



HAL
open science

Neural correlates of semantic number: A cross-linguistic investigation

Donald Dunagan, Shulin Zhang, Jixing Li, Shohini Bhattasali, Christophe Pallier, John Whitman, Yiming Yang, John Hale

► To cite this version:

Donald Dunagan, Shulin Zhang, Jixing Li, Shohini Bhattasali, Christophe Pallier, et al.. Neural correlates of semantic number: A cross-linguistic investigation. *Brain and Language*, 2022, 229, pp.105110. 10.1016/j.bandl.2022.105110 . hal-03849542

HAL Id: hal-03849542

<https://hal.science/hal-03849542>

Submitted on 11 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

Neural correlates of semantic number: A cross-linguistic investigation

Donald Dunagan^{a,*}, Shulin Zhang^a, Jixing Li^b, Shohini Bhattasali^c,
Christophe Pallier^d, John Whitman^e, Yiming Yang^f, John Hale^a

^a*Department of Linguistics, University of Georgia, GA, USA*

^b*Neuroscience of Language Lab, New York University Abu Dhabi, Abu Dhabi, UAE*

^c*Department of Linguistics, UMIACS, University of Maryland, MD, USA*

^d*Cognitive Neuroimaging Unit, INSERM-CEA, Gif-sur-Yvette, France*

^e*Department of Linguistics, Cornell University, NY, USA*

^f*Jiangsu Normal University, Xuzhou, Jiangsu, China*

Abstract

One aspect of natural language comprehension is understanding how many of what or whom a speaker is referring to. While previous work has documented the neural correlates of general number comprehension and quantity comparison, we investigate semantic number from a cross-linguistic perspective with the goal of identifying cortical regions involved in distinguishing plural from singular nouns. We use three fMRI datasets in which Chinese, French, and English native speakers listen to an audiobook of a children's story in their native language. We select these three languages because they differ in their number semantics. While Chinese lacks nominal pluralization, French and English nouns are overtly marked for number. We find a number of known semantic processing regions in common, including dorsomedial prefrontal cortex and the pars orbitalis, in which cortical activation is greater for plural than singular nouns and posit a cross-linguistic role for number in semantic comprehension.

Keywords: Neurolinguistics, Semantics, Typology, Number, Cognitive Neuroscience

*Corresponding author at: Department of Linguistics, 142 Gilbert Hall, University of Georgia, Athens, GA 30602-6205, USA

Email address: dgd45125@uga.edu (Donald Dunagan)

1. Introduction

One aspect of natural language comprehension is understanding how many of what or whom a speaker is referring to. While much work has been done to document the neural correlates of general number comprehension and quantity comparison (e.g., Castelli et al., 2006; Dehaene et al., 2003; Kadosh & Walsh, 2009), the neural correlates of semantic number are less well understood. We use the term *semantic number* because not all of the languages which we consider morpho-syntactically mark number. More detail regarding our terminological definitions and the semantics of number is given in section 1.3. Cross-linguistically, languages with singular/plural nominal¹ contrast tend to mark plural forms morphologically, but not mark singular forms (Corbett, 2000; Greenberg, 1963). In the semantics literature, de Swart & Farkas (2010) propose a weak singular/strong plural (unmarked singular/marked plural) account of the singular/plural contrast which respects Horn’s division of pragmatic labor (cf. Van Rooy, 2004). This is to say, in this account, plurality is morphologically and semantically marked and singularity is not. As the non-default form, we expect plural nouns to be more difficult to process than singular nouns. The first question we address is: “As measured with fMRI, do plural nouns elicit greater cortical activity than singular nouns?”

1.1. Number sense

One possibility which we consider is that semantic number will be subserved by the same system which subserves human *number sense*, “a short-hand for our ability to quickly understand, approximate, and manipulate numerical quantities” (Dehaene, 2001, p. 2). Natural numbers are thought to be represented as analog magnitudes along a *mental number line*. Dehaene (1992) proposes a tripartite account of number sense in the human brain. In this *triple-code* model, three portions of the parietal lobe perform different roles in number processing (Dehaene et al., 2003). The horizontal segment of the intraparietal sulcus serves

¹Nominal is used as a cover term for noun phrases and determiner phrases.

as the location of the mental number line and is augmented by an angular gyrus
30 verbal system and a posterior, superior parietal visual and attentive system.

1.2. *Language-specific versus domain-general processing*

Carreiras et al. (2010) ask if numerical processing is activated by grammatical number processing and, for stimuli with grammatical number violations, find an increase in activation in parietal regions previously implicated in number processing (Dehaene et al., 2003). Portions of the prefrontal and parietal
35 cortices, known as the multiple-demand (MD) network (Duncan, 2010), have been found to be responsive to a wide variety of cognitive demands such as: verbal and spatial working memory, the Stroop task, and important to this paper, an arithmetic task (Fedorenko et al., 2013). On one hand, these regions
40 have been shown to not track linguistic input as closely as language-selective regions (Blank & Fedorenko, 2017), and Fedorenko et al. (2011) find little or no overlap between cortical regions engaged in high-level linguistic processing and MD regions which respond to general working memory, cognitive control, and importantly here, mental arithmetic. On the other hand, Carreiras et al. (2010)
45 identify a link between number in language and general number in the brain. Our next question, then, is: “If plural nouns elicit greater cortical activity than singular nouns, do these regions of increased activation align with regions known for quantity and arithmetic processing or with regions that that are known for linguistic processing?”

