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# Morpho-syntactic complexity modulates brain activation in Persian-English bilinguals: An fMRI study

Mohammad Momenian[a,b,*], Reza Nilipour[c], Reza Ghafar Samar[b], Stefano F. Cappa[d,e,1], Narly Golestani[f,1]

[a] Laboratory for Communication Science, Division of Speech and Hearing Sciences, Faculty of Education, University of Hong Kong, Hong Kong
[b] Department of Applied Linguistics, Tarbiat Modares University, Tehran, Iran
[c] Department of Speech Therapy, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran
[d] Institute for Advanced Studies (IUSS), Pavia, Italy
[e] IRCCS S. Giovanni di Dio, Brescia, Italy
[f] Brain and Language Lab, Faculty of Psychology and Education Sciences, University of Geneva, Geneva, Switzerland

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ABSTRACT

The Persian language can be considered to have a relatively more complex and combinatorial morpho-syntax than languages like Chinese and English. For example, the Persian verbal system is largely constituted of light verb constructions, in which light verbs are combined with specific items coming from other grammatical classes to generate entirely new verbal entities. This study was designed to examine the mediating effect of language-inherent properties related to morpho-syntax on activation of the left inferior frontal gyrus (LIFG), a brain area involved in morpho-syntactic processing. To this end, 20 late Persian-English bilinguals were required to covertly generate verbs and nouns from object and action pictures, within a cued grammatical context. Consistent with predictions, the results of an ROI analysis revealed an interaction between task and language in BA 44 of the LIFG and its right homologue, with greater activation of this region during the production of Persian compared to English verbs. In contrast, there was greater activation of the BA 44 during the production of English compared to Persian nouns, consistent with the more effortful processing of their less proficient second language (English). The findings suggest that language-specific properties such as morpho-syntactic complexity can modulate the recruitment of Broca's area, over and above the more well-documented effects of language proficiency.

## 1. Introduction

The last two decades have witnessed a growing body of research on the neural underpinnings of multilingualism (Abutalebi, 2008; Liu, Hu, Guo, & Peng, 2010; Perani & Abutalebi, 2005; Peter Indefrey, 2006; Sebastian, Laird, & Kiran, 2011). This research shows that although the neural resources underlying speech processing in the first (L1) and second language (L2) largely overlap, factors such as the proficiency and age of acquisition (AoA) of the L2 modulate the underlying cognitive and neural resources (Abutalebi, Della Rosa, Gonzaga, et al., 2013; Chee, Soon, Lee, & Pallier, 2004; Newman, Tremblay , Nichols, Neville, & Ullman, 2012; Perani et al., 2003; Wartenburger et al., 2003). With respect to proficiency, functional neuroimaging studies have repeatedly shown differences in brain recruitment during L2 compared to L1 processing in bilinguals with lower levels of L2 proficiency. These differences involve classical language areas, such as the left inferior frontal gyrus (LIFG) and left inferior parietal cortex, as well as regions involved in language control, such as the anterior cingulate cortex, the left dorsolateral prefrontal cortex and the basal ganglia (Abutalebi, Della Rosa, Ding, et al., 2013; Abutalebi, Della Rosa, Gonzaga, et al., 2013; Abutalebi & Green, 2007; Sebastian et al., 2011). More specifically, many studies have shown more extensive activation of a number of left and right hemispheric brain regions in less compared to more proficient bilinguals, or in the less proficiently spoken language in bilinguals, in particular during language production tasks (see (Abutalebi, 2008; Golestani et al., 2006; Kovelman et al., 2008; Liu et al., 2010; Park, Badzakova-Trajkov, & Waldie, 2012; Rodriguez-Fornells, Rotte, Heinze, Nosselt, & Munte, 2002; Ruschemeyer, Fiebach, Kempe, & Friederici, 2005; Sakai, Miura, Narafu, & Muraishi, 2004; Stein et al., 2009; Tatsuno & Sakai, 2005).

* Corresponding author at: Laboratory for Communication Science, Division of Speech and Hearing Sciences, Faculty of Education, University of Hong Kong, Hong Kong.
*E-mail address:* momenian@hku.hk (M. Momenian).
[1] Joint Senior Authors.

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This is especially the case in the LIFG: the majority of these studies have revealed a negative relationship between the level of L2 proficiency and activation, with lower proficiency associated with higher activation in this brain region. The greater involvement of Broca's area during the processing of the less proficient language in bilinguals is likely to reflect more effortful linguistic processing and higher working memory demands (Abutalebi & Green, 2007; Golestani & Zatorre, 2004; Golestani et al., 2006).

Conversely, there is also evidence for the association of higher proficiency with greater activation, in particular during tasks engaging auditory comprehension. This is more commonly found in regions other than Broca's area (Archila-Suerte, Zevin, & Hernandez, 2015; Chee et al., 2004; Liu et al., 2010; Newman-Norlund, Frey, Petitto, & Grafton, 2006; Videsott et al., 2010; Vingerhoets et al., 2003; Wartenburger et al., 2003). Interestingly, there is also evidence that during L2 processing, especially when this language is not spoken proficiently or when it is learnt late, there is greater involvement of right hemispheric brain regions than during L1 processing (Dehaene et al., 1997). For example, the results of a recent quantitative meta-analysis on the neural basis of bilingualism have shown that regions including the right inferior frontal gyrus are more likely to be recruited during L2 processing in low proficient bilinguals (Sebastian et al., 2011). Fewer studies have examined the effect of age of acquisition, but at least two have shown that later ages of acquisition are also associated with greater right IFG involvement (Dehaene et al., 1997; Ding et al., 2003).

