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Research Report

The effect of lexical priming on sentence comprehension: An fMRI study

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ABSTRACT

This study used repetition priming to examine the influence of lexical processing on sentence comprehension processing. In order to do that the effect of the lexical priming of nouns and verbs on active compared to passive sentences was investigated. The results revealed that facilitating lexical access resulted in the facilitation of sentence comprehension processes. More specifically it was found that while lexical priming of the nouns and verbs within a sentence aids sentence comprehension processes – reduced reaction time to the comprehension probe – verb priming appears to have a greater impact, particularly on syntactic level processes. This is demonstrated by a priming effect observed in left BA 44, a region that has been linked to syntactic level processing, only for verb repetition. These results also support previous studies that have reported a differential neural representation for nouns and verbs; priming effects for these two grammatical classes were observed in different brain regions.

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1. Introduction

Sentence comprehension involves the access and integration of individual words. Several studies have shown that lexical access and sentence processes interact (Keller et al., 2001; Rayner and Duffy, 1986; Stanovich and West, 1983; Swinney, 1979). However, the primary focus has been on how the sentence context affects lexical access (Baumgaertner et al., 2002; Gennari et al., 2007; Glucksberg et al., 1986). For example, there have been a number of studies that have shown that sentence context can enhance or diminish the lexical ambiguity effect, showing how sentence processing can influence lexical processing. However, in the current study we are more concerned with how lexical access affects sentence processes.

Lexical and syntactic processes were shown to interact with each other in a study conducted by Keller et al. (2001). In that functional magnetic resonance imaging (fMRI) study they

manipulated the lexical frequency of nouns as well as the syntactic constructions used. The manipulation of lexical frequency was thought to affect comprehension processes. This is because the processing time for low frequency is greater than high frequency words. This increased lexical processing time delays when the word is available to other comprehension processes. Keller found that sentences containing low frequency words resulted in a larger syntactic complexity effect than those containing high frequency words. This result was found in both the behavioral results and the activation patterns in a number of left hemisphere regions such as the inferior frontal gyrus (IFG) and the posterior temporal cortex. These results show the impact lexical properties can have on sentence level processes.

While studies have shown that manipulating lexical properties of nouns can impact syntactic processing, many studies of syntactic priming have reported that it is the verb that is critical to syntactic priming in comprehension, not the

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noun (Arai et al., 2007; Pickering and Branigan, 1998; Pickering and Traxler, 2004; Traxler and Tooley, 2008). Verbs are critical to syntactic parsing because they determine the thematic roles, or argument relations (Levin, 1993). The argument structure, or sometimes referred to as the set of thematic roles the verb can take (e.g., the verb *hit* requires a hitter and an object to be hit), is thought to be stored in the lexicon with the verb (Arai et al., 2007; Traxler and Tooley, 2008; MacDonald et al., 1994; Ford et al., 1982; Pritchett, 1992). Support for this hypothesis has been found in studies that have shown that all information about a verb is activated when the verb is activated (Shapiro et al., 1987; Shapiro et al., 1991). For example, in studies using a dual-task paradigm in which participants were to comprehend sentences presented auditorily while performing a lexical decision task, it was found that reaction time increased with the number of thematic possibilities the verb allowed (Shapiro et al., 1987, 1989, 1991).

It appears that the lexical properties of both nouns and verbs can have an impact on sentence processing; however, these effects occur under different circumstances. This may be due to differences in the lexical properties of nouns and verbs; they have been found to differ in their conceptual-semantic, syntactic and morphological characteristics. The semantic features of verbs are different than those of nouns (Vigliocco et al., 2008); nouns have referential representations while verbs have relational representations (Gentner, 1978). Verbs also have syntactic information regarding how the words in a sentence are related. In addition, verbs have been shown to have a differential degradation pattern in aphasia compared to nouns (e.g., McCarthy and Warrington, 1985). There are an abundance of neuropsychological studies that have reported double dissociations between verb-specific impairments – associated with lesions of the left IFG – and noun-specific impairments — associated with lesions of the left temporal lobe (Caramazza and Hillis 1991; Damasio and Tranel, 1993; Daniele et al., 1994; Silveri and Di Betta, 1997). In addition to the neuropsychological evidence there is also evidence from neuroimaging studies of normal populations

that show different activation patterns for noun compared to verb processing with the left posterior middle temporal gyrus and/or left inferior frontal gyrus showing greater activation for verbs (Davis et al., 2004; Fiez et al., 1996; Perani et al., 1999; Shapiro et al., 2005; Shapiro et al., 2006; Tranel et al., 2005; Tyler et al., 2004; Yokoyama et al., 2006) while the left inferior temporal regions have shown greater activation for nouns (Shapiro et al., 2005; Shapiro et al., 2006). However, there are some studies that have failed to show such differences (Tyler et al., 2001; Vigliocco and Kita, 2006; Warburton et al., 1996).