50 1.3. *Formal semantic motivations*

Number in language is made a more interesting topic because languages can differ in their number semantics. We now review the semantics which underlie the three-way typological contrast which motivates our parallel analysis of Chinese, English, and French data. In this paper, we operate under a simplistic
55 account of the semantics of number in which singular nominals refer to individuals and plural nominals refer to sets of individuals (but see Rullmann, 2002; de Swart & Farkas, 2010, for more detailed accounts). In the proposal by Link

(1983), the entity domain to which nominals refer is a join-semilattice. Atoms are individuals and the non-atomic elements are the possible sums of multiple
60 atoms. In these terms, singular nominals choose referents from the domain of atoms and plural nominals chose referents from the domain of sums. We also consider nominals with general number (Corbett, 2000). These are nominals which are “neutral” or “unspecified” for number. Rullmann & You (2006) describe a system for languages with general number, like Mandarin Chinese², in
65 which atoms generate a complete semilattice and nouns choose referents from the domain of atoms and sums. It is important to note that nominals with general number are not ambiguous between singular and plural readings (see Rullmann & You, 2006, for additional discussion). Their number interpretation might best be given in English as, “one or more *X*.” We distinguish semantic
70 number from grammatical number, which is a grammatical category and which is expressed either through morphology or syntax.

A count noun (e.g., *cat*) is a noun which may be directly modified by a cardinal numerical and a mass noun (e.g., *sand*) is a noun which cannot. While (1a) is perfectly acceptable, (1b) is not acceptable on the intended reading. There is
75 a connection between the count/mass distinction and the counting/measuring distinction. While count nouns are counted (1a), mass nouns are measured (1c). It is not the case, however, that all languages make the count/mass distinction.

- (1) a. two cats
b. #two sands
80 c. three buckets of sand

Chierchia (1998) proposes the Nominal Mapping Parameter, which creates a three-way typological classification for languages based upon how they express counting. Chierchia’s account is neo-Carlsonian, that is, it is based upon Carlson’s (1977) investigation of bare plurals in English. Bare nouns are nouns
85 which occur without a determiner or a classifier. This account proposes that

²From here forward, we will simply say Chinese.

nouns can either be predicates at type $\langle e, t \rangle$, in which they denote a set of entities, or be arguments at type e , in which they denote kinds. The terms *predicate* and *argument*, here, are names for the semantic types $\langle e, t \rangle$ (functions from individuals to truth values) and e (entities of argumental type), respectively.

90 Kinds are generally understood as regularities. For the property of being a cat, there is a corresponding kind: the cat-kind. In the other direction, a kind will have a property with which it corresponds: the property of belonging to the kind.

A noun (N) may fill an argument position if it is an argument, but if it

95 is a predicate, it must combine with a determiner to reach the argument type. Chierchia's classification, then, is whether nouns in a language can occur as arguments, predicates, or both. From the features [+/-predicate] and [+/-argument], there are three possible language types: [+predicate, +argument], [-predicate, +argument], and [+predicate, -argument]. The type [-predicate, -argument] is

100 not valid. English is [+predicate, +argument], Chinese is [-predicate, +argument], and French is [+predicate, -argument]. Chierchia argues that a language will have morphosyntactic properties based upon its features. The following section reviews these properties with data from Rothstein (2017, pp. 147-148).

With English being [+predicate, +argument], the nouns of English are either

105 [+predicate] or [+argument]. Count nouns are predicates and mass nouns are arguments. Because they are predicates, singular count nouns must combine with a determiner to fill an argument position and it is predicted that bare singular count nouns are ungrammatical (2a). Plural count nouns can be shifted such that they yield a kind reading and thus can occur as bare arguments.

110 Mass nouns can occur bare in argument position (2b).

- (2) a. I saw #(a) dog.
b. I bought wine.

Chinese allows for noun phrases (NPs) consisting of bare nouns without classifiers, number morphemes, or other functional elements. Like other classifier

115 languages, Chinese is [-predicate, +argument]. In these languages, bare nouns

can occur as arguments (3). While nouns may occur bare, they may not be directly modified by cardinal numerals. Instead of directly taking bare nouns as complements, numerals take classifier (Cl) + N sequences (4).

- (3) a. wǒ kànjiàn gǒu le.
I see dog PART³
120 ‘I saw a dog/dogs, the dog(s).’
- b. wǒ mǎi le jiǔ.
I buy PFV⁴ wine
‘I bought wine.’
- (4) a. sān #(zhī) gǒu
three Cl_{small animal} dog
‘three dogs’
- 125 b. liǎng #(kē) shù
two Cl_{plant} tree
‘two trees’

In an analysis of bare noun phrases in Chinese, Yang (2001) identifies the same readings identified by Carlson (1977) for English bare plurals: kind, generic, and narrowest-scope indefinite. While French and English necessarily mark definite
130 NPs with determiners, Chinese does not have determiners and bare NPs have definite readings that are not available in English. Since all nouns have the same properties, and no N can be directly modified by a numeral, there is no clear way to differentiate mass and count nouns grammatically. As compared to languages with mass/count distinction ([+predicate, +/- argument]), Chierchia’s (1998)
135 view is that in [-predicate, +argument] languages, every lexical noun is mass-like. Because the plural operator does not apply to kind or mass terms, classifier languages do not have nominal pluralization. Bare nouns in these languages have a number interpretation which is general and includes the plural (3a).

French, like other Romance languages, is [+predicate, -argument] and makes

³Particle

⁴Perfective

140 the count/mass distinction. Count nouns will be marked either singular or plural
and all nouns (both count and mass) must occur with a determiner (5).

(5) a. J'ai vu #(un) chien.
I AUX⁵ saw a dog
'I saw a dog.'

b. J'ai acheté #(du) vin.
I AUX bought some wine
145 'I bought (some) wine.'

Interestingly, French is slightly more strict with its determiner requirement than Spanish and Italian which allow for bare plurals in well-governed conditions such as object (but not subject) position. The allowed bare plurals do not have kind or generic readings, though. Because English is [+predicate, +argument], its
150 count nouns are similar to French nouns and its mass nouns are similar to Chinese nouns.

1.4. Neural, cross-linguistic similarities and differences

While neural, cross-linguistic differences have been found in domains such as phonological access in a reading task (Paulesu et al., 2000), pitch contour
155 processing (Gandour et al., 2003), and nominal and verbal representation (Li et al., 2004), similarities have been found for syntactic processing (see Obleser et al., 2011; Pallier et al., 2011, for German and French results, respectively) and comprehending linguistic content (Honey et al., 2012). Our final question, then, is: "Although they differ in their number semantics, if French, English,
160 and Chinese display increased activation for plural nouns over singular nouns, does that activation occur in the same or different regions?"

