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Cross-linguistic Influences of L1 on L2 Morphosyntactic Processing: an fNIRS Study

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1 Introduction

Learning a second language (L2) yields both functional and neuroanatomical changes (e.g., Golestani & Zatorre, 2004; Jasińska & Petitto, 2013; Jasińska & Petitto, 2014; Jasińska et al., 2017; Klein et al., 2014; Mechelli et al., 2004). These changes occur at many levels of language processing, including phonology (e.g., Petitto et al., 2012; Tham et al., 2005), syntax (Jasińska & Petitto, 2013; Kovelman et al., 2008), and orthography (e.g., Jasińska et al., 2017). Some aspects of language, such as morphosyntax, are particularly difficult for L2 learners to master, especially if acquired at an older age (Clahsen et al., 2010). Morphosyntax includes inflectional processes such as affixation (e.g., walk -> walked), suppletion (e.g., go -> went), and allomorphy (e.g., English plural suffix has three allomorphs: /s/ in cats, /z/ is dogs, and /iz/ in horses) to express grammatical functions (e.g., tense, number, case, person; Krause et al., 2015). Languages have distinct morphosyntactic typologies, for example, Spanish commonly uses inflection (i.e., affixation) to mark number agreement, but Mandarin rarely uses inflection and does not express number agreement by any grammatical means. Rather, number is expressed in Mandarin through semantic processes (e.g., use of numerals: "*三只鸭子, three [classifier] duck(s)*") (Comrie, 1981). We investigated how cross-linguistic morphosyntactic differences in adult L2 learners' first languages (L1s) impact their L2 morphosyntactic processing. Specifically, we examined the neural processing of English subject-verb (SV) agreement –s, a conceptually difficult morphosyntactic feature, by adult L1 speakers of two languages with very different morphosyntactic typologies, Spanish and Mandarin.

1.1 Neural Basis of Morphological Processing

Morphological processing intersects with processing of phonological, lexical, and syntactic information and recruits the predominantly left hemisphere-based language network, including ventral and dorsal pathways that connect frontal and temporal language-relevant regions (Friederici & Gierhan, 2013; Rolheiser et al., 2011). Frontal regions include the left inferior frontal gyrus (L-IFG), which supports morphological, syntactic, and semantic processing (Friederici et al., 2003) as well as lexical retrieval and selection from competing alternatives (Hirshorn & Thompson-Schill, 2006; Thompson-Schill et al., 1997). More specifically, the anterior L-IFG is involved in retrieval of word meanings and morphosyntax, whereas the posterior L-IFG is involved in phonological processing (e.g, Bozic et al., 2007; Burton, 2001).Temporal regions include the L-STG, which supports speech (Hickok et al., 2000; Scott et al., 2000) and phonological (Buchsbaum et al., 2001; Graves et al., 2008) processing, and is also involved in syntactic and semantic processing (Friederici et al., 2003), as well as the left middle temporal gyrus (L-MTG), which supports semantic processing and language comprehension (Binder et al., 2009; Turken & Dronkers, 2011).

Within the language network, certain regions are important for morphological processing, including the L-IFG and the L-MTG. A number of studies have found L-IFG activation for inflected words (Bozic et al., 2007). For example, Knoll et al. (2012) and Skeide et al. (2016) observed increased brain activity in L-IFG in the processing of sentences containing later-acquired morphosyntactic structures (e.g., SV number agreement) in comparison to sentences containing earlier-acquired structures (such as canonical word order). In addition, Lehtonen et al. (2006) studied the neural correlates of morphological processing in Finnish, a highly inflected language, using functional MRI and a visual lexical decision task. The authors compared patterns of brain activation between inflected words (case-inflected nouns, e.g., uuni + ssa = ‘oven’ +

'in': "in the oven") and monomorphemic words and identified increased activation in the L-IFG when processing inflected words. On the other hand, L-MTG is involved in semantic processing and language comprehension (Binder et al., 2009). Binder et al. (2009) analyzed 120 functional neuroimaging studies focusing on semantic processing and identified L-MTG to be a key neural region involved in the storage and retrieval of semantic knowledge. Hagoort and Indefrey (2014) conducted a meta-analysis of studies that compared sentences with higher demands on syntactic or semantic processing. The authors found that the L-IFG, L-STG, and L-MTG were reliably activated while speakers were processing sentences with both high syntactic and semantic processing demands, albeit with differential activation in BA 44 and BA 45/47 for more syntactically and more semantically demanding sentences, respectively. Importantly, greater activation in the L-MTG was observed when processing sentences with higher semantic versus syntactic processing demands.

1.2 Cross-linguistic influence on L2 morphosyntactic processing

In this paper, we investigated behavioral and neural evidence for cross-linguistic influences of adult L2-learners' L1 on their processing of L2 morphosyntax. According to the Linguistic Interdependence Hypothesis (LIH; Cummins, 1979; 1981; 2005; 2021), knowledge in speakers' first language can transfer and influence second language acquisition. Although languages may have distinct vocabulary, pronunciation, or grammar, the LIH posits an underlying proficiency common to both of a bilingual's languages, which allows transfer of linguistic skills between languages. In addition, the learning of either first or second language can advance the progression of the shared proficiency underlying both languages. Therefore, observations of cross-linguistic influences could indicate the presence of an underlying proficiency that links L1 and L2 as claimed in LIH and suggests that language representations are stored in a shared cognitive operating system, instead of two separate systems.

In previous literature, cross-linguistic transfer/influence has been observed in a range of linguistic domains, including vocabulary (e.g., Bardel & Lindqvist, 2007; Ecke, 2015; Imai & Gentner, 1997; Sheng et al., 2016), phonology (Gut, 2010; Kim, 2009; Wrembel, 2015), morphology (Lam & Sheng, 2016; Lowie, 2000; Rameriz et al., 2011) and syntax (Cuza, 2013; Isurin, 2005); and studies on cross-linguistic influence have been conducted in L2 learners with different L1s, such as Spanish (e.g., Cawalho & Silva, 2006; Paradis & Navarro, 2003) and Mandarin (Kidd et al., 2015; Tsoi et al., 2019). Cross-linguistic influence on L2 learners' morphosyntax processing has been less investigated and the existing behavioral and neuroimaging studies present different results.