In the current study lexical repetition priming was used to examine how lexical access affects sentence processing. The question addressed here is do differences in the lexical properties and, therefore, the lexical access of nouns and verbs have differential effects on sentence processing. In order to answer this question we compared lexical priming of nouns and verbs within a sentence context. Based on the differences in these two grammatical classes we predicted that they would have differential effects on sentence processing. Due to the verb's role in syntactic analysis, verb repetition is expected to result in greater facilitation of syntactic processing than noun repetition. This may be expected to be observed in regions that have been implicated in syntactic processing such as the left inferior frontal gyrus (IFG); BA 44 in particular (Caplan et al., 1998, 1999, 2001; Caplan and Waters, 1999; Fiebach et al., 2001, 2005; Friederici et al., 2003, 2006; Just et al., 1996; Keller et al., 2001; Newman et al., 2003). In addition, the IFG is one of the regions found by previous studies to show differential activation to nouns and verbs. Noun repetition is also expected to influence sentence processing, again their repetition will allow for faster lexical access and, therefore, they will be available earlier to other processes. The priming effect for nouns is expected to be observed in inferior occipital/temporal regions due to that region being found to show greater activation for nouns than to verbs (Shapiro et al., 2005, 2006). However, noun repetition is predicted to have a significantly smaller effect on syntactic processing than verb repetition.

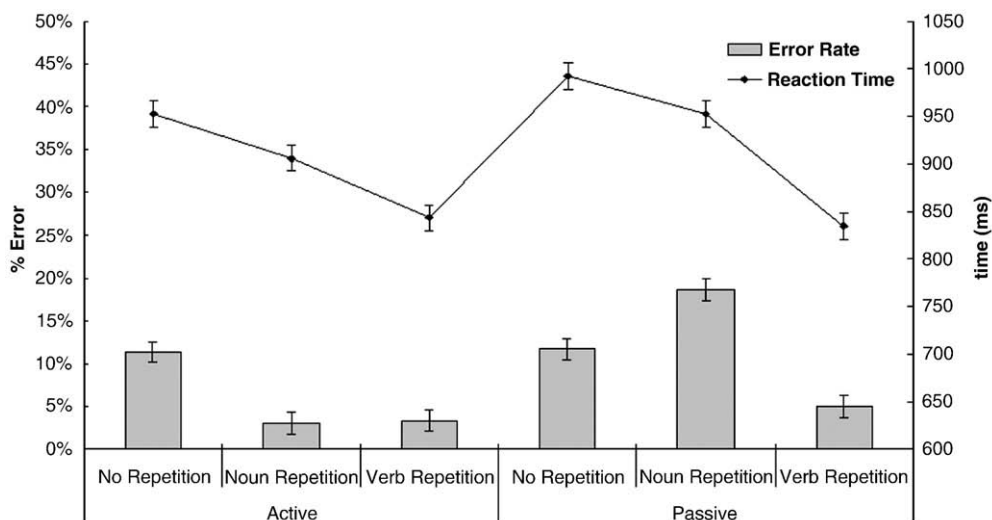


Fig. 1 – The figure depicts the behavioral results.

2. Results

2.1. Behavioral results

A 2×3 ANOVA was computed for both the reaction time and error data. Behavioral data from two participants were lost; therefore, the analysis includes the remaining fifteen participants. The reaction time measure revealed only a significant effect of lexical repetition [$F(2,15)=25.12, p<0.0001$]; the effect of complexity [$F(1,15)=1.13, p>0.3$] and the interaction [$F(2,15)=2.35, p>0.1$] both failed to reach significance (see Fig. 1). The error rate revealed significant main effects of complexity, lexical repetition and an interaction [$F(1,15)=14.12, p<0.005$; $F(2,15)=18.92, p<0.0001$; $F(2,15)=23.27, p>0.0001$, respectively]. However, a chi-square test was also performed on the error data due to its categorical nature and no significant results were obtained for either main effect (p 's>1).

2.2. fMRI results

The all sentence versus fixation contrast revealed activation in the language processing network including the inferior frontal, posterior temporal and inferior parietal cortex of the left hemisphere (see Table 2 and Fig. 2). In addition, regions of the inferior occipital cortex, precentral gyrus and right hemisphere regions also were involved. In order to better depict the

activation differences across the three lexical repetition conditions Fig. 3 shows the activation for each condition versus fixation when processing passive sentences. As can be seen there, verb repetition shows less activation in the IFG than does the no and noun repetition conditions while the noun repetition conditions shows less activation in the inferior temporal/occipital region than the other two conditions.