⁵Auxiliary

2. Data and Methods

2.1. Participants

The English dataset includes 51 healthy, right-handed, young adults (32 female, mean age = 21.3, range = 18-37). They self-identified as native English speakers, and had no history of psychiatric, neurological or other medical illness that could compromise cognitive functions. All participants were paid and gave written informed consent prior to participation, in accordance with the guidelines of the Human Research Participant Protection Program at Cornell University.

The French dataset includes 30 healthy, right-handed adults (age range = 20-40). They self-identified as native French speakers and had no history of psychiatric, neurological, or other medical illness that could compromise cognitive functions. All participants gave written informed consent prior to participation, in accordance with the guidelines of the Regional Committee for the Protection of Persons involved in Biomedical Research.

The Chinese dataset includes 35 healthy, right-handed, young adults (15 female, mean age = 19.3, range = 18-25). They self-identified as native Chinese speakers and had no history of psychiatric, neurological, or other medical illness that could compromise cognitive functions. All participants were paid and gave written informed consent prior to participation, in accordance with the guidelines of the Ethics Committee at Jiangsu Normal University.

2.2. Stimuli

The French audio stimulus is an audiobook version of *Le Petit Prince* (*The Little Prince*, de Saint-Exupéry, 1946), read by Nadine Eckert-Boulet. The English audio stimulus is an English translation of *The Little Prince*, read by Karen Savage. The Chinese audio stimulus is a Chinese translation of *The Little Prince*, read by a professional female Chinese broadcaster.

The English, French, and Chinese audiobooks are 94, 98, and 99 minutes in length, respectively. The presentations were divided into nine sections, each

lasting around ten minutes. Participants listened passively to the nine sections and completed four quiz questions after each section (36 questions in total). These questions were used to confirm participant comprehension of the story.

2.3. Data collection and preprocessing

195 The English and Chinese brain imaging data were acquired with a 3T MRI GE Discovery MR750 scanner with a 32-channel head coil. Anatomical scans were acquired using a T1-weighted volumetric magnetization prepared rapid gradient-echo pulse sequence. Blood-oxygen-level-dependent (BOLD) functional scans were acquired using a multi-echo planar imaging sequence with online re-
200 construction (TR = 2000 ms; TE's = 12.8, 27.5, 43 ms; F = 77°; matrix size = 72 x 72; FOV = 240.0 mm x 240.0 mm; 2 x image acceleration; 33 axial slices, voxel size = 3.75 x 3.75 x 3.8 mm).

The English and Chinese fMRI data were preprocessed using AFNI version 16 (Cox, 1996). The first 4 volumes in each run were excluded from analyses to
205 allow for T1-equilibration effects. Multi-echo independent components analysis (ME-ICA, Kundu et al., 2012) was used to denoise data for motion, physiology, and scanner artifacts. Images were then spatially normalized to the standard space of the Montreal Neurological Institute (MNI) atlas, yielding a volumetric time series resampled at 2 mm cubic voxels.

210 The French brain imaging data was collected with a Siemens Prisma Fit 3T scanner. T1-weighted anatomical images were acquired with a 1 mm isotropic resolution. The EPI functional images were acquired with a resolution of 3.75 x 3.75 x 3.8 mm (34 axial slices with an interleaved acquisition scheme). The 3 echo times were 10 ms, 25 ms, and 38 ms. Preprocessing was performed
215 with ME-ICA (Kundu et al., 2012) using the default parameters and spatial normalisation was done in MNI space. The final volumetric time series consists of 3.15 mm cubic voxels.

2.4. Observations of interest

In order to control for discourse factors which could modulate neural activity
220 during naturalistic language processing, we align the storybook texts and select

only parallel nouns for analysis, that is, nouns which occur in all three stories and in the same context. The first step in this process is aligning sentences, which is done with the Hunalign bilingual sentence aligner (Varga et al., 2007). The alignments were checked and corrected by hand. Next, we identify the parallel
225 nouns and filter the triplets with criteria which serve to maximize typological contrast between French, English, and Chinese nominals.

For the Chinese observations, we include only nouns which have no overt number marking, either morphological or through a number and classifier construction. This captures the [+argument] aspect of Chinese. For the French
230 observations, we include only count nouns indexed by the definite, common determiners: *le*, *la*, *l'*, and *les*. This captures the [+predicate] aspect of French and its requirement that definite nouns be marked with a definite determiner. For the English observations, we include only count nouns, but allow them to be definite, indefinite, or type-shifted bare plurals. This capture the [+predicate,
235 +argument] aspects of English.

While number annotation can be automated for the French nouns: *le*, *la*, and *l'* are singular and *les* is plural, and English count nouns are easily annotated for number based upon their overt number morphology, annotation for the Chinese nouns is more challenging because number is not overtly marked. Recall that
240 Chinese bare nominals are not ambiguous between singular and plural readings, but it is possible that different listeners will have different judgements. Because of this, we have two native Chinese speakers annotate the Chinese nouns with singular/plural judgments. Calculating Cohen's kappa coefficient (Cohen, 1960), a measure of inter-rater reliability, over the Chinese annotations results
245 in a $\kappa = 0.96$, a high degree of inter-rater reliability. We do not use any nouns in the analysis for which the two annotators disagreed in their number judgements.

The time resolution for all three of the fMRI data sets is 2.0 seconds, much slower than a natural speech rate. Because of this, we remove observations
250 where nouns of different number would occur together within the same volume. That is, if more than one singular noun occur in the same volume or if more than

one plural noun occur in the same volume, they are retained. If a singular and plural noun occur in the same volume, however, they are not kept for analysis. After this, we end up with 274 parallel observations: 245 singular and 29 plural
255 in the Chinese text, 245 singular and 29 plural in the French text, and 244 singular and 30 plural in the English text.

