Working-Memory Capacity Effects in the Processing of Non-adjacent Subject-Verb Agreement: An Event-Related Brain Potentials Study

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1. Introduction

One question that has received much attention in the past decade or so is whether grammatical processing in the second/foreign language (L2) relies on the same mechanisms as grammatical processing in the native language (L1). Behavioral studies on agreement morphology, in particular, have shown that L2 learners may or may not show sensitivity to such agreement in sentence comprehension (e.g., Bowden, Gelfand, Sanz, & Ullman, 2010; Coughlin & Tremblay, in press; Foote, 2011; Hopp, 2010; Jiang, 2004, 2007; Keating, 2009; McDonald, 2006; Neubauer & Clahsen, 2009; Sagarra & Herschensohn, 2010; Sato & Felser, 2010).While there is still no consensus on the matter, three different hypotheses (among others) have been proposed to address this issue.

Ullman's Declarative/Procedural Model (2001) stipulates that native speakers rely on two distinct memory systems to process morphosyntactic information such as agreement: the declarative memory system stores irregularly inflected words in their whole form (e.g., *ate*) whereas the procedural memory system decomposes morphologically complex words with regular inflections into a stem and affix (e.g., *talk+ed*). Ullman proposes that at initial stages of L2 acquisition, "late" L2 learners (i.e., learners who were first exposed to the target language at or after the onset of puberty) over-rely on declarative memory and thus store morphologically complex words in their whole form, but with increased proficiency they may come to rely more on the procedural memory system and decompose morphologically complex words (see also Paradis, 2004, 2009). Thus, according to Ullman's model, L2 learners show a qualitative shift in their processing of morphologically complex words, going from non-nativelike to nativelike processing with increasing proficiency. Ullman's model may be somewhat difficult to falsify, however, in that the absence of a qualitative shift in L2 processing could instead be attributed to insufficient variety in the proficiency of the L2 learners tested.

By contrast, according to Clahsen and Felser's (2006a) Shallow Structure Hypothesis, late L2 learners' grammatical processing differs qualitatively from that of native speakers, irrespective of L2 proficiency: unlike native speakers, L2 learners are unable to build detailed hierarchical syntactic structures and instead over rely on lexical and semantic information when interpreting sentences. Due to these shallow syntactic structures, L2 learners may have difficulty computing morphosyntactic dependencies between words, with nativelike processing being restricted to local domains such as "morphosyntactic agreement between closely adjacent constituents" (Clahsen & Felser, 2006b, p. 111). More recently, Clahsen, Felser, Neubauer, Sato, and Silva (2010) propose that unlike native speakers, L2 learners may not be able to decompose morphologically complex words (see also Neubauer & Clahsen, 2009; Silva & Clahsen, 2008). Clahsen and colleagues' view can be falsified by data showing that native speakers and L2 learners process morphologically complex words in a qualitatively similar way.

* This research was supported in part by the Center for the Study of Family Violence and Sexual Assault at Northern Illinois University and the Department of French at the University of Illinois. We would like to thank the SLRF audience and the anonymous reviewers for their valuable comments on this work.

Taking a cognitive approach to language processing, McDonald (2006) instead proposes that L2 learners' lack of sensitivity to morphosyntactic information is not founded in a non-nativelike grammar or in different storage mechanisms, but arises due to L2 learners' lower Working Memory (WM) capacity, slower processing abilities, and weaker decoding abilities (see also Hopp, 2006, 2010). In other words, the mechanisms that underlie L2 learners' use of grammatical information are similar to those that underlie native speakers' use of grammatical information; it is the greater cognitive demands imposed by the target language that impede L2 learners' use of morphosyntactic information. This also entails that higher-level L2 learners will be less affected by these cognitive demands than lower-level L2 learners, given that L2 processing is more effortful at lower levels of proficiency. McDonald supports this hypothesis by demonstrating that native speakers under WM and decoding stress performed similarly to unstressed L2 learners in grammaticality judgment tasks. McDonald's theory can be falsified by data showing that native speakers and L2 learners process morphologically complex words in a qualitatively different way.

The presents study aims to determine which of these three theories accounts best for L2 learners' online processing of agreement morphology. It focuses specifically on subject-verb (number) agreement, where the subject noun is either adjacent or not adjacent to the agreeing verb. This study also examines whether L2 learners' sensitivity to subject-verb agreement, especially in non-adjacent dependencies, can be predicted by their proficiency in the L2 (a variable known to influence L2 learners' responses on linguistic tasks) and by their WM capacity in the L1. Since computing subject-verb agreement involves holding the number feature of the noun in WM until the verb is parsed, we might expect that L2 learners' sensitivity to agreement information will increase as their WM capacity increases. Finding a significant relationship between the L2 learners' responses and their proficiency would provide some support for both Ullman's Declarative/Procedural model and McDonald's cognitive processing theory, and finding a relationship between L2 learners' responses and their WM capacity would provide some support for McDonald's cognitive processing theory.

These questions are investigated by measuring the Event Related Potential (ERP) brain responses that subject-verb agreement violations elicit for late L2 learners. Unlike online behavioral research methods, ERPs can shed some direct light on the nature of the processes that underlie grammatical processing, and thus on whether L2 learners and native speakers show qualitatively similar or qualitatively different processes. To our knowledge, no study has yet examined the relationship between L2 learners' ERP components to agreement violations and both their proficiency and WM capacity.

We begin with a brief review of the literature on the processes that ERPs have been shown to index in the L1 and in the L2.

2. Event-Related Potentials for Investigating L2 Grammatical Processing

The increasingly widespread use of the ERP technique over the last several decades has revealed much about the signatures of language processing in the L1 and L2. The first ERP signature of interest for the present study is the N400—a negative increase in voltage that occurs approximately 400 ms after the presentation of a semantically anomalous linguistic stimulus, as in *I took a bite of the* *windmill* (Kutas & Hillyard, 1980). This effect has been interpreted as an index of semantic integration, and its amplitude is modulated by a variety of factors relating to lexical semantics and context, including cloze probability, discourse context, world knowledge, speaker identity, and political beliefs (e.g., Hald, Steenbeek-Planting, & Hagoort, 2007; Kutas & Hillyard, 1984; Nieuwland & Van Berkum, 2006; Van Berkum, Holleman, Nieuwland, Otten, & Murre, 2009; Van Berkum, van den Brink, Tesink, Kos, & Hagoort, 2008). The reliability of the N400 effect is well established not only for the processing of native languages, but also for L2 processing. Ardal, Donald, Meuter, Muldrew, and Luce (1990) and Weber-Fox and Neville (1996) observed that semantic errors elicited reliable N400 effects in the L2, and that these effects displayed a slight delay in latency among bilinguals, but in other respects were nativelike. The finding that L2 learners display N400 effects for semantic anomalies has been replicated in many other studies (e.g., Hahne, 2001; Hahne & Friederici, 2001; McLaughlin, Osterhout, & Kim, 2004; Mueller, 2005, to name a few).