2.3. ROI results

A MANOVA was performed using the thirteen ROIs identified in the all sentence versus fixation contrast, three levels of priming and two levels of complexity. The analysis revealed significant effects of complexity [Wilks' Lambda: $F=80.26, p<0.0001$], prime [$F=56.96, p<0.0001$]; and an interaction [$F=79.14, p<0.0001$]. Although there were several regions that were found to be involved in the sentence processing task (as determined by the all condition minus fixation contrast), only a small subset of those regions revealed a differential response to the manipulations. Here we found that regions of the prefrontal cortex, two sub-regions of Broca's area, and the precentral gyrus of the left hemisphere, revealed an interaction between complexity and lexical repetition such that the passive condition revealed a larger effect for the verb repetition condition while the active condition failed to show a

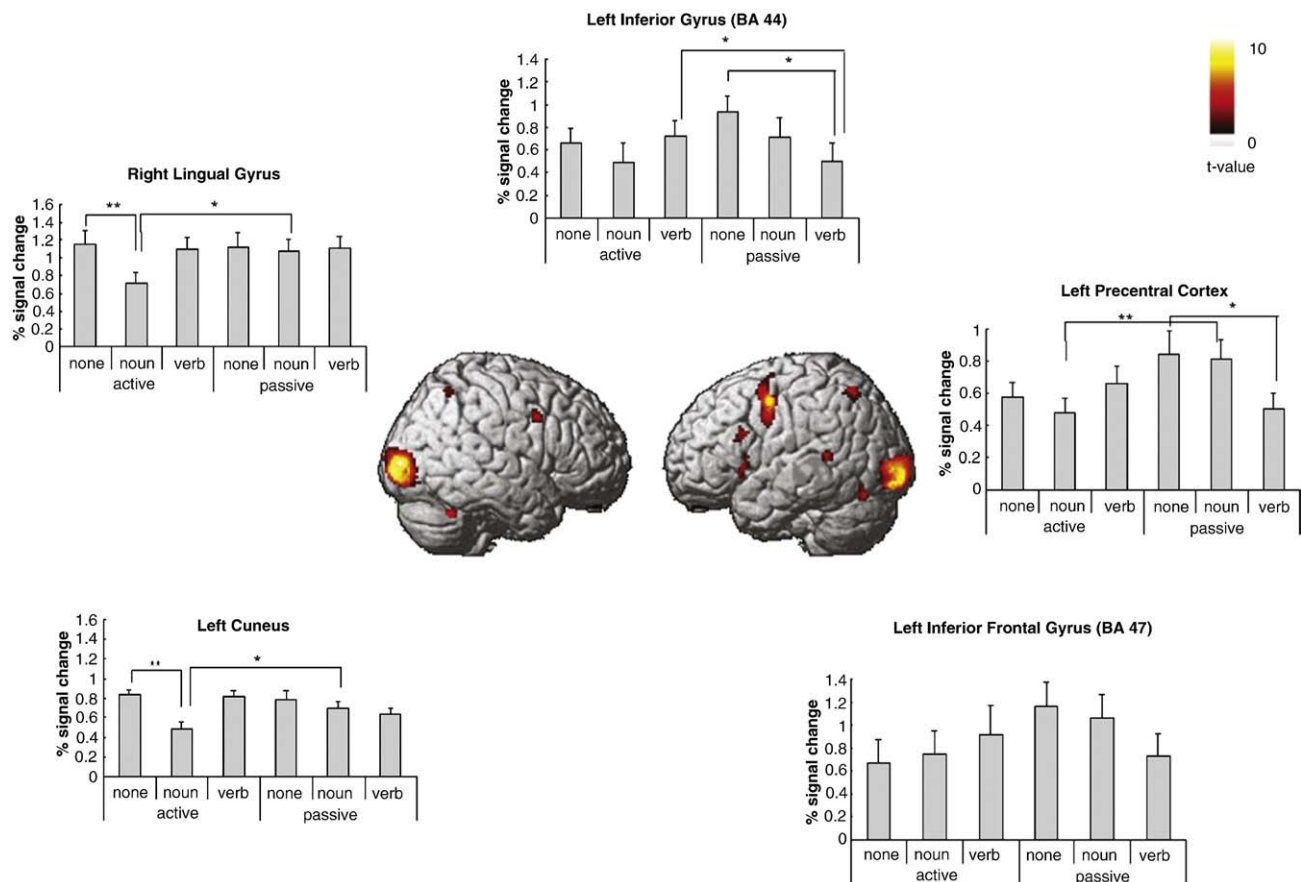


Fig. 2 – The figure depicts the activation map from the all conditions minus fixation contrast in the center. The bar graphs are the percent signal change for each condition in regions that revealed significant effects (see Table 2).

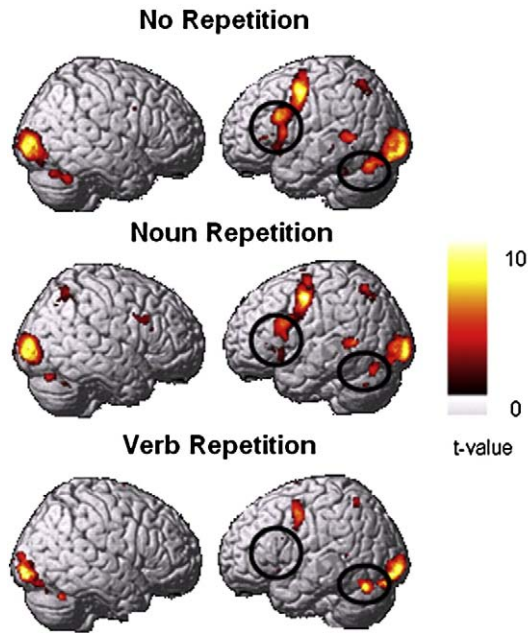


Fig. 3 – The figure shows the activation maps for the passive conditions versus fixation.

significant effect of lexical repetition (see Fig. 2 and Table 3). Regions of the inferior occipital cortex, the left and right lingual gyrus, revealed almost the reverse pattern, a larger effect for the noun repetition condition for active condition and no significant effects for the passive condition.