2.5. *Statistical analyses*

We run separate English, French, and Chinese general linear model (GLM) analyses using Nilearn (Abraham et al., 2014; Pedregosa et al., 2011, version
260 0.7.1). For the English and Chinese analyses, at the first level, we include binary regressors for singular and plural nouns as well as coregressors of non-interest for spoken word rate, log lexical frequency, root mean squared amplitude of the spoken narration (RMS), and speaker pitch. Speaker pitch is not available for the French audiobook, but all of the other coregressors are used. The core-
265 gressors are added to ensure that any results found are due to the differences between singular and plural nouns and not just effects of spoken language comprehension (cf. Bullmore et al. 1999; Lund et al. 2006). The singular and plural noun regressors are marked with a 1 at the offset of the nouns of interest, word rate is marked with a 1 at the offset of every word, except for the observations
270 of interest, log lexical frequency is marked at the end of every word, and RMS and pitch are marked every 10 ms.

Following the weak singular/strong plural (unmarked singular/marked plural) semantic account of number proposed by de Swart & Farkas (2010) (at least for French and English which make this distinction), our first-level contrast subtracts activity associated with singular nouns away from activity associated with plural nouns. At the second level, the first level contrast maps are used to perform one-sample t-tests. We apply an 8 mm full width at half maximum Gaussian smoothing kernel to counteract inter-subject anatomical variation. The by language, group-level results reported in the following section
275 underwent family-wise-error (FWE) voxel correction for multiple comparisons and are reported in terms of z-score. We only retain clusters greater than 100

mm³. Additionally, because we want to identify any common regions of increased activation between the three languages, we report the overlap of the separate results. The MNI2TAL tool from the Yale BioImage Suite⁶ (Lacadie
285 et al., 2008a,b, version 1.4) was referenced for brain region and Brodmann area labels.

3. Results

3.1. Chinese results

For the Chinese participants, we find an increase in activation for plural
290 nouns over singular nouns in the left pars triangularis (BA 45) and left pars orbitalis (BA 47), extending into left dorsolateral prefrontal cortex (BA 46), in left dorsomedial prefrontal cortex (BAs 8, 9), the left fusiform (BA 37), angular (BA 39), and middle temporal (BA 21) gyri, and the right cerebellum. These results can be seen in Fig. 1a and more detail can be found in Table 1.

⁶<https://bioimagesuiteweb.github.io/webapp/mni2tal.html>

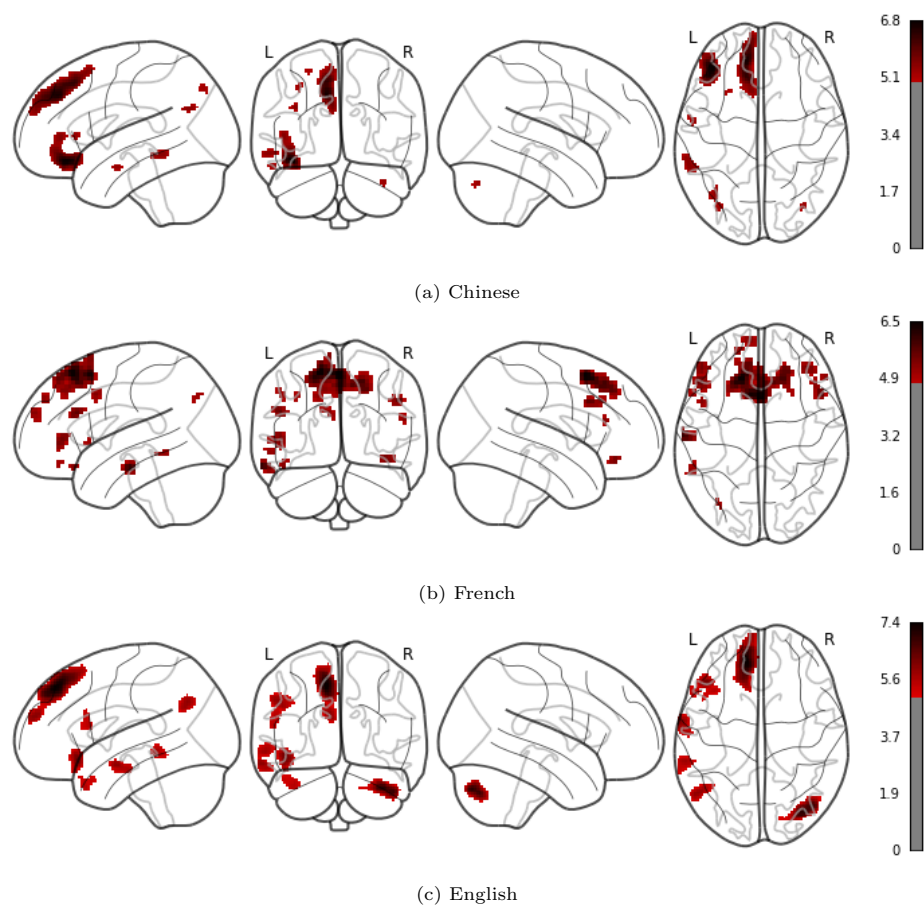


Figure 1: Significant clusters for PLURAL > SINGULAR contrast (z-valued) after FWE voxel correction for multiple comparisons with $p < 0.05$, cluster size $> 100 \text{ mm}^3$ for Chinese (a), French (b), and English (c).

Region	Cluster size (mm ³)	MNI coordinates			Peak stat (z)
		x	y	z	
L Pars Orbitalis (BA 47)	4936	-40.0	38.0	-16.0	6.85
L Dorsolateral Prefrontal Cortex (BA 46)		-46.0	42.0	2.0	5.62
L Dorsomedial Prefrontal Cortex (BA 9)	6952	-12.0	44.0	38.0	6.70
L Dorsomedial Prefrontal Cortex (BA 8)		-10.0	30.0	48.0	6.45
		-8.0	20.0	56.0	5.64
Left Fusiform Gyrus (BA 37)	768	-60.0	-42.0	-12.0	5.54
Left Angular Gyrus (BA 39)	304	-36.0	-64.0	26.0	5.54
Left Middle Temporal Gyrus (BA 21)	192	-56.0	-6.0	-22.0	5.44
L Pars Triangularis (BA 45)	208	-46.0	28.0	4.0	5.39
R Cerebellum	136	36.0	-76.0	-36.0	5.39
L Angular Gyrus (BA 39)	176	-34.0	-78.0	44.0	5.33
L Dorsal Prefrontal Cortex (BA 8)	104	-26.0	18.0	56.0	5.21

Table 1: Significant PLURAL > SINGULAR clusters for Chinese after FWE voxel correction for multiple comparisons with $p < 0.05$, cluster size $> 100 \text{ mm}^3$.

