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COGNITIVE NEUROSCIENCE

Neural capacity limits during unconscious semantic processing

Kimihiro Nakamura,[1] Michiru Makuuchi,[2] Tatsuhide Oga,[3] Tomomi Mizuochi-Endo,[2] Toshiki Iwabuchi,[2] Yasoichi Nakajima[2] and Stanislas Dehaene[4,5]

[1]Faculty of Human Sciences, University of Tsukuba, Tsukuba 305-8577, Japan
[2]National Rehabilitation Center for Persons with Disabilities, Tokorozawa 359-0042, Japan
[3]Toranomon Hospital Kajigaya, Kawasaki 213-0015, Japan
[4]Cognitive Neuroimaging Unit, CEA DSV/I2BM, INSERM, NeuroSpin Center, Université Paris-Sud, Université Paris-Saclay, 91191 Gif/Yvette, France
[5]Collège de France, 11 Place Marcelin Berthelot, 75005 Paris, France

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Abstract

A growing body of neuroimaging data suggests that direct measurements of brain activity can reveal subliminal effects that remain invisible with behavior measures alone. We examined whether sentence comprehension processes could be triggered by a sequence of masked words. On each trial, participants viewed a rapid sequence of masked or unmasked words, including a subject noun, three adverbs and followed by a visible target verb. To probe the capacity limits of unconscious processing, we measured event-related potentials associated with the semantic congruency between the noun and the verb, while varying the subject position in each sentence. Unmasked sentences produced significant behavioral effects of congruency, paralleled by robust N400 effects, independently of subject–verb distance. By contrast, masked sentences produced no behavioral effect and elicited N400 effects only when subjects and verbs were separated by 0 or 1 word. The present results suggest that semantic integration of multiple words can occur unconsciously only if the distance between the words to be integrated does not exceed two words. Although the possibility remains that even longer sequence of invisible words may produce similar neural effects in different experimental settings, our ERP data show that only conscious perception gives access to a buffer that enables robust sentence-level processing independently of temporal distance.

Introduction

Subliminal verbal messages have long been suspected to exert an impact on the human mind and behavior. In fact, a growing body of behavioral and brain imaging studies shows that earlier stages of language processing, including orthographic, phonological, and semantic analyses of written words, can automatically occur even without observers' conscious awareness (Dehaene *et al.*, 2006; Kouider & Dehaene, 2007). Here, we ask whether the integration of multiple words into a sentence can also occur without awareness. Understanding a multi-word sentence is thought to involve a temporary buffer which holds those word representations before they can be semantically and syntactically integrated (Makuuchi *et al.*, 2009; Kang *et al.*, 2011; Pallier *et al.*, 2011; Vagharchakian *et al.*, 2012), and such buffering is therefore likely to require access to a conscious workspace. Indeed, some behavioral studies with visual masking have suggested that complex cognitive operation with multiple words may exceed a 'capacity limitation' for unconscious language processing which may not go beyond the semantic analysis of single words (Greenwald & Liu, 1985; Draine, 1997). Or rather, unconscious processing may operate more flexibly without fixed capacity limits, as it is currently thought to be not fully automatic and sensitive to conscious behavior, such as spatiotemporal attention, task instructions, and executive control (see Dehaene *et al.*, 2006; Kouider & Dehaene, 2007 for review).

Interestingly, recent brain imaging data suggest that semantic or syntactic property of sentences, although undetectable as behavioral effects, can produce measurable changes in neural response during unconscious language processing. Using event-related potentials (ERPs) with an attentional blink paradigm, Batterink & Neville (2013) showed that the presence of a consciously undetectable syntactic violation in sequentially presented 10-word sentences (300 ms for each word) evokes a sustained negative response at 100–400 ms after stimulus onset during sentence processing. Moreover, using functional magnetic resonance imaging (fMRI) with continuous flash suppression (CFS), Axelrod *et al.* (2015) reported

Correspondence: Kimihiro Nakamura, as above. E-mail: kimihiro@human.tsukuba.ac.jp

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that the left frontotemporal region exhibits a very small but significant response during a non-conscious exposure to six-word sentences (presented at a rate of 400 ms per word). These findings suggest that the cerebral language network is capable of processing long word sequences even when conscious resources are diverted away from the stimuli.

However, subliminal processing may be much more restricted when sentence stimuli are rendered invisible by visual masking, because masking is known to induce primarily a short-lived activation in posterior brain areas (Dehaene *et al.*, 2006; Kouider & Dehaene, 2007). Importantly, such local neural activation is thought to have a cognitive processing limit which is estimated at about three or four items (Marois & Ivanoff, 2005; Buschman *et al.*, 2011). Taken together, it is possible that unconscious processing of masked words has a more constrained capacity limit than those obtained from other experimental settings such as CFS and attentional blink. In fact, a recent ERP study by van Gaal *et al.* (2014) showed that masked two-word primes (e.g., the words 'very bad' or 'not bad' presented for 33 ms) produced a significant modulation of the N400 component of ERPs evoked by a conscious target (e.g., 'murder'), while no effect was observed on behavioral measures. This observation indicates that the cerebral language network can maintain at least two masked items online during unconscious processing, but it remains open whether a brief and unconscious exposure to three or more words can produce a detectable impact on neural response measures. As described above, such longer sequences of masked words have been shown to produce no behavioral effects, but it is essential to examine if they elicit measurable brain responses during unconscious processing.