A 2×2 ANOVA with complexity and lexical repetition (either no vs. noun or no vs. verb repetition) was computed for the five ROIs that revealed significant effects for the 2×3 ANOVA. BA 44, a sub-region of Broca's area, revealed a marginally significant effect of prime for the no vs. noun comparison [$F(1,16)=4.16$, $p=0.058$], there was no effect of complexity [$F(1,16)=3.32$, $p>0.08$] or an interaction ($F<1$). For the no vs. verb comparison the main effects of complexity and lexical repetition both failed to reach significance [$F<1$; $F(1,16)=3.21$, $p>0.09$, respectively]. However, the interaction was significant [$F(1,16)=6.08$, $p<0.05$]. The interaction was due to a significant effect of prime for the passive condition [$F(1,16)=5.73$, $p<0.05$] but not the active condition ($F<1$). Additionally, the region revealed a complexity effect for the verb repetition condition such that the passive sentences elicited less activation than the active sentences [$F(1,16)=4.64$, $p<0.05$], see Fig. 2.

The left precentral gyrus, BA 6, revealed an effect of complexity [$F(1,16)=11.8$, $p<0.005$] for the no vs. noun comparison; however there was no effect of lexical repetition or a significant interaction ($F_s<1$). When examining the noun repetition condition, a significant effect of complexity [$F(1,16)=14.1$, $p<0.005$] was observed in the region (greater activation for passive compared to active sentences). For the no vs. verb comparison, no significant main effects of complexity or lexical repetition were observed [$F<1$; $F(1,16)=1.63$, $p>0.2$ respectively]; however a significant interaction was found [$F(1,16)=8.14$, $p<0.05$]. The region, like BA 44, revealed an effect of prime when examining the passive sentences only [$F(1,16)=5.76$, $p<0.05$].

A sub-region of Broca's area, BA 45/47, revealed no significant effects for the no vs. noun comparison. For the no vs. verb repetition condition, the region failed to show a main effect of complexity or prime ($F_s<1$). However, the region did reveal a significant interaction [$F(1,16)=4.55$, $p<0.05$] due to differential response of the region to lexical repetition for the active and passive sentences.

The right lingual gyrus revealed a significant effect of prime and a significant interaction [$F(1,16)=4.5$, $p<0.05$; $F(1,16)=10.58$, $p<0.01$, respectively], but no main effect of complexity [$F(1,16)=1.77$, $p>0.2$] for the no vs. noun repetition condition. The region also revealed a significant effect of prime for the active sentences [$F(1,16)=14.02$, $p<0.005$] but not the passive sentences. Additionally, there was a significant complexity effect observed for the noun repetition condition. The region revealed no significant effects for the no versus verb repetition comparison.

The left lingual gyrus responded similarly to the right lingual gyrus. The region revealed a significant effect of prime and a significant interaction [$F(1,16)=11.08$, $p<0.005$; $F(1,16)=10.09$, $p<0.01$, respectively], but no main effect of complexity [$F(1,16)=2.1$, $p>0.1$] for the no vs. noun repetition condition. The region also revealed a significant effect of prime for the active sentences [$F(1,16)=28.4$, $p<0.0001$] but not the passive sentences. Additionally, there was a significant complexity effect observed for the noun repetition condition. The region

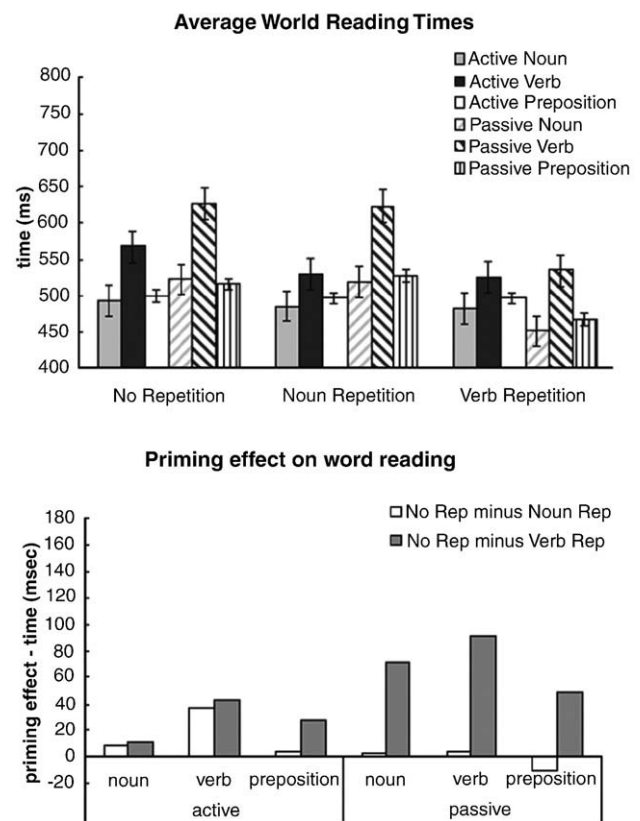


Fig. 4 – The word reading times (top) for the subject noun, verb and preposition noun obtained from the auxiliary study. The bottom graph shows the priming effect for each word type.

revealed no significant effects for the no versus verb repetition comparison.