The second ERP effect of interest for the current investigation is the P600 effect. This effect—a centro-parietal late positive shift 600 ms after the presentation of a morphosyntactic violation, as in

The cats won't <u>*eating*</u> *the food*—has been argued to index processes of syntactic reanalysis and integration (e.g., Friederici, Steinhauer, & Frisch, 1999; Kaan, Harris, Gibson, & Holcomb, 2000; Osterhout & Hagoort, 1999; Osterhout & Holcomb, 1992). In addition to verb tense errors, morphosyntactic anomalies that elicit a P600 effect include phrase structure anomalies, verb subcategorization anomalies, sentence-constituent movement anomalies, subject-verb agreement errors, and reflexive gender and number agreement errors (for an overview, see Osterhout, McLaughlin, & Bersick, 1997). For phrase structure and morphosyntactic violations, this effect is often preceded by a left anterior negativity (LAN) effect; however, the functional interpretation of the LAN effect is not clear (e.g., Friederici, Pfeifer, & Hahne, 1993; Hagoort, Brown, & Osterhout, 1999; for discussion, see Molinaro, Barber, & Carreiras, 2011).

In contrast to the qualitatively nativelike N400 effects observed for L2 learners' processing of semantic violations, L2 learners' processing of morphosyntactic errors does not necessarily elicit nativelike P600 effects. Instead, L2 processing signatures of morphosyntactic errors may lack a LAN effect for errors that normally elicit a LAN in native speakers (e.g., Clahsen & Felser, 2006; Hahne, Mueller, & Clahsen, 2006); they may consist of a P600 effect of reduced amplitude as compared to the P600 effects observed in native speakers (e.g., Weber-Fox & Neville, 1996); and, for lower-level L2 learners, they may consist of an N400 effect instead of a positive shift (e.g., Osterhout, McLaughlin, Pitkänen, Frenck-Mestre, & Molinaro, 2006). However, in light of the finding that L2 learners of a miniature artificial language can be trained to a sufficiently high proficiency at which they display a nativelike biphasic ERP pattern (e.g., Friederici, Steinhauer, & Pfeifer, 2002; cf. Morgan-Short, Sanz, Steinhauer, & Ullman, 2010), recent investigations have focused on the effect of L2 proficiency on the nativelikeness of ERP components. Besides global L2 proficiency, factors that have been found to modulate the nativelikeness of ERP signatures in the L2 include proficiency on specific L2 structures, L1 transfer, and rate of learning (e.g., Chow, White, Genesee, & Steinhauer, 2007; Foucart & Frenck-Mestre, 2011; Gillon Dowens, Vergara, Barber, & Carreiras, 2010; McLaughlin, Osterhout, & Kim, 2004; McLaughlin, Tanner, Pitkänen, Frenck-Mestre, Inoue, Valentine, & Osterhout, 2010; Ojima, Nakata, & Kakigi, 2005; Osterhout, McLaughlin, Pitkänen, Frenck-Mestre, & Molinaro, 2006; Rossi, Gugler, Friederici, & Hahne, 2006; Sabourin & Stowe, 2008; Steinhauer, White, King, Cornell, Genesee, & White, 2006; Tanner, Osterhout, & Herschensohn, 2009; White, Genesee, & Steinhauer, under revision).

Tying together the existing literature, Steinhauer, White, and Drury (2009) characterize L2 learners' ERP signatures in terms of a dynamic sequence of components that changes as L2 proficiency increases. Within this sequence of changing ERPs, low-proficiency learners display N400 effects for morphosyntactic violations because they are posited to rely on mechanisms of lexical processing rather than on mechanisms of morphosyntactic processing. As learners increase in proficiency, they are thought to increasingly rely on rule-governed processes for decomposing regularly inflected forms, a change that corresponds to the disappearance of the N400 effect in favor of a P600 effect. At even higher levels of proficiency, this P600 effect becomes fully nativelike in its amplitude and latency, and is preceded by a nativelike LAN effect in contexts where one appears among native speakers. Steinhauer et al.'s (2009) interpretation of the existing L2 ERP literature highlights the fact that differences between L1 and L2 ERPs can be qualitative (e.g., native speakers' P600 effects have a timing and polarity that differ substantially from those of the N400 effects seen among low-proficiency L2 learners for the same morphosyntactic anomalies) or quantitative (e.g., the augmentation of P600 amplitude among higher-level L2 learners as a function of their proficiency).

The ERP technique is therefore well suited for investigations such as the present study, in that it can shed crucial light on whether L2 learners' processing of morphosyntax is qualitatively or quantitatively different from that of native speakers. Furthermore, it can reveal whether the ERP components that L2 learners display can be predicted as a function of their proficiency in the L2 and their WM capacity in the L1. Support for Ullman's (2001) model would take the form of a qualitative shift in L2 learners' ERP signatures as their proficiency increases, eliciting an N400 effect among lower-level L2 learners but a P600 effect among higher-level L2 learners. Finding only an N400 effect whose amplitude does not vary as a function of WM capacity or proficiency would be consistent with the view espoused by Clahsen and colleagues. Finally, McDonald's (2006) cognitive processing theory would predict a P600 effect whose amplitude should be modulated by L2 learners' WM capacity and proficiency. In our design, we might also expect a stronger relationship between the participants' WM capacity and their ERP responses when the subject noun and verb are not adjacent as compared to when they are adjacent, given the greater memory load that the first condition imposes.

We investigate these questions with native English speakers at various proficiencies in French. Both English and French have subject-verb number agreement marking, but the agreement system of French is morphologically richer than that of English.

