

1 **Individual differences in representational similarity of first and second languages in the**
2 **bilingual brain**

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26

27 Abstract

28 Current theories of bilingualism disagree on the extent to which separate brain regions
29 are used to maintain or process one's first and second language. The present study took a novel
30 multivariate approach to address this question. We examined whether bilinguals maintain distinct
31 neural representations of two languages; specifically, we tested whether brain areas that are
32 involved in processing word meaning in either language are reliably representing each language
33 differently, and whether language representation is influenced by individual differences in
34 proficiency level and age of acquisition of L2. Thirty-one English-Mandarin bilingual adults
35 performed a picture-word matching task in both languages. We then used representational
36 similarity analysis to examine which brain regions reliably showed different patterns of activity
37 for each language. As a group, there were no regions that reliably represented languages
38 distinctly. However, both proficiency and age of acquisition predicted dissimilarity between
39 language representations in several brain areas within the language network as well as several
40 regions of the ventral visual pathway, demonstrating that top-down language knowledge and
41 individual language experience shapes concept representation in the processing stream. The
42 results support the model of an integrated language system in bilinguals, along with a novel
43 description of how representations for each language change with proficiency level and L2 age
44 of acquisition.

45 Keywords: bilingualism, word recognition, representational similarity analysis, individual
46 differences

47

48 **1. Introduction**

49 Current theories of bilingual language processing hold that bilingual speakers coactivate
50 their two languages during speech, and that they maintain similar, overlapping representations
51 for both¹⁻⁴. Additionally, past neuroimaging research has provided much evidence that a second
52 language (L2) is processed similarly to the speaker's first language⁵⁻⁹. Even when L1-L2
53 differences exist, such as more extensive activity in L2^{10,11}, there remains extensive overlap⁶.
54 This suggests that similar underlying language networks are engaged regardless of which
55 language is being used. The concept of language coactivation in bilinguals is widely accepted, as
56 is that of a single, integrated lexicon^{12,13}. While neuroimaging provides much support for an
57 integrated lexicon through activation of similar structures, the separation of patterns of activity
58 within the shared L1/L2 brain areas may provide evidence for some degree of distinction
59 between L1 and L2 lexicons.

60 Despite L1 and L2 sharing a network of structures, traditional univariate contrasts cannot
61 tell us how languages are being represented in those areas, and while there is extensive overlap
62 in brain areas that represent L1 and L2^{6,7,9,14}, how the languages are represented may vary. That
63 is, regions coding for language-specific information, such as spoken codes (e.g., left superior
64 temporal gyrus and left inferior frontal gyrus) may represent each language differently. In
65 contrast, regions involved in executive and attentional control (e.g., dorsolateral prefrontal cortex
66 and insula) are likely to show less differentiation in how each language is represented as the
67 function of these regions should not differ qualitatively from one language to another. Individual
68 differences in language ability and experience also play an important role in bilingual language
69 processing^{11,15,16}, and may affect the integration of the neural representation of each language.
70 Previous research indicates that low proficiency speakers and late L2 learners have greater

71 separation of their two languages' conceptual knowledge¹⁷, and this separation may also be
72 reflected in the neural representation of words and concepts within co-activated brain areas.

73 Representational Similarity Analysis (RSA) is an fMRI analysis technique relying on
74 reproducible spatial patterns of activity that correlate with distinct experimental conditions¹⁸,
75 and has been used in the past to identify regions that differentiate between languages during
76 reading¹⁹. RSA has been used to reveal differences between conditions within individual brain
77 regions that were previously undetectable using standard univariate methods; it reveals cortical
78 patterns sensitive to differences in stimuli even when the degree of activation is similar^{20–23}.

79 This technique may be particularly relevant to describing bilingual word processing, as it has the
80 potential to identify differences between languages that were previously thought to not exist.

81 RSA allows us to examine possible language-processing differences in areas that are assumed to
82 be engaged similarly for both languages, suggesting that they are representing L1 and L2
83 differently. Additionally, by measuring individual differences in bilingual experience, it is
84 possible to determine how the neural representation of each language changes with these
85 measures.

86 **Rationale for the Present Study**

87 The present study examined whether brain areas involved in both L1 and L2
88 representationally distinguish the two languages. English-Mandarin bilingual adults performed a
89 lexico-semantic recognition task in each language. We then examined whether brain regions
90 showed reliably different patterns of activity for each language within regions that significantly
91 activated to both. We predicted that, consistent with models of an integrated bilingual lexicon,
92 representational dissimilarity would decrease with increasing proficiency and earlier ages of L2

93 acquisition (AoA). In contrast, areas involved in domain general cognitive processes, such as
94 executive function, were not expected to show language-selective patterns.