In this study, we recorded ERPs during a novel masked priming paradigm in which an entire series of words was masked. On each trial, participants viewed a rapid sequence of seven masked or unmasked words, including a noun phrase and three adverbs and followed by a visible target verb (Fig. 1). Nouns could be either semantically congruent or incongruent with sentence-final target verbs (e.g., 'dog-run' vs. 'dog-open'). The distance between nouns and verbs varied from 0 to 3 words, as we inserted three adverbs at different positions in each sentence. Our goal was to determine the capacity limit of unconscious semantic processing by measuring how N400 effects elicited by the sentence-final verb would change as a function of the distance to a semantically incongruous noun preceding it. We predicted that an N400 response would appear for visible sentences, irrespective of the subject–verb distance, because conscious words can be buffered in short-term memory (Vagharchakian *et al.*, 2012). On the other hand, we hypothesized that ERP responses to unseen sentences would disappear when the number of words separating subjects and verbs exceeds the possible processing limit of the posterior brain areas (i.e., three or four items at maximum (Marois & Ivanoff, 2005; Buschman *et al.*, 2011)), as the short-lived neural activation induced by masked words is probably insufficient to support the effortful and time-consuming analysis of multiple words.

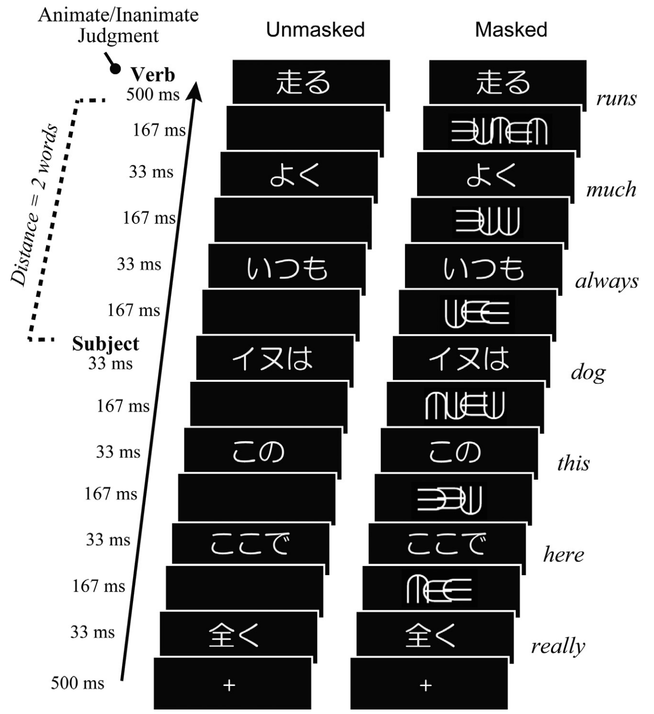

FIG. 1. Behavioral paradigm. Each trial started with a visible adverb ('really') followed by a timed sequence of six words including a noun phrase, three adverbs, and a visible target verb. The noun could be either semantically congruent or incongruent with the verb (e.g., 'dog-runs' vs. 'dog-opens'). We varied the distance between nouns and verbs from 0 to 3 words by inserting three adverbs at different positions in each sentence. Participants made animate vs. inanimate judgment about visible targets as quickly and as accurately as possible.

Methods

Participants

Twenty-four healthy volunteers participated in this study (ten women, age range 19–50 years, mean 25.3 years). All of them were right-handed, native speakers of Japanese. None of them had known neurological or psychiatric disorders. All had normal or corrected-to-normal vision and gave written informed consent prior to the experiments. The protocol of this study was approved by the ethical committee of the National Rehabilitation Center for Persons with Disabilities. All experimental procedures described below were performed in accordance with relevant guidelines and regulations. Six participants were excluded from behavioral and ERP analyses because of higher error rates (>15%) or excessive artifacts in EEG data (>30% trials).

Behavioral paradigm

We initially selected 26 nouns and 26 verbs of medium-to-high frequency in Japanese (mean lexical frequency = 25.5 par million for nouns and 50.9 par million for verbs, respectively, according to the BCCWJ corpus provided by the National Institute for Japanese Language and Linguistics (http://pj.ninjal.ac.jp/corpus_center/bccwj/en/)). Half of the nouns represented animals (e.g., dog) and the other half artifacts (e.g., shirt). Likewise, half of the verbs characterized animal behaviors (e.g., run), while the other half described the motions of objects (e.g., dry). All these verbs were intransitive and did not take objects. By coupling these nouns and verbs, we created 52 subject–verb pairs, half of which included semantically congruent subjects and verbs and the other half incongruent subjects and nouns (see Table 1, for example, stimuli). To construct sentence stimuli, we further coupled these subject–verb pairs with three adverbs, each of which represented time, place, and frequency of actions (i.e., 'today', 'here', 'often', respectively) and thus did not alter the nature of subject–verb semantic congruity. For each subject–verb pair, four different sentences were generated by inserting these adverbs at different positions before or after the noun phrase. This allowed us to keep the total number of words constant while manipulating the subject–verb distance such that subjects could appear immediately before verbs (distance = 0) or at a distance of 1, 2, or 3 words.

