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## Research Report

**ERP measures of auditory word repetition and translation priming in bilinguals**Natalie A. Phillips<sup>a,b,\*</sup>, Denise Klein<sup>c</sup>, Julie Mercier<sup>d</sup>, Chloé de Boysson<sup>e</sup><sup>a</sup>Department of Psychology/Centre for Research in Human Development, Concordia University, 7141 Sherbrooke Street West, Montréal, Québec, Canada H4B 1R6<sup>b</sup>Lady Davis Institute for Medical Research/Jewish General Hospital, Montréal, Québec, Canada<sup>c</sup>Cognitive Neuroscience/Montreal Neurological Institute/McGill University, Montréal, Québec, Canada<sup>d</sup>Department of Psychology, McGill University, Montréal, Québec, Canada<sup>e</sup>Université Bordeaux 1, Bordeaux, France

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## ABSTRACT

Motivated by the demonstration of similarly localized adaptation of the hemodynamic response in a first (L1) and second (L2) language, this study examined event-related brain potentials (ERPs) to spoken words in L1 and L2 in 15 English–French bilinguals. We examined whether the temporal pattern of N400 adaptation due to within-language repetitions (i.e., repetition priming) was similar in L1 and L2 and whether the release from adaptation elicited by a within-language word change was similar. Furthermore, using word changes across language, we examined the phonological mismatch negativity (PMN) and N400 components to determine the kind of information activated during translation priming. In contrast to within-language repetition, we expected between-language repetition (i.e., translations) to be characterized by conceptual rather than lexical/phonological word form priming. Overall, the pattern of adaptation and release from adaptation was similar in L1 and L2, with evidence of delayed semantic analysis in L2 in the form of a later N400 effect. A change in language (L1 to L2) elicited a similar pattern of PMN and N400 activity compared to a within-language change in meaning in L1, suggesting that neither word form nor conceptual information was available on-line for the forward translation. In contrast, the presence of strong PMN but minimal N400 effects for L2-to-L1 translations suggests that conceptual but not phonological information is available on-line for backwards translation. L2 proficiency influenced the extent to which conceptual representations were activated by translations. These data are discussed in light of current models of bilingual word processing and suggest modality differences in the pattern of activation of lexical and conceptual information.

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## 1. Introduction

Debate continues as to whether a first (L1) and second (L2) language are represented by common neural substrates (e.g., Paradis, 1997). One way to examine this question is via repetition or identity priming, which is the facilitated processing of a word that has been previously presented (e.g., Jacoby and Dallas, 1981). Repetition priming is generally thought to show that one or more of the underlying representations of a word are more easily accessed upon repeated presentation (e.g., orthography, phonology, or lexical-level information). Repetition priming has been frequently demonstrated in monolinguals (for a review, see Richardson-Klavehn and Bjork, 1988); however, one can also ask if repetition priming occurs across languages by examining whether processing is facilitated when a word is presented after the translation of that word in another language (e.g., CAT-CHAT or DOG-CHIEN). In this case, demonstration of repetition priming across languages would indicate that a word and its translation share at least some of the same underlying representations. In the case of translations which do not share some aspects of word form (i.e., non-cognates), the facilitation would have to take place beyond the point of lexical access, perhaps at a semantic level.

The studies cited below examined repetition priming in bilinguals using behavioral measures and demonstrated significant facilitation when a word is repeated within each language. However, the findings are mixed with respect to cross-language repetition (i.e., translations). For instance, some studies have not observed facilitation for cross-language translations (e.g., Gerard and Scarborough, 1989; Kirsner et al., 1980, 1984) suggesting that the bilingual's two languages are separate at the lexical level (for a review, see Smith, 1997). Other studies have found evidence of translation priming (e.g., Cristoffanini et al., 1986; de Groot, 1991; Jin, 1990; Keatley et al., 1994; Kirsner et al., 1984), the demonstration of which may be dependent on certain variables such as the participants' task, word characteristics (e.g., cognate status), or stimulus timing. The variable pattern for translation priming led Smith (1997) to conclude that between- versus within-language repetition priming are likely dependent on different underlying mechanisms, with within-language repetition priming reflecting lexical activation and between-language repetition priming (i.e., translations) reflecting semantic activation.

One way to approach this issue is to ask whether a bilingual's two languages are dependent on the same neuro-functional systems. These questions are just beginning to be investigated using neuroimaging techniques. Using a technique developed by Grill-Spector and Malach (2001), Chee et al. (2003) examined the effect of visually presented word repetitions within and across languages on the adaptation of the hemodynamic response as measured by functional magnetic resonance (fMR-adaptation or fMR-A). They observed adaptation of translation equivalents, suggesting the sharing of neuronal populations which represent semantic information across languages. Klein et al. (2006) investigated questions of the same nature in the auditory modality. They observed that similar regions were engaged in within-language release from adaptation in L1 and L2, namely, left and right lateral superior temporal gyri. With regard to changes in language (i.e.,

forward and backward translations), there was some similarity in the brain areas activated (i.e., both directions activated bilateral superior temporal gyri) but not complete overlap (i.e., the left inferior frontal region was activated for L1-to-L2-translations but not L2-to-L1 translations). In these studies, adaptation of the homodynamic response and recovery from adaptation was taken as evidence of repetition priming and provided valuable insight into the neuroanatomical substrates of bilingual language processing but relatively limited information on the temporal dynamics.

In the present paper, we used recordings of electrical brain activity (event-related brain potentials or ERPs) to provide online measurement of linguistic and cognitive processing during word repetition within and between L1 and L2. ERPs reflect voltage variations in electrical brain activity in response to various stimulus or cognitive processes and are extracted from the electroencephalogram (EEG) via signal averaging. ERP components are typically identified by their polarity (positive or negative), latency (occurrence after the eliciting stimulus, in ms), amplitude (in  $\mu\text{V}$ ), and topographical distribution across the scalp (Rugg and Coles, 1995). Moreover, because certain components can be linked to different stages of cognitive and linguistic processing, these measures could provide a useful window into the processing nature of translation priming.

Two components sensitive to the auditory processing of words are examined in the present paper. One is the N400 ERP component, first described by Kutas and Hillyard (1980). The N400 is a negative-going component which peaks at approximately 400 ms after word onset and has a central scalp distribution in the auditory modality (e.g., Connolly et al., 1992, 1993; Connolly and Phillips, 1994). The amplitude of the N400 varies *inversely* with the amount of semantic activation a word has in memory; that is, N400 amplitude is reduced when a word is preceded by a semantically related context, as demonstrated in word pairs (e.g., Brown and Hagoort, 1993), and written (e.g., Kutas and Van Petten, 1988; Connolly et al., 1995) and spoken (e.g., Connolly and Phillips, 1994) sentences. Although there is some disagreement as to the extent to which the N400 reflects aspects of relatively early automatic lexical/semantic processes (e.g., Kutas and Hillyard, 1989; Deacon et al., 2000; Holcomb et al., 2005; Kiefer, 2002; Luck et al., 1996; Vogel et al., 1998) or later post-lexical processes (e.g., Brown and Hagoort, 1993; Chwilla et al., 1995; Holcomb, 1993), it is clear that N400 amplitude is modulated by semantic or conceptual relations between words. Also important for our purposes, N400 amplitude is reduced when a word is repeated (e.g., Deacon et al., 2004; Doyle et al., 1996; Rugg, 1990; Rugg et al., 1995), suggesting that it will be a sensitive indicator of adaptation within and across languages.

The second component of interest is the phonological mismatch negativity (PMN; Connolly and Phillips, 1994), which is elicited when the phonological properties of a spoken word are not primed or do not match an expected input. This component peaks earlier than the N400, typically within a 250 to 350 ms time period, has a fronto-central distribution, and has been observed to words presented in sentences (e.g., Connolly and Phillips, 1994) and to words and non-words requiring phonological analysis (e.g., Connolly et al., 2001). Thus, in the present study, the PMN should provide

information on relatively early stages of phonological word processing in L1 and L2.

There are a growing number of studies that have used ERP measures to investigate bilingual language processing. Some have examined the processing of syntactic and/or semantic violations within sentences (e.g., Ardal et al., 1990; Hahne and Friederici, 2001; Moreno et al., 2002; Proverbio et al., 2002; Weber-Fox and Neville, 1996), the consequences of switching between languages (Jackson et al., 2001), or semantic priming using word pairs or lists (e.g., de Bruijn et al., 2001; Kotz, 2001; Phillips et al., 2004). Only a few studies, which were conducted in the visual modality, have examined translation priming (e.g., Alvarez et al., 2003; Fischler et al., 1987; Thierry and Wu, 2004; Vigil-Colet et al., 2000) and, of these, only two examined language-related components like the N400 response (i.e., Alvarez et al., 2003; Fischler et al., 1987).