Additional factors may also be responsible for differences in brain activation between L1 and L2, beyond proficiency and AOA. Language-inherent morpho-syntactic and combinatorial properties have been neglected to some extent, and need to be taken into serious consideration (see Finocchiaro, Basso, Giovenzana, & Caramazza, 2010; Hasegawa, Carpenter, & Just, 2002; Li, Jin, & Tan, 2004; Momenian, Nilipour, Samar, Oghabian, & Cappa, 2016; Suh et al., 2007; Yokoyama et al., 2006). Brain imaging studies have only begun to address the modulating effect of morpho-syntactic complexity across languages in bilingual individuals (Hasegawa et al., 2002; Suh et al., 2007; Yan, Zhang, Xu, Chen, & Wang, 2016; Yokoyama et al., 2006). The impact of morpho-syntactic complexity on brain activity within a single language has, however, been studied more extensively. Studies have, for example, focused on the comparison between the comprehension of sentences containing centre-embedded object-relative clauses or containing non-canonical word orders, and simpler sentence structures (see for reviews, Hagoort & Indefrey, 2014; Zaccarella, Meyer, Makuuchi, & Friederici, 2017). The findings of these investigations converge with those of lesion studies in showing the importance of Broca's area in processing more complex sentence structures, and also in showing the involvement of the left posterior temporal (LPT) regions and of dorsal fronto-temporal functional connections in this (Ben-Shachar, Hendler, Kahn, Ben-Bashat, & Grodzinsky, 2003; Ben-Shachar, Palti, & Grodzinsky, 2004; Friederici, Fiebach, Schlesewsky, Bornkessel, & von Cramon, 2006; Suh et al., 2007; Tatsuno & Sakai, 2005; Thompson et al., 2007).

Broca's area consists of several subregions (Amunts & Zilles, 2012; Amunts et al., 2010; Keller, Crow, Foundas, Amunts, & Roberts, 2009), which are preferentially involved in the processing of semantic, phonological, and (morpho)syntactic information. Although during natural language processing these different aspects of linguistic information are not processed independently, there is support for the preferential processing of phonetic and syntactic information in the left pars opercularis (i.e. BA 44, the posterior portion of Broca's area), as compared to preferential processing of lexico-semantic information in the pars triangularis (i.e. BA 45, the more anterior part of Broca's area; Friederici, 2002, 2016; Friederici, Opitz, & von Cramon, 2000; Golestani, 2016; Heim et al., 2005; Schell, Zaccarella, & Friederici, 2017). More specifically, there's evidence for a role of the pars opercularis, and in some studies more specifically of the anterior portion of BA44 (i.e. on the border of the pars triangularis), in the processing of relatively more complex morpho-syntax from studies having selectively varied the degree of embeddedness of sentences (Jeon & Friederici, 2013; Makuuchi, Bahlmann, Anwander, & Friederici, 2009). In addition, a recent quantitative meta-analysis of connectivity-based parcellation on data from a wide range of neuroimaging experiments (from the BrainMap database) has revealed the presence of five distinct functional clusters within BA44 (Clos, Amunts, Laird, Fox, & Eickhoff, 2013). Of those five clusters, the anterior-ventral one (Cluster 3) and the posterior-dorsal one (Cluster 1) were shown to be strongly associated with various aspects of language processing including syntax.

Given the large range of studies examined here, and the multi-faceted nature of the function of Broca's area subregions, these regions are likely not solely involved in syntactic (complexity) processing, but rather have been consistently linked with different aspects of syntax processing over a large number of studies (Clos et al., 2013). LIFG and its sub-regions have been implicated in syntactic working memory demands (Caplan, Alpert, Waters, & Olivieri, 2000), syntactic transformations (Ben-Shachar et al., 2003; Grodzinsky, 2000), and 'linearization' of hierarchical syntactic structures (Bornkessel, Zysset, Friederici, von Cramon, & Schlesewsky, 2005; Fiebach, Schlesewsky, Lohmann, von Cramon, & Friederici, 2005; Grewe et al., 2005). Beyond syntax, these regions have also been shown to be involved in cognitive control processes both at linguistic and also at more general levels (see Abutalebi & Green, 2007; Fedorenko, Duncan, & Kanwisher, 2012; Thompson-Schill, 2003; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997), and in working memory more generally (Grodzinsky & Santi, 2008).

The dual-systems framework proposed by Marslen-Wilson, Bozic, and Tyler (2014) offers an account for the neural correlates of morpho-syntactic complexity. This framework posits the existence of two complementary neural systems underlying language processing. The first is a domain-general network involving bilateral temporal regions, which supports sound-to-meaning mapping. The second system is a domain-specific, left lateralized fronto-temporal network in charge of morpho-syntactic processing (Tyler & Marslen-Wilson, 2008). Within this framework, it is predicted that morpho-syntactic complexity can modulate activation of different brain networks depending on which aspect of complexity varies. Inflectional morphology, which is computationally more complex, is expected to induce activation in the left hemisphere fronto-temporal regions (i.e., dorsal BA44 and pSTG), while derivational morphology is expected to engage bilateral temporal regions (i.e., STG and MTG; Klimovich-Gray, Bozic, & Marslen-Wilson, 2017). These predictions are borne out in studies having examined specific languages having different degrees of morpho-syntactic complexity, such as English, Arabic, Polish, Russian, and Italian (Boudelaa, Pulvermuller, Hauk, Shtyrov, & Marslen-Wilson, 2010; Bozic, Fonteneau, Su, & Marslen-Wilson, 2015; Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Carota, Bozic, & Marslen-Wilson, 2016; Klimovich-Gray et al., 2017).

The notion of cross-linguistic differences in complexity is a controversial issue (Dahl, 2004). The definition of "complexity" has been operationalised using different approaches (see for example, Sadeniemi, Kettunen, Lindh-Knuutila, & Honkela, 2008). Few studies have examined languages with differing morpho-syntactic complexity, and have reported greater activation for "more complex, less proficient" L2s in a variety of brain regions, including the bilateral dorsal lateral prefrontal cortex (DLPFC), BA47, superior temporal gyrus (BA22), middle temporal gyrus (BA21 and BA37), left supramarginal gyrus, and left supplementary motor area (Hasegawa et al., 2002; Yan et al., 2016). These studies, however, did not control for the morphological complexity of the languages that were studied (Mandarin, English, and Japanese), thus making it difficult to determine whether greater activation in the L2 arises from lower proficiency or from higher linguistic complexity.

