that a global recurrent feedback loop is essential for visual awareness and semantic processing.

The current finding is also consistent with recent research suggesting that multiple words cannot be integrated in time without visual awareness (Mongelli et al., 2019; Tu et al., 2019; Yang, Tien, et al., 2017; Zhou et al., 2016). These findings could be explained by the fact that unconscious integration is limited to a short integration window (Faivre & Koch, 2014; Nakamura et al., 2018) or by low-level information processing (See Mudrik, Faivre, & Koch, 2014 for a review). In other words, integrating semantic information across time necessitates accessing and retaining the meaning of each word in working memory. While recent research has found that suppressed stimuli under CFS matching information being held in working memory can be detected faster than mismatched information (Gayet, Paffen, & Van der Stigchel, 2013; Pan, Lin, Zhao, & Soto, 2014), the contents of working memory were encoded during conscious states rather than unconscious states. As a result, semantic information may be swiftly lost without consciously holding the meaning of each word in working memory.

4.5. Conclusion

What are the limits of unconscious processing during reading? In the behavioral results, participants had better recognition memory for idioms than random sequences in both the localizer task and the superimposed condition. Nonetheless, there was no such difference in memory performance in the CFS condition. In the fMRI results, viewing idioms or random sequences of Chinese words activated STG and IFG in both the localizer and superimposed conditions. Nonetheless, these higher-level, semantics-processing areas in the brain were not activated in the CFS condition. On the contrary, viewing idioms or random sequences of Chinese words activated lower-level, orthography-processing FG and IOG not only in the localizer and the superimposed conditions but also in the CFS condition. Collectively, the behavioral and fMRI results suggest that while single words were unconsciously processed in the brain, visual awareness was essential for successfully integrating multiple words over time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandc.2022.105916.

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