Thus, despite the obvious relevance to spoken communication, very little work has been conducted in the auditory modality with regard to either bilingual language processing or the ERP repetition effect. Following from the fMR-adaptation study of Klein et al. (2006), we used ERPs to study repetition priming and adaptation within and across languages in fluent bilinguals. Using the fMR-A technique, one can only assume that neural adaptation has taken place by comparing the summated hemodynamic response to trains of stimuli in which the final word does or does not deviate from the sequence. In contrast, given the superior temporal resolution of ERPs, we should be able to determine the time course of repetition priming within and across languages with greater precision because one can measure ERP responses time-locked to each position in the sequence. Thus, the time course of adaptation of the neural signal can be examined for each repeated word and, for words that deviate from the sequence, release from adaptation can be directly measured on the eliciting word.

With respect to the general goals of the present study, we were first interested in whether the adaptation due to the repeated presentation of a word within a language was equivalent in L1 and L2. One might expect such repetition priming to be more pronounced in L2 than in L1. This would be due to the fact that, although fluent, our participants acquired their L2 after their L1 and would be somewhat less familiar with words in their L2. Thus, L2 words could benefit more from stimulus repetition. However, the results from Klein et al. suggest that the effects of auditory repetition might be equivalent in both languages and, given the similarities in our paradigms, we hypothesized equivalent repetition effects within L1 and L2 (i.e., similarly reduced PMN and N400 amplitudes to within-language repeated words). Second, we evaluated repetition priming across languages (i.e., translation priming). Previous behavioral studies have provided evidence both for and against repetition priming using translations (see Smith, 1997). We used the well-known ERP repetition effect involving the N400 component (e.g., Rugg, 1990) as a measure potentially more sensitive to differences between languages. We also looked for evidence of translation priming early in the processing stream prior to the N400 (i.e., in the time window of the PMN) to determine what kind of information might be activated during translation priming (e.g., phonological word form

versus conceptual-level information). Using the terminology of the fMR-A literature, we were interested in whether cross-language adaptation occurred and, if so, whether it has similar characteristics to that of within-language adaptation. For translated words, we expected to see continued evidence of the PMN (since the lexical or phonological word form differs between translations) but an N400 reduced in amplitude (providing evidence for priming at a conceptual level).

These goals were pursued by measuring the ERP responses to five-word sequences presented in L1 or L2. The first four words were repetitions of the same word which allowed for the examination of within-language adaptation of the time-locked ERP activity. To explore cross-language adaptation and release from adaptation, we examined responses to the fifth word of a sequence, which could be a within-language word unrelated to the meaning of the repeated words (i.e., a change in meaning), a switch in language to a translation equivalent of the repeated words (i.e., a change in language), or a switch in language to an unrelated word (i.e., a change in meaning and a change in language) (Table 1).

## 2. Results

### 2.1. Statistical analyses

The ERP repeated measures analyses of variance (ANOVAs) reported below used SPSS v.11.0 statistical software and employed the Greenhouse and Geisser (1959) non-sphericity correction for effects with more than one degree of freedom in the numerator. Following convention, unadjusted degrees of freedom are reported, along with the Greenhouse–Geisser epsilon value ( $\epsilon$ ) and adjusted  $p$ -value. Mean square error values reported are those corresponding to the Greenhouse–Geisser correction. All main effects involving the experimental

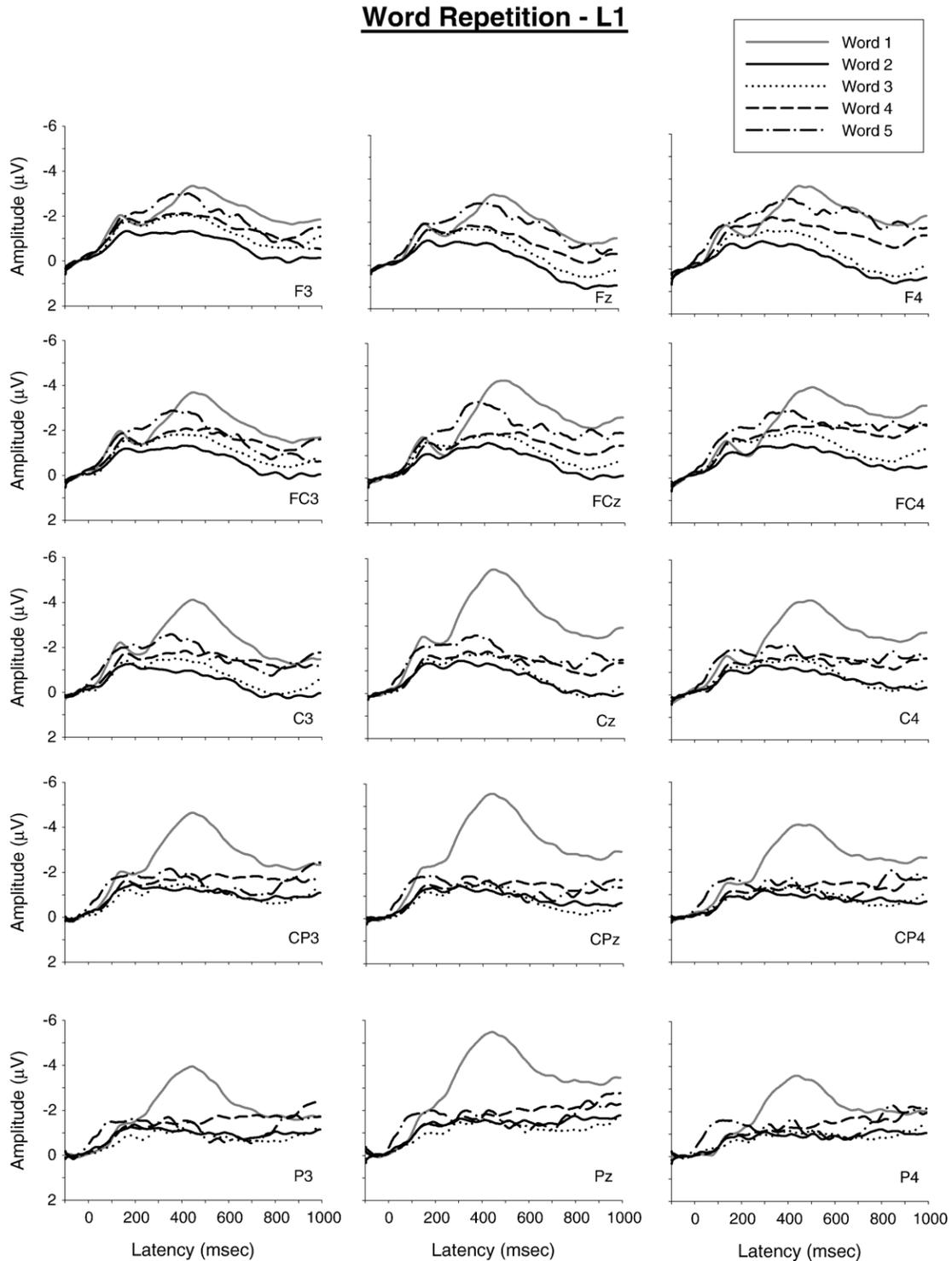
**Table 1 – Stimulus design**

Condition	Repeated word				Final word
	Word 1	Word 2	Word 3	Word 4	Word 5
1 L1-L1 same	bed	bed	bed	bed	bed
2 L1-L1 related	bed	bed	bed	bed	sleep
3 L1-L1 unrelated*	bed	<i>bed</i>	bed	bed	sky
4 L1-L2 translation*	bed	<i>bed</i>	bed	bed	lit
5 L1-L2 related	bed	bed	bed	bed	dormir
6 L1-L2 unrelated*	bed	<i>bed</i>	bed	bed	ciel
7 L2-L2 same	jupe	jupe	jupe	jupe	jupe
8 L2-L2 related	jupe	jupe	jupe	jupe	pantalon
9 L2-L2 unrelated*	jupe	<i>jupe</i>	jupe	jupe	fenêtre
10 L2-L1 translation*	jupe	<i>jupe</i>	jupe	jupe	skirt
12 L2-L1 related	jupe	jupe	jupe	jupe	pants
12 L2-L1 unrelated*	jupe	<i>jupe</i>	jupe	jupe	window