To further address the issue of the impact of differences in morpho-syntactic complexity on brain activity in bilinguals, here we present the results of a study in Persian-English bilinguals. The verbal system of the L1 (Persian) is morpho-syntactically more complex and combinatorial than that of the L2 (English), thus allowing to dissociate the effects of proficiency and of complexity. In particular, the Persian verbal system carries relatively more complex and combinatorial morpho-syntax to express tense, aspect, mood, number and person compared to several European and Asian languages such as English and Chinese. A very distinctive feature of this verbal system is that apart from less than two hundred simple verbs, the rest of the verbal system is constituted of light verb constructions (LVCs) (Family, 2014). LVCs are constituted of light verbs combined with specific nouns, adjectives, adverbs, prepositions and prepositional phrases to generate an entirely new verbal meaning. For example, */zamin khordan/*, literally translated as "earth eat", means "to fall down". The nonverbal element which is attached to the light verb always comes first, regardless of its grammatical category. The verbal part of the LVC carries person-number inflections, while pronominal clitics (PC) indicating the object of the verb can be attached to the verb or to the nonverbal part of the construction (Mahootian, 2010). Persian nouns, on the other hand, like in the majority of other Indo-European languages, express only number and person.

The aim of the present study was to characterize how morpho-syntactic complexity modulates the neural processing of language in bilinguals over and above differences that might arise from proficiency. Late Persian-English bilingual participants performed a sentence completion task requiring the generation of both verbs and nouns in both the L1 and L2, where they needed to retrieve morphological and syntactic features of the generated items in order to successfully perform the task. Given the higher morpho-syntactic and combinatorial complexity of Persian verbs relative to English ones but the lower level of proficiency in English compared to Persian, we expected to find a dissociation in the effects of complexity and of proficiency in the neural processing of the two languages. We predicted that, consistent with previous studies on the effects of proficiency on neural bases of bilingualism, we would find greater activation in the LIFG and possibly in its right hemisphere homologue during the generation of English compared to Persian nouns, due to the more effortful requirements of the task in the L2 (English). For verbs, however, given the more complex and combinatorial morpho-syntactic structure of Persian compared to English verbs, in line with previous studies having shown greater recruitment of the pars opercularis of Broca's area during the processing of more morpho-syntactically complex structures, we predicted that the difference between Persian and English would be reduced, or even reversed in these regions. Given our a priori predictions about the pars opercularis, we focus on region-of-interest (ROI) analyses on data extracted from BA44 of Broca's area, and also on data extracted from two dorsal and ventral clusters (Clusters 1 and 3) within BA44 (Clos et al., 2013), given the known involvement of these pars opercularis subregions in the processing of syntax (Bornkessel et al., 2005; Fiebach et al., 2005; Grewe et al., 2005; Jeon & Friederici, 2013; Makuuchi et al., 2009; Schell et al., 2017). Given evidence from several studies in monolinguals regarding the preferential involvement of the anterior part of BA44 in processing more complex morpho-syntax, we predicted within the BA44 subregions we would find preferential involvement of the anterior-ventral Cluster 3 in the processing of Persian verbs (Schell et al., 2017).

## 2. Methods

### *2.1. Subjects*

Twenty Persian-English late bilinguals participated in this study (8 males, mean of age = 27.25, mean of education = 19 years). They reported having started learning English at school after the age of 12. Their English proficiency level was assessed using a standard proficiency test (Oxford University Press, 2001); their proficiency levels were variable (minimum: 17 (out of 60), maximum: 57, mean: 39.65, SD: 13.24). The participants had normal or corrected to normal visual acuity, and reported no history of neurological or psychiatric disorders. They were all right-handed, as assessed by the Edinburgh Inventory (Oldfield, 1971). Before participation, they gave written consent, and they received monetary compensation for their time spent in the study. The study was approved by the local ethical committee of the brain imaging center of Imam Khomeini Hospital, which is affiliated with Tehran University of Medical Sciences.

### *2.2. Materials*

We selected 64 action pictures and 64 object pictures[2] from both English and Persian naming batteries (Bakhtiar, Nilipour, & Weekes, 2013; Druks & Masterson, 2000; Nilipour, Momenian, Bakhtiar, & Weekes, 2016; Snodgrass & Vanderwart, 1980). We included both transitive and intransitive entities in the action pictures, and animals and tools in the object pictures, both in equal proportion. The stimuli used in Persian and English were exactly the same (see Appendix A for a list of the stimuli used). The psycholinguistic characteristics of both object and action pictures, such as name agreement, visual complexity, AoA, imageability, and familiarity were all matched between languages. The number of phonemes in the stimuli differed between languages since ¾ of the verbs used in Persian condition were LVCs, which, by nature of being longer, had more phonemes compared with their English counterparts.[3]

### *2.3. Experimental design and task*

The conditions (2 languages and 2 grammatical classes) were blocked in this study, and there were two experimental runs. Each run consisted of an alternation of 48 s naming blocks and 15 s rest periods, during which participants looked at a fixation cross. The naming blocks consisted of object or action naming, either in Persian or English. Each experimental block consisted of 16 trials, and during each, a picture lasting 3000 ms was presented on the screen, with no inter-stimulus fixation, and participants were required to generate their verbal response during that time. There were four blocks per condition, for a total of 64 trials per condition. The design was counterbalanced for language: participants were randomly divided in two groups, one starting with Persian and the other with English.