2.4. Auxiliary behavioral study

In order to examine word level processing with the sentences used here a behavioral study was conducted in which word reading times were measured. The same sentences as in the fMRI study were used and were presented using the same procedure. The exception is that the sentences were presented one word at a time in the center of the monitor and participants pressed a keyboard button to advance to the next word. The participants consisted of a total of 49 individuals (24 females), the age range was 17–32, with a mean age of 21.64 (SD=2.98). They were all undergraduate introductory psychology students seeking academic credit for their participation. All were native speakers of American English and right-handed. The participants gave written informed consent approved by the Indiana University Institutional Review Board prior to participation.

The priming effects for the subject noun, verb, and the preposition were examined. The results are presented in Fig. 4 and show that repeating the verb results in greater priming of each word type, particularly during passive sentences. In addition, the syntactic complexity effect (longer verb reading time for passive compared to active sentences) was greatly reduced when the verb is repeated [noun repetition: $F(1,48)=43.94$, $p<0.0001$; verb repetition: $F(1,48)=3.66$, $p=0.06$].

3. Discussion

The aim of the current study was to investigate how the facilitation of lexical processing, via repetition priming, affects sentence comprehension processes. There were two important findings. First, priming the verb resulted in a greater processing benefit. While there was facilitation of processing when the noun was repeated, participants' response time to the probe was most improved when the verb was repeated. Second, differential priming effects were observed for noun and verb repetition: the noun repetition condition elicited an effect in bilateral inferior occipital cortex while the verb repetition condition elicited an effect in the left IFG and the left precentral gyrus.

Nouns and verbs have been suggested to differ on a number of linguistic dimensions including semantic (Breedin et al., 1998; Marshall et al., 1996), grammatical and lexical dimensions (Shapiro and Caramazza, 2003). Also, previous studies have shown activation differences for noun and verb processing in which verbs tended to activate IFG more so than nouns (e.g., Perani et al., 1999) and nouns tend to activate inferior temporal/occipital regions more so than verbs (Shapiro et al., 2005; Shapiro et al., 2006). For example, in a recent semantic priming study using a lexical decision task noun–noun, verb–verb and verb–noun prime–target pairs were compared using fMRI methodology (Lee and Newman, 2008). They found differential activation for the noun–noun and verb–verb pairs. The noun–noun condition elicited a priming effect in the left posterior fusiform gyrus while the other pairs did not. The verb–verb pair failed to elicit a priming effect in

any region while the verb–noun condition elicited a priming effect in many regions including the left IFG. These results indicate that priming, in this case semantic priming, for nouns and verbs may impact different neural systems. We found support for this idea here using a sentence context — priming effects were observed in IFG for verb repetition and in the lingual gyrus for noun repetition.

One of the major results presented here is that noun and verb lexical facilitation has differential effects on sentence processing. While the current study cannot be defined as a syntactic priming study, a review of that literature may be informative. Syntactic priming is the facilitation of subsequent production and/or comprehension of a syntactic structure that has been recently encountered. The majority of the early syntactic priming research focused on syntactic priming in production tasks where clear evidence of such facilitation has been reliably observed (Bock, 1987; Pickering and Branigan, 1998; Branigan et al., 2000; Hartsuiker et al., 2004). Until recently, finding syntactic priming effects during comprehension has been elusive, with most studies finding that priming is lexically-dependent and occurs only when the verb is repeated (Arai et al., 2007; Cleland and Pickering, 2003; Pickering and Branigan, 1998; Pickering and Traxler, 2004; Traxler and Tooley, 2008). One explanation is that the argument structure representations that are critical to syntactic parsing are stored with the verb and get primed when the verb is repeated (Arai et al., 2007; Traxler and Tooley, 2008; MacDonald et al., 1994). The results presented here also demonstrate that lexical priming of the verb can facilitate sentence level processing. We see that in both our imaging data – reduced activation in a syntactic processing region, IFG – and in the ancillary behavioral study — a reduced syntactic complexity effect for verb repetition and a larger priming effect at the preposition.