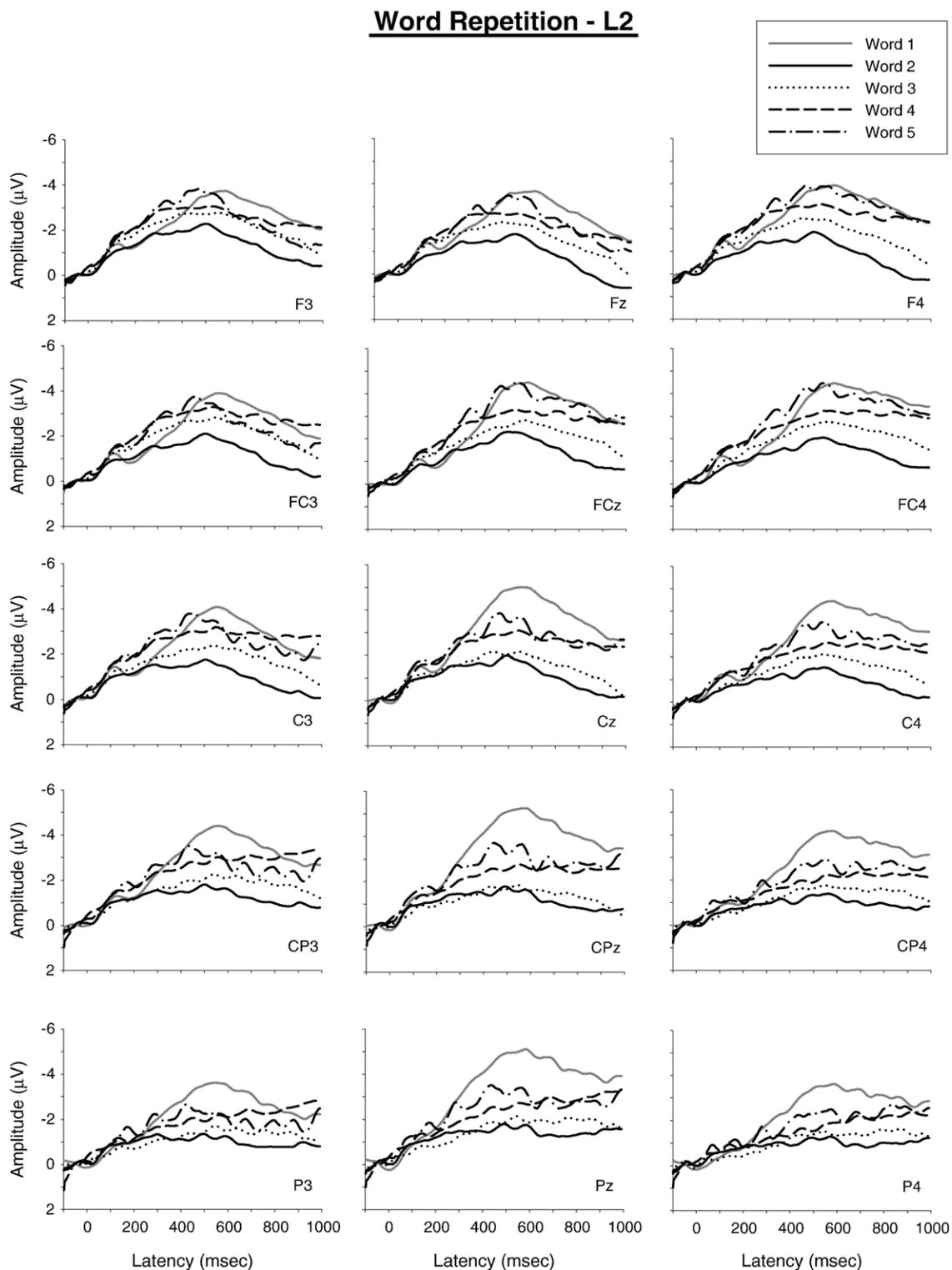
The entire study comprised twelve experimental cells. Condition cells shaded in gray indicate the cells compared for the habituation analyses. Condition names indicated by \* indicate the conditions involved in the Change in Meaning or Change in Language analyses, where the fifth word of the sequence (*italicized*) was compared to theL habituated ERP response on Word 2 (*italicized*). Note that words did not repeat across conditions; the examples listed here are for illustrative purposes.

variables of interest are reported first (e.g., Language, Condition, or Word Position) followed by the highest-order significant interaction effects, if present. Unless otherwise stated, significant main effects involving more than two means and/or interactions were further assessed using Bonferroni-corrected simple effects analyses. All effects reported below are significant at least at  $p < .05$ . ANOVAs were conducted

separately for midline sites (Fz, FCz, Cz, CPz, Pz; yielding a factor of Site) and medio-lateral sites (left hemisphere, anterior to posterior: F3, FC3, C3, CP3, P3; right hemisphere, anterior to posterior: F4, FC4, C4, CP4, P4; yielding the factors Hemisphere and Site). Results from the lateral site analyses are reported only when they provide additional or different information than that derived from the midline sites analyses.



**Fig. 1** – Grand average waveforms for serially repeated words (Word 1 through Word 5) for L1. Note the PMN-N400 activity elicited by the first presentation of the word (Word 1) which is substantially reduced upon repeated presentations.



**Fig. 2 – Grand average waveforms for serially repeated words (Word 1 through Word 5) for L2. Note that, similar to L1, the PMN-N400 activity elicited by the first presentation of the word (Word 1) is substantially reduced upon repeated presentations.**

## 2.2. Adaptation analyses

Figs. 1 and 2 show the grand averaged waveforms elicited at each repeated word position (i.e., Word 1 through Word 5) for

L1 and L2, respectively. The pattern was remarkably similar in L1 and in L2. As seen in both figures, a large N400 was elicited by Word 1, which was sharply reduced in amplitude for Words 2 through 4, a pattern which is most evident at central to

parietal sites. Interestingly, there appeared to be a subtle release from adaptation for Word 5 at fronto-central sites, such that Word 1 and Word 5 were of equivalent amplitudes. These observations were substantiated by the following analyses.

The effect of adaptation to repeated word presentation was evaluated by computing the mean amplitude from 250 to 650 ms. The midline sites revealed a main effect of Language,  $F(1,14)=8.27$ ,  $MSE=7.89$ ,  $p=.012$ , indicating that, overall, N400 activity elicited in L2 was more negative compared to L1. There was a main effect of Word Position,  $F(4,56)=13.0$ ,  $MSE=17.94$ ,  $p<.001$ ,  $\epsilon=.538$ , which was modified by a Word Position  $\times$  Site interaction,  $F(16,224)=8.58$ ,  $MSE=1.38$ ,  $p<.001$ ,  $\epsilon=.275$ . Bonferroni-corrected simple effects conducted on this interaction compared Word Position and revealed that Words 2, 3, and 4 were significantly less negative than Word 1. This effect had a centro-parietal distribution (Cz, CPz, Pz). There was a release from adaptation for Word 5 such that the mean amplitude of Word 5 differed significantly from Word 2 at fronto-central sites, but did not differ reliably from Word 1 at any electrode site. Importantly, the Language  $\times$  Position interaction was not significant,  $F(4,56)=1.88$ ,  $MSE=5.43$ ,  $p=.16$ ,  $\epsilon=.65$ , indicating that the overall pattern of adaptation did not differ between L1 and L2.

Analyses of the lateral electrode sites yielded comparable results, revealing a main effect of Language,  $F(1,14)=7.45$ ,  $MSE=14.57$ ,  $p=.016$ , a main effect of Word Position,  $F(4,56)=10.0$ ,  $MSE=24.59$ ,  $p<.001$ ,  $\epsilon=.65$ , and a Word Position  $\times$  Site interaction,  $F(16,224)=4.61$ ,  $MSE=5.51$ ,  $p=.01$ ,  $\epsilon=.17$ . Simple effects conducted on the latter result confirmed and clarified the centro-parietal distribution of the adaptation effect, with Word 1 being more negative than all other positions at centro-parietal and parietal electrodes and Word 2 being least negative compared to all other conditions at all electrode sites. Finally, there was a significant Language  $\times$  Hemisphere interaction,  $F(1,14)=5.29$ ,  $MSE=0.60$ ,  $p=.04$ . Post hoc simple effects analyses contrasting hemisphere revealed no significant asymmetry in either L1 or L2; however, simple effects contrasting language indicated that the difference in N400 amplitude for L2 compared to L1 (i.e.,  $L2>L1$ ) was greater over the left hemisphere than over the right, although both contrasts were significant.