A cued, covert sentence completion task was employed in this study (Abel, Maguire, Naqvi, & Kim, 2014; Momenian et al., 2016; Yu, Bi, Han, & Law, 2013; Zaca, Jarso, & Pillai, 2013). A cue phrase,[4] written above the picture, was simultaneously presented with the object or action picture, and participants were required to complete the description of the picture based on the cue phrase context, as fast as possible. Specifically, for object pictures, participants were required to covertly produce the singular form of the object, and for action pictures, they were required to produce the progressive present form of the action. The cue phrase in the object condition was "This is a/an …", and the cue phrase in the action condition was "He/She/It is ...". A linguistic analysis of sample sentences that participants were expected to produce both in English and Persian is presented in Table 1. Participants were

[2] We are aware that a distinction is made between noun/verb and object/action categories, the former referring to the grammatical class and the latter to the semantic class (Vigliocco, Vinson, Druks, Barber, & Cappa, 2011). We used objects and actions to prompt the generation of speech during the two conditions, however, participants produced speech output in the context of sentences.

[3] Persian has about 200 simple words which are mostly archaic now. Almost all spoken verbs in Persian are LVCs.

[4] The rationale behind providing cue phrases was to decrease task-related processing demands as much as possible. Also, we wanted to make sure that the subject was not dropped in Persian.

**Table 1**
The expected verb and noun forms in the current experiment.

| | Persian | English |
|---|---|---|
| Verb | /mæn dar-æm negah -mi-kon-æm/[a]<br>Transliteration: "I have-Duration-1S watch -Duration-do-1S"<br>Translation: I am watching. | /I am watch-ing/<br>Transliteration: "I 1S-Duration watch-Duration"<br>Translation: I am watching. |
| Noun | /in ketab ast/<br>Transliteration: "This book is"<br>Translation: This is a book. | /This is a book/<br>Transliteration: "This is a book"<br>Translation: This is a book. |

[a] Unlike English where the present progressive tense is formed with 'to be' verbs (I am doing), in Persian 'to have' fulfils this function (I have doing). An auxiliary verb /*daštæn*/, or 'to have', is used before the main verb. Both the auxiliary and the main verb are morphologically marked with the same suffixes for person, number as well as tense.

explicitly instructed and trained in the practice session not to produce the object of the sentence when the verbs were transitive.[5] Written instructions were presented before each run, signalling the language in which the participants were to produce the stimuli.

### 2.4. Procedures

Participants took part in two sessions, with the exception of four individuals who did not participate in the second, behavioural session due to availability reasons. All the instructions were given verbally by the researcher in Persian before the imaging and behavioural sessions. During the first, imaging session, participants first performed 15 min of practice outside the scanner in order to become completely familiarized with the experimental tasks. In order to avoid repetition priming effects, the pictures used during the practice were not the same as those used during scanning. Then, on the same day, participants performed the same tasks with new stimuli during fMRI scanning. The pictures were presented to the participants via a projector in the control cabin, connected to a computer equipped with the Presentation® software (Version 14.9, www.neurobs.com). Participants saw the pictures via a mirror placed on a standard head coil.

During the second, behavioural session, which took place a week later, the same speeded task was used once again outside the scanner, with the same stimuli as used during the brain imaging session, but this time during overt speech production. The purpose of this session was to collect performance data and to thus have an explicit index of performance in the form of response times, in order to be able to draw inferences about differences between the tasks in processing demands. The participants were asked to sit comfortably in front of a PC, and to provide overt responses, which were recorded with a microphone. In both the imaging and behavioural sessions, the order of the language conditions was counterbalanced across participants.

### 2.5. Imaging data acquisition

A Siemens Magnetom Trio 3-T MRI scanner at the brain imaging centre of Imam Khomeini Hospital, Tehran, Iran, was used for the present study. A T2*-weighted gradient- Echo Planar Imaging (EPI) sequence was used for acquiring the Blood Oxygenated Level Dependent (BOLD) fMRI images, using the following parameters: TR = 3000 ms; TE = 30 ms; Field of View (FOV) = 192 mm ; FA = 90°; matrix size = 64 × 64; slice thickness = 3 mm; and voxel size = 3 mm × 3 mm × 3 mm. High-resolution anatomical images (1mm × 1 mm × 1 mm) were also acquired for each participant, using a T1-weighted, 3D MPRAGE (Magnetization-Prepared Rapid Gradient-Echo) sequence (TR = 1800; TE = 3.44; FA = 7°, FOV = 256 × 256).

### 2.6. fMRI data preprocessing and analysis

Functional images obtained for each participant were analysed with SPM12b (Wellcome Trust Center of Neuroimaging, University College London). The first ten functional volumes were discarded to minimize the transition effects of hemodynamic responses. The remaining images were first realigned for motion correction, coregistered, and then spatially normalized to the standard MNI (Montreal Neurological Institute) template. Images were then smoothed using an 8 mm FWHM isotropic Gaussian kernel.

The data for each participant was modelled using a general linear model. Conditions were modelled in a block design, and the BOLD signal was convolved with a standard HRF (Hemodynamic Response Function). For each participant, individual contrast images between the experimental and rest conditions were created, in a first level, fixed-effects analysis, and movement parameter estimates produced by the realignment procedure were entered as regressors at this first level. In this first level analysis, the effects of each of the four conditions (Persian nouns, Persian verbs, English nouns and English verbs) minus rest was estimated. For the whole-brain fMRI analysis (results reported in the Supplementary Materials), the resulting contrast images were then used in a second-level, random-effects analysis. These were analyzed using a 2-way full factorial repeated-measures ANOVA, with the following factors: language (2 levels: Persian and English) and task (2 levels: verb and noun generation).