Behaviorally, morphosyntax has been identified as one of the most challenging areas of L2 acquisition and processing (e.g., DeKeyser, 2005). A number of studies have found that L2 learners' accuracy rates for the use of morphosyntax are far below those of native speakers in spontaneous production across different L2 proficiency levels and different L1 backgrounds (e.g., Bailey et al., 1974; Ellis, 1988; Perkins & Freeman, 1975; Wei, 2000). Even in immersion environments, L2 learners also showed little gains in morphosyntax knowledge. Lardier (1998) and Long (1997) investigated English development of two L2 speakers. Both participants were married to an English native speaker and had lived in the U.S. for over 20 years or more by the end of the longitudinal study. However, neither participant showed significant improvement in morphosyntax over 8.5 and 10 years of time, respectively. This morphosyntax "fossilization" was shown in other longitudinal studies (e.g., Schmidt, 1983; Shapira, 1978) and other case studies of English language learners with high English proficiency and many years of residence in English-speaking countries (e.g., Aaronson & Ferres, 1987; Krashen & Pon, 1975). L2 morphosyntax appears to "fossilize" despite speakers' improvement in general L2 proficiency.

L2 learners' limited performance on morphosyntax has also been observed in comprehension and judgment tasks (e.g., Chen et al., 2007; Keating, 2009; Jiang, 2004). Given the generalized difficulty of morphosyntax in various L2 learner groups, some researchers argued against cross-linguistic influence of L1 characteristics on L2 morphosyntax (Sato, 2007; Silva & Clahsen, 2008). Sato (2007) tested three groups of English learners from typologically different L1 backgrounds (Mandarin, Japanese, German) on a grammaticality judgement task. German is similar to English. Both languages mark case and SV agreement. Japanese marks case but not SV agreement, and Mandarin lacks both case and SV agreement markings. The stimuli in Sato (2007) are simple three-word sentences targeting case and number agreement in English, such as "*We regularly sneezes*" or "*He admires she*". All sentences are ungrammatical in the final word. Native English speakers showed comparable performance (accuracy and response time) between identifying case and number agreement violations, and all three L2 learner groups showed lower accuracy and longer response time for recognizing SV agreement violations than case violations. German, Japanese, and Mandarin groups showed the same pattern with reduced sensitivity to SV number agreement (-s) compared to the pronominal case (e.g., she vs. her), regardless of whether these categories are expressed in their L1s or not. Sato (2007) concluded that there was no evidence of L1 transfer of morphosyntactic knowledge in their results, with all three learner groups showing the same performance pattern.

Similarly, Silva and Clahsen (2008) conducted a masked priming experiment to investigate the regular past-tense forms in different groups of advanced L2 learners of English (Mandarin, German, and Japanese) as well as English native speakers. Participants saw a forward mask consisting of a series of Xs on the computer screen, followed by a prime word, which was immediately followed by a target word. There were three target-prime conditions: repetition prime (e.g., pray -> pray), inflected prime (e.g., prayed -> pray), and unrelated (e.g., bake -> pray). The native speaker group showed evidence of both inflected and repetition priming effects. However, all L2 groups only showed the repetition priming effects, irrespective of different L1 background. The results in Silva and Clahsen (2008) suggested no evidence of cross-linguistic influence of tense agreement as well.

Although cross-linguistic influence on L2 morphosyntax was not observed using behavioral measures, evidence for influence of L1 characteristics on L2 morphosyntactic processing was evident in neuroimaging studies. Tokowicz and MacWhinney (2005) used event-related brain potentials (ERP) to test adult English-speaking learners of Spanish on a grammaticality judgement task targeting different inflectional morphemes in Spanish: tense-marking (formed similarly in the L1, English, and L2, Spanish), determiner number agreement (formed differently in the L1 and L2), and determiner gender agreement (unique to L2). Participants' sensitivity to the grammatical violations was measured by comparing the P600 response in grammatical and ungrammatical sentences. They found that L2 speakers' sensitivity to grammatical violations was affected by the similarity of the specific constructions between their L1 and L2. Participants were sensitive (demonstrated by different brain responses to grammatical and ungrammatical sentences) to the violation of constructions that are formed similarly in L1 and L2, but they were not sensitive to constructions that are formed differently in L1 and L2. This study suggested that cross-linguistic influence could occur at the neural level and the L1 influence on L2 morphosyntax depends, in part, on the typological distance of the specific construction between the speakers' two languages.

Furthermore, Chen et al. (2007) tested Mandarin-speaking English learners and English native speakers on a grammaticality judgement task targeting subject-verb agreement. While undergoing ERP, participants were presented with written sentences, either grammatical (e.g., The price of the cars was too high) or ungrammatical (e.g., The price of the cars were too high), and were asked to judge the grammaticality of the sentences. The authors found that L2 learners were able to detect morphosyntactic violations (accuracy: 88%), however, L2 learners showed distinct neural responses compared to native English speakers when processing morphological features that were absent in their L1, Mandarin. There was a biphasic LAN-P600 syntactic processing profile found in native English speakers, which represents a fine-grained syntactic analysis/reanalysis or integration. However, it was absent in L2 learners. The authors suggested that the L1 Mandarin speakers' non-nativelike ERP responses to SV agreement errors in L2 English may result from the cross-linguistic influence of the absence of number marking in Mandarin. However, the results in Chen et al. (2007) require further investigation as the study only included one L2 learner group. It is possible that the differences between Mandarin-speaking L2 learners and English native speakers only reflect the difficulty of acquiring morphosyntactic structures in L2, irrespective of speakers' L1s (see Clahsen et al., 2010).