We conducted an additional analysis to examine (1) whether there was a difference between L1 and L2 in the magnitude of the repetition priming effect and (2) whether there was a delay in the timing of the L2 response compared to L1. To do so, we conducted a Language  $\times$  Position  $\times$  Site  $\times$  Time ANOVA, where mean amplitude was examined in consecutive 50 ms windows, beginning at 200 ms (i.e., 200–250, 250–300... 500–550 ms). For the Position factor, we contrasted ERP amplitude to Word 1 versus Word 2 only since the repetition effect was greatest on Word 2. There was a significant Language  $\times$  Site interaction,  $F(4,56)=10.7$ ,  $MSE=1.1$ ,  $p<.001$ ,  $\epsilon=.78$ , which revealed a strong centro-parietal distribution for L1 and an equipotential distribution for L2. Interestingly, the Language  $\times$  Position interaction was not significant,  $F(1,14)=3.5$ ,  $MSE=25.4$ ,  $p=.084$ , indicating that the magnitude of the N400 repetition effect *per se* did not differ reliably between L1 and L2. However, there was a significant Language  $\times$  Word Position  $\times$  Site  $\times$  Time interaction,  $F(24,336)=3.52$ ,  $MSE=0.23$ ,  $p=.015$ ,  $\epsilon=.13$ , which indicated that the time course of the repetition

effects differed between the two languages. Simple effects contrasting Language revealed that the Word 1 waveform in L1 was negative-going earlier (starting at 200 ms) than the Word 1 waveform in L2, at electrode sites Cz to Pz. Simple effects contrasting Word Position (i.e., the repetition effect) revealed that, in L1, Word 2 was significantly less negative than Word 1 beginning at 200 ms, at CPz and Pz (with the effect starting somewhat later at FCz and Cz). For L2, the repetition effect began approximately 100 ms later, starting at 300 ms from electrodes Cz through Pz. The comparable ANOVA conducted on the lateral sites did not reveal any different or additional findings from those reported for the midlines sites.

### 2.3. Change in meaning/change in language analyses

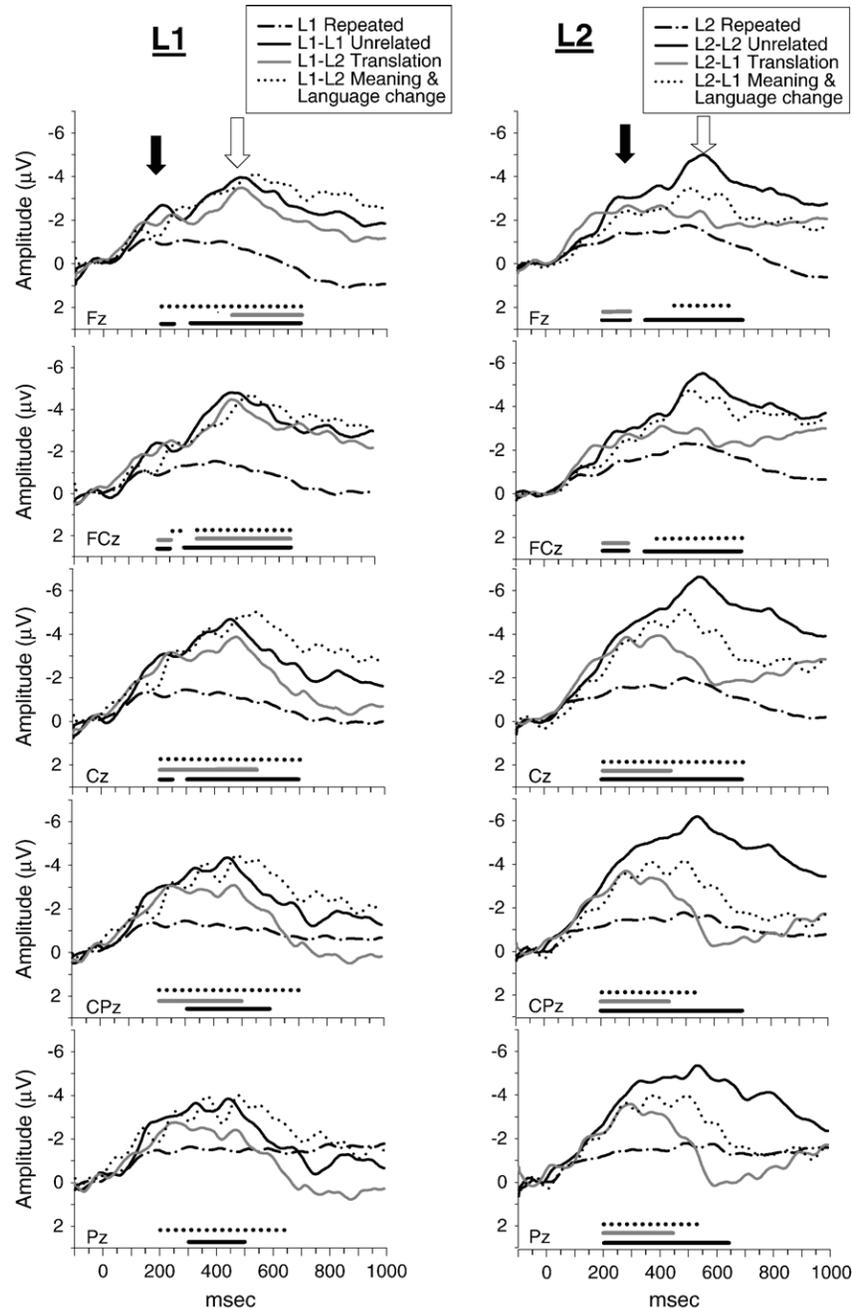
Repeated measures ANOVAs were conducted to determine whether there was a release from adaptation when the fifth word represented a change in the sequence, compared to the response when the N400 was most attenuated (i.e., at Word 2).<sup>1</sup> Analyses were conducted separately for L1 and L2 and for each fifth word condition. Referring to Table 1, these conditions were: a within-language unrelated word, representing a change in meaning (L1: condition 3; L2: condition 9), a translation equivalent, representing a change in language (L1: condition 4; L2: condition 10); or an unrelated word in the other language, representing a change in meaning and a change in language (L1: condition 6; L2: condition 12). The waveforms (described below) were characterized by a differing pattern of PMN, N400, and late positivity activity, with temporal courses which varied as a function of condition. In order to best capture these temporal dynamics, we quantified average amplitude in consecutive 50 ms windows, spanning 200 to 700 ms post-stimulus. Thus, the ANOVAs included the factors Condition, Site, and Time. In all instances, there was a significant Condition  $\times$  Site  $\times$  Time interaction, which was decomposed with simple effects analyses contrasting the mean amplitude of the fifth word with that of Word 2. The statistical effects are illustrated in Fig. 3, detailed in Table 2, and are described below.

Fig. 3 shows the grand averaged waveforms for the fifth word when it represents a change in meaning (a within-language unrelated word, black line), a change in language (i.e., a translation, gray line), or a change in meaning and language (dotted line) plotted against the first repetition of the word (i.e., Word 2) for L1 (left column) and L2 (right column). Visible in the waveforms and depending on the condition, there is either an early distinct negativity (the Phonological Mismatch Negativity, PMN), an N400 negativity, or both. Based on prior literature, we took significant effects in the 200 to

<sup>1</sup> An alternative is to compare words in the same sequential position, namely the fifth repetition of the word from condition 1 and 7 (Table 1) compared to the fifth word in change conditions. The results (all  $F$ 's  $>2.1$ , all  $p$ 's  $<.04$ ) were essentially identical to those using Word 2 as the reference condition. The only exception was a non-significant difference for the Change in Language/Change in Meaning for L2. However, because our goal was to evaluate the ERP response to word changes (i.e., release from adaptation) compared to the most habituated response observed, we chose to report the data relative to Word 2 as the most relevant and logical comparison.

300 ms time window to be evidence of PMN activity, and effects in the 300 to 550 ms window to be evidence of N400 activity. Following the N400, there is also a late positivity in the translation condition which is evident at posterior electrode locations (CPz and Pz) and was analyzed in a

separate ANOVA. The horizontal lines above the time axes indicate the 50 ms time periods in which significant amplitude differences were observed relative to Word 2. Only significant effects are presented below; however, all statistical tests involving condition are reported in Table 2.



**Fig. 3 – Change in Language/Change in Meaning comparisons.** Grand average waveforms for the fifth word when it represents a within-language change in meaning (Unrelated; solid black line), (2) a change in language (i.e., Translation; solid gray line), or a meaning and language change (dotted line), plotted against the first repetition of the word (i.e., Word 2; dotted and dashed line) for L1 (left panel) and L2 (right panel). The solid black arrow indicates the PMN; the unfilled arrow indicates the N400. The horizontal lines above the time axes indicate the 50 ms time periods in which significant amplitude differences were observed for a specific condition (Unrelated=solid black line; Translation=solid gray line; Meaning/Language Change=dotted line) relative to Word 2. For L1 waveforms, the change in meaning, change in language, and change in meaning and language conditions correspond to Conditions 3, 4, and 6, respectively, in Table 1. For L2 waveforms, the change in meaning, change in language, and change in meaning and language conditions correspond to Conditions 9, 10, and 12, respectively, in Table 1.