Given our a-priori predictions for effects of proficiency and of morpho-syntactic complexity in the left and right pars opercularis (BA44) of the IFG, we performed an ROI analysis on percent signal change extracted from this Broca's area sub-region and in its right hemisphere homologue. For this, the ROIs were determined using the left and right Brodmann's areas 44 from the Juelich Histological Atlas (Amunts et al., 1999, 2004), and the Percent Signal Change (PSC) was extracted from these regions for the different experimental conditions using MarsBaR 0.44 (Brett, Anton, Valabregue, & Poline, 2002). These data was then analyzed using a 3-way language by task by hemisphere repeated-measures ANOVA in SPSS (Version 22), and planned comparisons were then performed on the relevant significant interactions.

Based on the results of a meta-analysis on the functional roles of Clusters 1 and 3 within left BA44 in syntax processing, as well as on recent evidence for a central role of the most anterior-ventral Cluster 3 in combinatorial syntactic operations (M. Schell et al., 2017), we performed further ROI analyses on PSC data extracted from these two left BA44 Clusters, again determined using the Juelich Histological Atlas (Clos et al., 2013). These data were then submitted to a 2-way language by task repeated-measures ANOVA in SPSS (Version 22).

## 3. Results

### 3.1. Behavioural results

For the behavioural results obtained during the second testing session outside of the scanner, we discarded trials on which the voice key failed to record (14.38%) and those on which the subjects made a mistake in naming (6.49%) A language by task repeated-measures ANOVA was performed on the response times (i.e. time taken from the moment the picture was shown to the moment the participant started verbalizing). There was a significant main effect of language ($F$ (1, 15) = 28.89, $p < 0.001$, partial eta squared = 0.66), with participants responding more quickly in Persian compared to English. There was also a main effect of task ($F$ (1, 15) = 37.09, $p < 0.001$, partial eta squared = 0.71), with participants responding more quickly in the

[5] We couldn't check this during scanning since the task was performed covertly. However, in the overt behavioural phase of the study where we recorded whether participants were producing the object or not, we did not observe any serious violation. Note that the fact that participants were asked not to produce the objects of transitive verbs may have resulted in a somewhat artificial production scenario, and that it may have introduced some variance in the data (e.g. due to possible differences in how object drop is used across languages).

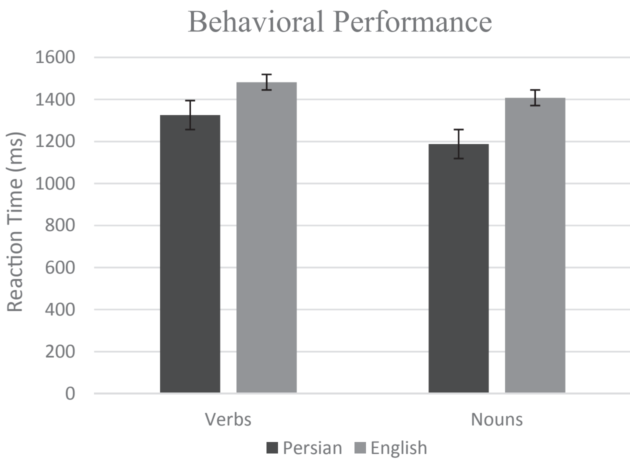


**Fig. 1.** Mean reaction times of behavioural performance across the tasks. Error bars indicate Standard Error of the Mean (SEM).

noun compared to the verb generation condition (see Fig. 1). There was no language by task interaction ($F(1, 15) = 2.70$, $p = 0.12$, partial eta squared = 0.15). The latency difference between verbs and nouns was larger in Persian than in English, but failed to reach significance.

### *3.2. ROI analysis in BA 44*

The language by task by hemisphere repeated-measures ANOVA on the PSC extracted from left BA 44 and its right homologue revealed a significant main effect of hemisphere (hemisphere: $F$ (1, 19) = 34.05, $p < 0.001$, partial eta squared = 0.64), with the left hemisphere showing significantly ($p < 0.001$) higher PSC than the right one. There was also a significant language by task interaction ($F$ (1, 19) = 21.30, $p < 0.001$, partial eta squared = 0.52), see Fig. 2. Planned comparisons were performed, based on the a-priori prediction that PSC would be higher in this ROI during the production of English compared to Persian nouns, but that during verb production PSC would be higher in Persian compared to English. The results revealed that consistent with what was expected, during noun production (see right-most bars in Fig. 2), PSC was significantly higher in English compared to Persian (F(1,19) = 4.403, $p < 0.05$), while during verb production (see left-most bars in Fig. 2), Persian verbs showed higher PSC compared to English verbs (F(1,19) = 6.301, $p < 0.025$). Note that there was a similar pattern of signal change across conditions in the left and right IFG in the whole brain fMRI analysis, despite the fact that the language by task interaction in these regions only revealed a trend for significance (results reported in the Supplementary Material). There were no other significant results in the present 3-way ROI analysis.

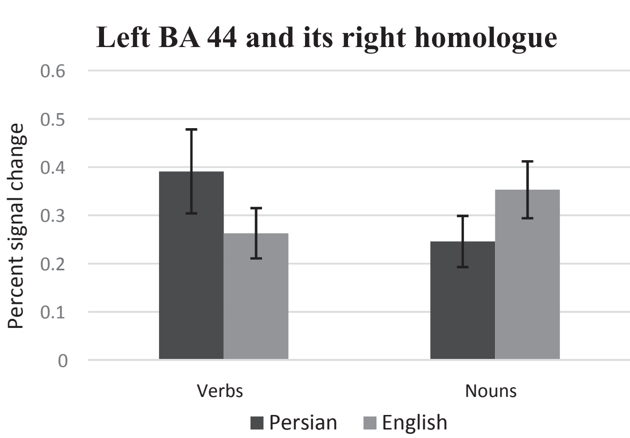


**Fig. 2.** Mean percent signal change in left and right BA 44 across the different experimental conditions. Error bars indicate standard error of the mean (SEM).