3. Method

3.1. Participants

The participants were 10 right-handed native speakers of American English (age 18–25; seven females) who began learning French at or after the age of 10. Given the difficulty involved in locating native French speakers in the United States, the participants completed the main experiment in both their L2 (French) and their L1 (English), and their ERP signatures on the two experiments were examined. Hence, the control comparison for this study comes from the same participants.

The participants completed a language background questionnaire in which they provided information such as their age of first exposure to French, their number of years of instruction in French, their number of months of residence in a French-speaking environment, and their percent weekly use of French. The participants also completed a cloze test that assessed their global proficiency in French. The particular test that was used had independently been shown to provide valid and reliable estimates of global L2 proficiency in French (e.g., Tremblay, 2011; Tremblay & Garrison, 2010). The participants' language background information and their cloze test scores are provided in Table 1.

Table 1. Language Background Information of the Participants

	First Exposure to French (age)	Instruction on French (years)	Residence in French-Speaking Environment (months)	Weekly Use of French (percent)	Cloze Test Scores (/45)
Mean	13.5	6.8	0.75	15.8	20.8
SD	2.6	3.1	1.3	8.7	5.7
Range	10–18	3–12	0–4	3–30	12–31

Note. SD = Standard Deviation

It is clear from the information in Table 1 that the participants were quite heterogeneous in their experience with and thus proficiency in French. Given our interest in the individual differences that can predict L2 learners' sensitivity to morphosyntactic information in processing, this variability is in fact desirable for the analysis of our results.

3.2. Materials

The participants read sentences that contained or did not contain subject-verb agreement violations. Two variables were manipulated: (i) whether the subject and the verb agreed in number; and (ii) whether or not the subject was adjacent to the verb. These conditions are illustrated in (1) for the French experiment and in (2) for the English experiment.

(1) a. Pour ce grand poète, les filles <u>rôtissent</u> un gros jambon. [grammatical, adjacent]
b. *Pour ce grand poète, les filles <u>rôtit</u> un gros jambon. [ungrammatical, adjacent]
'For this great poet, the daughters roast(*s) a ham.'
c. Les filles de ce grand poète <u>rôtissent</u> un gros jambon. [grammatical, non-adjacent]
d. *Les filles de ce grand poète <u>rôtit</u> un gros jambon. [ungrammatical, non-adjacent]
'The daughters of this great poet roast(*s) a ham.'

(2) a. For this great poet, the daughter <u>roasts</u> a big ham. [grammatical, adjacent]
b. *For this great poet, the daughter <u>roast</u> a big ham. [ungrammatical, adjacent]
c. The daughter of this great poet <u>roasts</u> a big ham. [grammatical, non-adjacent]
d. *The daughter of this great poet <u>roast</u> a big ham. [ungrammatical, non-adjacent]

In both experiments, the verbs in the grammatical sentences were overtly marked for number, whereas those in the ungrammatical sentences did not have any number marking. Given the research showing that L2 learners drop agreement markers more than they supply unnecessary agreement markers in production (for discussion, see Lardiere, 2006), we judged it was crucial to test morphosyntactic violations where the correct agreement morphology was missing rather than superfluous (i.e., present when not needed). Given this criterion, in the French experiment the grammatical verbs were marked for plural and the ungrammatical verbs had their plural marking missing, whereas in the English experiment the grammatical verbs were marked for third-person singular *–s* and the ungrammatical verbs had this marking missing. Thus, the subject nouns in the French experiment were always plural and the subject nouns in the English experiment were always singular. The intervening prepositional phrases in the non-adjacent conditions were singular in both languages in order to avoid potential agreement attraction errors, which are far more frequent with intervening plural nouns than with intervening singular ones (e.g., Bock & Miller, 1991; for discussion, see Wagers, Lau, & Philips, 2009).[1] In the French experiment, all the critical verbs were regular *–ir* verbs that require the number marking *–ssent* on the third-person plural form. These verbs are among the first verb types that French students learn, and the agreement marking on these forms are always realized phonologically in spoken French (for discussion of how the phonological realization of the agreement marking influences the ERP signatures of native French speakers, see Frenck-Mestre, Osterhout, McLaughlin, & Foucart, 2008).

The two experiments included 30 critical sentences per condition (total = 120 sentences). Each trial, illustrated in (3), was as follows: the participant read a context on the screen (3a); this context was followed by a question about it (3b) and by a licit or illicit cleft response (3c), which served as filler sentence; a second question followed this cleft response (3d), and the critical sentence served as answer to this second question (3e). This contextualization of the filler and critical sentences served as a way to encourage the participants to focus on the meaning of the sentences rather than on their form. Twenty-five percent of the trials were followed by an additional true-or-false question (3f)). For each sentence, if the question had false as answer in the French experiment, it had true as answer in the English experiment (and vice versa). Meaning-focused questions (here, true-or-false questions) were asked instead of form-focused questions (such as acceptability judgments) to ensure that the ERP signatures that L2 learners display at the morphosyntactic violations are automatic and do not depend on their focusing on the form of the words in the sentences. The test items were randomized across participants.

(3) a. Context: Tomorrow, it will be the birthday party of the great poet Paul. His daughters will be present: a policewoman, a pastry chef, and a coordinator. Someone needs to bake a cake.
b. Question 1: Who is it who bakes the cake?
c. Cleft sentence: It is the pastry chef who bakes the cake.
d. Question 2: What does one of the daughters do for Paul's birthday party?
e. Agreement sentence: For this great poet, the daughter roasts a big ham.
f. True-or-false question: The great poet will eat cake and roast beef for his birthday.

To examine the relationship between the participants' sensitivity to morphosyntactic information and their WM capacity, a reading-span task in English adapted from Waters and Caplan (1996) was administered. The sentences in this task included 28 semantically acceptable and 28 semantically unacceptable sentences (e.g., *It was the movie that terrified the child because it showed a monster*; **It was the child that terrified the movie because it showed a monster*. The semantically unacceptable

[1] As a result, only the French experiment could determine with certainty whether the participants established a dependency between the non-adjacent subject noun and verb. In other words, because neither the subject noun nor the intervening noun agreed with the verb in the ungrammatical sentences of the English experiment, the participants' detection of a morphosyntactic violation at the verb did not establish with certainty whether they created an agreement dependency between the non-adjacent subject noun and the verb. Because the focus of this study is on L2 (rather than L1) processing, and since the participants are expected to show nativelike ERP signatures in their L1, we did not judge this limitation as a serious concern for the interpretation of our results.

sentences were created by inverting the subject and the object of the verbs, which had specific animacy requirements (for details, see Coughlin & Tremblay, in press).