Each trial included a rapid sequence of seven words which presented an unmasked and visible adverb ('really'), a subject phrase (a determinant and a noun), three adverbs for 33 ms each, respectively and a final verb target for 500 ms (Fig. 1). In half of trials, each of the nouns and three adverbs preceding verb targets was masked by a string of character-like symbols (167 ms) so that participants were unable to perceive them consciously, whereas, in the other half of trials, each word in a sentence was followed by a blank screen for 167 ms. Note that the presentation rate of sentence stimuli was very fast (300 words per minute (WPM)) but likely optimal for fluent reading comprehension (Carver, 1992; Rayner *et al.*, 2016). Participants were not informed about the presence of masked stimuli. On each trial, they were requested to press, as quickly and as accurately as possible, a key with right index finger when visible targets represented animal actions or a different key with the left index finger when otherwise. The 52 sentence stimuli were presented, either with or without masking, in a pseudo-random order. The experiment was therefore a 2 × 2 × 4 factorial design which included the semantic congruency (congruent and incongruent), masking (masked and unmasked), and subject–verb distance (0, 1, 2 and 3 words) as within-participant factors. Participants received a total of 416 trials divided into three blocks, each lasting ~ 11 min (139 trials in the initial two blocks and 138 trials in the final block, respectively), such that there were 26 trials for each trial type (thus each of the 26 target verbs was presented 16 times in total during the ERP experiment). Prior to ERP recording, participants received 36 practice trials with example stimuli which were not used in the main experiment.

We recruited a separate group of 27 native Japanese speakers (ten women, age range 19–25 years, mean 21.1 years) to examine the visual discriminability of masked sentences in the ERP experiment. These participants were slightly but significantly younger than those in the main experiment (t_{43} = 2.64, P = 0.012) and thus served as a good index of stimulus visibility during ERP recording, as age-related decline in visual processing is well-known to begin even in young adulthood (Busey *et al.*, 2010; Costello *et al.*, 2010; Owsley, 2011). Here, we examined whether participants were able to consciously recognize multiple words in the present rapid serial visual presentation paradigm. Each trial consisted of the same sequence of masked or unmasked words as in the main experiment. At the end of the trial, participants were presented with three possible combinations of nouns and adverbs (e.g., 'this dog often (runs)', 'this dog today (runs)', 'this dog here (runs)') and requested to decide which of the three choices was included in the preceding sentence without time pressure (104 trials). In this visibility test, mean accuracy (SD) for unmasked trials was 63.1 (11.1) % and far exceeded the chance level of 33% (t_{26} = 13.91, $P = 1.49 \times 10^{-13}$, two-tailed). While those unmasked stimuli were clearly visible and intelligible as sentences, the relatively low level of accuracy can be attributed to the fact that the visual word presentation rate was close to the processing limit of the left-hemisphere language system (Vagharchakian *et al.*, 2012) and thus probably too fast for retrieving the exact order of words (see Discussion). In contrast, mean accuracy (SD) for masked trials was 35.1 (6.26) % and did not differ from chance level (t_{26} = 1.41, P = 0.17). This effect of masking on visibility was highly significant ($F_{1,26}$ = 94.75, $P = 3.71 \times 10^{-10}$) and did not change with subject–verb distance ($F < 1$). These findings therefore suggest a categorical difference in visibility between masked and unmasked trials, whereby participants are unable to consciously perceive the contents of masked sentence stimuli.

TABLE 1. Examples of subject–verb pairs (English translations) used in the ERP experiment. Target verbs represented movements/actions of living animals ('animate') or those of non-living objects ('inanimate'). In sentence stimuli, target verbs could be either semantically congruent or incongruent with subject nouns. Note that all verbs were intransitive and did not take objects in Japanese (see Methods)

Category	Target verbs Exemplars	Subject nouns	
		Congruent	Incongruent
Animate	Taberu (eat)	Hitsuji (sheep)	Naifu (knife)
	Aruku (walk)	Usagi (rabbit)	Garasu (glass)
	Nemuru (sleep)	Kirin (giraffe)	Raito (light)
Inanimate	Kireru (cut)	Naifu (knife)	Hitsuji (sheep)
	Wareru (break)	Garasu (glass)	Usagi (rabbit)
	Hikaru (shine)	Raito (light)	Kirin (giraffe)

EEG recording and data analysis

Continuous EEG was recorded from 64 scalp electrodes and digitized at a sampling rate of 250 Hz with a BrainAmp amplifier (BrainProducts, Germany). All scalp electrodes were referenced to the average of the left- and right-mastoid leads. Electrode impedances were kept below 10 kΩ. EEG data were preprocessed and analyzed using the FieldTrip toolbox (http://fieldtrip.fcdonders.nl/). Trials containing transient activities exceeding 80 μV were removed from analysis. The remaining trials were averaged and band-pass filtered (0.1–30 Hz) and corrected for baseline over a 167 ms (i.e., the offset of words immediately preceding targets). Epochs containing the pre-stimulus baseline and 1 s post-stimulus time were averaged with respect to trial type.

We first determined the ERP time-windows associated with semantic violations by contrasting congruent and incongruent trials. This congruency effect on target-locked ERPs was calculated by pooling the EEG data from masked and unmasked trials across the four levels of subject–verb distance. Over 24 selected electrodes in left and right frontal (F1/F3/F5/FC1/FC3/FC5, F2/F4/F6/FC2/FC4/FC6) and central-posterior (CP1/CP3/CP5/P1/P3/P5, CP2/CP4/CP6/P2/P4/P6) regions, we examined a moving average of 40 ms shifting every 10 ms between 0 and 800 ms after target onset (see Batterink & Neville, 2013; Jimenez-Ortega *et al.*, 2014; van Gaal *et al.*, 2014 for similar electrode selection procedures). In this analysis, we identified ten time-windows around 450 ms each showing significant negative effects of congruency ($P < 0.05$, corrected for multiple comparisons with false discovery rate [FDR]).