While the importance of the verb in syntactic priming has been demonstrated, a recent study has found that the subject noun may also play a larger role than initially thought (Carminati and Van Gompel, 2008). In that study double object dative and prepositional object dative structures were used; and either the subject noun and the verb were repeated or just the verb was repeated. There it was found that subject noun repetition enhanced the priming effect. This finding was interpreted as suggesting that “exposure-based” syntactic information is represented at the noun as well as the verb. This idea fits the explanation for the lexical boost provided by Chang et al. (2006). They state that in syntactic priming in production a “repeated content word serves as a cue to the memory of the prime and this biases the speaker to repeat its structure” (p. 256). Therefore, the repeated noun, just as the repeated verb, may be expected to serve as a memory cue; although the verb may be a stronger cue to the structure. In the current study we found facilitation effects when the noun and when the verb was primed, as shown in the behavioral results. However, the priming effects were larger for the verb repetition condition. The results presented here do provide some support for the Carminati and Van Gompel proposal in that facilitated lexical access for both the noun and the verb caused facilitation of comprehension processes.

The inferior portion of the IFG, BA 45/47 has been implicated in word level semantic processing (Bookheimer,

2002; Fiez, 1997; Gold et al., 2005; Wagner et al., 2000) and it has been suggested that the region is involved in the controlled access of lexical/semantic information (Gold et al., 2005). In the current study, this region revealed an interaction between complexity and lexical repetition, but no main effects of lexical repetition. This seems to contradict what has been found at the single word level. In a review, Bookheimer (2002) discussed four studies (Demb et al., 1995; Wagner et al., 2000, 1997; Buckner et al., 2000) all of which found priming effects in the left IFG in a region analogous to BA45/47. Another region that has been implicated in semantic level processing is the posterior temporal cortex, BA 21 which overlaps with the classic language processing region, Wernicke's area (Demonet et al., 1992; Friederici et al., 2003; Keller et al., 2001; Price et al., 1997). BA 21 revealed no significant effects in the current study. Finding no effects of repetition in BA 45/47 and posterior BA 21 – regions that have been implicated in semantic level processing – would seem to suggest that the effects of lexical priming in the context of a sentence affects syntactic level processing more so than semantic level processing. In a study examining the processing of verb argument structure in Broca's and Wernicke's aphasia patients it was found that patients with Wernicke's aphasia were insensitive to the thematic properties of verbs (e.g., they did not show the normal RT difference to two-complement compared to four-complement verbs) (Shapiro et al., 1993). Shapiro et al. stated that the semantic deficit exhibited by Wernicke's patients may be due to a failure to access the conceptual roles associated with verbs. Assuming the posterior temporal cortex is involved in accessing those conceptual roles, given that there were no effects of verb repetition in posterior temporal cortex, it seems that the access to those representations does not get primed. In other words, repeating the verb in subsequent sentences does not appear to facilitate the access to thematic information. This seems to contradict the explanation provided by studies of syntactic priming which suggest that repeating the verb facilitates subsequent syntactic processing because the verb contains argument structure information that gets primed when it is repeated.

The region that did reveal an effect of verb repetition is the more superior, posterior portion of the IFG, BA 44, as well as the portion of the precentral gyrus that is adjacent to it. This region has been previously implicated in syntactic level processing and in many neuroimaging studies have been found to be more involved in non-canonical syntactic constructions than canonical constructions (Caplan et al., 2001; Cooke et al., 2001; Keller et al., 2001; Newman et al., 2009). One possible function the region may be involved in is building syntactic representations of a sentence, and in particular the region may be performing functions such as determining how sentence constituents are related to each other. This idea fits well with Hagoort's (2005) unification theory in which he argues that the left IFG "recruits lexical information ... and unifies them into overall representations that span multi-word utterances" (p. 419). Again, because the verb contains this information (i.e., thematic roles, number of complements), by repeating the verb the same thematic or syntactic frame/structure can be used in subsequent sentences; thereby reducing the processing load of the region. Shapiro et al. (1993) found that patients with Broca's aphasia

showed normal sensitivity to the thematic roles of verbs, meaning that access to the conceptual roles associated with verbs remain intact. The patients, however, do show difficulty integrating that information with the content of the sentence. In other words, they have difficulty using that information to generate a syntactic representation of the sentence. This suggests that the verb representation is not stored in BA 44, but rather that it uses that information in subsequent syntactic processes. When this idea is combined with the findings presented here the picture that emerges is that BA 44 uses the argument structure information that is stored with the verb and that the process of generating the syntactic representation – integrating argument structure information with sentence information – gets primed with verb repetition.

Interestingly, the effect of noun and verb repetition on brain activation was observed in different syntactic constructions. The effect of noun repetition was observed only for the active sentences and the effect for verb repetition was observed only for the passive sentences. The canonical active sentences require little syntactic analysis; participants know which roles each noun will play – the first noun is the agent and the second noun is the patient. As a result, repeating the verb may have little effect on facilitating syntactic analysis during active sentences, resulting in no effect in regions like BA 44. However, repeating the verb may be expected to have a more significant impact during passive sentences because they are non-canonical and require more syntactic analysis. The question of why such great facilitation in responding to the probe for both active and passive structures remains open; however that may be more related to response habituation effects than syntactic processing per se. Further studies are necessary to disentangle this issue.