3.3. Procedure

The participants completed the tasks in two sessions. During the first session, which was administered in French, the participants completed the reading ERP experiment in French, the language background questionnaire, and the cloze test. During the second session, which was administered in English, the participants completed the reading ERP experiment in English and the WM task in English.

The EEG data were recorded from nine electrode channels (Fz, F3, F4, Cz, C3, C4, Pz, P3, P4) of an elastic electrode cap using the 10-20 placement system (Electro-Cap International, Inc.). These channels were referenced to the linked average of the right and left mastoid. The data were acquired using amplifiers and software from Biopac Systems, Inc; additional analyses were conducted using EEGLAB (Delorme & Makeig, 2004). Recordings from electrodes placed above and below the right eye (VEOG channel) were used to measure eye blinks. A right earlobe electrode served as ground, and all data were subjected to an analog bandpass filter from 0.1 to 35 Hz. All impedances were kept below 5 kΩ, and the data were sampled at a rate of 250 Hz.

The participants were seated in a shielded, sound attenuating booth in front of a computer monitor. The critical sentences were presented one word at a time on the computer screen, with each word onscreen for 290 ms plus 30 ms per letter, up to a maximum of 590 ms, with a 150 ms interval between words. A true-or-false question followed the presentation of 25% of the sentences. Stimuli for the ERP session were presented with the Superlab stimulus presentation software (Cedrus Corp.).

The reading-span task was administered with the software E-Prime (Psychology Software Tools; Schneider, Eschman, & Zuccolotto, 2002). The participants read sets of two, three, four, or five sentences one region at a time. The regions were presented using a non-cumulative moving window procedure, and the participants pressed the space bar to advance to the next region. After each sentence, the participants were asked if the meaning of the sentence they had just read was acceptable, and after each set, they were prompted to recall the last word of the sentences in that set in the order in which the sentences had appeared. A brief practice session preceded the main task. No feedback was given in the practice session or main experiment for either the participants' judgment accuracy or their word recall accuracy. The participants' accuracy rates and reaction times on the acceptability judgments and their word recall responses were recorded.

3.4. Data Analysis

The electro-encephalographic (EEG) data were analyzed at the verb position in the critical sentences. This one-word epoch consisted of a 100-ms pre-stimulus onset baseline followed by a 900-ms span post-stimulus onset. Epochs with extreme values of ±150 µv in the VEOG channel were screened for eye blink artifacts or excessive movement and were rejected from further analysis. The overall blink rejection rate was 3.4%. The rejection rate was lower for the test-items in the subject-verb adjacent conditions (2.6%) than for the test items in the subject-verb non-adjacent conditions (4.2%), and comparable across the grammatical (3.3%) and ungrammatical (3.4%) items.[2] To examine the ERP components elicited by our experiment, the EEG data were averaged across test items for each participant on each condition.

The participants' WM capacity was computed following Waters and Caplan's (1996) analysis: the accuracy rates and response times on the acceptability judgments, and the largest number of words recalled in the correct order for three out of four sets (with an additional .5 word if two of the four sets of the immediately following span size were correctly recalled) were each transformed into z-scores so that they would be on a comparable scale and could be averaged together.

The ERP and WM data were analyzed using linear mixed models, a method that is widely used in other areas of psycholinguistics (e.g., Baayen, 2008) and that has been successfully adapted to the analysis of electrophysiological data (e.g., Davidson, 2009). The ERP data were analyzed in two time windows: a 300-500 ms time window post-stimulus-onset for examining possible early negativity

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[2] The English data from one speaker were affected by a hardware problem, and were excluded from the analysis.

(N400, LAN) effects, and a 600-900 ms window for examining possible P600 effects. In the first set of analyses, we examined the effects of our independent variables of interest: the grammaticality of the verb (1 = grammatical, 2 = ungrammatical), the adjacency of the subject noun and verb (1 = adjacent, 2 = non-adjacent), and the interaction between these two variables. The models also included frontal-to-parietal (1 = Front, 2 = Central, 3 = Parietal) and left-to-right (1 = left (3), 2 = mid (z), 3 = right (4)) localizations, as well as time (4-ms increments within 300-500 ms or within 600-900 ms). Time was not a variable of critical interest, but it was entered in the models to account for a great deal of variance that could not be attributed to the other independent variables. Localizations and time were entered in the models as simple terms, and the models included participants as random variable. These analyses were conducted separately on the English data and on the French data.

A second set of analyses were performed on differential waves—we subtracted the ERP data in the grammatical conditions from the ERP data in the corresponding ungrammatical conditions, with positive differential ERP data reflecting a positivity effect and negative differential ERP data reflecting a negativity effect. These models included proficiency (cloze test scores), WM capacity in English, frontal-to-parietal and left-to-right localizations, and time as independent variables, all of which were entered in the model as simple terms. We entered the last three variables in the model so that they account for a great deal of the variance while leaving the remaining variance to be explained by proficiency and WM capacity. These models, which also included participants as random variable, were performed separately on the English and French data, with proficiency entering the models only for the French data.

4. Results

4.1. English Data

We begin our presentation of the results with the English data. Figures 1 and 2 show the ERPs elicited by the grammatical and ungrammatical English sentences in, respectively, the adjacent and non-adjacent conditions.

A first linear mixed model on the ERP data in the 300-500-ms time window revealed significant effects of grammaticality, $t(16192)=11.93$, $p<.001$, and adjacency, $t(16192)=21.14$, $p<.001$, and a significant interaction between grammaticality and adjacency, $t(16192)= -20.19$, $p<.001$, indicating that the effect of grammaticality is not the same in the adjacent and non-adjacent conditions. This model also revealed significant effects of frontal-to-parietal localization, $t(16192)=13.15$, $p<.001$, and left-to-right localization, $t(16192)= -5.65$, $p<.001$, as well as a significant interaction between grammaticality and frontal-to-parietal localization, $t(16192)= -9.58$, $p<.001$, indicating that the (negative) effect of grammaticality increases from frontal to parietal regions, and a significant interaction between grammaticality and left-to-right localization, $t(16192)=5.73$, $p<.001$, indicating that the (negative) effect of grammaticality decreases from left to right regions. Finally, this model also revealed a significant effect of time $t(16192)= -19.6$, $p<.001$.