**Table 2 – Summary of ANOVAs examining change in meaning, change in language, and change in meaning/change in language for L1 and L2**

		F	df	MSE	p ≤	ε
<b>L1</b>						
Change in Meaning	Condition	14.06	1, 14	119.55	.002	1.000
	Condition × Site	1.58	4, 56	30.7	.229	.399
	Condition × Time	2.47	9, 126	22.7	.107	.207
	Condition × Site × Time	11.38	36, 504	1.77	.001	.140
Change in Language	Condition	6.81	1, 14	112.12	.021	1.000
	Condition × Site	2.97	4, 56	27.64	.075	.444
	Condition × Time	1.71	9, 126	13.73	.192	.269
	Condition × Site × Time	13.18	36, 504	2.98	.001	.113
Change in Meaning/Change in Language	Condition	20.95	1, 14	97.68	.001	1.000
	Condition × Site	1.82	4, 56	15.81	.174	.582
	Condition × Time	6.6	9, 126	7.03	.001	.414
	Condition × Site × Time	6.62	36, 504	2.5	.001	.108
<b>L2</b>						
Change in Meaning	Condition	25.58	1, 14	128.48	.001	1.000
	Condition × Site	7.1	4, 56	6.93	.001	.703
	Condition × Time	4.28	9, 126	14.8	.018	.256
	Condition × Site × Time	3.12	36, 504	1.78	.02	.117
Change in Language	Condition	2.59	1, 14	103.6	.130	1.000
	Condition × Site	1.32	4, 56	17.71	.281	.421
	Condition × Time	3.04	9, 126	31.3	.06	.237
	Condition × Site × Time	7.42	36, 504	3.33	.001	.100
Change in Meaning/Change in Language	Condition	16.26	1, 14	69.61	.001	1.000
	Condition × Site	1.13	4, 56	27.89	.327	.392
	Condition × Time	1.28	9, 126	16.64	.294	.263
	Condition × Site × Time	4.29	36, 504	7.28	.021	.059

### 2.3.1. L1

As shown by the solid black line in the left column of Fig. 3, a change in meaning within L1 (L1–L1 unrelated) elicited a PMN in the 200–250 ms time period followed by a large and sustained N400 response at all midline electrodes, compared to the habituated response to Word 2. This yielded a main effect of Condition and a significant Condition × Site × Time interaction. Simple effects analysis of the latter indicated that the effect was due to some variation across sites of the time periods during which the conditions differed rather than due to a topographical difference in the N400 effect *per se*. Analysis of the change in language condition (i.e., the L1–L2 translation; gray line) also yielded a main effect of Condition and a Condition × Site × Time interaction. This indicates that a change in language elicited topographically circumscribed PMN and N400 effects that were generally significant during the 200 to 250 ms and 350 to 550 ms period and generally centrally distributed (i.e., significant at FCz, Cz, and CPz). Moreover, as is evident at the Pz site, this condition exhibited a late positivity compared to Word 2. An additional analysis conducted on the waveforms in the 600–800 ms period yielded a Condition × Site × Time interaction,  $F(12,168)=9.70$ ,  $MSE=0.411$ ,  $p<.001$ ,  $\epsilon=.26$ , which showed that the translation waveform was significantly more positive than Word 2 at Pz during the 700–800 ms period. Finally, an L1–L2 change in language and meaning (dotted line) elicited a very similar response to that of a change in meaning, with PMN and N400 effects widespread across the midline and generally significant from 200 to 700 ms. Regarding the analyses of the lateral sites, there was no main effect of hemisphere and no

reliable interactions between Condition and Hemisphere for any of the comparisons reported above (all  $F$ 's < 3.3, all  $p$ 's > .06).

### 2.3.2. L2

As shown by the solid black line in the right column of Fig. 3, a change in meaning within L2 (L2–L2 unrelated) elicited a significantly larger negativity which had a widespread (frontal to parietal) distribution, compared to Word 2. The distinction between the PMN and the N400 is somewhat less distinct in L2 comparisons, but is most obvious at Fz and FCz. The N400 appears to peak at 550 to 600 ms, approximately 100 ms later than in L1. For the change in language comparison (i.e., the L2–L1 translation; gray line), there was an early negativity consistent with the PMN which was significant starting at 200 ms and resolved between 300 and 450 ms, but little subsequent evidence of the N400 activity that is so strongly evident in the L2–L2 unrelated condition. The translation condition also exhibited a strong posterior positivity, although earlier than that seen in L1. The analysis conducted on the waveforms in the 500–600 ms period yielded a Condition × Site × Time interaction,  $F(8,112)=3.52$ ,  $MSE=0.834$ ,  $p=.04$ ,  $\epsilon=.29$ , and showed that the translation waveform was significantly more positive than Word 2 at Pz during the 550–600 ms period. Finally, an L2–L1 change in language and meaning (dotted line) elicited a similar response to that of a change in meaning in L2, differing from Word 2 beginning as early as 200 ms (Cz to Pz) and lasting to 550 ms (posterior sites) to 700 ms (anterior sites). Regarding the analyses of the lateral sites, there was no main effect of hemisphere and no

interactions between Condition and Hemisphere for any of the comparisons (all  $F$ 's < 2.4, all  $p$ 's > .11).

It is noted that the results reported above did not involve direct comparisons between L1 and L2 because our approach was to test whether a critical condition involving word change (either a change in meaning, language, or both) differed from its baseline condition. However, the results remain essentially the same when we compare conditions directly within language (e.g., comparing L1–L1 unrelated waveforms to L1–L2 translation waveforms) or across languages (e.g., comparing L1–L2 translation waveforms to L2–L1 translation waveforms). The only additional finding this approach revealed was that the L2–L2 unrelated condition was significantly more negative than the L1–L1 unrelated condition from 550 ms onwards (all  $F$ 's > 6.5,  $p$ 's < .023).

#### 2.4. L2 proficiency analyses

Since asymmetry in L1 and L2 proficiency has the greatest implications for translation performance (cf. Smith, 1997; Kroll and de Groot, 1997), we conducted a post hoc analysis to ask whether participants grouped into high- versus low-L2 proficiency differed with respect to translation priming. Even though our participants were recruited to be fluent in their second language, we explored whether there were subtle between-subject differences in L1 and L2 asymmetry. To do so, subtraction waveforms were computed for the L1-to-L2 translation waveform minus Word 2 in L1 and for the L2-to-L1 translation waveform minus Word 2 in L2, such that a more negative waveform indicated a larger N400 effect. These are illustrated in Fig. 4. Mean amplitudes in 50 ms windows (200 to 700 ms) were subjected to a Translation Direction  $\times$  Site  $\times$  Time  $\times$  Proficiency Group ANOVA. This yielded a trend towards a main effect of Proficiency Group,  $F(1,13)=3.8$ ,  $MSE=285.5$ ,  $p=.07$ , suggesting larger N400 effects to translated words in low-proficient participants compared to highly proficient subjects. There was a significant Translation Direction  $\times$  Site  $\times$  Proficiency Group interaction,  $F(4,52)=3.1$ ,  $MSE=13.4$ ,  $p=.045$ . Simple effects contrasting proficiency groups showed that low-proficient participants differed from highly proficient participants at Fz and FCz in the forward translation direction (L1 to L2) but not in the backward direction (L2 to L1). Simple effects contrasting translation direction revealed larger N400 subtraction waveforms only for the low-proficient participants for the forward translation compared to the backward translation at Fz and FCz. Both of these contrasts are consistent with the interpretation that the low-proficient participants were not translating forward into their weaker second language. There were no additional or substantively different findings produced by the analysis of the lateral electrode sites (all  $F$ 's < 3.0, all  $p$ 's > .06).

Since the above analysis was based on rather a crude dichotomous distinction between the subgroups, we also examined whether the N400 subtraction waveform to the translations varied as a function of the asymmetry in each participant's self-rated proficiency in L1 and L2. The prediction here is that a larger asymmetry (i.e., weaker L2 proficiency) would yield a significant negative correlation (more negative amplitude, indicating less semantic activation of the translation) in the L1-to-L2 translation direction than vice versa.