In addition, while the effect of N400 is known as a good neural index of fast and automatic lexico-semantic processing (Kutas & Federmeier, 2011), we also examined the effect of P600, or a late-stage ERP component which has been associated with syntactic processing (Van Petten & Luka, 2012), or conscious semantic integration (Schotter *et al.*, 2014). We isolated another set of three time-windows showing a positive effect of congruency ($P < 0.05$) and peaking around 620 ms and two adjacent time points showing the same trend (P = 0.073 and 0.083). Based on these initial analyses, we examined the effects of N400 and P600 by computing the ERP differences between 400 ms and 500 ms and those between 610 ms and 650 ms, respectively (see Fig. 3). For each of the ERP effects, we performed a 2 × 2 × 4 × 2 analysis of variance

(ANOVA) which treated participants as a random effect and included the semantic congruency (congruent and incongruent), masking (masked and unmasked), subject–verb distance (0, 1, 2, and 3 words), and region (frontal and posterior) as within-participant factors.

Results

Behavioral results

Participants made few errors during the semantic classification task (mean error rate (SD) = 3.59 (2.22) %). Mean reaction times for correct responses are illustrated in Fig. 2. These reaction time data were examined with a 2 × 2 × 4 ANOVA treating the semantic congruency (congruent and incongruent), masking (masked and unmasked), and subject–verb distance (0, 1, 2, and 3 words) as within-participant factors. The main effect of masking was significant, with participants overall responding 18 ms faster on unmasked trials than on masked trials ($F_{1,17}$ = 13.56, P = 0.002). This finding concurs with a recent behavioral study showing that visual masking induces a steep decline in reading rate under rapid serial presentation (Primativo *et al.*, 2016). The main effect of congruency was also significant ($F_{1,17}$ = 7.13, P = 0.016), with participants responding 12 ms faster when subjects and verbs were congruent than when incongruent. The magnitude of this congruency effect was 14 ms for unmasked trials and 3 ms for masked trials, a difference which fell short of significance ($F_{1,17}$ = 3.56, P = 0.076). Indeed, when the analysis was restricted to unmasked trials, the effect of congruency was significant ($F_{1,17}$ = 10.29, P = 0.005) and did not interact with that of distance (F < 1). This finding suggests that on unmasked trials, participants extracted sentence meanings from the rapid sequences of words irrespective of the subject–verb distance. By contrast, the congruency effect for masked trials neither approached significance nor interacted with the effect of distance (F < 1). The main effect of distance was neither significant nor interacted with the effect of congruency (F < 1). In addition, no significant congruency effect was observed, even at the shortest distances of 0 word (F < 1) or 1 word ($F_{1,17}$ = 1.45, P = 0.246).

ERP results

ERP waveforms averaged over 24 electrodes on the left and right hemispheres are illustrated in Fig. 3. We observed that semantic

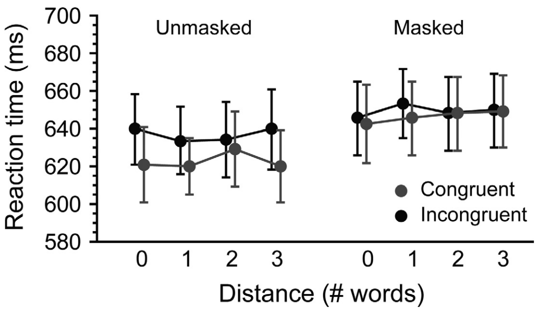

FIG. 2. Behavioral results. Participants responded more quickly when subjects and verbs were congruent than when they were incongruent. However, this congruency effect tended to be greater on unmasked trials (14 ms) than on masked trials (3 ms), creating a marginally significant masking-by-congruency interaction. On unmasked trials, the effect of congruency was significant and its effect size did not change with distance. On masked trials, the congruency effect neither approached significance nor interacted with the effect of distance (see Results for detail).

violations elicited a negative-going effect at 400–500 ms after target onset (N400) and a positive-going response at 610–650 ms (P600), respectively. We first assessed the effect of N400 using a 2 × 2 × 4 × 2 ANOVA that included semantic congruency (congruent and incongruent), masking (masked and unmasked), subject–verb distance (0, 1, 2, and 3 words), and region (frontal and posterior) as within-participant factors. The main effect of region was highly significant ($F_{1,17}$ = 28.25, P = 5.70 × 10^{-5}), suggesting that the magnitude of ERP was greater in the posterior region than in the frontal region (2.08 μV vs. 0.77 μV). The effect of masking was marginally significant, suggesting that overall ERPs tended to be larger on unmasked trials than on masked trials (1.63 μV vs. 1.21 μV, $F_{1,17}$ = 3.90, P = 0.065). In parallel with the behavioral RT data, the effect of distance was non-significant ($F_{1,17}$ = 1.54, P = 0.232), suggesting that the overall magnitude of ERP did not change with distance. In Fig. 4, we additionally plotted ERPs waveforms averaged from left centro-posterior electrodes (C3/CP3/P3) showing the highest effect of semantic congruency in the grand-average ERPs according to the number of words intervening between subjects and verbs.

During the period 400–500 ms after target onset, the main effect of congruency was highly significant, suggesting that the amplitude of ERPs decreased on incongruent trials relative to congruent trials (0.96 μV vs. 1.88 μV, $F_{1,17}$ = 18.43, P = 4.93 × 10^{-4}). This effect of congruency, which had a topography characteristic of the N400 (Fig. 3), interacted with the effect of masking, suggesting that the magnitude of the difference between congruent and incongruent trials was greater on unmasked trials than on masked trials (1.29 μV vs. 0.55 μV, $F_{1,17}$ = 11.52, P = 3.45 × 10^{-3}). There was also a significant three-way interaction between congruency, distance, and region ($F_{1,17}$ = 3.15, P = 0.033). Other interactions were all non-significant (P > 0.2 for all). To further assess this triple interaction, we examined the effect of congruency separately for unmasked and masked trials.