95 2. Material and methods

96 2.1 Participants

97 Thirty-two (13 female) neurologically healthy right-handed native speakers of English
98 were recruited via posters and word of mouth in Beijing, China. All participants were second-
99 language learners of Mandarin, aged 18-37 ($M = 23.84$, $SD = 4.59$), and had begun learning
100 Mandarin between the ages of 0-28 years ($M = 18.09$, $SD = 7.10$). This study was approved by
101 the Beijing Normal University research ethics board and all participants gave informed consent
102 prior to participation. Demographic and language information is summarized in Table 1.

Table 1. Participant demographic and language information

Measure	M (SD)
N	32
Sex	13 female, 19 male
Age (years)	23.84 (4.59)
Age of L2 acquisition	18.90 (7.10)
<i>Proficiency (%)</i>	
English	88.93 (5.88)
Mandarin	38.54 (18.15)
<i>Reaction Time (ms)</i>	
English	1203.60 (202.21)
Mandarin	1607.88 (231.78)
<i>Accuracy (%)</i>	
English	94.17 (4.21)
Mandarin	83.07 (10.35)

103

104 2.2 Behavioral tests

105 L1 English and L2 Mandarin proficiency levels were assessed prior to scanning using a
106 subset of 48 questions from the Test of English as a Second Language (ETS, Princeton, NJ) and

107 48 questions from the Hanyu Shuiping Kaoshi (HSK Centre, Beijing, China), respectively. Both
108 tests consisted of three sections, grammar, reading comprehension, and vocabulary, which were
109 combined to give a final score for each language, representing overall proficiency in these three
110 domains.

111 Age of acquisition was obtained by self-report, defined as the age at which individuals
112 first began learning Mandarin. To verify handedness, participants completed an abridged version
113 of the Edinburgh Handedness Inventory²⁴. Behavioral measures, informed consent and task
114 instructions were administered in English, aside from the Mandarin proficiency test, which was
115 administered in Mandarin.

116 **2.3 fMRI Task**

117 Participants completed a picture-word matching task during scanning, in alternating runs
118 of English and Mandarin. Pictures were presented via LCD projector to the center of a screen
119 mounted at the head of the scanner bore, which was viewed through a mirror placed above the
120 head coil. At the same time, a word was played binaurally through insert earphones
121 (Sensimetrics Corporation, Malden, MA). Participants were required to indicate as quickly as
122 possible with a button press whether the picture and word matched. Each picture was visible for
123 2.5 s. They viewed a fixation crosshair between trials as baseline. Stimulus presentation and
124 response recording was controlled with E-Prime software (Psychology Software Tools, Inc.,
125 Sharpsburg, PA) and a Windows laptop.

126 The scanning session was divided into 8 alternating English and Mandarin runs. Four
127 English runs were interleaved with four Mandarin runs, with starting language counterbalanced,
128 so that a run in the first language was always followed by a run in the other language. Four
129 orderings were produced: one version starting with English, one version starting with Mandarin,

130 and an additional version of each in which runs were presented in the reverse order. Each run
131 began with an image reminding participants of which buttons to respond with, and the language
132 in which the next run would be performed. Each run consisted of 20 trials for a total of 160 trials
133 (80 in each language, with 40 matching and 40 mismatching). A short break was provided
134 between each 3.5-minute scanning run. Each image appeared twice during the experiment, once
135 in a matching pair and once in a semantically unrelated mismatching pair. Each trial was 2.5 s in
136 duration, with inter-trial interval jittered between 2.5 and 12.5 s in 2.5 s increments, to optimize
137 the deconvolution of the blood oxygen level dependent signal.

138 Stimulus words consisted of 40 common single-word concepts with the constraint that
139 they are expressed as single two-syllable words in both English and Mandarin, and have
140 frequencies greater than 40 per million in both languages (English: CELEX Lexical Database ²⁵
141 and Mandarin: SUBTLEX-CH ²⁶). In a separate pilot study involving different participants, we
142 asked groups of native speakers of English or Mandarin to rate the imageability and familiarity
143 of the stimulus words, as well as the correspondence of the pictures to target words, on a Likert
144 scale of 1-7. Both groups showed equally high ratings on familiarity ($M_{Mandarin} = 5.78$, $M_{English} =$
145 5.48) and picture/word correspondence ($M_{Mandarin} = 6.08$, $M_{English} = 5.95$).