Focusing on the spatial patterns of neural activation, Arredondo et al. (2019) used functional Near infrared spectroscopy (fNIRS) to investigate Spanish-English bilingual children's cortical activation for processing English inflections (past tense and SV number agreement). The bilingual group exhibited greater activation in the L-IFG compared with monolingual children, suggesting that early bilingualism influences children's cortical organization for morphosyntactic processing. Although not the main focus of the study, the results could also suggest cross-linguistic influences. Since the L-IFG was activated during the processing of inflected words (Bozic et al., 2007) and Spanish has a more complex inflection system than English (Ramirez et al., 2010), this result can also be interpreted as evidence for the cross-linguistic influence of L1 morphological typology on speakers' L2 inflection processing. Similar to Chen et al. (2007), as only one bilingual pairing was included in Arredondo et al. (2019), it remains unclear whether this greater activation in L-IFG in L2 compared to L1 speakers during SV number agreement processing is attributed to the specific L1 tested in the study, or to L2 language processing more generally. To address this outstanding limitation in the existing neuroimaging literature, in the present study, we included two groups of English L2 learners with distinct L1 typology (Spanish, Mandarin) to investigate L2 processing of SV number agreement using fNIRS.

SV number agreement is expressed differently in English, Spanish, and Mandarin (as shown in Table 1). In English, SV agreement is expressed by combining the suffix "-s" with the verb stems to mark the singular subject. In Spanish, the same agreement is expressed by combining the suffix "-n" with the verb stem to mark the plural subject. As a typologically distinct language, Mandarin rarely uses inflectional morphemes, and SV number agreement is not expressed by any grammatical means, but is expressed by semantic processes (e.g., use of numerals, as shown in Table 1 Mandarin plural a; use of cluster determiners, as shown in Mandarin plural b; and use of plural determiners, as shown in Mandarin plural c). The underlined words in Mandarin examples (游泳) are the verb "swim". The verb form remains the bare verb form for both singular and plural sentences. In other words, Mandarin does not indicate numbers syntactically; instead, Mandarin speakers need to use lexical-semantic means to express and comprehend number information.

Insert Table 1 about here

1.3 Study Predictions

In the current study, we investigated whether the language typology of L2 learners' L1s would affect behavioral/neural processing of L2 morphosyntax. If cross-linguistic influences are observed, the results could be indicative that L2-learners' two languages are stored under one cognitive operating system and there is an underlying language proficiency shared between two languages, aligning with the claims in the Linguistic Interdependence Hypothesis. We included two groups of L2 learners with contrasting L1s (Mandarin and Spanish) to examine whether the neural patterns supporting the processing of L2 (English) SV number agreement would be influenced by the specific features of L1, Mandarin and Spanish. We used fNIRS neuroimaging to measure brain activation while Spanish-speaking English learners (Spanish ELs), Mandarin-speaking English learners (Mandarin ELs), and native English speakers completed a sentence-picture matching task targeting the SV number agreement -s (i.e., the ducks swim, the duck swim**s**). fNIRS measures the brain's hemodynamic responses using infrared light providing spatial patterns of neural activation and has been widely used to study human language and higher cognition because of its quietness and tolerance of movement (for a review, see Quaresima et al., 2012).

We tested the hypothesis that typologically distinct L1s will differentially influence L2 morphosyntactic processing of English SV number agreement -s. Behaviorally, as SV number agreement -s has been found to be difficult for L2 learners irrespective of L1 backgrounds (e.g., Bailey et al., 1974; Clahsen et al., 2010; Ellis, 1988; Krashen et al., 1977; Perkins & Freeman, 1975; Sato, 2007; Wei, 2000), we predicted that the two L2 learner groups, Spanish ELs and

Mandarin-ELs, would both show lower accuracy than English native speakers, but that no differences will be observed between the two L2 learner groups. Neurally, we predicted different neural activation patterns between the two L2 learner groups that correspond to their L1 characteristics. Specifically, as Spanish has a rather complex inflection system which uses inflectional morphemes to mark number and gender agreement (Ramirez et al., 2011), and L-IFG is involved in the processing of inflected words, we predicted that Spanish ELs would show greater activation in the L-IFG compared to English native speakers while processing English morphosyntax. On the other hand, as meanings in Mandarin are primarily conveyed by semantic processes and numbers are expressed within the noun phrase by lexical-semantic means (e.g., see Table 1), we predicted that Mandarin-ELs would recruit the L-MTG, the region involved in semantic processing, to a greater extent compared to English monolinguals while processing English morphosyntax.

The current study is one of few neuroimaging studies to include two groups of English learners with contrasting L1s to investigate cross-linguistic influence on the processing of L2 morphosyntactic knowledge. Including two L2 learner groups with contrasting L1s allows us to directly address whether different neural activation patterns between native English speakers and L2 learners are attributed to L1 cross-linguistic influence, or they may reflect general L2 processing and would therefore be common to both groups of L2 learners. As such, examining L2 learners' neural activation during English SV agreement processing has the potential to add new neural evidence of cross-linguistic influence on L2 morphosyntactic processing, which behavioral measures alone may fail to detect. In doing so, we amass a fuller understanding of the possible variation of language processing in the multilingual brain.

2 Methods

2.1 Participants

Fifty-three adults participated in the current study: Mandarin ELs (N=18, mean age= 23.93, range=19-30), Spanish ELs (N=16, mean age=24.81, range=18-33), and English native speakers (N=19, mean age=21.13, range=18-27). A total of 112 participants were recruited. Twenty-three participants were excluded because they did not meet the inclusion criteria (e.g., left handedness, concussion, ADHD). Data from 28 participants were not included due to experimenter error (n=10), low quality recording for more than 10 channels (n=12), and technical errors (missing triggers which indicate the start of trials; n=6). Eight participants did not complete the tasks and were excluded. All participants were healthy right-handed adults with no brain injuries or neurological abnormalities, no psychiatric disorders, learning disabilities, language impairments, or vision/hearing problems. Participants were recruited from the XXX and surrounding community through advertisements and word-of-mouth. The study received ethical approval from the institutional review board at the XXX. Informed consent was obtained for each participant prior to the start of experimental tasks.