295 *3.2. French results*

For the French participants, we find an increase in activation for plural nouns over singular nouns in the left and right pars opercularis (BA 44), left pars triangularis (BA 45), left and right pars orbitalis (BA 47), left (BAs 8, 9, 10) and right (BA 8) dorsomedial prefrontal cortex, left (BAs 8, 46) and right
300 (BA 9) dorsolateral prefrontal cortex, and the left middle temporal (BA 21), fusiform (BA 37), and angular (BA 39) gyri. These results can be seen in Fig. 1b and more detail can be found in Table 2.

Region	Cluster size (mm ³)	MNI coordinates			Peak stat (z)
		x	y	z	
Dorsomedial Prefrontal Cortex (BA 8)	14917	-14.0	30.0	60.0	6.48
		2.0	15.0	56.0	6.45
		-8.0	18.0	56.0	6.34
		17.0	30.0	50.0	5.91
L Middle Temporal Gyrus (BA 21)	1040	-65.0	-17.0	-19.0	6.07
R Pars Opercularis (BA 44)	914	52.0	18.0	34.0	5.66
R Dorsolateral Prefrontal Cortex (BA 9)		46.0	27.0	34.0	5.25
L Pars Opercularis (BA 44)	1040	-49.0	27.0	25.0	5.62
L Dorsolateral Prefrontal Cortex (BA 46)	946	-49.0	40.0	3.0	5.43
R Pars Orbitalis (BA 47)	630	39.0	40.0	-13.0	5.38
L Dorsolateral Prefrontal Cortex (BA 8)	473	-49.0	11.0	41.0	5.29
R Dorsolateral Prefrontal Cortex (BA 9)	220	55.0	30.0	18.0	5.27
L Dorsomedial Prefrontal Cortex (BA 10)	693	-8.0	62.0	25.0	5.26
L Pars Orbitalis (BA 47)	157	-46.0	30.0	-19.0	5.23
L Dorsomedial Prefrontal Cortex (BA 9)	378	-17.0	56.0	37.0	5.21
L Fusiform Gyrus (BA 37)	378	-58.0	-45.0	-10.0	5.13
L Pars Triangularis (BA 45)	189	-55.0	18.0	-0.0	5.04
L Angular Gyrus (BA 39)	220	-33.0	-74.0	41.0	5.03
L Pars Orbitalis (BA 47)	157	-49.0	43.0	-19.0	5.01

Table 2: Significant PLURAL > SINGULAR clusters for French after FWE voxel correction for multiple comparisons with $p < 0.05$, cluster size $> 100 \text{ mm}^3$.

3.3. English results

For the English participants, we find an increase in activation for plural
 305 nouns over singular nouns in the left pars opercularis (BA 44), left pars trian-
 gularis (BA 45), left pars orbitalis (BA 47), left dorsomedial prefrontal cortex
 (BAs 8, 10), the left temporal pole (BA 38), the left middle temporal (BA 21)
 and angular gyri (BA 39), and the the right cerebellum. These results can be

seen in Fig. 1c and more detail can be found in Table 3.

Region	Cluster size (mm ³)	MNI coordinates			Peak stat (z)
		x	y	z	
L Dorsomedial Prefrontal Cortex (BA 8)	9176	-12.0	44.0	46.0	7.43
L Dorsomedial Prefrontal Cortex (BA 10)		-8.0	64.0	22.0	6.00
R Cerebellum	3232	36.0	-80.0	-38.0	7.04
		44.0	-74.0	-42.0	6.89
		18.0	-86.0	-38.0	5.18
L Pars Orbitalis (BA 47)	1616	-44.0	28.0	-14.0	6.22
L Angular Gyrus (BA 39)	1512	-52.0	-64.0	34.0	5.96
Left Middle Temporal Gyrus (BA 21)	1272	-66.0	-6.0	-18.0	5.94
		-62.0	-14.0	-22.0	5.63
		1088	-62.0	-38.0	-8.0
L Temporal Pole (BA 38)	728	-38.0	20.0	-36.0	5.52
		-46.0	16.0	-32.0	5.31
L Pars Opercularis (BA 44)	648	-54.0	20.0	22.0	5.48
L Pars Triangularis (BA 45)		-56.0	18.0	14.0	5.47

Table 3: Significant PLURAL > SINGULAR clusters for English after FWE voxel correction for multiple comparisons with $p < 0.05$, cluster size > 100 mm³.

310 3.4. Cross-linguistic overlap

Overlaying the significant clusters from the Chinese, French, and English main results, we find voxel-wise overlap between all three languages in the left pars orbitalis (BA 47) and left dorsomedial prefrontal cortex (BAs 8, 10), as indicated in black in Fig. 2. We find voxel-wise overlap between two languages
315 in the left pars orbitalis (BA 47), left dorsomedial prefrontal cortex (BA 8), left dorsolateral prefrontal cortex (BA 46), the left middle temporal (BA 21) and fusiform (BA 37) gyri, and the right cerebellum, as indicated in red in Fig. 2. More detail can be found in Table 4. Additionally, while we do not observe

voxel-level overlap, all three languages show an increase in activation in the left
 320 pars triangularis (BA 45), and the left angular gyrus (BA 39).