Another possibility for the differences in the effect of verb repetition in passive compared to active sentences is that passive verb-auxiliary complexes are more computationally demanding due to their more complex morphological form. Sahin et al. (2006) have suggested that many of the grammatical effects that have been observed in the left IFG, including BA 44, are related to morphological differences opposed to syntactic differences. For example, in a study that explored the role of inflectional morphology on the processing of nouns and verbs it was found that activation of the left IFG was related to morphological processing not to verb processing in particular (Tyler et al., 2004). More specifically, they found greater involvement of the left IFG when comparing regularly inflected nouns and verbs but in a previous study using the same procedures (Tyler et al., 2001) they found no differences in the left IFG when comparing non inflected nouns and verbs (or stems). Sahin et al. (2006) also found similar involvement of the left IFG when comparing inflected compared to regular nouns and verbs in a covert sentence completion task. Therefore, morphology does impact the same regions that have been implicated in syntactic processing. As a result, the differential effect of verb repetition observed for active and passive constructions may be more related to the morphological differences in the verb forms than to the syntactic, structural differences of the two sentence types.

The lack of a significant priming effect for the nouns during the processing of passive structures is puzzling,

particularly given that the lingual gyrus is not thought to be involved in syntactic processing. The region is however, thought to be involved in object processing (Kraut et al., 2002; Humphreys, 1996; Vandenberghe et al., 1996; Murtha et al., 1999). One possible explanation is that top-down processes – the additional processing necessary for non-canonical structures – are reducing the priming effect. It may be that because there is little need to re-access or reinterpret the noun during active sentences (it is placed in the appropriate thematic role initially) it allows for a priming effect, or reduced processing of the noun on subsequent trials. However, during the processing of non-canonical structures there is a ‘re-evaluation’ of the thematic roles initially ascribed and possible additional processing of the nouns which may eliminate the priming effect during passive sentences. While we do admit that this is speculative and needs further investigation, top-down influences have been found to reduce the priming of objects (Rotshtein et al., 2001; Bentley et al., 2003). For example, Bentley et al. found that when compared to neutral faces, the repetition priming of fearful faces was significantly reduced. Therefore, it is possible that top-down influences (i.e., syntactic processing) can reduce lexical priming effects.

In summary, the results presented here show that facilitating lexical access via priming results in the facilitation of sentence processes. Here we found that while lexical priming of the nouns and verbs within a sentence both facilitate sentence processes – reduced reaction time to the probe – verb priming appears to have a greater impact, particularly on syntactic level processes. This is demonstrated by the priming effect observed in BA 44, a region that has been linked to syntactic level processing. These results also support previous studies that have reported a differential neural representation for nouns and verbs; we found priming effects in different brain regions for these two grammatical classes.

4. Experimental procedures

4.1. Participants

17 participants (11 female, age=23±2.8) took part in the experiment. They were all from the Indiana University community and were all without any history of neurological disorders. Before scanning, all participants were administered the Edinburgh handedness inventory and the Daneman and Carpenter (1980) reading span test to obtain a measure of working memory capacity. Participants were all right-handed and their reading span scores ranged from 2 to 5.5 (Mean=3.5, SD=1.0). All participants gave written informed consent which was approved by the Indiana University Institutional Review Board.

4.2. Design and materials

The experiment was a 2×3 design with syntactic complexity (active versus passive — all included agentive by-phrases) and lexical repetition (noun versus verb versus none) as within-participant variables. There were twenty sentences for each of the six conditions; the sentences were equated for word

Table 1 – Example stimuli.

Noun repetition/ Active	The frog chased after the sheep.
	The frog chased.
	The frog looked after the sheep.
	The sheep looked.
	The frog jumped over the sheep
	The frog jumped.
	The frog hid from the sheep.
	The sheep hid.
	The frog stared at the sheep.
	The sheep stared.
Verb repetition/ Active	The banana grew on the tree.
	The tree grew.
	The apple grew on the house.
	The house grew.
	The lettuce grew on the ground.
	The lettuce grew.
	The corn grew on the farm.
	The corn grew.
	The beans grew on the stem.
	The stem grew.
Noun repetition/ Passive	The referee was corrected by the outfielder.
	The outfielder corrected.
	The referee was shot by the outfielder.
	The referee shot.
	The referee was cut by the outfielder.
	The referee cut.
	The referee was burdened by the outfielder.
	The referee burdened.
	The referee was answered by the outfielder.
	The outfielder answered.
Verb repetition/ Passive	The cow was bitten by the sheep.
	The cow bit.
	The mule was bitten by the donkey.
	The donkey bit.
	The moose was bitten by the chipmunk.
	The moose bit.
	The wolf was bitten by the fox.
	The fox bit.
	The dolphin was bitten by the shark.
	The shark bit.

length; the words within the sentences were equated for lexical frequency and animacy across conditions. Each trial was composed of a sentence, presented one word at a time, except for the passive verbs (e.g., *was told*). A comprehension probe that asked who did what to whom questions followed each sentence; the probe sentence was presented all at once (not one word at a time).