2.2 Language Background

Native English speakers were exposed to English from birth, whereas both groups of L2 learners were exposed to their native languages from birth and began learning English before the age of 18. At least one of the L2 learners' parents spoke their native language to the participant in childhood and used the language consistently at home. All of the L2 learners were asked to complete a Bilingual Language Background and Use Questionnaire for detailed information on language background and exposure (see Holowka et al., 2002; Jasińska & Petitto, 2013; 2014; Jasińska et al., 2017; Kovelman et al., 2008).

Participants' English language proficiency was measured using the Woodcock Johnson (W-J) IV Picture Vocabulary test (Schrank et al., 2018). Additionally, the Spanish ELs completed the Spanish version of the Woodcock Johnson IV Picture Vocabulary test as a measure of Spanish language proficiency. As no Mandarin version of the W-J IV test is currently available, the Mandarin EL group completed the Multilingual Naming Test (MINT), in both Mandarin and English as measures of their proficiency in both languages (Gollan et al., 2012; Ivanova et al., 2013; Sheng et al., 2014). L2 learners were also asked to rate their English proficiency level on a 7-point scale. Participants' demographic information, average English use, vocabulary scores (WJ standard scores), and English self-rating scores are presented in Table 2. English native speakers showed significantly higher English W-J vocabulary scores than Spanish ELs ($t(33)=4.76$, $p<.01$) and Mandarin ELs ($t(35)=$, 20.0, $p<.01$). Spanish ELs showed significantly higher English W-J vocabulary scores than Mandarin ELs ($t(32)=2.98$, $p<.01$). Spanish ELs and Mandarin ELs showed comparable English AoA in years ($t(32)=1.10$, $p=0.278$). Furthermore, paired-sample t-tests showed that Mandarin ELs scored significantly higher on Mandarin MINT than English MINT ($t(15)=3.701$, $p<.01$); and Spanish ELs scored significantly higher on Spanish W-J test than English W-J test ($t(14)=2.680$, $p<.01$).

Insert Table 2 about here

2.3 fNIRS task and stimuli

While undergoing fNIRS neuroimaging, participants completed a picture-sentence matching task. The task was presented on a Macintosh computer using PsychoPy software (Peirce, 2009). Our task was designed to target the subject-verb number agreement -s. We adapted the auditory SV agreement -s task used in Johnson et al. (2005). Participants were presented with a picture and an auditory sentence (e.g., *The duck swims*.) which either matched or mismatched the number information in the picture (e.g., one duck or two ducks). Each sentence contained an animate noun and an intransitive verb, and the experiment was designed such that all of the intransitive verbs started with /s/ (e.g., swim, sleep, swim), rendering the SV number agreement marker –s the only cue to infer the subject number (e.g., the duck **s**wim**s** vs. the ducks swim).

As shown in Figure 1, on each trial, participants saw a picture on the computer screen and heard a sentence. Participants were asked to decide by button press whether the sentence they heard matched the picture they saw. Two conditions were included, a plural condition (in which the sentence ‘The artists sleep’ was presented) and a singular condition (in which the sentence ‘The artist sleeps’ was presented). Fifty percent of trials in each condition contained a matching picture and sentence, and 50% of trials in each condition contained a non-matching picture and sentence. All possible sentence-picture combinations were equally assigned to four different versions of the task (singular-match, singular-nonmatch, plural-match, plural-nonmatch), and the four versions were counterbalanced among participants. Since the same nouns and verbs were used for the four conditions, word length and frequency were not different across conditions.

Insert Figure 1 about here

The task was a 7-min task, presented in two 3.5-minute runs. A resting period of 30 seconds was presented at the beginning of each run. Ten trials were presented in each run; plural matching, plural non-matching, singular matching, and singular non-matching trials were presented in random order. In total, across the 20 trials in both runs, five trials of each condition type were presented. Each trial was presented for 4s, followed by a 6-17s jittered rest period with a fixation cross. The response time was calculated starting from the onset of the audio files. Prior to the test items, participants completed a practice session containing 4 items to familiarize them with the task format. Figure 2 presents the procedure of the inflection task: *'The pets sit'* and *'The elephant sips'*. A power analysis showed that for between-within ANOVA, with a sample size of 53 participants and five measurements per condition, we are at 80% power to detect a minimum effect size of $f = .35$ for the between-group factor; $f = 0.16$ for the within-group factor; and an $f = 0.18$ for the interaction. We were more powered to detect within-group and interaction effects compared to between-group effects. The power analyses were conducted in G*Power (Faul et al., 2007).

Insert Figure 2 about here

2.4 Procedure

Participants were tested individually in a quiet room. A Shimadzu LightNIRS Near Infrared Spectroscopy system with 47 channels (with 15 pairs of source and detector), data acquired at 7.4 Hz, was used to measure the hemodynamic response. Participants were seated while a 10x3 probe array was positioned over the left and right hemispheres and frontal lobe (see Figure 3). The distance between each source and detector probe was three centimeters. The optimal signal to noise ratio was tested for each channel, using Shimadzu fNIRS built-in software. While completing the task, the participants were instructed to minimize their body movements and avoid crossing their arms or legs to minimize the effects of Mayer waves.

Insert Figure 3 about here

2.5 Behavioral Data Analysis

A repeated measures ANOVA was conducted using the ez package (Lawrence, 2016) in R statistics (R core team, 2013) to examine the main effects of group, number condition (singular/plural), matching/nonmatching condition and the three-way interaction for both participants' accuracy and response time (RT). In the RT analysis, only correct trials were included, and RTs longer than 4.31 seconds (3SD above the mean, 10 trials) and shorter than 0.64 seconds (3 SD below the mean, 8 trials) were excluded. Post-hoc t-tests were conducted to further investigate the main effects and interactions.