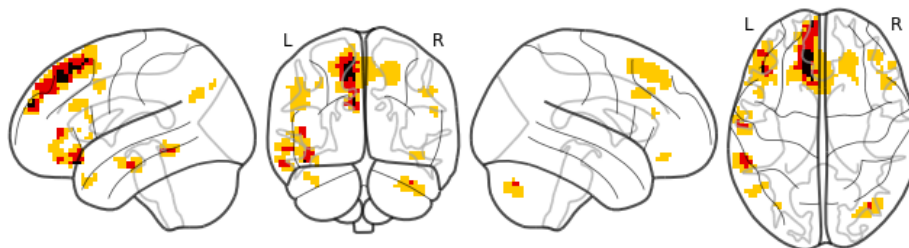


Figure 2: Overlap of Chinese, French, and English main results. Yellow indicates significant PLURAL > SINGULAR clusters for 1 language, red for 2 languages, and black for all 3 languages.

Region	Cluster size (mm ³)	MNI coordinates			Overlapping languages
		x	y	z	
L Pars Orbitalis (BA 47)	504	-46.0	27.0	-19.0	3.0
L Dorsomedial Prefrontal Cortex (BA 10)	504	-8.0	62.0	25.0	3.0
L Dorsomedial Prefrontal Cortex (BA 8)	4194	-14.0	30.0	53.0	3.0
		-11.0	40.0	47.0	3.0
		-8.0	24.0	56.0	3.0
		-21.0	30.0	53.0	2.0
L Middle Temporal Gyrus (BA 21)	189	-62.0	-14.0	-23.0	2.0
L Fusiform Gyrus (BA 37)	220	-58.0	-42.0	-10.0	2.0
L Dorsolateral Prefrontal Cortex (BA 46)	220	-46.0	43.0	3.0	2.0
L Pars Orbitalis (BA 47)	126	-46.0	40.0	-16.0	2.0
L Dorsomedial Prefrontal Cortex (BA 8)	31	-5.0	27.0	50.0	2.0
R Cerebellum	63	36.0	-74.0	-35.0	2.0

Table 4: Clusters resulting from overlap of Chinese, French, and English PLURAL > SINGULAR main results. Only clusters where 2 or more languages overlap are presented.

4. Discussion

In contrasting neural activation between plural and singular nouns, we observe several common regions of increased activation between the three languages: the left pars orbitalis (POrb), left pars triangularis (PTri), left dorso-medial (DMPFC) and dorsolateral (DLPFC) prefrontal cortex, the left middle
325 temporal (MTG), fusiform, and angular gyri (AG), and the right cerebellum. We observe voxel-level overlap between all three languages in the left POrb and left DMPFC. Our findings do not align with what would be expected if semantic number were subserved by the same brain network as triple-code number
330 processing and quantity comparison (Dehaene et al., 2003). Instead, the brain regions which we identify are more similar to those identified for semantic processing (e.g., Binder et al., 2009; Huth et al., 2016). More specifically, they align with regions previously implicated in fMRI studies of multi-word semantic comprehension (e.g., Graessner et al., 2021; Graves et al., 2010). Our interpretation
335 of the results is that it is more difficult to process plural nouns than it is to process singular nouns.

4.1. Quantity comparison

The triple-code model (Dehaene, 1992) proposes a tripartite account for making sense of numbers and quantities with three portions of the parietal lobe
340 facilitating this in different manners (Dehaene et al., 2003). The horizontal segment of the intraparietal sulcus (HIPS) serves as an internal number line which keeps track of size and distance between numbers and which is responsible for number representation, the left AG aids in processing heard numbers without processing quantities directly, and the posterior, superior parietal lobe (PSPL)
345 orients attention both in space and on the internal number line. While the HIPS would be a plausible candidate for our PLURAL > SINGULAR contrast, a significant difference in activation is not observed there. Even though Carreiras et al. (2010) observe an increase in activation for grammatical number disagreement in the right HIPS and right PSPL, they believe it unlikely that

350 the parietal regions are specifically involved when processing language and it
more likely that the activation is from quantity computation engaged by the
grammatical judgement task. Indeed, they perform SINGULAR > PLURAL
and PLURAL > SINGULAR contrasts for the identified parietal regions, but
find no effect. While we do identify the left AG, we, importantly, do not identify
355 the HIPS in our contrast of plural and singular nouns. If quantity comparison
specific processing were happening, we would expect to identify the HIPS.

4.2. *Semantic processing*

Binder et al. (2009) and Huth et al. (2016) demonstrate that the semantic
network is both distributed and diverse. The regions which we find for our
360 semantic number contrast are not out of place when compared to their results.
However, their focus is on conceptual knowledge storage. In the case of Binder
et al. (2009), the reviewed studies typically only identify one region or one of
the region groups, depending on the semantic contrast. In the case of Huth
et al. (2016), they find that while a concept like *self* may be selected for by
365 portions of more than one region (e.g., PFC, AG, and MTG), those portions
are small and interspersed among portions which select for other concepts in
that region. In comparison, we identify a multitude of regions with our single
contrast. Additionally, while our stimuli are embedded in naturalistic sentences,
our analysis is not a data-driven one like that of Huth et al. (2016). The
370 divergence of our results from theirs shows that linguistic plurality is not a
concept stored in one brain region.

Another facet of semantics is multi-word comprehension. For explicit, two-
word semantic composition Graessner et al. (2021) find an increase in activation
in the left IFG, left DMPFC, bilateral AG, left pMTG, left ATL, right fusiform
375 gyrus, and the right cerebellum, among other regions and Graves et al. (2010)
find an increase in activation in the right AG, bilateral DMPFC, and bilateral
posterior cingulate and precuneus. For semantic comprehension of sentence-
length stimuli, Pallier et al. (2011) identify the left ATL, left anterior superior
temporal sulcus (STS), and left temporo-parietal junction and Humphries et al.

380 (2006) identify bilateral STS, MTG, inferior temporal gyrus, and AG (the frontal lobe was not included in their analysis). Our stimuli are in-between those of these two modalities: our observations of interest are not sentences, but neither are they two-word noun phrases. Our results are most similar to those of Graessner et al. (2021), though.