The trials were presented in blocks of five sentence/probe pairs (see Table 1 for example stimuli). There were six block types, one for each condition. The sentences in each block had the same syntactic structure. The sentences in the verb repetition block all contained the same verb, but different nouns. Sentences in the noun repetition block all contained the same nouns (both subject and object), but different verbs. Finally, sentences in the no-repetition block contained different nouns and different verbs.

4.3. Procedure

A trial began with a sentence being presented in the middle of the screen. The total duration of each sentence was 3 s. The duration of each word was determined by the length of the

Table 2 – Activation clusters from all conditions minus fixation.

ROI	Cluster size	Z-score	Coordinates x, y, z	
Location	BA			
Left inferior frontal gyrus	47	52	5.46	-54, 16, -2
Left inferior frontal gyrus	44	45	5.07	-46, 16, 24
Left precentral	6	419	6.02	-44, -2, 46
Right precentral	9	45	5.72	46, 6, 38
Left superior frontal	6	68	5.45	-10, 0, 62
Left middle temporal gyrus	21	34	5.74	-52, -44, 10
Left parietal	7	169	6.44	-26, -58, 50
Right parietal	7	31	5.55	32, -56, 56
Left fusiform	19	50	5.28	-38, -70, -18

word such that longer words were presented for a longer time period; this was done because studies have shown a word length effect in word reading times. Following each sentence was a comprehension probe that was presented for 2 s with a cue (i.e. F/T). The cue indicated the appropriate response (a right index finger for true and the left index finger for false). Each block was 25 s in duration and was followed by a 15 s rest period. The study was divided into 2 functional runs. Each run contained 12 experimental blocks along with three 24 s fixation periods (fixation to a star sign, *) in order to obtain a common baseline measure. In the beginning of the first fMRI run, four practice trials were included to remind participants how to perform the task.

4.4. fMRI acquisition and analysis

Functional MRI was conducted on a 3 T Siemens TRIO scanner with an 8-channel radio frequency head coil located in the Imaging Research Facility at Indiana University. Functional images were obtained in eighteen oblique axial slices with 5 mm thickness and a 1 mm gap (TR=1000 ms, TE=25 ms, flip angle=60°, matrix size=64×64, FOV=240×240 mm²) by a gradient echo planar imaging (EPI) sequence. Before the statistical analysis, for all the functional images, conventional preprocessing procedures such as slice timing correction, head motion

correction by realignment and spatial normalization were conducted by using the SPM2 software (Wellcome Department of Imaging Neuroscience; <http://www.fil.ion.ucl.ac.uk/spm>). In the spatial normalization step, all functional images were warped directly to the Montreal Neurological Institute (MNI) EPI template and resampled to the 2×2×2 voxel dimensions which were supported by the SPM package. Spatial smoothing was performed with an 8 mm Gaussian kernel. A conventional statistical inference was performed on the smoothed functional images from each individual by using the general linear model and Gaussian random field theory (Friston et al., 1995). A canonical hemodynamic response function (HRF) was used with onset and duration for each block to generate a statistical parametric map (SPM).

A region of interest (ROI) approach was used here. ROIs were computed with the use of the all sentence conditions versus baseline contrast. This was done in an attempt to obtain ROIs that were not biased by any one condition. The contrast images from each participant were entered into the second level analysis and group-level activation maps were generated using a one sample t-test. Activation clusters surviving a threshold of $p < 0.05$ corrected for multiple comparisons using family wise error correction (FWE) were used in the subsequent analysis — as ROIs. The functional ROIs were defined as a sphere with a radius of 5 mm centered at the activation peak for each cluster (see Table 2). The timecourses from each ROI were extracted using the Marsbar toolbox (Brett et al., 2002). The timecourse data from all the voxels within the ROI were extracted from each participant's imaging dataset and sorted by experimental condition and averaged. The averaged timecourses across all trials were converted into percent signal change (PSC) using the formula $(\text{signal} - \text{baseline}) / \text{baseline} \times 100$ for each time point, where the baseline constant was the mean signal of the fixation periods. Then, the PSC timecourses were baseline corrected to 0. For each individual subject, baseline corrected PSCs for the 25 s block (from 6 to 31 s, the first 6 s were taken out for the delayed hemodynamic response) were averaged to compute the mean signal change for each condition for each ROI. The averaged PSC value was considered as a representative activation level of each ROI for each subject. With these values, a MANOVA (syntactic complexity×repetition) was used to test the main effects and the interaction between the two factors for each ROI.

Table 3 – F-values for the signal change analysis.

ROI	BA	2×3 ANOVA			Active Prime	Passive Prime
		Complexity	Prime	Interaction		
Left Inferior Frontal Gyrus	45/47	1.86	<1	3.24*	<1	2.31
Left Inferior Frontal Gyrus	44	<1	3.03	4.12*	2.57	4.1*
Left Precentral	6	4.54*	1.02	6.12**	2.02	3.83*
Left Occipital Lobe, lingual	18	<1	4.92*	7.2**	16.67**	1.1
Right Occipital Lobe, lingual	18	1.29	3.83*	4.22*	8.24**	<1

The bold numbers indicate statistical significance.

* $p \leq 0.05$.

** $p \leq 0.005$.

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