2.6 fNIRS Data Analysis

Light intensities in the fNIRS signals were analyzed using a set of open-source Matlab functions, which are part of the NIRS AnalyzIR toolbox (Santosa et al., 2018). First, we checked that all stimulus triggers (which indicate trial starts) were recorded in each data file, and we excluded participants for whom triggers were missing due to technical error (n=6). Each data file was trimmed to match the exact length of the experiment, by excluding data points before the start of the first trial, and after the end of the last rest period (i.e., data recorded while participants were reading and/or listening to instructions). Motion artifacts were corrected using a kurtosis-based wavelet algorithm (Chiarelli et al., 2015) for fNIRS implemented in Homer2 (Huppert et al., 2009) and adopted in AnalyzIR toolbox. Data was bandpass filtered with a high pass filter of 0.02 Hz and low pass filter of 1 Hz using the hmrBandpassFilt function (Mazzoli et al., 2019). Optical density values were converted into concentration changes in oxygenated and deoxygenated hemoglobin (HbO and HbR respectively) using modified Beer-Lambert law (Cope et al., 1988). Each stimulus event was labeled as plural or singular and as matching or non-matching to allow us to contrast the effects of each manipulation. A GLM was conducted to estimate task-level effects.

A mixed-effects model was performed to examine the main effect of group (Mandarin vs. English vs. Spanish), number condition, matching/nonmatching condition, and the three-way interaction while controlling for random effects of subject. Subsequent post-hoc t-tests were conducted for the non-matching condition to evaluate the specific pair-wise differences among groups and number conditions. The non-matching condition, which contained the morphosyntactic number-agreement violation, was retained for further analysis, as the analysis of morphosyntactic violation (non-matching) is standardly used to examine language processing and has been applied to the study of many languages (e.g., Allen et al., 2003; Newman et al., 2007; Chen et al., 2007; Linares et al., 2006).

2.7 Spatial Registration

Prior to the experiment, the fNIRS cap was placed on each participant seated in front of a 3D magnetic digitizer stylus (PATRIOT, Polhemus, Colchester, VT) to obtain the relative locations of five "10-20" standard positions (Nz, LPA, RPA, Cz, Oz, as shown in figure 3 bottom right) and fNIRS optodes in a real-word coordinate system. This allows us to adapt the location of NIRS channels to the shape of a single participant's skull (Okamoto et al., 2004). We used the registerprobe1020 function from nirs AnalyzIR Toolbox to register each individual's probes (sources, detectors) into the same coordinate space. For subsequent analyses, an average registered probe was created by averaging each optode's position across all participants, and the average probe was applied to all participants. Probe positions were visualized using brainstorm (Tadel et al., 2019; see figure 2 A and B).

We projected the average probe into MNI space (Tzourio-Mazoyer et al., 2002) to identify Brodmann areas covered by each measurement channel corresponding to the projected space between each source and detector pair using the convertlabels2roi function from nirs AnalyzIR Toolbox. After estimation of the channel-wise model, the group-level results were interpreted using the roiAverage function from nirs AnalyzIR Toolbox to report effects in each Brodmann area, based on the channels that were located in each region, according to the cortical registration of the average probe. Each Brodmann area can be covered by multiple channels with different weights based on the intersection of the path from source to detector with that region.

3 Results

3.1 Behavioral Results

3.1.1 Accuracy

There was a main effect of group ($F(2,192)=14.40$, $p<.001$). Post-hoc analysis revealed that English native speakers performed significantly better than both Spanish ($t(33)=2.430$, $p=0.021$) and Mandarin EL groups ($t(35)=3.789$, $p<.001$). However, there were no significant differences between the two EL groups on the accuracy of the morphosyntax task ($t(32)=1.182$, $p=0.25$). There was no significant main effect of number condition ($F(1,192)=0.001$, $p=0.97$); participants performed comparably on plural and singular conditions. There was also no significant main effect of matching/nonmatching condition ($F(1, 192)=0.03$, $p=0.86$); participants performed comparably on matching and non-matching conditions. Furthermore, there was no significant three-way interaction among group and the two conditions ($F(4,192)=0.58$, $p=0.68$). Figure 4 shows the group accuracy (proportional) on the morphosyntax task.

Insert Figure 4 about here

3.1.2 Response Time

There was no main effect of group ($F(2, 191)=2.02$, $p=0.14$), number condition ($F(1, 191)=0.03$, $p=0.86$), matching/nonmatching condition ($F(1, 191)=3.05$, $p=0.08$), and no significant three-way interaction ($F(4, 191)=1.15$, $p=0.33$). Figure 5 shows the response time data (in seconds). The response time was calculated starting from the onset of the test sentences, thus the values presented below include the length of the audio files.

Insert Figure 5 about here

3.2 Neuroimaging Results

3.2.1 Group and Condition Main Effects

The three-way ANOVA showed significant main effects of group (Mandarin ELs, Spanish ELs, English native speakers), number condition, and a significant three-way interaction among group, number condition and matching/nonmatching condition, see Table 3. In the following section, we report the post-hoc comparisons in the non-matching condition (as detailed in our data analysis section above).

Insert Table 3 about here

3.2.2 Singular vs Plural Condition by Group Interaction

First, neural activation patterns associated with processing the plural and singular conditions were compared in the three groups separately. The response differences are shown in Table 4 and Figure 6. The directionality of the differences was determined following the criteria that: 1) if the difference is an HbO signal with a positive beta value OR if the difference is an

HbR signal with a negative beta value, the difference is in the direction of the contrast; 2) if the difference is an HbO signal with a negative beta value OR if the difference is an HbR signal with a positive beta value, the difference is in the opposite direction of the contrast. Results in the brain areas that showed significant differences in the ANOVA were presented and interpreted. The results showed that the English native speakers showed greater activity for singular than plural sentences in the left rostral IFG and dlPFC (BA-46). On the other hand, English native speakers showed greater activity for plural than singular sentences in right frontal and temporal regions: the right medial temporal lobe (BA-48), right premotor cortex (BA-6), right frontal eye field (BA-8), and right MTG (BA-21).