Given the significant interactions between grammaticality and adjacency, subsequent mixed models were conducted separately for the adjacent and non-adjacent conditions. These subsequent models, reported in Table 2, revealed a significant effect of grammaticality for both the adjacent and non-adjacent conditions, though in the opposite direction.

Table 2. Subsequent Mixed Models on Adjacent vs. Non-Adjacent Conditions, 300-500 ms, English

Variable	Adjacent Condition			Non-Adjacent Condition		
	df	*t*	*p*	*df*	*t*	*p*
Grammaticality	8094	3.56	.001	8094	–6.12	.001
Frontal-to-parietal localization	8094	15.73	.001	8094	3.72	.001
Left-to-right localization	8094	–7.16	.001	8094	–1.142	.253
Grammaticality × Frontal-to-parietal localization	8094	–11.54	.001	8094	–2.61	.009
Grammaticality × Left-to-right localization	8094	8.12	.001	8094	<1	.843
Time	8094	–13.50	.001	8094	–16.76	.001

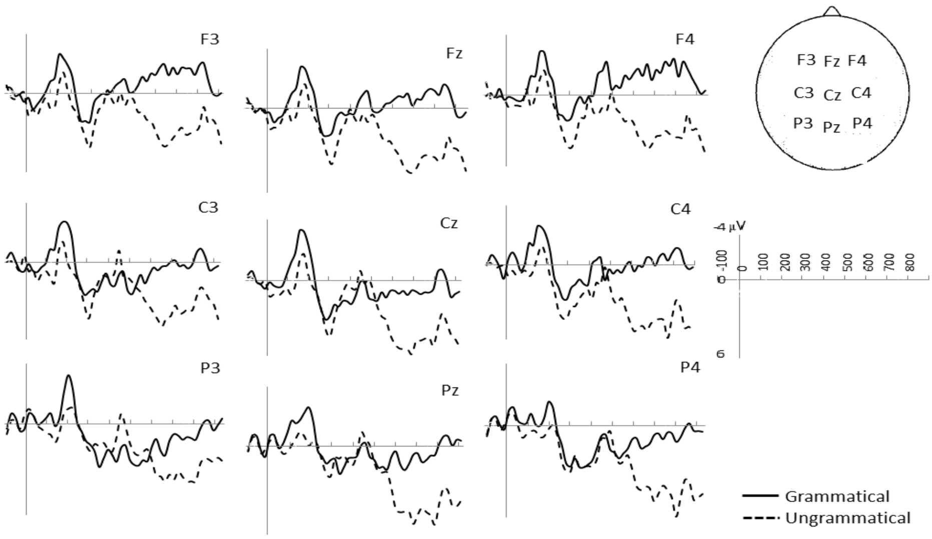

Figure 1. Average ERPs in the adjacent subject-verb conditions, English task

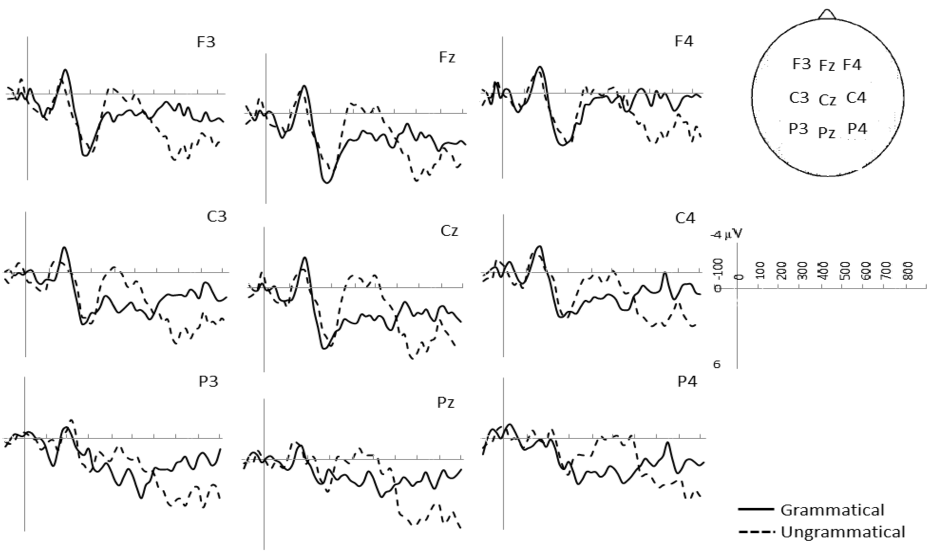

Figure 2. Average ERPs in the non-adjacent subject-verb conditions, English task

The positivity found in the adjacent condition of the 300-500-ms time window may be a P300 effect, which has been associated with expectancy and oddball stimuli (e.g., Sutton, Braren, Zubin, & John, 1965). If the participants noticed the subject-verb agreement errors in the sentences, this may have led them to expect these morphosyntactic errors, which may in turn have yielded a P300 effect, one that would not be observed in the non-adjacent condition due to the size of the observed negativity in the latter condition. The localization of this positivity effect is consistent with this interpretation (e.g., Polich, 2007). Alternatively, the positivity found in the adjacent condition of the 300-500-ms time window may be due to differences in the timing of the large positivity effect observed for the 600-900-ms time window, which numerically would result in the appearance of an earlier positivity.

On the other hand, the negativity found in the non-adjacent condition has all the characteristics of an N400 effect in both its timing and localization (e.g., Kutas & Hillyard, 1982). The negativity effects typically associated with morphosyntactic violations are LAN effects. As their name suggests, these negativity effects tend to be larger in left and frontal regions (e.g., Neville, Nicol, Barss, Forster, & Garrett, 1991; Osterhout & Nicol, 1999). Other studies, however, have shown that morphosyntactic violations can elicit biphasic responses, namely a P600 effect that is preceded by an N400 effect or by a non-left-lateralized negativity in the same time window (e.g., Frisch, Hahne, & Friederici, 2004; Gunter & Friederici, 1999; see also Experiment 2 of Osterhout & Nicol, 1999). The negativity effect we find in this study resembles an N400 more than a LAN effect in its localization. Why should we observe such an effect in the non-adjacent condition but not in the adjacent one? We further examined our test items and observed that some of the ungrammatical verbs in the non-adjacent conditions could potentially be interpreted as nouns (e.g., *The daughters of this great poet roast…,* where *roast* could be temporarily interpreted as the complement of *daughters*). This would result in semantically implausible sentences, which could in turn elicit an N400 effect. This effect would be more likely to be obtained in the non-adjacent condition than in the adjacent condition (e.g., *For the great poet the daughters roast…*), because the former provides a syntactic context that is less constraining toward the expectation of a verb than the latter. A closer examination of our ERP data for each individual participant revealed that 7/9 showed this negativity effect.