### *3.3. ROI analysis in Clusters 1 and 3 within left BA 44*

The results of the language by task repeated-measures ANOVA on data extracted from Cluster 3 revealed a significant interaction between language and task ($F$ (1,17) = 25.09, $p < 0.001$, partial eta squared = 0.61) (see Fig. 3a). Planned comparisons revealed that in this cluster, as predicted, Persian verbs had higher PSC than English ones (F(1,17) = 26.270, $p < 0.001$), and that English nouns had higher PSC than Persian nouns (F(1,17) = 6.880, $p < 0.025$). There were no main effects in the data extracted from Cluster 3. In Cluster 1, the main effect of language was significant ($F$ (1,18) = 4.92, $p < 0.05$, partial eta squared = 0.21), with there being higher PSC in English compared to Persian. There was also a significant language by task interaction ($F$ (1,18) = 5.95, $p < 0.025$, partial eta squared = 0.24). Planned comparisons showed that the difference between English verbs and Persian verbs was not significant (F(1,18) = 1.405, $p > 0.05$), while the difference between English nouns and Persian nouns was significant (F(1,18) = 22.898, $p < 0.001$), with English nouns having higher mean PSC (see Fig. 3b).

## 4. Discussion

In this study on the generation of verbs and nouns in Persian-English bilinguals, we have found that although Persian was the more dominant and proficiently spoken language of our participants, verb generation in this language gives rise to greater activation in BA 44 of Broca's area and in its right hemisphere homologue. These findings are in line with our prediction that due to the higher morpho-syntactic complexity of the Persian verbal system, we would find greater involvement of Broca's area and of its right hemisphere homologue during Persian compared to English verb production. In contrast, and in line with previous work on the effect of language proficiency in bilingual language processing (Golestani et al., 2006; Jeong et al., 2007; Liu et al., 2010; Park et al., 2012), we find that during noun generation, left BA 44 and its right hemisphere homologue are more strongly recruited in the less proficiently spoken second language (i.e. English), likely due to more effortful linguistic processing in the L2. Persian nouns, like in the majority of languages, express only number and person, and are thus similar in terms of morpho-syntactic complexity to English nouns. Also, in line with recent studies showing a role for the anterior ventral portion of left BA44 in processing more complex morpho-syntax (Schell et al., 2017), we find that this dissociation in the modulating effects of complexity and of proficiency is, within the left hemisphere, specific to the anterior-ventral Cluster 3 within BA44.

Our finding of greater activation in BA44, and more specifically in Cluster 3 of this region, during verb production in the more proficiently spoken first language (Persian) is not in line with most neuroimaging studies on bilingualism. These have typically shown greater left IFG activation during the processing of the less proficient or of the later acquired language, likely due to more effortful linguistic processing and to greater cognitive control and working memory requirements. Our findings, based on bilinguals who speak two languages which differ in morpho-syntactic complexity, support the idea that morpho-syntactic complexity can modulate activation in BA44 over and above the influences of proficiency and AoA, with greater activation in this region during processing of more complex morpho-syntactic features. Our results extend previous evidence for a role for the LIFG in processing linguistic complexity within one language (e.g., Ben-Shachar et al., 2003; Ben-Shachar et al., 2004; Caplan, Alpert, & Waters, 1998, 1999; Just, Carpenter, Keller, Eddy, & Thulborn, 1996; Röder, Stock, Neville, Bien, & Rösler, 2002; Stromswold, Caplan, Alpert, & Rauch, 1996) to a cross-linguistic context.

As described in the introduction, the Persian verbal system has distinctive morpho-syntactic features; our findings of greater activation in the left BA 44 of Broca's area and in its homologue may arise from these. Seventy-five percent of the action pictures used in this study were

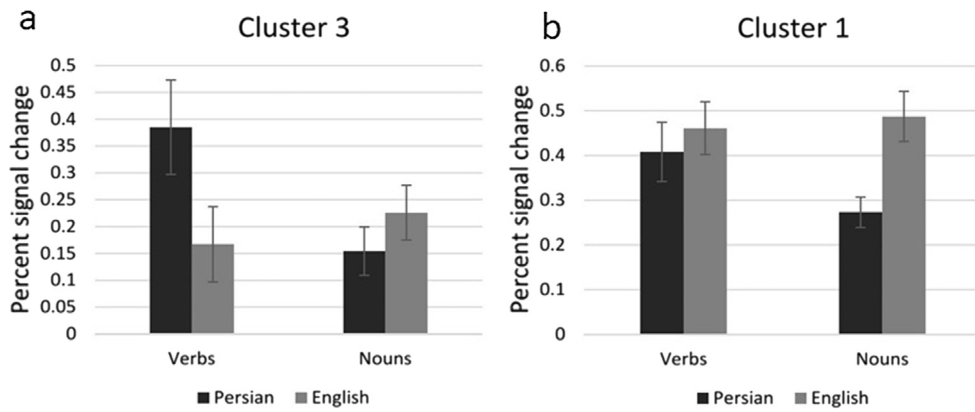


**Fig. 3.** Mean percent signal change in Clusters 3 and 1 ROIs within left BA44 across the different experimental conditions. Error bars indicate standard error of the mean (SEM).

LVCs. Persian LVCs consist of two elements: one nonverbal and one verbal. The nonverbal element can consist of a noun (e.g. */gerye kardan/*, literal translation: "tear-to do", meaning *to cry*), an adjective (e.g. */daagh kardan/*, literal translation: "hot-to do", meaning */to get mad/*), a prepositional phrase (e.g.*/az bar kardan/*, literal translation: "of-on-to do", meaning *to memorize*), an adverbial phrase (e.g. */pish bordan/*, literal translation: "forward-to take", meaning *to succeed*), or a complex nominal phrase (e.g. */sar be sar gozaashtan/*, literal translation: "head-to-head-to put", meaning *to tease*[6]). We expected that the processing of and combining the distinctive morpho-syntactic characteristics of both the nonverbal and verbal elements of Persian LVCs would give rise to more extensive activation in LIFG compared to languages such as English, in which these specific properties are absent. We found support for this prediction in BA44 of the IFG, and more specifically in the anterior-ventral Cluster 3 of left BA44, a Broca's area subregion known to be preferentially involved in syntactic and combinatorial processing (Cooke et al., 2002; Dapretto & Bookheimer, 1999; Fiebach, Schlesewsky, & Friederici, 2001; Friederici, 2002, 2016; Friederici, Meyer, & von Cramon, 2000; Friederici, Meyer, & von Cramon, 2000; Heim et al., 2005; Schell et al., 2017).