Mandarin ELs showed greater activity for singular than plural sentences predominantly in the left temporal cortex and bilateral prefrontal cortex, including the left MTG (BA-21) and subcentral area (BA-43). On the other hand, Mandarin ELs showed greater activity for the plural than singular sentences in the right MTG (BA-21) and right premotor cortex (BA-6). Lastly, Spanish ELs showed greater neural activity for plural than singular sentences in multiple regions, including the right premotor cortex (BA-6), right primary somatosensory cortex (BA-1), left subcentral area (BA-43), and right MTG (BA-21).

Insert Table 4 about here

Insert Figure 6 about here

Furthermore, we compared the patterns of neural activations between native English speakers and the two EL groups in the singular and plural non-matching conditions (see Table 5, Table 6 and Figure 7). While processing singular SV agreement violations, native English speakers showed greater activity in the left IFG (BA-45) relative to both Spanish and Mandarin

ELs. Native English speakers also showed greater neural activity in right premotor, somatosensory, and temporal cortices (BA-6, BA-1, BA-21) relative to Spanish ELs, but not relative to Mandarin ELs. While processing plural SV agreement violations, no neural activation differences were observed between Spanish ELs and English native speakers. Mandarin ELs showed greater neural activity in left somatosensory (BA-2) cortex compared to native English speakers. On the other hand, English native speakers showed greater neural activity in right premotor and medial temporal cortices (BA-6, BA-21, BA-48).

Insert Table 5 about here

Insert Table 6 about here

Insert Figure 7 about here

4 Discussion

In the present study, we asked whether L2 learners' L1 typology (Spanish vs. Mandarin) had an impact on the processing of their L2 (English) morphosyntax (SV number agreement). Spanish and Mandarin differ with respect to how they express SV number agreement. Spanish commonly uses inflection (i.e., affixation) to mark number agreement. However, Mandarin rarely uses inflection and does not express number agreement by any grammatical means, rather, number is expressed through semantic processes (e.g., use of numerals: "*三只鸭子*, three ducks"). We tested the hypothesis that those structural differences between L2 learners' L1s will differentially influence L2 morphosyntactic processing during a picture-sentence matching task targeting the English SV number agreement -s. By including two L2 learner groups, the current study allowed us to test differences between the L2 speakers that are attributed to the specific influence of cross-linguistic differences on morphosyntax. The results showed that cross-linguistic influences were only observed at the neural level, but not the behavioral level. Both L2 learner groups showed different patterns of neural activation corresponding to the specific linguistic features of their L1.

4.1 Behavioral performance

Using a picture-sentence matching task targeting the third person singular -s construction (e.g., *'the duck swims'*), our behavioral data indicate that the SV number agreement is a relatively difficult morphosyntactic process to master in the L2. Consistent with our hypothesis, native English speakers were more accurate compared to Spanish and Mandarin ELs. Our results corroborate previous extensive findings that morphosyntax is a particularly challenging area of L2 acquisition and processing (e.g., DeKeyser, 2005). Additionally, our results corroborated Sato (2007) and Silva and Clahsen (2008)'s findings that L2 learners with different L1 backgrounds showed the same *behavioral* performance on morphosyntax, irrespective of L1 typology. To further investigate potential cross-linguistic influence of L1 characteristics on L2 morphosyntactic processing, we examined patterns of neural activation between the two L2 learner groups and native speakers during online processing of the same morphosyntactic information.

4.2 L1 influence on neural activation for L2 morphosyntactic processing

We hypothesized that the morphological typology of L2 learners' L1 will influence their processing of L2 sentences containing the third person singular -s. Specifically, we predicted that Spanish ELs would show greater activation in the L-IFG than English native speakers because of the rich inflectional system in their L1; Mandarin ELs would show greater activation in the L-

MTG than English native speakers due to the common use of lexical morphology in Mandarin. Processing inflectional morphology has previously been shown to engage the L-IFG (Binder et al., 2009), whereas lexical-semantic processing has been shown to engage the L-MTG (Lehtonen et al., 2006). However, our results did not align with these specific predictions.

No greater L-MTG activation in Mandarin ELs or greater L-IFG activation in Spanish ELs were observed relative to L1 speakers in either singular or plural conditions. Instead, native English speakers showed greater activation particularly in the IFG, a region associated with morphosyntactic processing, relative to both the Spanish and Mandarin ELs. Although the observation of greater IFG activation in native English speakers was contrary to our prediction, it follows from our behavioral observations. Vocabulary test results indicated that both the Spanish and Mandarin ELs had significantly lower English language proficiency relative to the native English speakers, and both Spanish and Mandarin ELs showed lower English language proficiency relative to their L1 proficiency. Moreover, both the Spanish and Mandarin ELs showed significantly lower accuracy on the picture-sentence matching task relative to native English speakers. Together, these behavioral results indicate a significant language proficiency difference between the two EL groups and native English speakers, which are reflected in the neuroimaging results. Namely, our EL groups did not show ‘native-like’ English neural activation during morphosyntactic processing, whereas native English speakers did show a characteristic morphosyntactic neural activation pattern (i.e., greater L-IFG activation; Knoll et al., 2012; Luke et al., 2002; Skeide et al., 2016; Skeide & Friederici, 2016) relative to ELs.

We expect that group comparisons between English speakers, and Spanish and Mandarin ELs would reveal patterns of neural activation in support of our prediction (i.e., greater L-MTG and L-IFG activity for Mandarin and Spanish ELs, respectively) if ELs have native-like English proficiency. For example, Arredondo et al. (2019) found greater activation in the L-IFG for Spanish-English bilingual children compared with English monolingual children during number and tense agreement processing. The participants in Arredondo et al. (2019) were bilingual children (mean age = 10 years old) who received Spanish exposure from birth, and English exposure prior to age 5. By comparison, the participants in this study were adults (mean age=25 years old) who are English learners who were more proficient in L1 than L2 and learned English after the age of 5. Indeed, Arredondo et al. (2019) attributed their findings to the influence of *early* bilingualism.