146 **2.4 Data acquisition and processing**

147 Imaging was conducted on a Siemens Magnetom TIM Trio whole-body 3 Tesla scanner
148 with a 32-channel head coil. T2*-weighted functional scans were acquired in the transverse plane
149 with 45 slices per volume (TR = 2.5 s; TE = 38 ms; flip angle = 80°; FOV = 192 x 192 mm;
150 voxel size 3x3x3 mm³) using an iPAT parallel acquisition sequence (generalized auto-calibrating
151 partially parallel acquisition [GRAPPA]; acceleration factor = 2), providing full coverage of the
152 cerebrum and the superior portion of the cerebellum. A total of 576 functional scans were

153 acquired for each participant over 8 runs (3.5 min per run). After the final functional run, a
154 whole-head high-resolution 3D anatomical scan was acquired in the sagittal plane, using a 3D
155 pulse sequence weighted for T1 contrast (MPRAGE; TR = 2.3 s; TE = 2.98 ms; FOV = 256 x
156 256 mm; voxel size = 1 mm³; 176 slices; GRAPPA acceleration factor = 2).

157 Raw data were converted from DICOM to BIDS format and preprocessed using
158 FMRIprep version 1.0.0²⁷ a Nipype^{27,28} based tool. Each T1 weighted volume was corrected
159 for bias field using N4BiasFieldCorrection v2.1.0²⁹ and skullstripped using
160 antsBrainExtraction.sh v2.1.0 (using OASIS template). Cortical surface was estimated using
161 FreeSurfer v6.0.0³⁰. The skullstripped T1w volume was coregistered to skullstripped ICBM 152
162 Nonlinear Asymmetrical template version 2009c³¹ using nonlinear transformation implemented
163 in ANTs v2.1.0³².

164 Functional data was slice time corrected using AFNI³³ and motion corrected using
165 MCFLIRT v5.0.9³⁴. This was followed by co-registration to the corresponding T1-weighted
166 volume using boundary based registration 9 degrees of freedom - implemented in FreeSurfer
167 v6.0.0³⁵. Motion correcting transformations, T1 weighted transformation and MNI template
168 warp were applied in a single step using antsApplyTransformations v2.1.0 with Lanczos
169 interpolation.

170 Three tissue classes were extracted from T1w images using FSL FAST v5.0.9³⁶. Voxels
171 from cerebrospinal fluid and white matter were used to create a mask in turn used to extract
172 physiological noise regressors using aCompCor³⁷. Mask was eroded and limited to subcortical
173 regions to limit overlap with gray matter, six principal components were estimated. Frame-wise
174 displacement³⁸ was calculated for each functional run using Nipype implementation. For more
175 details of the pipeline see <https://fmripred.readthedocs.io/en/latest/workflows.html>.

176 **2.5 First- and second-level statistics**

177 Single-subject statistical maps were formed in the context of the General Linear Model
178 using AFNI 3dDeconvolve function. Linear trends in the functional data were removed, and
179 first-level analysis was conducted by modeling all English trials together and all Mandarin trials
180 together. The statistical maps were formed in the context of the General Linear Model using
181 AFNI 3dDeconvolve function. Additional regressors were included for the six motion
182 parameters, physiological noise from the preprocessing step, and the response times. This led to
183 one English and one Mandarin output per subject that we used to compute the univariate
184 contrasts. One sample t-tests against zero were then computed for each language (AFNI
185 3dttest++) and a conjunction analysis (AFNI 3dcalc) was performed to identify areas that
186 significantly activated for both English and Mandarin. The result was a conjunction map
187 thresholded at 2.596 ($p = 0.01$ uncorrected); a fairly liberal threshold was used at this stage in
188 order to include as many areas in the search space as possible. A brain mask was then created
189 using the results of this conjunction analysis. Finally, first-level single-subject statistics were
190 recomputed for English and Mandarin, this time creating separate models for even and odd runs.
191 Only correct trials were included in both first-level analyses, with accuracy ranging from 81.25%
192 to 100% correct on the English task and ranging from 61.25% to 96.25% correct on the
193 Mandarin task.