When the analysis was restricted to unmasked trials, the effect of congruency was highly significant ($F_{1,17}$ = 27.00, P = 7.29 × 10^{-5}) but did not interact with the effect of region (F < 1). The effects of congruency and distance interacted neither with each other nor with the effect of region (F < 1 for both). On the other hand, when restricted to masked trials, the effect of congruency was significant ($F_{1,17}$ = 5.67, P = 0.029) and showed a marginally significant triple interaction with the effects of distance and region ($F_{1,17}$ = 3.83, P = 0.067), suggesting that the magnitude of N400 decreased with distance more greatly in the posterior region than in the frontal region.

For each region, we then examined eight pairwise comparisons between congruent trials and incongruent trials (i.e., subject–verb distance (0 to 3 words) × masking (unmasked and masked)), FDR corrected for multiple comparison (Fig. 5A). In the posterior region, unmasked trials produced significant effects of N400 at all levels of distance (P = 0.015 for distance 0; P = 9.79 × 10^{-4} for distance 1; P = 0.036 for distance 2; P = 0.036 for distance 3). However, on masked trials, the effect of N400 was significant or marginally significant only when the subject–verb distance was 0 (P = 0.061) or 1 word (P = 0.036), and not when subjects and verbs were separated by 2 words (P > 0.5) or 3 words (P = 0.14). In the frontal region, unmasked trials also produced significant effects of N400 at almost all levels (P = 0.016 for distance 0; P = 7.67 × 10^{-3} for distance 1; P = 0.016 for distance 2; P = 0.062 for distance 3), whereas this was not the case for masked trials, irrespective of the subject–verb distance (P > 0.11 for all).

We next examined the effects present in the later time-window (610–650 ms, corresponding to the P600), using the same ANOVA as

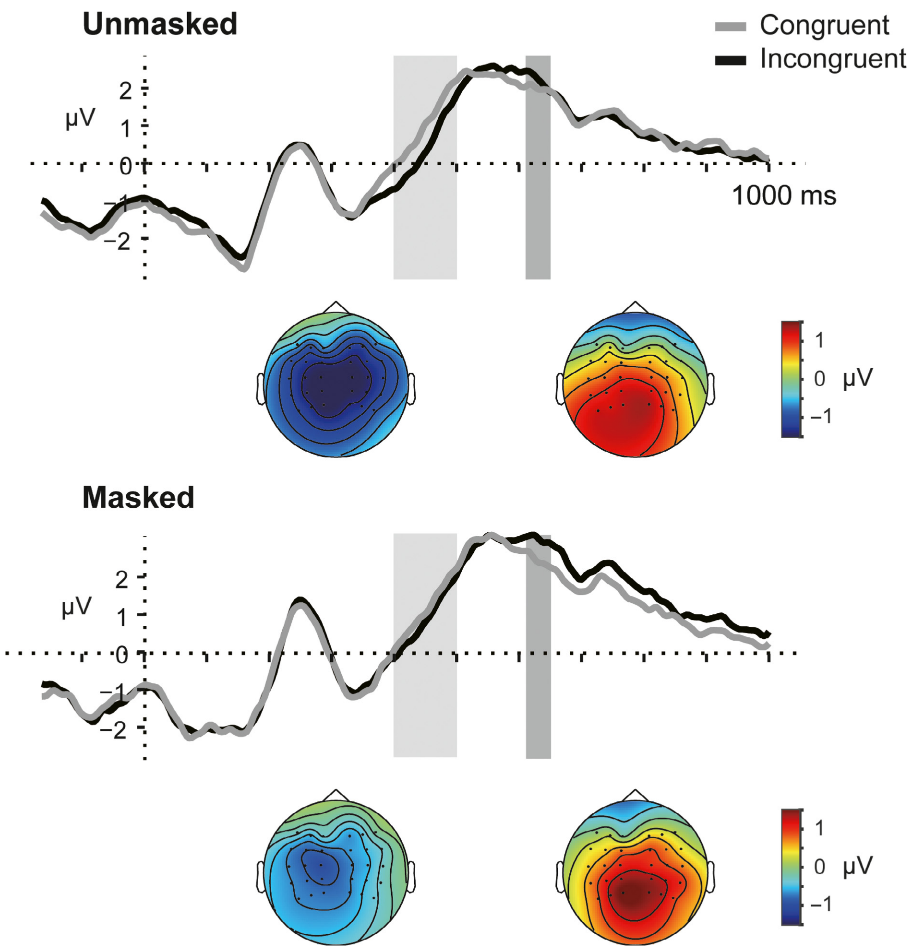

FIG. 3. Grand-average ERP waveforms recorded from 24 electrodes in the frontal and posterior regions. Semantic incongruency elicited a negative-going effect at 400–500 ms after target onset (N400, in light gray) and a positive-going response at 610–650 ms (P600, in dark gray). [Colour figure can be viewed at wileyonlinelibrary.com].

described above. Overall, the magnitude of ERP was much greater in posterior than in frontal region (5.31 μV vs. 2.45 μV, $F_{1,17}$ = 55.94, $P = 9.45 \times 10^{-7}$). The effects of masking and distance did not change the magnitude of ERPs (F < 1 for both). By contrast, incongruent trials elicited larger ERPs than congruent trials (3.63 μV vs. 4.13 μV, $F_{1,17}$ = 7.74, P = 0.013), whereas this P600 effect was larger in the posterior than in the frontal region (0.72 μV vs. 0.29 μV, $F_{1,17}$ = 7.45, P = 0.014). Unlike the effects of N400, there was no trend of interaction between congruency and masking (0.37 μV vs. 0.64 μV, F < 1), suggesting that the magnitude of P600 did not differ between unmasked and masked trials.