Although our specific predictions were not supported in group comparisons, we observed evidence of L1 influence on L2 morphosyntactic processing in specific comparisons of singular vs. plural conditions for each group that align with our hypothesis. Mandarin ELs showed greater activation in L-MTG (involved in semantic processing) for singular than plural sentences. The other two groups did not show this pattern. This finding illustrated that the lexical-semantic route was more activated when Mandarin ELs were processing the inflected (marked) singular forms compared to the unmarked plural forms. It is possible that instead of processing the S-V agreement -s as a separate inflectional suffix that is combined with the bare verb, Mandarin ELs processed the whole inflected word as an independent lexeme. This may reflect the feature of their L1, Mandarin, which lacks inflectional morphemes and conveys meanings through lexical-semantic means. Furthermore, Spanish ELs showed greater neural activity predominantly for the plural versus singular condition. Unlike English, which uses the suffix -s to mark the singular form, Spanish uses the suffix –n to mark the plural form (e.g., the duck swims – el pato nada; the duck swim – los patos nadan), which may lead to greater neural activation for the marked plural form compared to the unmarked singular form in Spanish. Therefore, this greater activation in plural than singular condition in Spanish ELs may reflect the influence of L1 (Spanish) on L2 (English) morphosyntax.

To sum up, the Spanish and Mandarin EL groups demonstrated indistinguishable behavioral performance on the picture-sentence matching task. If no cross-linguistic influence exists, we would predict the same behavioral and neural patterns for the two groups when processing the same inflectional morphology in their L2. However, the two L2-learner groups showed divergent patterns at the neural level, and the patterns in each group were in line with the characteristics of their L1. In addition, comparing two L2-learner groups with contrasting L1s to native speakers allowed us to conclude that the differences come from specific cross-linguistic influences instead of general L2 processing patterns, as each group demonstrated unique neural patterns that are explainable by their L1 features. This study provided support to the existence of cross-linguistic influences in L2 morphological processing. These results are suggestive of a common learning mechanism across L2-learners' two languages and is in line with the Linguistic Interdependence Hypothesis.

4.3 Limitations and future directions

Bilingual populations are inherently heterogeneous, which was reflected in our sample. The Spanish ELs demonstrated higher English ability than Mandarin ELs, as measured by the W-J vocabulary test. Additionally, the average age of English acquisition was younger for Spanish ELs compared to Mandarin ELs. Although our sample did represent the characteristics of these two populations in the U.S, AoA and proficiency are important factors that could modulate patterns of neural activation for L2 morphosyntactic processing. A number of studies have shown that L2 learners with higher L2 proficiency and earlier AoA showed neural activation patterns that resembles more of native speakers (e.g., Dowens et al., 2010; Liu & Cao, 2016; Roncaglia-Denissen & Kotz, 2016). Therefore, future studies should strive to include two groups of L2 learners that have similar L2 AoA, as well as similar L2 proficiency to reduce the potential confound brought by differences in those language-related factors. In addition, our L2 learners have not achieved native-like English proficiency, and we did not observe the predicted group differences (greater L-MTG activity in Mandarin Els and greater L-IFG activity in Spanish Els). Future studies may focus on learners with native-like L2 proficiency to test the role of L1 influence on L2, which may be able to reveal the predicted group differences.

In order to provide a more robust test of L1 cross-linguistic influence on L2, this study can be extended to include the same language pairs with different L1s (e.g., English-speaking learners of Mandarin; English-speaking learners of Spanish) or to test other linguistic constructions (e.g., relative clauses). We would expect cross-linguistic influences to be observed regardless of the language pairs or constructions. Moreover, this study can be extended to younger bilingual speakers who are actively acquiring these morphological structures. It is possible that the L1 influence we observed in this study is more prominent in adult learners who acquire their L2 at a relatively late age. By examining younger bilingual speakers, we can investigate how the developing brain organizes and processes two languages, and whether greater brain plasticity associated with a younger age may mitigate the impact of L1 on acquisition and processing of L2. Important future directions for this line of research therefore include extending our findings in the abovementioned ways, and as part of a larger call for replication in language research, to conduct replication studies.

5 Conclusion

The current study provided supporting evidence to the hypothesis that typologically distinct L1s would differentially influence L2 morphosyntactic processing in linguistically principled ways. Cross-linguistic influences were only observed at the neural level, but not the behavioral level, revealing that different neural activity patterns underpin similar behavioral results. Both L2-learner groups showed different patterns of neural activation corresponding to the specific linguistic features of their L1. Overall, this study advances our understanding of how morphosyntactically-distinct languages are organized and processed in L2 learners.

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be constructed as a potential conflict of interest.

7 Author Statement

Danyang Wang: conceptualization, formal analysis, investigation, data curation, writing-original draft. **Sarah Wang**: conceptualization, methodology, investigation, data curation, resources. **Benjamin Zinszer**: software, formal analysis, writing-review & editing. **Li Sheng**: conceptualization, methodology, writing-review & editing. **Kaja Jasińska**: conceptualization, methodology, writing-review & editing, funding acquisition.

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Tables and Figures

Table 1. SV number agreement in English, Spanish, and Mandarin

	English	Spanish	Mandarin
Singular	The duck swim**s**	El pato nada	一只鸭子游泳。 One duck swim.
Plural	The ducks swim	Los patos nada**n**	a.三只鸭子游泳。 Three ducks swim. b.一群鸭子游泳。 A group of ducks swim. c.那些鸭子游泳。 Those ducks swim.