194 **2.6 Split-half correlation searchlight analysis**

195 Searchlight RSA was then performed to identify regions in which the representations of
196 L1 and L2 were reliably different, regardless of groupwise differences in activation levels. The
197 search space for the analysis was constrained to regions within the English-Mandarin
198 conjunction mask, shown in Figure 1. To conduct RSA, a split-half correlation searchlight was

199 performed within the CoSMoMMPA Matlab toolbox³⁹, using a search sphere radius of 3 voxels.
200 Within each searchlight sphere Pearson correlations were performed for activity patterns
201 between even and odd runs, within-language (English-English and Mandarin-Mandarin) and
202 between-language (English-Mandarin), yielding a 2×2 similarity matrix for each individual at
203 each point of the searchlight. Next, the degree of dissimilarity of between-language vs. within-
204 language patterns (on-diagonal vs. off-diagonal) was computed using a pairwise *t*-test based on
205 the difference of Fisher-transformed mean correlations⁴⁰. Significant differences in an area
206 within the searchlight sphere indicated this region differentially encodes L1 and L2. The center
207 of the searchlight was then moved to the next location of the search space, and the statistical
208 analysis was repeated, ultimately yielding a statistical map of all voxels falling within the
209 conjunction map. Analyses were performed using coefficient maps in MNI space. Once single-
210 subject searchlight results were computed, a group statistic was created via a one-sample *t*-test,
211 which identified voxels showing significantly greater representational similarity within-language
212 than between-languages. Next, we computed random-effect cluster statistics corrected for
213 multiple comparison (*cosmo_montecarlo_cluster_stat*) with a mean of zero under the null
214 hypothesis and 10,000 iterations, and significant clusters were converted to *z*-scores.

215 **2.7 Regression with proficiency and age of acquisition**

216 We then conducted linear regression to examine whether AoA and the difference in
217 proficiency level between L1 and L2 predicted the degree of representational dissimilarity
218 within-subject. Two linear models were constructed, the first with the difference in L2-L1
219 proficiency as a continuous regressor and adjusting for AoA, the second with AoA as a
220 continuous regressor and adjusting for the difference in L2-L1 proficiency. The minimum
221 cluster-size threshold was determined in two steps. First, we estimated the smoothness of the

222 residuals for each subject output by 3dDeconvolve using the autocorrelation function (ACF)
223 option (AFNI 3dFWHMx), and the mean smoothness level was calculated. Next, minimum
224 cluster size was determined using a 10,000 iteration Monte Carlo simulation (AFNI 3dClustSim)
225 at a voxelwise alpha level of $p = 0.01$, using bi-sided thresholding and first-nearest neighbour
226 clustering. Correction for multiple comparisons at $p = 0.01$ was achieved by setting a minimum
227 cluster size of 7 voxels.