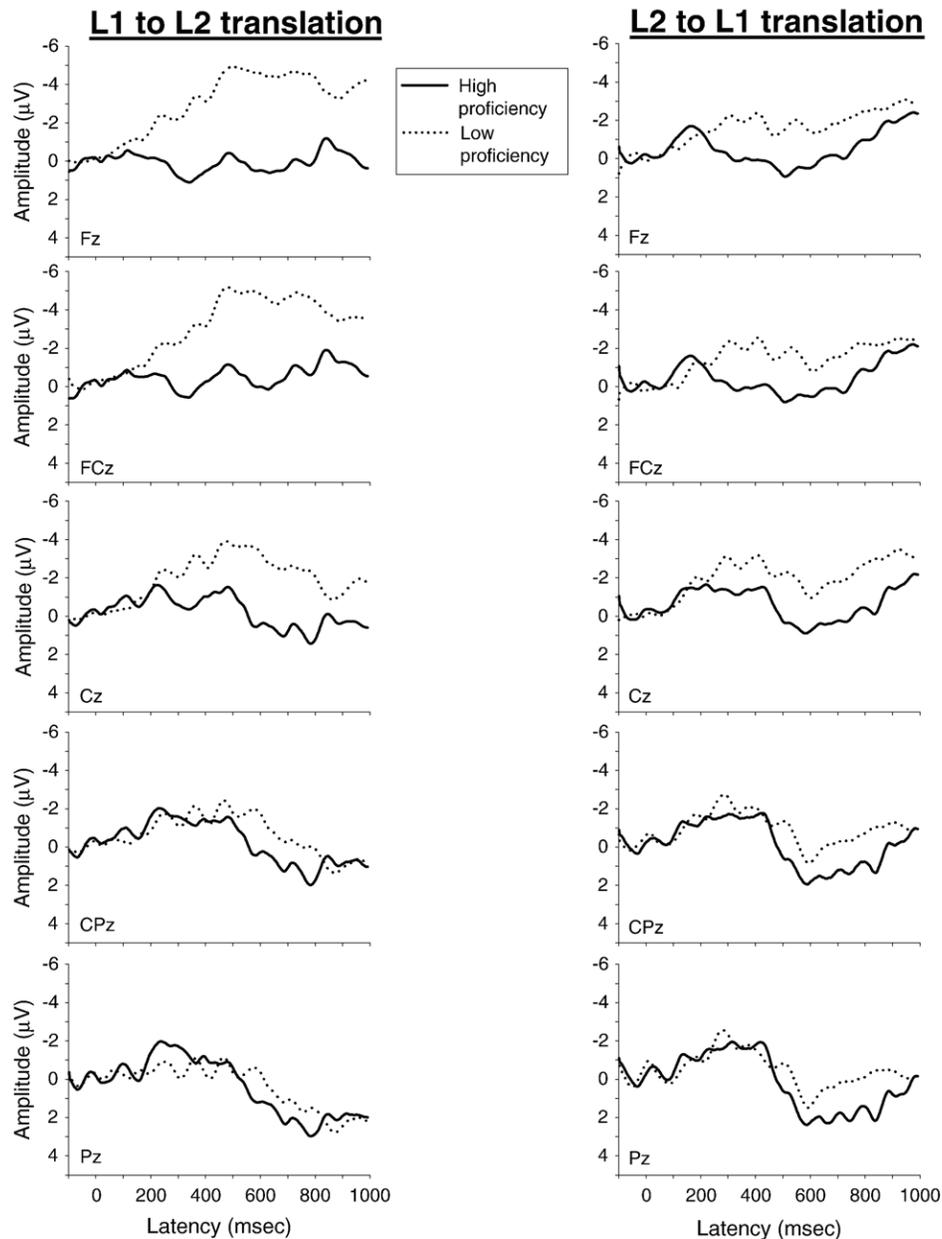
Based on the topographical findings above, we conducted one-tailed correlations at the two sites where group differences were most (Fz) and least (Pz) pronounced. This yielded a significant correlation for the L1-to-L2 translation waveform at Fz ( $r=-0.65$ ,  $p=.005$ ) but not at Pz ( $r=-0.04$ ,  $p=.44$ ) and no significant correlations for the L2-to-L1 direction (Fz:  $r=-0.37$ ,  $p=.09$ , Pz:  $r=-0.08$ ,  $p=.39$ ).

### 3. Discussion

The overall goals of this study were two-fold: first, to examine the pattern and time course of adaptation to the repeated presentation of a word in L1 and in L2, and second, to examine the release from adaptation when the fifth word in the sequence changed. With respect to the first goal, the results were quite straightforward. As would be expected, the first presentation of a word in a sequence elicited a PMN and a large N400 response which were then markedly attenuated when the word was repeated in sequence three times more. The N400 response was delayed in L2 versus L1, but the overall pattern of adaptation, its topographical distribution, and the magnitude of the effect did not differ between L1 and L2. These effects were reliable beginning in the 200–250 ms period in L1 and in 300–350 ms period in L2, which is earlier than other word repetition effects reported for monolingual stimuli in the auditory modality (e.g., Rugg et al., 1993, 1995), which may have to do with the frequent repetition of our prime.

With respect to the second goal, we observed a number of interesting findings. Compared to the most habituated response (Word 2), a PMN and a large N400 response were elicited when the fifth word of a sequence was a within-language change in meaning (i.e., a word phonologically and semantically unrelated to the previous sequence). This pattern was similar in both languages, although the N400 peak in L2 was larger, delayed by approximately 100 ms, and had a more posterior distribution compared to the effects in L1. Although we are limited in our ability to attribute ERP topographical findings to specific neuroanatomical regions, the adaptation findings indicate that the within-language word repetition effect is mediated by similar brain areas in L1 and L2. However, the release from adaptation (i.e., the response to a within-language change in meaning) appears to be mediated by somewhat different areas. The fact that the N400 is delayed in L2 is consistent with previous reports (e.g., Ardal et al., 1990; Moreno and Kutas, 2005; Phillips et al., 2004) and is consistent with the idea that processing is slowed in one's second language. The fact that an unrelated L2 word elicited a larger N400 than an unrelated L1 word may simply reflect the fact that, generally speaking, any word in one's native language is easier to process, may activate more semantic information, and/or may be easier to integrate than a word in one's second language even when those words are unrelated.

When the fifth word was a translation equivalent of the sequence, that is, a change in language, a different pattern emerged for the two languages in the sample of participants as a whole. The L1-to-L2 translation was associated with a PMN/N400 complex, indicating that neither the phonological



**Fig. 4** – Grand average subtraction waveforms of the translation repetition (translations minus Word 2) for participants with relatively high proficiency ( $n=7$ ) or low proficiency ( $n=8$ ) in L2, plotted for L1-to-L2 translations (left panel) and L2-to-L1 translations (right panel). Note the larger N400 effect for low-proficient bilinguals, indicating a relative lack of priming for translated words, particularly for the L1-to-L2 translation.

nor semantic/conceptual representation of the L2 equivalent was activated on-line. In other words, there was little evidence that participants were forward-translating into their second language. This is despite the fact that participants had heard the word four times (giving them ample time to process and translate the word) and in the context of an experiment where the final word of the sequence crossed languages 50% of the time. However, for the L2-to-L1 condition, when the fifth word was an L1 translation following an L2 sequence, a PMN was elicited but there was minimal evidence of N400 activity when compared to the L2-L2 unrelated condition. This indicates that participants were

engaging in backwards translation into their L1 and suggests that this translation consisted of the on-line activation of the semantic/conceptual equivalent of the translation but not its word form or phonological representation. This is consistent with the view that non-cognate translations (i.e., the translation equivalents predominantly used in this study) share conceptual features but not lexical features (Sánchez-Casas and García-Albea, 2005). Our future work will examine the extent to which phonological information is activated in cognate and non-cognate translations.

Interestingly, both the L1-to-L2 and L2-to-L1 translations were associated with a late posteriorly distributed positivity

which was not present in the other conditions. This suggests that late in the recording epoch participants became explicitly aware that the word was a translation. For the L1-to-L2 translation, the presence of the late positivity and the minimal N400 activity suggests that participants were able to recognize that the word was a translation in their weaker L2 (which is to be expected) relatively late in the recording epoch, but that they had activated relatively little of the conceptual representation of the word. This is contrary to what a dominant model in the literature would predict. The Revised Hierarchical Model (RHM) posits that L1-to-L2 translations are mediated conceptually, whereas L2-to-L1 translation takes place directly via lexical links (Kroll and Stewart, 1994; Kroll and Tokowicz, 2005). However, in the present experiment, the presence of an N400 to the L1-to-L2 translation and the minimal N400 activity to the L2-to-L1 translation indicates that conceptual processing was more strongly engaged in the latter condition than the former. Thus, our results agree with those of La Heij et al. (1996) who found evidence of greater semantic context effects for backwards translation than forward translation.