Table 2. Participants' age, English age of acquisition (AoA) and language scores / mean (SD)

	Mandarin ELs	Spanish ELs	English native speakers
Age (years)	23.75 (3.64)	24.74 (4.45)	21.13 (2.16)
Female percentage	56%	69%	68%
English AoA (years)	10.0 (4.2)	7.7 (4.8)	-
English self-rating (out of 7)	5.3 (1.0)	6.3 (0.8)	-
Average English use at home	1.2 (0.4)	1.6 (0.7)	-
Average English use outside of home	3.3 (1.0)	4.0 (1.2)	-
W-J (English standard score)	48.0 (7.4)	77.1 (16.9)	98.5 (6.1)
W-J (Spanish standard score)	-	93.4 (13.1)	-
MINT (English accuracy)	70% (0.1)	-	-
MINT (Mandarin accuracy)	88% (0.1)	-	-

*Average English use was measured using a five-point likert scale: 1=never, 2=1-20%, 3=20-50%, 4=50-80%, 5=80-100%

Table 3. Overall ANOVA results

	Region	Brodmann area	HbO/HbR	F	p
Main effect of group	Left anterior prefrontal cortex	L 10	HbR	6.27	0.01
	Left MTG	L 21	HbO	4.17	0.04
	Left dlPFC	L 46	HbR	7.46	0.006
Main effect of number condition	Right MTG	R 21	HbR	5.20	0.02
	Right medial temporal cortex	R 48	HbR	4.11	0.04
	Right premotor cortex	R 6	HbR	4.30	0.04
Group by number condition by matching/nonmatching condition interaction	Right primary somatosensory cortex	R 1	HbO	4.32	0.04
	Left primary somatosensory cortex	L 2	HbR	5.447	0.02
	Left subcentral area	L 43	HbR	4.23	0.04
	Left IFG	L 45	HbO	4.48	0.03
	Right frontal eye field	R 8	HbO	4.15	0.04

Table 4. singular vs. plural comparison in the three groups

Contrast	Direction	Region	Brodmann area	HbO/HbR	beta	t
Singular – plural in English native speakers	Singular > Plural	Left rostral IFG and dlPFC	L 46	HbR	-265.9	-2.00*
	Plural > singular	Right medial temporal cortex	R 48	HbO	-351.8	-2.67**
		Right premotor cortex	R 6	HbO	-330.0	-2.61**
		Right frontal eye field	R 8	HbO	-261.7	-2.59*
		Right MTG	R 21	HbR	220.2	2.12*
Singular - plural in Mandarin ELs	Singular > plural	Left MTG	L 21	HbR	-391.5	-3.18**
		Right primary somatosensory cortex	R 1	HbR	-288.7	-2.07*
		Left subcentral area	L 43	HbR	-264.9	-2.38*
		Right frontal eye field	R 8	HbR	-225.9	-3.45**
	Plural>singular	Right MTG	R 21	HbO	-345.4	-2.50*
		Right premotor cortex	R 6	HbO	-330.4	-2.66**
Singular - plural in Spanish ELs	Plural > singular	Right premotor cortex	R 6	HbR	451.5	5.42**
		Right primary somatosensory cortex	R 1	HbR	329.1	2.90**
		Left subcentral area	L 43	HbR	285.8	2.76**
		Right MTG	R 21	HbR	220.6	2.50*

Note: *p<0.05; **p<0.01; Beta value was arranged from the highest to the lowest

Table 5. Group comparison in the singular, non-matching condition

Contrast	Direction	Region	Brodmann area	HbO/HbR	Beta	t
Spanish ELs – English native speakers	Spanish > English	Right frontal eye field	R 8	HbO	240.9	2.40*
	English > Spanish	Right premotor cortex	R 6	HbR	370.3	3.76**
		Left IFG	L 45	HbR	325.5	2.94**
		Right primary somatosensory cortex	R 1	HbR	296.8	2.25*
		Left subcentral area	L 43	HbR	272.8	2.26*
		Right MTG	R 21	HbR	240.9	1.99*
Mandarin ELs – English native speakers	Mandarin > English	Left subcentral area	L 43	HbO	425.9	2.63**
		Left primary somatosensory cortex	L 2	HbO	423.6	2.20*
		Right frontal eye field	R 8	HbO	247.9	2.28*
	English > Mandarin	Left IFG	L 45	HbR	246.9	2.25*

Note: *p<0.05; **p<0.01; Beta value was arranged from the highest to the lowest

Table 6. Group comparison in the plural, non-matching condition

Contrast	Direction	Region	Brodmann area	HbO/HbR	Beta	t
Spanish ELs – English native speakers	-	-	-	-	-	-
Mandarin ELs – English native speakers	Mandarin > English	Left primary somatosensory cortex	L 2	HbO	474.59	2.41*
	English > Mandarin	Right MTG	R 21	HbR	273.22	2.46*
		Right medial temporal cortex	R 48	HbR	245.96	2.26*
		Right premotor cortex	R 6	HbR	244.58	2.29*

Note: *p<0.05; **p<0.01; Beta value was arranged from the highest to the lowest

Figure Captions

Figure 1. Illustration of the picture-sentence matching task (a. Singular matching condition; b. Singular non-matching condition; c. Plural non-matching condition; d. Plural matching condition)

Figure 2. Illustration of the procedure of the picture-sentence matching task

Figure 3. Illustration of probe arrays (A and B show the probe position on the participant's head, generated by Brainstorm (Tadel et al., 2019); C shows the probe and cap placement on a study participant; D shows the position of Cz, Nz, Oz, LPA and RPA fiducial points)

Figure 4. Participants' accuracy on the picture-sentence matching task shown by group and condition (Mandarin=Mandarin ELs; English=English native speakers; Spanish=Spanish ELs)

Figure 5. Participants' response time on the picture-sentence matching task shown by group and condition (Mandarin=Mandarin ELs; English=English native speakers; Spanish=Spanish ELs)

Figure 6. Neural difference for singular vs. plural comparison in the three groups

Figure 7. Neural differences for group comparisons in singular and plural conditions