228 **3. Results**

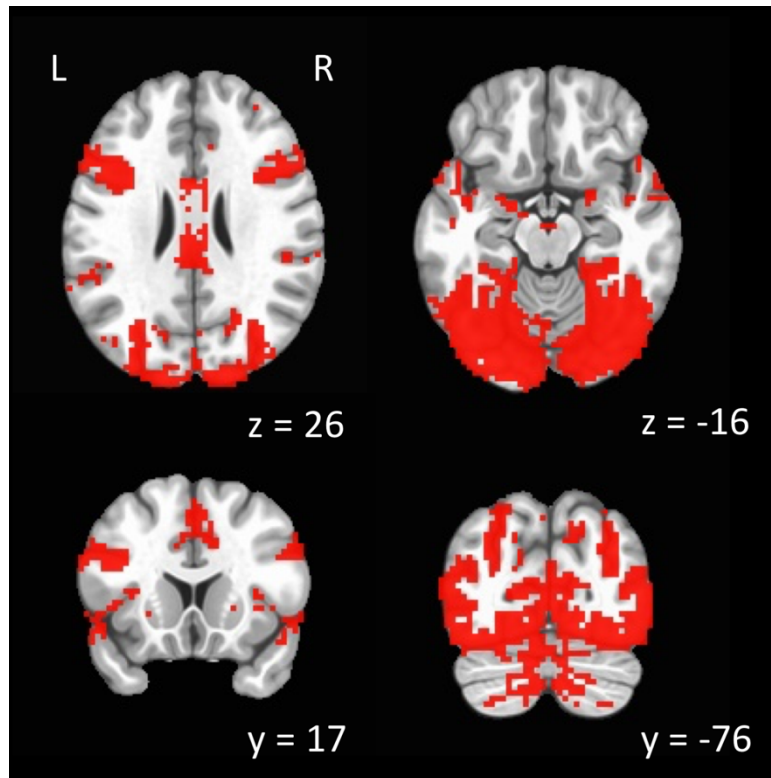
229 **3.1 Behavioural**

230 Performance on the L1 (English) proficiency test ranged from 72.92% to 100%, and
231 performance on the L2 (Mandarin) proficiency test ranged from 12.5% to 77.08%. Analysis of
232 the proficiency test data acquired prior to scanning indicated that L2 proficiency was
233 significantly lower than L1 proficiency ($M = 88.93\%$, $SD = 5.88$, $M = 38.54\%$, $SD = 18.15$,
234 respectively; $t(31) = -15.93$, $p < .001$, 95% CI [43.94, 56.84]). L2 proficiency did not
235 significantly correlate with L2 AoA ($r(30) = -0.21$, $p = .255$). Participants responded faster on
236 English trials than Mandarin trials ($M = 1203.60$ ms, $SD = 202.21$, $M = 1607.88$ ms, $SD =$
237 231.78, respectively; $t(31) = -14.67$, $p < .001$, 95% CI [-460.48, -348.09]) and were more
238 accurate on English trials than Mandarin trials ($M = 94.17\%$, $SD = 4.21$, $M = 83.07\%$, $SD =$
239 10.35; $t(31) = 6.84$, $p < .001$, 95% CI [7.78, 14.40]).

240 **3.2 Conjunction analysis**

241 Results of the conjunction analysis are shown in Figure 1 and Table 2. Both L1 English
242 and L2 Mandarin produced significant activation at a voxelwise p -value of 0.01 (uncorrected) in
243 an extensive network of bilateral brain regions including the Heschl's gyrus, superior temporal
244 gyrus (STG), inferior frontal gyrus (IFG), fusiform and lingual gyri, and occipital and parietal

245 cortices.



246

247 **Figure 1.** Areas that significantly activated for both L1 English and L2 Mandarin at $p = .01$
248 uncorrected. Results are overlaid on a stereotaxic brain in MNI space. L=Left, R= Right.

249

250 3.3 Searchlight with split-half correlation analysis

251 3.3.1 Group-level RSA

252 As a group, no regions showed significantly greater representational similarity within-
253 language (Mandarin-Mandarin and English-English) compared to between-language (Mandarin-
254 English).

255 3.3.2 Regression with proficiency and age of acquisition

256 In order to determine whether proficiency or AoA predicted the degree of difference in
257 representational similarity within- and between-language, subject-wise searchlight maps were

258 submitted to linear regression. L2-L1 Proficiency difference predicted greater within-language
259 representational similarity than between-language similarity in several areas including the left
260 fusiform, IFG, bilateral STG, and right lingual gyrus, shown in Figure 2 and Table 3. All areas
261 showed a positive relationship, indicating that as the difference in proficiency between languages
262 increased, so did the degree of difference in representation between English and Mandarin.

263 The relationship between AoA and representational similarity is shown in Figure 3 and
264 Table 3. AoA positively predicted greater within-language than between-language
265 representational similarity in the left middle temporal gyrus and right inferior occipital gyrus,
266 indicating that later AoAs were associated with larger differences between L1 and L2 in these
267 areas. In contrast, AoA showed a negative correlation with the left inferior parietal lobe and right
268 insula and calcarine sulcus, indicating that earlier AoAs were associated with smaller L1-L2
269 representational differences in these areas.

270

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Table 3. Regions where proficiency or AoA significantly predicted z-score

Predictor	Region	MNI			Voxels	<i>t</i>	<i>p</i>
		coordinates					
		<i>x</i>	<i>y</i>	<i>z</i>			
L2-L1 Proficiency	R Cerebellum	6	-81	-30	35	5.23	< .001
	L Occipital fusiform gyrus	-33	-75	-18	96	4.72	< .001
	L Supramarginal gyrus	-66	-45	21	13	4.2	< .001
	L Precentral gyrus	-33	-9	66	12	4.1	< .001
	L Pars opercularis	-39	3	24	20	4.07	< .001
	R Cerebellum	33	-66	-48	25	4.03	< .001
	R Middle occipital gyrus	51	-81	0	9	3.97	< .001
	L Anterior intra-parietal sulcus	-36	-48	42	9	3.9	.001
	R Primary visual cortex	18	-60	9	26	3.88	.001
	R Inferior temporal gyrus	48	-51	-24	12	3.76	.001
	L Lingual gyrus	-15	-45	-9	13	3.71	.001
	R Supramarginal gyrus	66	-45	24	17	3.7	.001
	R Orbitofrontal cortex	33	33	-3	10	3.63	.001
	L Pars triangularis	-51	33	18	8	3.61	.001
	R Visual cortex ventral V3	21	-78	-6	8	3.51	.001
R Cerebellum	3	-57	-45	7	3.31	.003	
AoA	R Visual cortex ventral V3	42	-93	-6	8	5.09	< .001
	L Middle temporal gyrus	-54	-24	-9	9	4.34	< .001
	L Anterior intra-parietal sulcus	-39	-45	48	15	-3.5	.002
	R Insula	39	21	0	16	-3.46	.002
	R Calcarine sulcus	18	-51	9	8	-3.32	.002