A second linear mixed model on the ERP data in the 600-900-ms time window revealed significant effects of grammaticality, $t(16192)=37.26$, $p<.001$, and adjacency, $t(16192)=31.91$, $p<.001$, and a significant interaction between grammaticality and adjacency, $t(16192)= -28.73$, $p<.001$, suggesting that the effect of grammaticality is larger in the adjacent condition than in the non-adjacent condition. This model also revealed significant effects of frontal-to-parietal localization, $t(16192)=19.09$, $p<.001$, and left-to-right localization, $t(16192)= -3.80$, $p<.001$, and a significant interaction between grammaticality and frontal-to-parietal localization, $t(16192)= -12.40$, $p<.001$, indicating that the (positive) effect of grammaticality decreases from frontal to parietal regions. The interaction between grammaticality and left-to-right localization was not significant, $t(16192)=1.75$, $p<.08$. Finally, this model also revealed a significant effect of time $t(16192)=10.70$, $p<.001$.

Given the significant interactions between grammaticality and adjacency, subsequent mixed models were conducted separately for the adjacent and non-adjacent conditions. These subsequent models, presented in Table 3, revealed a significant effect of grammaticality for both the adjacent and non-adjacent conditions.

Table 3. Subsequent Mixed Models on Adjacent vs. Non-Adjacent Conditions, 600-900 ms, English

Variable	Adjacent Condition			Non-Adjacent Condition		
	df	*t*	*p*	*df*	*t*	*p*
Grammaticality	8094	22.63	.001	8094	13.59	.001
Frontal-to-parietal localization	8094	20.84	.001	8094	8.16	.001
Left-to-right localization	8094	–5.99	.001	8094	<1	
Grammaticality × Frontal-to-parietal localization	8094	–12.78	.001	8094	–6.09	.001
Grammaticality × Left-to-right localization	8094	6.82	.001	8094	–4.38	.001
Time	8094	2.71	.007	8094	13.93	.001

The timing of the positivity effect found in the 600-900-ms time window is typical of a P600 effect associated with morphosyntactic violations (e.g. Kaan & Swaab, 2003). This effect is also stronger in the adjacent than in the non-adjacent conditions. This, however, could be due to the N400 effect that was elicited in the 300-500-ms time window, which may have reduced the amplitude of the subsequent P600 effect. In light of this N400 effect, we examined the ERP data of our individual participants, found that 6/9 participants showed a positivity effect, and of these 4/9 also showed a negativity effect. We are therefore not dealing with a bimodal distribution. Hence, the reduced amplitude that we find in the 600-900-ms time window for the non-adjacent condition may be due to the co-occurrence of the observed N400 effect.

4.2. French Data

Figures 3 and 4 show the ERPs elicited by the grammatical and ungrammatical French sentences in, respectively, the adjacent and non-adjacent conditions.