Although the effect of masking produced no significant impact on P600, we plotted its effect size for each region in parallel with N400 (Fig. 5B) and performed eight pairwise comparisons between congruent trials and incongruent trials for each region. In the posterior region, the effect of congruency did not reach significance at any of the four levels, neither for masked trials nor for unmasked trials (P > 0.2 for all). Likewise, no significant effect of P600 was observed at any of the four levels in the frontal region, irrespective of the effect of masking (P > 0.4 for all). These results therefore suggest that, under the present design, P600 appeared only as a weak effect even during conscious sentence processing. Indeed, the overall magnitude of P600 was much smaller than that of N400 (0.43 μV vs. 0.92 μV). This finding may be attributed to the fact that the present behavioral paradigm taps the semantic association between nouns and verbs and does not directly require syntactic processing. In fact, the P600 response seems to be weak or absent even during visible sentence processing when behavioral tasks impose only low processing demands at the syntactic level (Service *et al.*, 2007; Batterink *et al.*, 2010; Busey *et al.*, 2010; Kos *et al.*, 2010; Van Petten & Luka, 2012).

Discussion

At the behavioral level, we obtained a significant effect of subject–verb congruency on unmasked trials across the four levels of subject–verb distance. In contrast, the same effect was absent on masked trials regardless of the subject-–verb distance, even when target verbs appeared immediately after subjects. Overall, the observed patterns of congruency priming well concur with the previous studies showing that behavioral changes associated with phrase- or sentence-level meaning are detectable only for conscious processing (Greenwald & Liu, 1985; Draine, 1997; van Gaal *et al.*, 2014). In a novel behavioral study with CFS, Sklar *et al.* (2012) recently proposed that multiple word expressions can be processed without conscious awareness. However, the present findings are more consistent with subsequent studies supporting the more conservative view that consciousness is required for complex cognitive tasks such as sentence comprehension and arithmetic (Moors & Hesselmann, 2018; Rabagliati *et al.*, 2018).

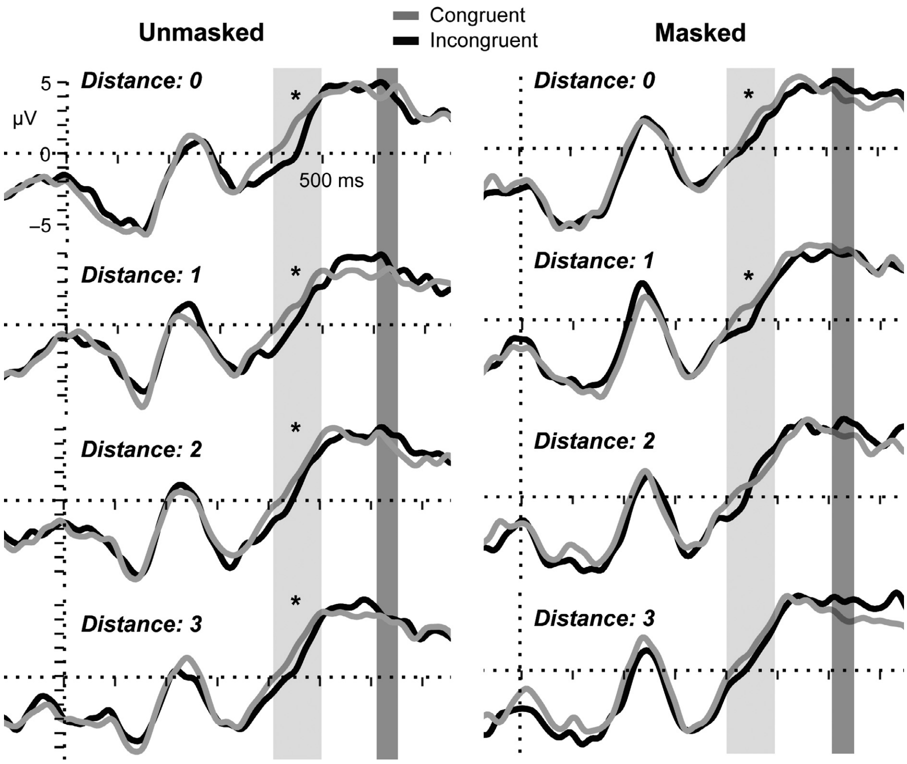

FIG. 4. ERPs waveforms as a function of subject–verb distance. ERPs responses were averaged from left centro-posterior electrodes (C3/CP3/P3) showing the highest effect of semantic congruency in the grand-average ERPs (see Fig. 3) and plotted according to the number of words intervening between subjects and verbs. During the time-window of interest (400–500 ms, light gray), unmasked trials produced the negative-going effect of congruency irrespective of the subject–verb distance, whereas masked trials elicited the same effect only when the subject–verb distance was either 0 or 1 word (*). The effect of P600 measured in the later time-window (610–650 ms, in dark gray) was overall weaker and more variable across different types of trials (see Results for further analyses).