Note. Coordinates denote the location of peak activation. L/R = Left/Right.

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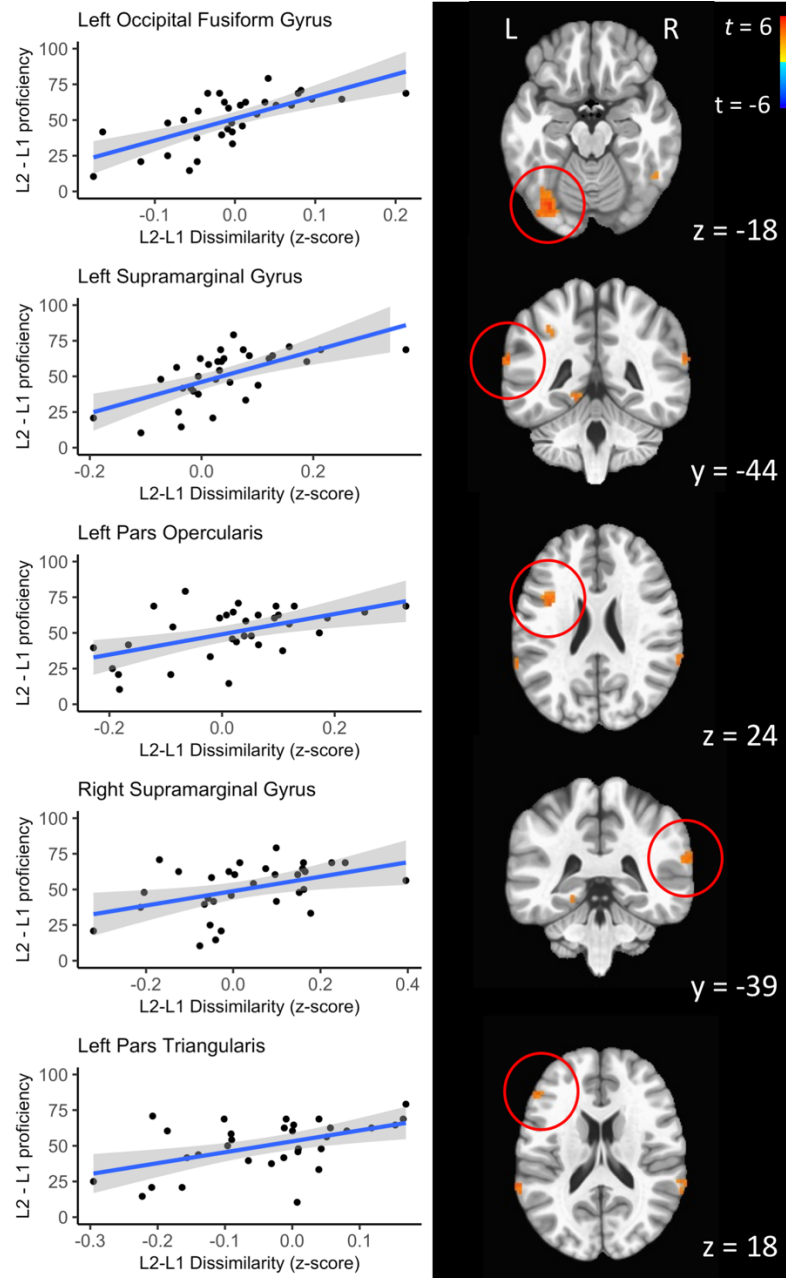
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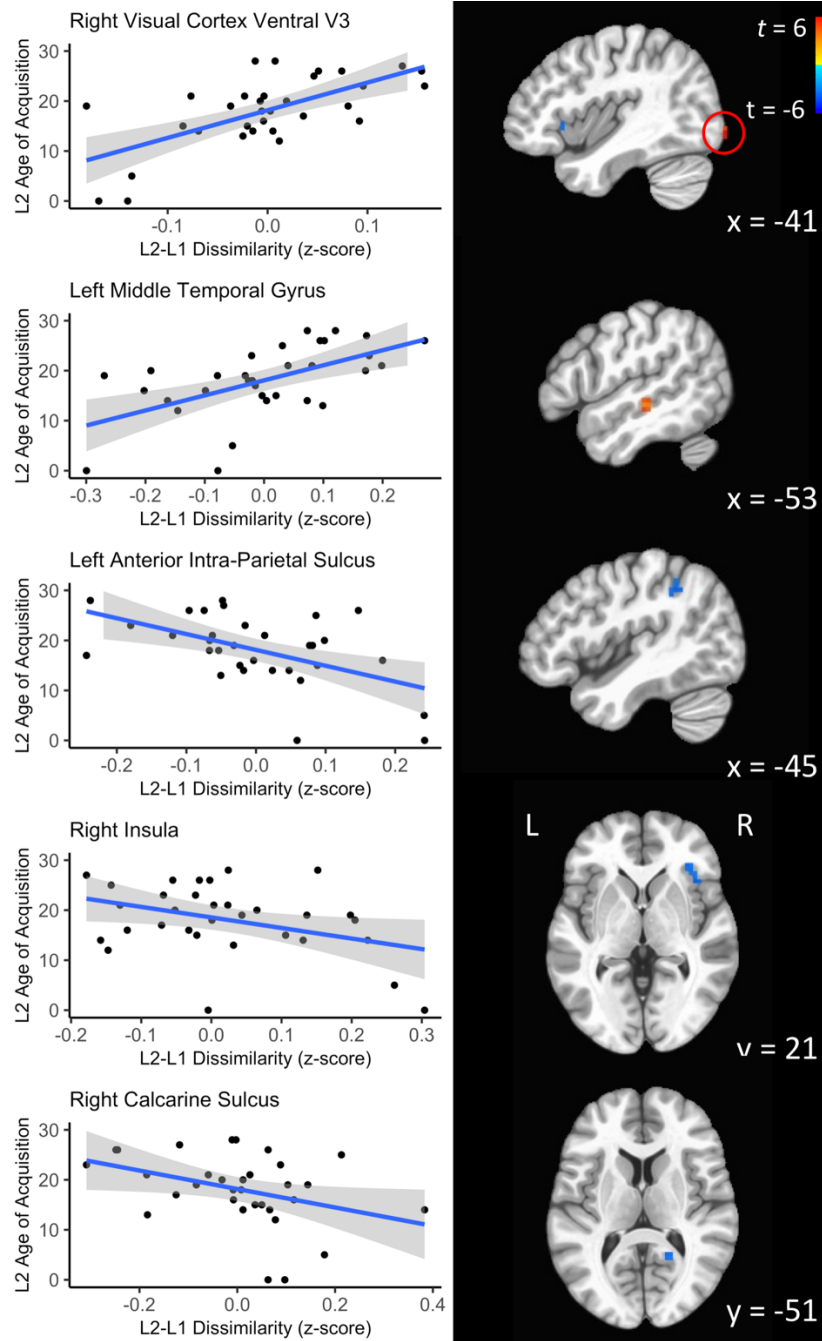
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283 **Figure 2.** The relationship between difference in L2-L1 proficiency and L2-L1 similarity. Z-
284 score values represent the mean across the entire ROI. Higher z-scores indicate greater
285 differences between correlation values between-language vs. within-language. Statistical maps
286 are thresholded at $p = .01$, overlaid on an MNI brain atlas. L = left, R = right. Cluster locations
287 and sizes are reported in Table 3.



288

289 **Figure 3.** The relationship between L2 AoA and L2-L1 dissimilarity. Z-score values represent
290 the mean across the entire ROI. Higher z-scores indicate greater differences between correlation
291 values between-language vs. within-language. Statistical maps are thresholded at $p = .01$,
292 overlaid on an MNI brain atlas. L = left, R = right. Cluster locations and sizes are reported in
293 Table 3.