We also found evidence for increased recruitment of the right IFG during the production of Persian compared to English verbs. This result supports the idea that morpho-syntactic operations, even in the first language of bilinguals, are also partially subserved by the right BA44, at least when these operations are relatively more complex, as they are in the Persian language. This interpretation is consistent with the results of a recent functional imaging study showing greater bilateral IFG involvement during the processing of more difficult, center-embedded relative constructions compared to during the processing of easier, right-branching relative clause constructions in monolingual children and adults, and in the first language of bilingual children and adults (Jasinska & Petitto, 2013). Other studies have also found involvement of the right IFG in monolingual adults looking at syntactic complexity (Just, et al.. , 1996; Moro et al., 2001) and ambiguity (Snijders et al., 2009), and at linguistic complexity more generally (Jung-Beeman, 2005).

The involvement of the right BA 44 in our and other studies are not fully aligned with the dual-systems framework (Marslen-Wilson et al., 2014), which predicts only left hemispheric activation in this brain region during the processing of complex morpho-syntax. The possible involvement of the right IFG during the processing of more complex morpho-syntax in Persian can, however, arise from other language-related roles of this brain region, which are likely modulated by syntactic complexity. The right IFG has been shown to be involved during linguistic error processing (Indefrey, Hagoort, Herzog, Seitz, & Brown, 2001), but also during the processing of linguistic discourse, which requires meaning unification (Menenti, Petersson, Scheeringa, & Hagoort, 2009), this being an inherent function of syntax in naturalistic language processing. In line with this, the results of a large meta-analysis on 128 studies supports the role of the right IFG in the processing of linguistic context (see also Price, 2010), where its involvement seemed to be related to the recruitment of attentional and working memory areas (Vigneau et al., 2011). Working memory is an inherent component of syntax processing, since for successful syntax processing information needs to be integrated and interpreted across multiple linguistic elements. Thus, results from our and other studies showing involvement of the right IFG in syntactic processing may be related in part to the use of context and to the working memory requirements of syntax.

Numerous studies have also shown the role of the left IFG in verbal working memory (e.g., (Caplan et al., 2000; Fiebach et al., 2005; Hasegawa et al., 2002; Just & Carpenter, 1992; Kaan & Swaab, 2002; Petrides, 2005; Ramnani & Owen, 2004; Thompson-Schill et al., 1997). This brain region has also been shown to be implicated in the processing of higher cognitive load and in selection demands (Abutalebi, 2008; Abutalebi, Della Rosa, Ding, et al., 2013). Given the specific linguistic properties of Persian, it is difficult to determine whether the larger activation of the left BA44 and its right homologue during verb production in Persian is due to processing demands or to language-inherent features. Persian has a subject-object-verb (SOV) word order, with verbs being at the end of sentences by default (Family, 2014; Mahootian, 2010). In our study, sentences were not fully generated but only completed. It may nonetheless be more demanding to process information regarding tense, aspect, number, person and argument structure assignment for the two or more constituents of LVCs during verb generation in Persian. Therefore, it's possible that the higher activity in left BA44 and its right homologue arises from generally higher cognitive load, processing demands and/or working memory requirements during Persian compared to English verb production. This interpretation is in line with previous proposals that because languages often have more morphologically inflected verb than noun forms, performance on verbs may place greater demands on the selection and decision processes known to be subserved by the left IFG (Vigliocco et al., 2006).

Alternatively, it can be argued that general task difficulty differences, ones partly arising also from the longer length of the Persian verbs in our study, underlie our brain imaging findings. However, examination of the pattern of response latencies that we obtained in the behavioural phase of our study lends us to believe that our findings of greater recruitment of BA44 during verb generation in Persian is not driven by general task difficulty differences. In particular, as would be expected based on general task difficulty due to English being the less

[6] Examples provided are taken from Shabani-Jadidi (2015).

fluent language of our participants, the production of English verbs took longer than did that of Persian verbs (see Fig. 1). The activation patterns in bilateral BA44, however, showed the opposite pattern (see Figs. 2 and 3), with higher recruitment of these regions during verb generation in Persian, despite this being the native and thus more proficiently spoken and automated language for our participants.

Our findings in left and right BA44 may arise from the multiple combinatorial requirements of LVCs. In particular, Persian LVCs have two morpho-syntactic combinatorial requirements: (1) at a first stage, the verbal and nonverbal elements of the LVC have to be combined into a single unit, much like as is required in derivational morphology, and (2) at a second stage, inflectional morphology has to be applied to the linguistic unit created at the previous stage. The first stage may be related to more domain general aspects of syntactic processing, while the second is likely to be more specifically aligned with inflectional requirements underlying more complex morpho-syntactic operations. Evidence for recruitment of left BA44 in our study, and more specifically of the anterior-ventral cluster of left BA44 may be related to this latter combinatorial requirement of Persian LVCs. This interpretation of our brain imaging results are aligned with the predictions of the dual-systems framework described in the introduction (Marslen-Wilson et al., 2014; Tyler & Marslen-Wilson, 2008), where it's expected that inflectional morphology will rely on brain regions including the left IFG. Other studies, including ones that have been designed to probe this framework, have also observed more extensive activation of left BA44 with increasing combinatorial load where inflectional morphology was involved (Bozic et al., 2007, 2015; Carota et al., 2016; Klimovich-Gray et al., 2017; Schell et al., 2017). The specificity of our findings to the anterior-ventral Cluster 3 of BA44 is consistent with recent brain imaging findings on variations in combinatorial load within one language (Schell et al., 2017). Our findings are also in line with the results of an event-related potential study, where it was found that there was a processing cost in frontal regions of the brain during the processing of German LVCs compared with non-LVCs (Wittenberg, Paczynski, Wiese, Jackendoff, & Kuperberg, 2014).