On unmasked trials, the behavioral effect of subject–verb congruency was associated with a significant negative-going ERP difference between congruent and incongruent trials that appeared ~450 ms after target in bilateral centro-posterior regions and thus corresponded to the well-known N400 component evoked by semantic incongruity (Kutas & Hillyard, 1980; Holcomb, 1993; Van Petten & Luka, 2006; Hagoort & van Berkum, 2007). In parallel with the behavioral effect of congruency, the magnitude of this N400 response did not differ across the four levels of subject–verb distance, suggesting that when a sentence is consciously processed, the temporal distance induced by the presence of other intermediate words does not result in any decay of the effects of word congruity. While the N400 effect during sentence comprehension is known to be sensitive to contextual predictability (Kutas & Federmeier, 2011; Wlotko & Federmeier, 2012), our finding is in good accordance with a recent magnetoencephalography study showing that the magnitude of N400 induced by visible words is held constant over a long time frame (200 ms to 800 ms after stimulus onset) (Lau & Nguyen, 2015), which corresponds to the longest stimulus-onset asynchrony (SOA) between subjects and verbs in the present study. The observed behavioral- and neural-level invariance to subject–verb distance is likely to reflect a sentence comprehension mechanism whereby consciously seen words are temporally buffered in the left inferior frontal region and then subject to higher-level semantic integration in the left frontotemporal area (Vagharchakian *et al.*, 2012).

Compared to the robust neural effects during unmasked trials, the overall magnitude of N400 during masked trials was reduced and localized to the left centro-posterior region. In this region, we still found a significant N400 effect induced by a masked sentence when the subject–verb distance was 0 or 1 word, but the effect disappeared when subjects and verbs were separated by 2 or 3 words. This finding suggests that the amount of lexico-semantic activation that can be unconsciously kept online does not exceed two consecutive words (i.e., a subject and an adverb in the present study). This conclusion is consistent with the recent ERP study showing a significant N400 effect using masked two-word primes (van Gaal *et al.*, 2014). Such drastic reduction in buffering capacity during masked sentence processing can be explained by the notion that degraded visual stimuli elicit only weak and short-lived activation (Dehaene *et al.*, 2006; Kouider & Dehaene, 2007). In fact, intracranial recording data show that neural activation induced by masked words is primarily confined to occipital and temporal cortices and decays to a low level by about half a second after stimulus onset (Gaillard *et al.*, 2006, 2009). Such weak and localized activation of the posterior regions is likely to be responsible for the observed capacity limit during masked sentence processing, as single-unit recording data suggest that capacity limitations during visual processing occur immediately upon stimulus encoding in a bottom-up fashion (Buschman *et al.*, 2011).

Indeed, the approximate duration of local neural activation, around half a second, fits with the SOA between subjects and verbs when they were separated by one word in the present study. It may explain why the processing of target verbs was influenced by the prior presentation of masked nouns only when the subject–verb distance was 0 word (SOA = 200 ms) or 1 word (SOA = 400 ms). We cautiously note, however, that in the present experiment words were presented at a fixed rate, where the variables of number of words and temporal distance are confounded. That is, it can be

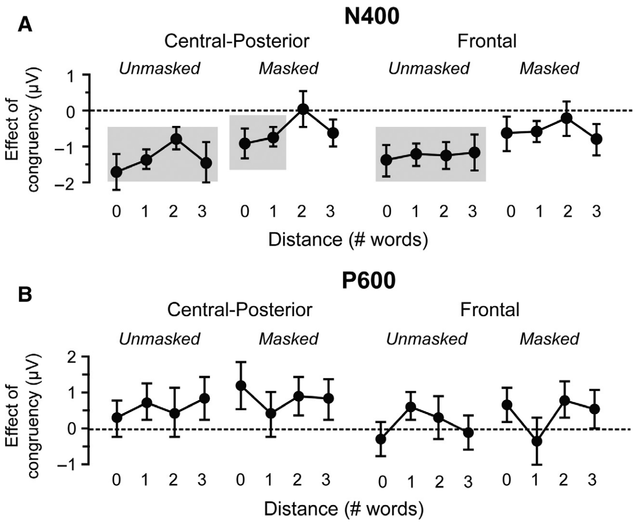

FIG. 5. ERP effects of semantic congruency as a function of subject–verb distance. For each region, the effect of semantic incongruity was calculated by subtracting the mean ERP amplitudes on congruent trials from those on incongruent trials, and plotted against subject–verb distance. Error bars represent standard error of the mean. Significant effects of congruency surviving FDR-correction are shown as shaded areas (see Results). (A) N400. On unmasked trials, significant effects of N400 were obtained at all levels of distance. On masked trials, however, the N400 reached significance only in the posterior region when subjects and verbs were separated by 0 or 1 word. (B) P600. When analyzed separately for each level of distance, neither the posterior region nor the frontal region exhibited significant effects of P600, irrespective of masking. This is likely because in the present paradigm, P600 in itself was much weaker in effect size than N400 even during conscious sentence processing (0.43 μV vs. 0.92 μV).

argued that even longer sequences of masked words (e.g., three or more words) might produce similar ERP effects if they were presented at faster rates and within the time frame of 400 ms prior to target onset. This is possible asthe speed limits of reading rate, although slowing down under visual masking, are shown to lie around 400 WPM during reading aloud (Primativo *et al.*, 2016), which seems to exceed the word presentation rate during masked trials in the present study (300 WPM). Conversely, however, it is also possible that such higher WPM rates produce only weaker ERP effects, as there is a trade-off between speed and accuracy in reading comprehension, that is, an optimal WPM for fluent sentence comprehension is thought to be approximately 300 WPM (Carver, 1992; Rayner *et al.*, 2016), whereas higher WPMs are prone to impede meaning analysis (Schotter *et al.*, 2014; Benedetto *et al.*, 2015).