294

4. Discussion

295

The present study investigated the hypothesis that bilinguals maintain similar,

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overlapping lexical representations for both of their languages. Using a lexico-semantic

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recognition task, we found both similarity and dissimilarity in the representation of bilinguals'

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two languages within the bilingual word recognition network. There were no regions that

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significantly differed in their representation of English and Mandarin at the group level, however

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both proficiency and AoA predicted the degree of representational similarity in several areas.

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That is, individual differences predicted differentiation in the representation of bilinguals' two

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languages in areas that were significantly activated during the word recognition task in both

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Mandarin and English. These results extend behavioral and ERP findings that bilinguals have a

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single, integrated lexicon^{12,41-43}, demonstrating how the neural representations within activated

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regions change with language experience. While prior meta-analyses and reviews have argued

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this on the basis of relative intensity of fMRI activity^{6,12}, degree of activation cannot tell us

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about how each language is being represented.

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Consistent with our hypotheses, several regions of the language network showed patterns

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of representation that differentiated languages depending on individual differences. For example,

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one of these regions was the left IFG (including both the pars opercularis and the pars

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triangularis), an area engaged in representing and planning articulatory codes for speech and tone

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⁴⁴⁻⁴⁷. Indeed, these features differ between English and Mandarin in that each language has

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phonological features that are not present in the other (e.g., tone in Mandarin, consonant clusters

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in English). The left IFG showed greater representational similarity between languages when the

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difference between L1 and L2 proficiency was smaller, suggesting that as bilinguals become

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more matched in proficiency across their two languages, the phonological representations

317 become more integrated. Similarly, language similarity within the bilateral supramarginal gyrus
318 was greater with smaller proficiency differences, an area important for auditory-motor
319 integration during word recognition ⁴⁸.

320 One notable result was that of representational dissimilarity in lower L2 proficiency and
321 later AoA speakers throughout the ventral visual stream, a cortical pathway responsible for
322 object recognition and concept representation ⁴⁹. The separate representation in visual areas is
323 especially interesting as participants in the present study saw the same images in each language;
324 the manipulation here was only the language in which they heard the names of these objects. As
325 a result, language-dependent differences in this region indicate that this reflects a top-down
326 modulation of high-level visual processing by the linguistic input. Although visual processing of
327 the same images may appear to be a domain-general process, support for it being language-
328 specific comes from the label-feedback hypothesis, which suggests that language modulates
329 ongoing cognitive and perceptual processing ⁵⁰. In line with this hypothesis, each language's
330 verbal label for the paired image influences the perception of that image. Thus, while the image
331 remains the same, the top-down influence of the language is producing separable representations
332 in high-level visual areas, distinguishing between the visual perception of the spoken word *table*
333 vs. that of the spoken word 桌子 (the Mandarin word for *table*).

334 There have been numerous studies showing activation differences between L1 and L2,
335 showing greater activation in language areas for one language versus another ^{7,51,52}, or showing
336 additional areas recruited for L2 processing vs. L1 processing ⁹. These differences have largely
337 been attributed to later acquisition of L2, differences in proficiency, or other external factors
338 affecting how L2 was acquired ^{6,51,53}. In contrast, matched bilinguals tend to show overlapping
339 activity in language regions, with little or no differentiation between languages at the univariate

340 level^{54–56}. L2 speakers in the present study showed experience-dependent representational
341 differences between L1 and L2 in both the language network as well as throughout the ventral
342 visual stream, providing further evidence for integration of bilinguals' two languages but only
343 when speakers are matched in ability across those two languages.

344 **Conclusion**

345 We investigated first and second language representation in English-Mandarin bilinguals.
346 Using RSA, we identified both regions in which individual differences predicted differentiation
347 in representation between English and Mandarin. Experience-modulated within-language
348 representational similarity was present in language-network areas (e.g., portions of the left IFG)
349 as well as several regions of the ventral visual pathway, indicating that top-down language
350 knowledge shapes concept representation in the processing stream.

351 A logical extension of present study is the examination of representational differences in
352 different types of second language processing. For instance, results may differ when comparing
353 two languages that are more similar than English and Mandarin, such as Spanish and French, or
354 when using items that vary in similarity, such as cognates and non-cognates. Additionally, word
355 processing does not involve grammatical processing, which is also an important aspect of
356 bilingual language processing that can differ greatly between L1 and L2. Univariate approaches
357 that contrast degree of brain activation may miss important differences in this regard. The
358 multivariate approach used here may thus provide a way forward in our ability to fully discern
359 how L1 and L2 are represented in the brain.

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365

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367

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