While our findings are consistent with those of other studies having examined how language-specific features can modulate neural processing (Jeong et al., 2007; Willms et al., 2011), there are also studies that have not detected neural processing differences during the processing of typologically distinct languages such as English and Chinese (Chee, Hon, Lee, & Soon, 2001; Chee, Tan, & Thiel, 1999; Klein, Milner, Zatorre, Zhao, & Nikelski, 1999). In these latter studies, the negative findings may arise from several factors, the most important being that the tasks employed in these studies did not place specific demands on morpho-syntactic processing.

The findings of the present study have important implications for the literature on the neural bases of bilingual language processing. Until now, the vast majority of studies have suggested that second language proficiency and AoA are the most important variables affecting the neural processing of language (Abutalebi, Della Rosa, Ding, et al., 2013; Chee et al., 2004; Newman, et al., 2012; Perani et al., 2003; Wartenburger et al., 2003). Studies having examined language-inherent properties of the languages under investigation are lacking, and have mainly been examined in monolingual contexts (Finocchiaro et al., 2010; Li et al., 2004). Our results show that language-specific properties can contribute to modulating neural processing over and above the influences of proficiency and of AoA. Future studies on the neural basis of bilingualism will further elucidate the influence of cross-linguistic differences and of language-specific linguistic properties on the neural processing of language.

## Conflict of interest

We have no conflict of interest to declare.

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**Appendix A. List of stimuli (nouns and verbs) used in this study.**

| Noun condition | | Verb condition | |
|---|---|---|---|
| Persian | English | Persian | English |
| تمساح | Alligator | گدایی کردن | Begging |
| مورچه | Ant | دولا شدن | Bending |
| سبد | Basket | گاز گرفتن | Biting |
| خرس | Bear | فوت کردن | Blowing |
| تختخواب | Bed | شانه کردن | Combing |
| زنبور | Bee | آشپزی کردن | Cooking |
| زنگوله | Bell | گریه کردن | Crying |
| کمربند | Belt | بیل زدن | Digging |
| دوچرخه | Bicycle | شیرجه رفتن | Diving |
| پروانه | Butterfly | نقاشی کردن | Drawing |
| شتر | Camel | خواب دیدن | Dreaming |
| کلاه | Cap | سوراخ کردن | Drilling |
| گربه | Cat | رانندگی کردن | Driving |
| زنجیر | Chain | پرواز کردن | Flying |
| صندلي | Chair | اتو کردن | Ironing |
| مرغ | Chicken | شوت کردن | Kicking |
| گاو | Cow | بافتن | Knitting |
| فنجان | Cup | در زدن | Knocking |
| گوزن | Deer | خندیدن | Laughing |
| سگ | Dog | تکیه دادن | Leaning |
| ماهي | Fish | لیسیدن | Licking |
| طبل | Drum | روشن کردن | Lighting |

| | | | |
|---|---|---|---|
| اردک | Duck | رژه رفتن | Marching |
| عقاب | Eagle | باز کردن | Opening |
| فیل | Elephant | رنگ زدن | Painting |
| نرده | Fence | کاشتن | Planting |
| پرچم | Flag | بازی کردن | Playing |
| مگس | Fly | پست کردن | Posting |
| چنگال | Fork | ریختن | Pouring |
| روباه | Fox | کشیدن | Pulling |
| قورباغه | Frog | هل دادن | Pushing |
| لیوان | Glass | باریدن | Raining |
| دستکش | Glove | خواندن | Reading |
| تفنگ | Gun | دویدن | Running |
| چکش | Hammer | شلیک کردن | Shooting |
| اسب | Horse | آواز خواندن | Signing |
| خرچنگ | Lobster | غرق شدن | Sinking |
| كتري | Kettle | نشستن | Sitting |
| بادبادک | Kite | اسکی کردن | Skiing |
| چاقو | Knife | طناب زدن | Skipping |
| نردبان | Ladder | خوابیدن | Sleeping |
| شیر | Lion | سیگار کشیدن | Smoking |
| میمون | Monkey | شنا کردن | Swimming |
| موش | Mouse | راه رفتن | Walking |
| جغد | Owl | شستن | Washing |
| قلمو | Paintbrush | نوشتن | Writing |
| مداد | Pencil | آب شدن | Melting |
| خرگوش | Rabbit | هم زدن | Stirring |
| خروس | Rooster | تایپ کردن | Typing |
| خطکش | Ruler | خدا حافظی کردن | Waving |
| پیچ | Screw | مسواک زدن | Brushing |
| گوسفند | Sheep | چکه کردن | Dripping |
| کفش | Shoe | خوردن | Eating |
| حلزون | Snail | ماهی گیری کردن | Fishing |
| مار | Snake | کوبیدن | Hitting |
| جوراب | Sock | بلند کردن | Lifting |
| عنکبوت | Spider | پوست گرفتن | Peeling |
| قاشق | Spoon | نوازش کردن | Petting |
| چمدان | Suitcase | نواختن | Playing |
| کراوات | Tie | پارو زدن | Rowing |
| ببر | Tiger | بریدن | Cutting |
| چتر | Umbrella | پاره کردن | Tearing |
| چرخ | Wheel | تماشا کردن | Watching |
| گورخر | Zebra | آب دادن | Watering |

## Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.bandl.2018.07.001.

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