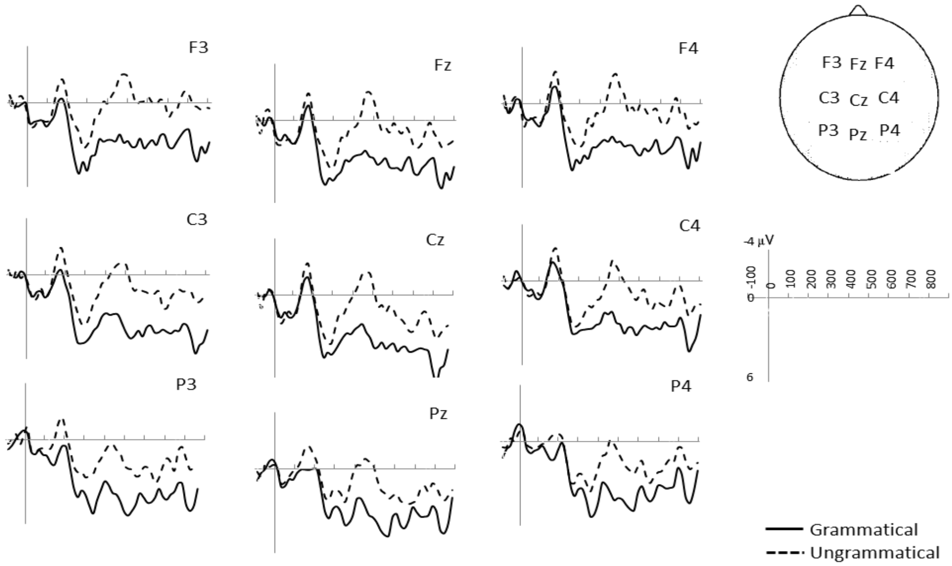

Figure 3. Average ERPs in the adjacent subject-verb conditions, French task

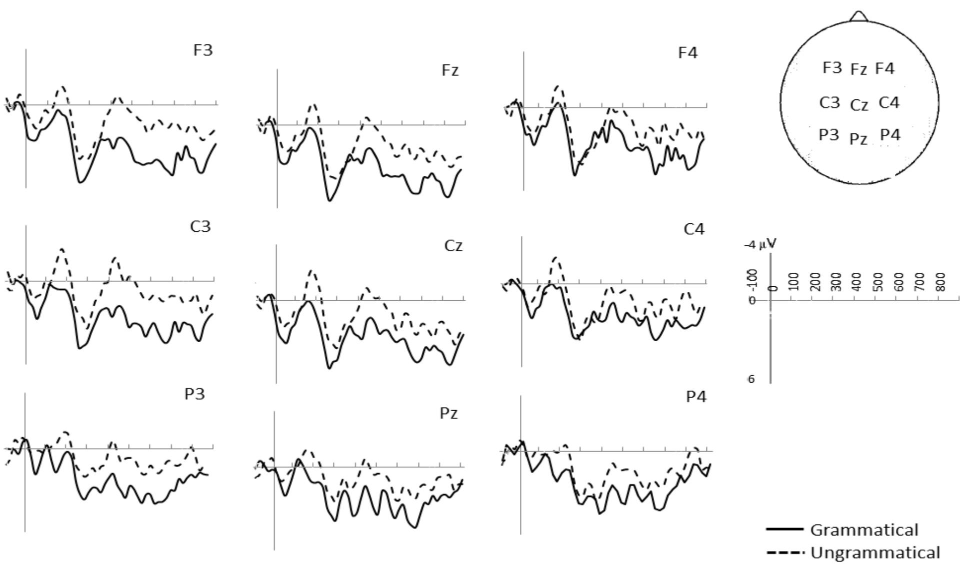

Figure 4. Average ERPs in the non-adjacent subject-verb conditions, French task

A first linear mixed model on the ERP data in the 300-500-ms time window revealed significant effects of grammaticality, $t(17992)= -24.59$, $p<.001$, and adjacency, $t(17992)= -14.27$, $p<.001$, and a significant interaction between grammaticality and adjacency, $t(17992)=14.49$, $p<.001$, indicating that the effect of grammaticality is larger in the adjacent condition than in the non-adjacent one. This model also revealed significant effects of frontal-to-parietal localization, $t(17992)=4.13$, $p<.001$, and left-to-right localization, $t(17992)= -5.46$, $p<.001$, and a significant interaction between grammaticality and left-to-right localization, $t(17992)=7.56$, $p<.001$, indicating that the (negative) effect of grammaticality decreases from left to right regions. The interaction between grammaticality and frontal-to-parietal localization did not reach significance, $t<|1|$. Finally, this model also revealed a significant effect of time $t(17992)= -31.02$, $p<.001$.

Given the significant interactions between grammaticality and adjacency, subsequent mixed models were conducted separately for the adjacent and non-adjacent conditions. These subsequent models, reported in Table 4, revealed a significant effect of grammaticality for both the adjacent and non-adjacent conditions.

Table 4. Subsequent Mixed Models on Adjacent vs. Non-Adjacent Conditions, 300-500 ms, French

Variable	Adjacent Condition			Non-Adjacent Condition		
	df	*t*	*p*	*df*	*t*	*p*
Grammaticality	8994	–18.46	.001	8994	–11.59	.001
Frontal-to-parietal localization	8994	1.87	.062	8994	4.37	.001
Left-to-right localization	8994	–2.45	.014	8994	–5.79	.001
Grammaticality × Frontal-to-parietal localization	8994	3.26	.001	8994	–3.37	.001
Grammaticality × Left-to-right localization	8994	3.01	.003	8994	8.41	.001
Time	8994	–27.20	.001	8994	–19.59	.001

These results suggest that in French, the speakers show a prototypical N400 effect, which has the latency and localization of usual N400 effects (e.g., Kutas & Hillyard, 1982). This effect was found to be weaker when the subject noun was not adjacent to the verb than when it was adjacent to the verb, suggesting that the length of the agreement dependency decreases the size of the negativity. Since none of the verbs in the French task were fully ambiguous with nouns, we are confident that the observed N400 effect reflects L2 learners' qualitatively different processing of the subject-verb agreement violations rather than their interpreting the verbs as nouns.

A second linear mixed model on the ERP data in the 600-900-ms time window revealed significant effects of grammaticality, $t(17992)= -25.17$, $p<.001$, and adjacency, $t(17992)= -6.03$, $p<.001$, and a significant interaction between grammaticality and adjacency, $t(17992)=7.18$, $p<.001$, indicating again that the negative effect of grammaticality is larger in the adjacent condition than in the non-adjacent one. This model also revealed significant effects of frontal-to-parietal localization, $t(17992)= -4.47$, $p<.001$, and left-to-right localization, $t(17992)= -7.60$, $p<.001$, a significant interaction between grammaticality and frontal-to-parietal localization, $t(17992)=7.29$, $p<.001$, indicating that the (negative) effect of grammaticality decreases from frontal to parietal regions, and a significant interaction between grammaticality and left-to-right localization, $t(17992)=7.51$, $p<.001$, suggesting that the (negative) effect of grammaticality decreases from left to right regions. Unlike the previous models, this model did not reveal a significant effect of time, $t<|1|$.

Given the significant interactions between grammaticality and adjacency, subsequent mixed models were conducted separately for the adjacent and non-adjacent conditions. These subsequent models, presented in Table 5, revealed a significant effect of grammaticality for both the adjacent and non-adjacent conditions.

These results indicate that the negativity that the speakers show in the 300-500-ms time window is sustained in the 600-900-ms time window, and it is again weaker when the subject noun and verb were not adjacent than when they were adjacent. We suggest this sustained negativity was caused by the N400 effect in the previous time window. Importantly, unlike in their L1, the participants fail to show a P600 effect to morphosyntactic violations in both the adjacent and non-adjacent conditions. However, as mentioned earlier, our group of L2 learners of French is far from homogenous. Let us thus turn to analyses of variables such as proficiency in French and WM capacity in English that might predict the size of the grammaticality effect found in the 300-500 and 600-900 time windows.

Table 5. Subsequent Mixed Models on Adjacent vs. Non-Adjacent Conditions, 600-900 ms, French

Variable	Adjacent Condition			Non-Adjacent Condition		
	df	*t*	*p*	*df*	*t*	*p*
Grammaticality	8994	–19.27	.001	8994	–21.36	.001
Frontal-to-parietal localization	8994	1.27	.204	8994	–8.42	.001
Left-to-right localization	8994	–3.38	.001	8994	–8.31	.001
Grammaticality × Frontal-to-parietal localization	8994	5.44	.001	8994	5.61	.001
Grammaticality × Left-to-right localization	8994	2.87	.004	8994	8.74	.001
Time	8994	3.08	.002	8994	3.07	.002

4.3. Proficiency in French and WM Capacity in English as Predictors of ERP Responses

Linear mixed models were run on the participants' differential ERP data (i.e., the amplitude on grammatical sentences subtracted from the amplitude on ungrammatical sentences), first with WM capacity in English as predictor of the participants' responses on the English task, and second with both proficiency in French (cloze test scores) and WM capacity in English as predictors of the participants' responses on the French task. These models also included frontal-to-parietal and left-to right localizations and time as fixed variables and participants as a random variable; however, we report only the results for the proficiency and WM capacity variables, as the localization and time effects are the same as those reported in the previous two subsections.