The conclusions of the previous paragraph must be tempered by the findings when the sample was subdivided into participants who had relatively high and low proficiency in their L2. As a group, our participants evidenced conceptual priming in the L2-to-L1 direction but not in the L1-to-L2 direction. In other words, there was evidence of conceptual processing when participants were listening to words that changed from the weaker to the stronger language, but not vice versa. Thus, our post hoc expectations for the subgroup analysis were that (1) both groups would show an equivalently reduced N400 to the L2-to-L1 translation because participants were translating into their first language which would be equally strong in both subgroups, and (2) for the L1-to-L2 translation, the low-proficient participants would show a large N400 effect because the word was switching to their substantially weaker second language and that the high-proficient participants would show a reduced N400 since they were more equally balanced in their two languages. This is exactly what we observed. Echoing this result was the fact that participants reporting greater asymmetry between their L1 and L2 showed larger N400s to translations than did the more balanced bilinguals, but only in the forward translation direction. Of course, these results are based on a relatively small number of participants who were not selected *a priori* to differ in their proficiency. Nevertheless, based on the correlational analysis, it appears that even subtle differences between self-rated proficiency in one's L1 and L2 relate to the extent to which one activates one's second language. In the future, we will examine larger sample sizes of high- and low-proficient bilinguals to provide a more thorough and fine-grained test of directionality effects.

A number of methodological differences exist between the present study and those that have been taken in support of the RHM. First, there is a paucity of studies conducted in the auditory modality and, therefore, it is difficult to directly compare our results. Second, the tasks and stimuli are quite different (i.e., passive listening in the present study versus picture naming, word list presentation, translation recognition, etc. in the extant literature). Third, we used a somewhat

unusual procedure in that the “prime” word was presented multiple times prior to the translation. Lastly, the measurement techniques differed (electrical brain activity sensitive to on-line semantic processes versus naming or reaction time, measures which comprise the end-point of a number of processes). Whether it is these methodological differences or the fact that the electrophysiological data have revealed a qualitatively different viewpoint on these processes remains to be determined.

Of interest, however, is a study by Alvarez et al. (2003) which examined repetition priming within and across languages in the visual modality. Our studies differ in the presentation modality, use of prior context (i.e., single word versus multiple word repetition), in the contrasts selected for comparison, and likely the proficiency of our samples (i.e., beginning–intermediate bilinguals versus highly fluent bilinguals). Together, these differences warrant caution when making direct comparisons of the results. Nevertheless, there were some interesting differences between the findings of the two studies. First, our within-language change in meaning condition revealed a later N400 effect in L2 than L1, a finding consistent with previous studies (Ardal et al., 1990; Weber-Fox and Neville, 1996; Phillips et al., 2004), whereas no such latency shifts were reported in Alvarez et al. (2003). Second, Alvarez et al. observed trends towards larger repetition effects in L2 than L1, whereas we observed no evidence for this. Indeed, our pattern of results indicated that L1 and L2 repetition effects were remarkably similar. Third, Alvarez et al. interpreted their L2-to-L1 translation effects as providing evidence for the activation of both lexical and semantic information of the L1 translation equivalent. Our findings were not consistent with theirs with respect to word form (i.e., lexical) activation. In our study, the presence of a PMN and the absence of an N400 in the L2-to-L1 condition indicated that the phonology of the L1 translation was not activated whereas conceptual-level information was. Although caution must be taken when making direct comparisons between these two different studies, the discrepancies between the results might point to important differences in the time course and in the kind of information activated as a function of listening versus reading in one's first and second languages. Another direction of our future work will examine the extent to which phonological and orthographic word form is activated in bilinguals.

As indicated above, the fact that we presented the repeated word multiple times in sequence differs from stimulus presentations typically used in N400 repetition studies. Instead, our design was analogous to studies employing the fMRI adaptation technique, specifically the work of Klein et al. (2006). Again, it is difficult to make direct comparisons between the results of the two studies given that the fMRI method is largely sensitive to spatially distributed hemodynamic changes whereas the ERP method provides information about neuroelectric activity along a temporal dimension, with relatively limited spatial information. Nevertheless, some comparisons between the results may be drawn. For a within-language change in meaning, Klein et al. observed a similar pattern of activation for both languages (bilateral superior temporal gyri and the posterior left inferior frontal region). Although we cannot attribute our ERP topographies to these brain regions specifically, the fact that we observed

generally similar topographical effects in L1 and L2 is congruent with their findings of similar regional activation for both languages. Moreover, Klein and colleagues observed that a change in language from L1 (i.e., L1-to-L2 translation) activated a similar pattern of activity as did a change in meaning within L1, congruent with our observation of large N400 effects in both of these conditions. Finally, in Klein et al., a change in language from L2 (i.e., L2-to-L1 translation) activated the superior temporal region but not the left inferior frontal regions, a different pattern from their within-L2 meaning change condition. These conditions were qualitatively different in the present study as well, with PMN and N400 activity elicited in the within-L2 change in meaning, whereas only PMN activity was observed in the L2-to-L1 translation. There is some evidence that one primary source of the PMN is in the left inferior frontal cortex, with a primary source of the N400 along left perisylvian regions (D'Arcy et al., 2004). Curiously, given these localizations, the specific patterns of the fMRI activations in Klein et al. are not easily reconciled with the presence/absence of the PMN and N400 components across conditions in our study. Our next study will directly compare ERP responses to fMRI activation using a similar experimental paradigm in the same bilingual participants in order to allow more direct comparisons.

Finally, one might wonder how our findings compare to studies which have examined code switching or used tasks where participants are required to translate aloud. There is, indeed, a growing literature examining neural activation during translation (e.g., Hernandez et al., 2001; Price et al., 1999; Rodriguez-Fornells et al., 2005); however, these studies required overt productive responses from the participant (e.g., in Hernandez et al., 2001, participants switched between naming pictures in their two languages), whereas ours was a passive receptive task. Nevertheless, some preliminary comparisons may be drawn with this emerging literature. Using fMRI activation, Price et al. (1999) compared L1-to-L2 and L2-to-L1 translation relative to reading and found decreased activation in brain regions associated with semantic processing (i.e., left extrasyllabic temporal and temporo-parietal cortex), irrespective of the direction of the translation. These findings bear some resemblance to ours, at least for the L2-to-L1 direction, and are similarly difficult to reconcile with the RHM prediction that conceptual mediation only occurs for forward translations. Using ERPs and fMRI, Rodriguez-Fornells et al. (2005) found evidence of phonological interference on name production across languages in bilinguals, whereas our PMN data indicate that phonological information was not activated in our study. However, attention to the phonological features of the input and tacit naming were central tasks for the participants in Rodriguez-Fornells et al. (2005). Moreno et al. (2002) examined ERPs to within-language lexical switches (i.e., synonyms) and code switches (i.e., a translation of the expected word) to visually presented sentence terminal words. They observed a negativity in the N400 time period to code switches in non-idiomatic sentences only, albeit with a non-typical distribution (a frontal-central distribution which was dominant over left hemisphere electrodes). Interestingly, Moreno et al. also observed a pronounced late positive component to the code switches, which appears similar to

the late positivity we observed to translated words in this study. The functional significance of this activity remains to be determined, but one speculation is that it may relate to the retrieval or recognition of the word's translation from long-term memory (cf., Van Petten et al., 1991).

### 3.1. Summary and conclusions

The present study revealed several important effects concerning within- and between-language processing of spoken single words in English–French bilinguals. First, the attenuation or adaptation of the N400 response to within-language repeated presentations of a word was equivalent in L1 and L2 with respect to the topographical distribution and the magnitude of the repetition effect. Second, a within-language change in meaning elicited similar qualitative PMN and N400 effects in L1 and L2, with evidence of delayed semantic analysis in L2 in the form of a later N400 effect. Third, for translations, a change in language from L1 to L2 elicited a similar pattern of PMN and N400 activity as did a within-language change in meaning in L1, indicating that neither phonological word form nor conceptual information was available on-line for the forward translation. In contrast, the presence of strong PMN but minimal N400 effects for L2-to-L1 translations suggests that conceptual but not phonological information is available on-line for backwards translations. Finally, we had evidence that proficiency in one's second language influenced the extent to which conceptual representations were available on-line when listening to translations from and into one's second language. When considered along with the results of studies conducted in the visual modality, these data suggest that there may be important modality differences in the pattern of activation of lexical and conceptual information. Our future research will directly compare the two modalities to further explore this issue. In addition, when considered along with the emerging literature on neural activation during bilingual language processing, these data paint a different picture about asymmetries in lexical and conceptual organization in the bilingual's two languages compared to conclusions drawn from studies relying on behavioral measures. Although these results warrant replication, the goal of future research should be to attempt to reconcile results of these complementary methods of studying bilingual language processing.