Another remaining possibility worth considering is that inserted adverbs in each sentence might interfere with direct semantic integration between subjects and nouns. It can be argued that the subject–verb semantic integration might persist at SOAs longer than 400 ms if no adverbs are presented between nouns and verbs. However, this seems rather unlikely because electrophysiological data, as argued above, show that the occipitotemporal response to masked words peaks around 250 ms and rapidly fades away by about half a second after stimulus onset (Gaillard *et al.*, 2006, 2009), meaning that neural activation triggered by masked nouns should also decay even when no other words intervene before the onset of target verbs. Nevertheless, it remains possible that semantic integration of multiple subliminal words can occur at the neural level in different experimental settings. Thus, further experiments would be needed to examine whether three or more invisible words can produce similar neural effects, possibly using higher WPMs or a simultaneous presentation of multiple words.

The present study is, as far as we know, the first to use repeated masking of successive words to render an entire sentence invisible. It is important to note that the observed N400 effect in visual masking relies on different neural mechanisms from those observed in earlier studies using the attentional blink (Batterink & Neville, 2013) and inter-ocular suppression (Axelrod *et al.*, 2015), as the extent of neurocognitive processing elicited by unconscious stimuli is known to vary depending on the nature of experimental procedures used to render stimuli invisible (Raymond *et al.*, 1992; Fogelson *et al.*, 2014). Specifically, activation reduction in early visual cortex has been shown to play a key role in the disruption of subjective awareness during attentional blink (Williams *et al.*, 2008; Hein *et al.*, 2009) and CFS (Jimenez-Ortega *et al.*, 2014, 2017). By contrast, briefly flashed words under visual masking can produce strong feedforward activation of the occipitotemporal cortex as well as weak and transient activation of the frontoparietal cortex (Dehaene *et al.*, 2006; Kouider & Dehaene, 2007). The present results therefore allow us to determine the hypothesized capacity limit of the occipitotemporal region during unconscious semantic processing and suggest that subliminal processing of masked sentences has a more constrained capacity limit than those obtained from other experimental settings (Batterink & Neville, 2013; Axelrod *et al.*, 2015). This might reflect an inherent capacity limitation of the visual association cortex that seems capable of buffering about three items online (Marois & Ivanoff, 2005; Buschman *et al.*, 2011). This interpretation may also concur with the finding that the magnitude of N400 during masked trials dropped suddenly when the subject–verb distance exceeded two words and did not decrease linearly with the number of words separating subjects and verbs. As described above, such sudden and non-linear collapse is likely to reflect the all-or-none nature of neural network operations (Buschman *et al.*, 2011; Kang *et al.*, 2011).

In addition, although the effect of syntax was not manipulated in the present experiment, our ERP data suggest that participants were sensitive to the syntactic category of masked words (nouns and adverbs) as the positional changes of nouns produced the detectable impact on ERP measures. This, in turn, suggests that the initial stage of syntactic classification occurs for unconsciously perceived words and well concurs with a recent ERP study showing that the first-pass parsing of word category runs automatically and unconsciously (Jimenez-Ortega *et al.*, 2014). Moreover, a previous fMRI study by Devlin *et al.* (2004) has shown that fast morphological processing of masked words occurs in the left lateral temporal cortex which largely overlaps the occipitotemporal cortex involved in orthographic and semantic processing. Given that first-pass parsing of word category also relies on the posterior temporal region, it is expected that such fast syntactic activation, like subliminal semantic activation explored in the present study, may be kept online for later-stage processing only during a limited range of time. This is, again, because neural activation by masked words is generally restricted in those posterior regions and does not induce much activity in distant frontal regions involved in working memory (Dehaene *et al.*, 2006; Kouider & Dehaene, 2007). In future research, it is therefore interesting to determine whether the possible capacity limit for fast syntactic processing differs from the one for semantic activation during subliminal sentence processing.

In conclusion, we observed that briefly presented masked sentences produced no effect of semantic congruency at the behavioral level, irrespective of the length of sentence stimuli. However, our ERP data revealed a significant neural-level sensitivity to sentence meanings when the subject–verb distance did not exceed two words. This capacity limit of unconscious processing concurs with the previous finding of a significant N400 effect elicited by masked two-word primes (van Gaal *et al.*, 2014). The observed sudden and non-linear reduction in processing capacity is likely to reflect the brain's limited buffering capacity for unconscious stimuli. While unconscious working memory has been reported in some perceptual paradigms (Soto & Silvanto, 2014; Eriksson *et al.*, 2015), the effect is typically barely above chance level, and the present results suggest that it may not be sufficient to allow for multiple words at a high-enough signal-to-noise level to detect the incongruity of a final word. As previously suggested (Dehaene & Naccache, 2001), one of the key functions of conscious perception appears to be the online maintenance of information for an indefinite duration, related to the ability of global workspace neurons in frontoparietal cortex to maintain a sustained level of activation long after a stimulus is gone.

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Conflict of interest

The authors declare no competing financial interests.

Data accessibility

The behavioral and ERP datasets analyzed in the present study are available from the corresponding author on reasonable request.

Author contributions

KN, MM, and SD designed research; KN, TO, TME, TI and YN performed research; KN and MM analyzed data; KN, MM and SD wrote the manuscript.

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