For the English data, these analyses did not reveal a significant effect of WM capacity in any of the time windows for any of the conditions, all $t<|1|$. By contrast, for the French data, these analyses revealed a marginally significant effect of WM capacity on the differential ERP data in the 300-500-ms time windows only for the non-adjacent condition, $t(4495)=-1.69$, $p<.091$, indicating that the (negative) effect of grammaticality increases with higher WM capacity; 600-900-ms time window: $t(4495)= -1.47$, $p<.142$; all other $t<|1|$. None of these analyses revealed a significant effect of proficiency in any of the time windows for any of the conditions: 600-900-ms time window for the non-adjacent condition: $t(4495)= -1.07$, $p<.268$; all other $t<|1|$. These results suggest that WM capacity, but not proficiency, modulated the effect of grammaticality found in the French data, but only in the non-adjacent condition, where the WM memory demands are greater. We now turn to a discussion of these results and their implication for understanding the factors that influence L2 learners' responses to agreement violations.

5. Discussion and Conclusion

The results of the present study indicate that the participants showed qualitatively different responses in their L1 and L2. In English, they showed a P600 effect in the adjacent condition and a biphasic N400-P600 French in the non-adjacent condition, with the N400 effect being possibly due to the nature of the grammatical manipulations (see also Frisch, Hahne & Friederici, 2004; Gunter & Kutas, 1999; Osterhout & Nicol, 1997). By contrast, in French they showed only N400 effects, the size of which increased as the participants' WM capacity in English increased. The N400 effects we found are in line with the view of L2 grammatical processing espoused by Clahsen and colleagues (e.g., Clahsen et al., 2010; Neubauer & Clahsen, 2009; Silva & Clahsen, 2008), suggesting that our L2 learners treated subject-agreement violations as lexical or semantic violations rather than as morphosyntactic violations. These effects are also in line with Ullman's (2001) Declarative/Procedural model insofar as our participants may not have been sufficiently proficient to show a P600 effect. The fact that we did not find a significant relationship between L2 proficiency (as measured by cloze test scores) and the amplitude of the N400 effects somewhat weakens this interpretation of the results, however. At last, the N400 effects in our L2 data are not compatible with McDonald's (2006) cognitive processing theory, which does not posit a qualitative difference between L1 and L2 processing, even among lower-level L2 learners.

Although our results are consistent with both the Shallow Structure Hypothesis and the Declarative/Procedural Model, they do not necessarily provide evidence for these views. That is, the absence of either a P600 or a relationship between proficiency and the size of the observed ERP effect in the L2 results does not entail that L2 learners cannot (eventually) process the L1 and the L2 similarly. As shown in their language background information, the participants' exposure to and use of French were relatively limited, and their cloze test scores were typical of those of intermediate (rather than advanced) L2 learners. Previous ERP studies have shown that L2 learners at high proficiencies can show ERP signatures that are qualitatively similar to those of native speakers (e.g., Friederici et al., 2002; Weber-Fox & Neville, 1996). Hence, our participants may not have been sufficiently advanced to show either a P600 effect or a significant relationship between proficiency and the size of the ERP effect, even if they varied somewhat in their proficiency in French. One may also argue that our L2 learners' lexicalized interpretation of agreement violations does not necessarily imply that these learners cannot use syntactic information in sentence processing. Studies examining the processing of syntactically complex sentences (e.g., island constraints) may shed more light on this issue (for examples of such studies, see Aldwayan, Fiorentino, & Gabriele, 2010; Felser, Cunnings, Batterham, & Clahsen, 2012; Omaki & Schultz, 2011).

The results of our study also showed that the size of the L2 learners' N400 effect decreased when the subject noun was not adjacent to the verb as compared to when it was adjacent to the verb. These findings could suggest that L2 learners' sensitivity to subject-verb agreement decreases as the length of the dependency (and thus WM load) increases. The significant relationship observed between L2 learners' WM capacity in English and the size of the N400 effect in the non-adjacent condition is consistent with this hypothesis. This suggests that L2 learners who excel at performing simultaneous linguistic operations such as reading sentences for meaning and holding sentence-final words in memory (i.e., reading-span task) also excel at holding subject nouns in memory when processing non-adjacent agreement dependencies (i.e., ERP task). These results, though not the nature of the ERP effects, were predicted by McDonald's (2006) cognitive processing theory. An alternative interpretation of our data exists, however. Our experimental sentences in the non-adjacent condition of the French task had a plural subject noun, an intervening singular noun, and a plural or singular verb (e.g., *Les filles de ce grand poète* *rôtissent* *un gros jambon* 'The daughters of this great poet roast a big ham'). The reduced N400 effect in the non-adjacent condition could be due to the singular number of the intervening noun, creating some sort of agreement attraction error (though such errors are far more common when the intervening noun is plural; for discussion, see Wagers et al., 2009). In other words, it is unclear from the present study whether the reduced effect of grammaticality in the non-adjacent condition is due to the length of the agreement dependency alone or to the intervening noun (or both). Either way, WM capacity appears to modulate the size of the ERP effects that subject-verb agreement violations elicit in the non-adjacent condition.

Although this study raises questions for further research, it also highlights the need for investigating the role of individual variables such as WM capacity in L2 morphological processing. Focusing on this and other predictors of individual differences is perhaps the most promising direction that research on L2 grammatical processing with late learners may take.

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Selected Proceedings of the 2011 Second Language Research Forum: Converging Theory and Practice

edited by Erik Voss,
Shu-Ju Diana Tai, and Zhi Li

Cascadilla Proceedings Project Somerville, MA 2013

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ISBN 978-1-57473-458-4 library binding

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This paper can be cited as:

Reichle, Robert V., Annie Tremblay, and Caitlin E. Coughlin. 2013. Working-Memory Capacity Effects in the Processing of Non-adjacent Subject-Verb Agreement: An Event-Related Brain Potentials Study. In *Selected Proceedings of the 2011 Second Language Research Forum*, ed. Erik Voss et al., 54-69. Somerville, MA: Cascadilla Proceedings Project. www.lingref.com, document #2905.