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## 4. Experimental procedures

### 4.1. Participants

Fifteen young right-handed adults (12 females, 3 males; mean age=24.6 years,  $SD=5.4$ ; mean education=17 years,  $SD=3.5$ ) were recruited from the Concordia University population. Participants were recruited by advertisement within the campus as well as by class recruitment and word of mouth. In a preliminary telephone assessment, participant's handedness was assessed (Annett, 1967; Briggs and Nebes, 1975) and they were excluded if they reported health conditions that could possibly affect cognitive functioning. Participants received course credit or modest

payment, and the study was approved by the University research ethics board.

The sample consisted of native speakers of English (L1) with a self-reported high level of proficiency in speaking French (L2; see Table 3) which they began to acquire in childhood ( $M=6.9$  years old,  $SD=2.0$ ). Participants reported that they had reached self-rated L2 proficiency at approximately 11.3 years old ( $SD=3.2$ ). Current levels of proficiency in L1 and L2 were assessed through self-rated abilities and weekly engagement in speaking, reading, and writing using a five-point Likert-type scale. On average, our participants rated their ability at speaking their second language as moderate to very good, their ability at reading as very good, and their ability at writing as moderate.

We also conducted subgroup analyses to determine whether the ERP patterns reported differed as a function of participants' proficiency in their L2. High and low proficiency groups were determined based on the mean self-rating data for L1 and L2 (N.B.: weekly engagement in L2 writing was excluded from the computations, as it was much less frequent compared to other L2 activities). For each participant, a difference score was calculated by subtracting the mean L2 rating from the mean L1 rating, yielding a median L1–L2 difference of 1.9 (range=1.0–2.6). A larger difference score represents a larger discrepancy between L1 and L2 self-rated ability, hence a lower level of proficiency in L2. Participants with scores above the median were included in the low proficiency subgroup ( $n=8$ ), whereas those with scores below the median were included in high proficiency subgroup ( $n=7$ ).

#### 4.2. Materials and apparatus

This report formed part of a larger study designed to investigate both adaptation and within- and across-language priming in L1 and L2. This report focuses on the adaptation, release from adaptation, and translation contrasts, but the design of the entire study will be described briefly. As can be seen in Table 3, each trial consisted of the presentation of a

series of five words, the first four of which were the same word. Half of the four-word sequences were presented in L1 (conditions 1 to 6), and half were presented in L2 (conditions 6 to 12). The fifth word was either the presentation of the same word again (L1: condition 1; L2: condition 7); a within-language word unrelated to the meaning of the repeated words (i.e., a change in meaning (L1: condition 3; L2: condition 9)); a switch in language to a translation equivalent of the repeated words (i.e., a change in language; (L1: condition 4; L2: condition 10)); or a switch in language to an unrelated word (i.e., a change in meaning and a change in language (L1: condition 6; L2: condition 12)). Relatively few of the words in either of the translation conditions were cognates (e.g., laitue/lettuce; L1-to-L2=16%; L2-to-L1=28%). Of those translations which could be considered to be orthographic cognates, a post hoc rating indicated that there was relatively little phonological similarity using a 1- to 5-point rating scale where 1 indicated complete overlap and 5 indicated very little overlap, (L1-to-L2 translation condition mean=4.9; L2-to-L1 translation condition mean=4.2).

The stimuli consisted of lists of nouns matched across languages and conditions on word frequency, concreteness, imagery, and written word length taken from the MRC Psycholinguistic Database ([http://www.psy.uwa.edu.au/mrcdatabase/uwa\\_mrc.htm](http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm); Coltheart, 1981; Wilson, 1998). The French words were translations of English words for which the association, word frequency, concreteness, imagery, and word length values were available. Although it would have been preferable to have been able to find statistics for the French words themselves, sufficient Quebecois French norms were not available for the majority of stimuli; thus, we reasoned that the values of the English words would be valid estimates for the French words. Conditions were defined by the nature of the fifth word. There were 50 trials per experimental condition cell, which were presented in a pseudo-random order. One-hundred-and-twenty filler sequences were also presented, in which words switched from ear to ear. Participants were asked to listen to all sequences in order to detect those in which a word switched between ears.

The English and French words were spoken by a fluently bilingual female speaker. A total of 720 words were recorded and edited with the software CoolEdit (Syntrillium Software Corporation, Seattle, WA, USA). Using the NeuroScan Stim system, a pulse used to trigger the EEG recording software was placed at the onset of each word based on visual and auditory inspection. Words were presented monoaurally at a listening level of 70–80 dB using Telephonics earphones (Neuroscan, El Paso, TX, USA). Gentask software (NeuroScan, version 2.4.18) was used to present the stimuli. For all experimental trials, words were presented to the right ear, while the presentation switched from the right to the left ear at some point during filler sequences.

#### 4.3. Procedure

Participants were tested individually in a single session, which required approximately 3 h to complete. Short breaks were given when required. Following the application of the EEG electrodes, participants were comfortably seated in front

**Table 3 – Participants' self-reported level of ability and time spent using both their L1 and L2 on a five-point Likert scale (means and standard errors)**

Participants' rating	Language	
	English (L1)	French (L2)
Level of ability		
Speaking	5 (0)	3.6 (0.5)
Reading	5 (0)	4.1 (0.8)
Writing	5 (0)	3.1 (0.9)
Time spent each week using language		
Speaking	5 (0)	3.1 (0.9)
Reading	5 (0)	2.3 (0.9)
Writing	5 (0)	1.4 (0.6)

Note. For the level of ability, the rating scheme was the following: 1=no ability at all; 2=very little; 3=moderate; 4=very good; and 5= native-like ability. For the weekly engagement using each language, the rating scheme was as follows: 1=never or almost never; 2=one to three times/week; 3=four to six times/week; 4=more than six times but less than their main language; and 5=main language used.

of a computer monitor located approximately 1 m away. They were instructed to listen to words presented monaurally and take note of whether words switched between ears by responding on a keypad. This task ensured that participants attentively listened to the words during the experiment. Following brief training on the switch monitoring task, participants listened to sequences of five words. At the end of each trial sequence, a prompt appeared on the screen for participants to record their response to the incidental ear-switching task. There was a 500 ms inter-stimulus interval (ISI) between words within a sequence and a 500 ms delay interval between the offset of the last word of a sequence and the appearance of the prompt screen. The delay guaranteed a period of time in which the N400 could be clearly examined without the risk of contamination from sensory responses evoked by the next sequence of words. The next 5-word sequence began 500 ms after the participant's response.

#### 4.4. Electrophysiological recordings

The EEG was recorded from five midline sites (Fz, FCz, Cz, CPz, Pz) and 22 lateral sites (frontal left: FP1, F3, F7, FT7; frontal right: FP2, F4, F8, FT8; central left: CP3, P3; parietal right: CP4, P4; occipital: O1, O2) using a commercially available nylon EEG cap containing 32 Ag/AgCl electrodes (Easy Cap, Herrsching-Breitbrunn, Germany). An electrode on the left earlobe served as the implicit reference during recording. The right earlobe was recorded actively. All EEG data were re-referenced off-line to a linked ear reference. A cephalic (forehead) location served as ground. Electro-oculogram activity (EOG) was recorded from electrodes placed at the outer canthi of both eyes (horizontal EOG, HEOG) and above and below the left eye (vertical EOG, VEOG). EEG was recorded continuously with critical EEG epochs time-locked to the onset of each word, amplified using Neuroscan Synamps in a DC–100 Hz bandwidth, sampled at 500 Hz for 1090 ms (100 ms pre-stimulus), and processed off-line using Neuroscan Edit 4.3 software.

Off-line processing of the data from each participant consisted of the following steps. First, following re-referencing of the file, we applied a DC drift correction (Hennighausen et al., 1993) to the continuously recorded EEG file. We then employed a spatial filter correction technique (Method 2, NeuroScan Scan 4.3 manual, 2003), which is equivalent to spatial principal components analysis (PCA) without rotation of components. In addition to specifying and correcting for VEOG artefact, we also included in the procedure data from a recording of EEG containing no EOG artefact in order to retain legitimate EEG signal at the EEG electrodes. Having corrected for the VEOG artefact, the file was epoched into single EEG trials according to stimulus onset. We then applied a two-stage artefact rejection procedure, first to reject trials contaminated by horizontal EOG (HEOG) activity ( $\pm 50 \mu\text{V}$ ), and, second, to reject trials in which the EEG epoch ( $\pm 100 \mu\text{V}$ ) was contaminated by clipping, movement artefact, etc. The remaining EEG trials were then averaged into ERP waveforms for each participant for each language and word position condition yielding a maximum of 50 trials for each experimental cell. Individual averages were low-pass-filtered down

to 8 Hz to remove any alpha activity present (likely due to the length of the experiment).

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