385 Our interpretation of this conflict is that we are tapping into a semantic representation intermediate between two-word noun phrases and full-fledged sentences and that there is an effect for nominal semantic number. That is, it is more difficult to integrate plural nouns into the current, working semantic representation than singular nouns. It is understandable that whether there are
390 *one* or *many* of someone or something would play a role in constructing meaning during language comprehension and that being morphologically (Corbett, 2000; Greenberg, 1963) and semantically (de Swart & Farkas, 2010) marked, plural nominals would elicit greater activation than singular nominals.

It is interesting that we only identify the left ATL in the English results,
395 but not the Chinese or French results, given its importance in the literature on semantic composition (e.g., Bemis & Pykkänen, 2011, 2013; Li et al., 2020). The anterior temporal lobes can be susceptible to signal loss during fMRI imaging (Devlin et al., 2000), however, and we perform full-brain analyses, which reduces statistical power.

400 4.3. Similarities and differences between the results

The similarities that we see between the Chinese, English, and French results are not unprecedented. In bilinguals, previous research has found overlap between the L1 and L2 regions which subserves lexicosemantic comparison (Crinion et al., 2006; Klein et al., 2006). Honey et al. (2012) expand this to narrative
405 level stimuli, analyzing neural activity for monolingual English speakers and bilingual, Russian native, English L2 speakers in two conditions: listening to a Russian story and listening to an English translation of that story. When the participants listen to the story in their native language, they find a number of areas in common which reliably respond to the content of the narrative:

410 the STS, the AG, the supramarginal gyrus, the IFG, the precuneus, the middle frontal gyrus, and orbitofrontal cortex. These results, like ours, show that neural response patterns can be shared across groups despite differences in linguistic form. Importantly, we find that plurality conveyed through discourse cues (Chinese) elicits a similar response to overtly marked plurality (French
415 and English).

With regard to the the differences between the Chinese, English, and French results, we observe some differences in the regions which show an increase in activation. Only in the English results do we identify the left ATL and the French results are much more bilateral than the English and Chinese results. Curiously,
420 though, the French results do not implicate the right cerebellum. Some possible explanations for the observed differences include differences in salience and location of number marking. While the semantic number of our non-number marked Chinese observations is conveyed to the listener through discourse cues, for the French observations, number is overtly marked on the determiner which
425 occurs before the noun and for the English observations, number is morphologically marked on the noun itself. Another potential factor is the differences between the three datasets. They were collected by different researchers in different facilities and the Chinese and English datasets have a higher resolution than the French dataset, which leads to a more aggressive FWE correction.

430 5. Conclusion

In this project, we investigate the neural correlates of semantic number from a cross-linguistic perspective. We find that plural nouns elicit greater cortical activity than singular nouns. This is consistent with the account of de Swart & Farkas (2010) in which plural is semantically and morphologically marked and
435 singular is not. While Chinese does not overtly mark bare nominals for number, French and English count nouns are overtly marked for number. Despite the differences in their semantics and the resulting morphosyntactic properties, there is much overlap between the regions of the three languages in which we

observe an increase in activation for plural over singular nouns. We observe
440 voxel-level overlap in the left pars orbitalis and left dorsomedial prefrontal cortex. We discuss our findings with respect to previous cognitive neuroscience and neurolinguistic research and argue that semantic comprehension (e.g., Graessner et al., 2021; Graves et al., 2010) and not quantity comparison specific (Dehaene et al., 2003) processing is occurring when listeners process semantic number.

445 The neurobiology of language research domain (e.g., Bornkessel-Schlesewsky & Schlewsky, 2016; Kemmerer, 2016; Poeppel et al., 2012) is interested in explaining how language is implemented in the human brain and one aspect that must be accounted for in any comprehensive model is the similarities and differences between languages described by research in linguistic typology. Our research advances this goal by investigating Chierchia's (1998) typological counting distinction in which nouns can be predicates, arguments, or both, using
450 French, Chinese, and English, as representative languages.

References

- Abraham, A., Pedregosa, F., Eickenberg, M., Gervais, P., Mueller, A., Kossaifi,
455 J., Gramfort, A., Thirion, B., & Varoquaux, G. (2014). Machine learning for neuroimaging with scikit-learn. *Frontiers in Neuroinformatics*, 8, 14.
- Bemis, D. K., & Pykkänen, L. (2011). Simple composition: A magnetoencephalography investigation into the comprehension of minimal linguistic phrases. *Journal of Neuroscience*, 31, 2801–2814.
- 460 Bemis, D. K., & Pykkänen, L. (2013). Basic linguistic composition recruits the left anterior temporal lobe and left angular gyrus during both listening and reading. *Cerebral Cortex*, 23, 1859–1873.
- Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? a critical review and meta-analysis of 120 functional
465 neuroimaging studies. *Cerebral Cortex*, 19, 2767–2796.

- Blank, I. A., & Fedorenko, E. (2017). Domain-general brain regions do not track linguistic input as closely as language-selective regions. *Journal of Neuroscience*, *37*, 9999–10011.
- 470 Bornkessel-Schlesewsky, I., & Schlewsky, M. (2016). The importance of linguistic typology for the neurobiology of language. *Linguistic Typology*, *20*, 615–621.
- Bullmore, E. T., Brammer, M. J., Rabe-Hesketh, S., Curtis, V. A., Morris, R. G., Williams, S. C., Sharma, T., & McGuire, P. K. (1999). Methods for diagnosis and treatment of stimulus-correlated motion in generic brain
475 activation studies using fMRI. *Human Brain Mapping*, *7*, 38–48.
- Carlson, G. N. (1977). *Reference to kinds in English..* Ph.D. thesis University of Massachusetts at Amherst.
- Carreiras, M., Carr, L., Barber, H. A., & Hernandez, A. (2010). Where syntax meets math: Right intraparietal sulcus activation in response to grammatical
480 number agreement violations. *NeuroImage*, *49*, 1741–1749.
- Castelli, F., Glaser, D. E., & Butterworth, B. (2006). Discrete and analogue quantity processing in the parietal lobe: A functional mri study. *Proceedings of the National Academy of Sciences*, *103*, 4693–4698.
- Chierchia, G. (1998). Reference to kinds across language. *Natural Language*
485 *Semantics*, *6*, 339–405.
- Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, *20*, 37–46.
- Corbett, G. G. (2000). *Number*. Cambridge: Cambridge University Press.
- Cox, R. W. (1996). Afni: software for analysis and visualization of functional
490 magnetic resonance neuroimages. *Computers and Biomedical Research*, *29*, 162–173.

- Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., Aso, T., Urayama, S., Fukuyama, H., Stockton, K. et al. (2006). Language control in the bilingual brain. *Science*, *312*, 1537–1540.
- 495 Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*, 1–42.
- Dehaene, S. (2001). Précis of the number sense. *Mind & Language*, *16*, 16–36.
- Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*, 487–506.
- Devlin, J. T., Russell, R. P., Davis, M. H., Price, C. J., Wilson, J., Moss, H. E.,
500 Matthews, P. M., & Tyler, L. K. (2000). Susceptibility-induced loss of signal: comparing pet and fmri on a semantic task. *Neuroimage*, *11*, 589–600.
- Duncan, J. (2010). The multiple-demand (md) system of the primate brain: mental programs for intelligent behaviour. *Trends in Cognitive Sciences*, *14*, 172–179.
- 505 Fedorenko, E., Behr, M. K., & Kanwisher, N. (2011). Functional specificity for high-level linguistic processing in the human brain. *Proceedings of the National Academy of Sciences*, *108*, 16428–16433.
- Fedorenko, E., Duncan, J., & Kanwisher, N. (2013). Broad domain generality in focal regions of frontal and parietal cortex. *Proceedings of the National Academy of Sciences*, *110*, 16616–16621.
510
- Gandour, J., Dziedzic, M., Wong, D., Lowe, M., Tong, Y., Hsieh, L., Saththamnuwong, N., & Lurito, J. (2003). Temporal integration of speech prosody is shaped by language experience: An fmri study. *Brain and Language*, *84*, 318–336.
- 515 Graessner, A., Zaccarella, E., & Hartwigsen, G. (2021). Differential contributions of left-hemispheric language regions to basic semantic composition. *Brain Structure and Function*, *226*, 501–518.

- Graves, W. W., Binder, J. R., Desai, R. H., Conant, L. L., & Seidenberg, M. S. (2010). Neural correlates of implicit and explicit combinatorial semantic processing. *Neuroimage*, *53*, 638–646.
- 520
- Greenberg, J. H. (1963). *Universals of language*. Cambridge, MA: MIT Press.
- Honey, C. J., Thompson, C. R., Lerner, Y., & Hasson, U. (2012). Not lost in translation: neural responses shared across languages. *Journal of Neuroscience*, *32*, 15277–15283.
- Humphries, C., Binder, J. R., Medler, D. A., & Liebenthal, E. (2006). Syntactic and semantic modulation of neural activity during auditory sentence comprehension. *Journal of Cognitive Neuroscience*, *18*, 665–679.
- 525
- Huth, A. G., De Heer, W. A., Griffiths, T. L., Theunissen, F. E., & Gallant, J. L. (2016). Natural speech reveals the semantic maps that tile human cerebral cortex. *Nature*, *532*, 453–458.
- 530
- Kadosh, R. C., & Walsh, V. (2009). Numerical representation in the parietal lobes: Abstract or not abstract? *Behavioral and Brain Sciences*, *32*, 313–328.
- Kemmerer, D. (2016). Do language-specific word meanings shape sensory and motor brain systems? the relevance of semantic typology to cognitive neuroscience. *Linguistic Typology*, *20*, 623–634.
- 535
- Klein, D., Zatorre, R. J., Chen, J.-K., Milner, B., Crane, J., Belin, P., & Bouffard, M. (2006). Bilingual brain organization: A functional magnetic resonance adaptation study. *Neuroimage*, *31*, 366–375.
- Kundu, P., Inati, S. J., Evans, J. W., Luh, W.-M., & Bandettini, P. A. (2012). Differentiating bold and non-bold signals in fmri time series using multi-echo epi. *Neuroimage*, *60*, 1759–1770.
- 540
- Lacadie, C., Fulbright, R., Arora, J., Constable, R., & Papademetris, X. (2008a). Brodmann areas defined in mni space using a new tracing tool in

- bioimage suite. In *Proceedings of the 14th annual meeting of the organization*
545 *for human brain mapping*. volume 771.
- Lacadie, C. M., Fulbright, R. K., Rajeevan, N., Constable, R. T., & Pa-
pademetris, X. (2008b). More accurate talairach coordinates for neuroimaging
using non-linear registration. *Neuroimage*, *42*, 717–725.
- Li, J. et al. (2020). Disentangling semantic composition and semantic association
550 in the left temporal lobe. *bioRxiv*, .
- Li, P., Jin, Z., & Tan, L. H. (2004). Neural representations of nouns and verbs
in chinese: an fmri study. *Neuroimage*, *21*, 1533–1541.
- Link, G. (1983). The logical analysis of plurals and mass terms: A lattice-
theoretical approach. *Formal Semantics: The Essential Readings*, *127*, 147.
- 555 Lund, T. E., Madsen, K. H., Sidaros, K., Luo, W.-L., & Nichols, T. E. (2006).
Non-white noise in fMRI: does modelling have an impact? *Neuroimage*, *29*,
54–66.
- Obleser, J., Meyer, L., & Friederici, A. D. (2011). Dynamic assignment of neural
resources in auditory comprehension of complex sentences. *Neuroimage*, *56*,
560 2310–2320.
- Pallier, C., Devauchelle, A.-D., & Dehaene, S. (2011). Cortical representation of
the constituent structure of sentences. *Proceedings of the National Academy*
of Sciences, *108*, 2522–2527.
- Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa,
565 S. F., Cotelli, M., Cossu, G., Corte, F., Lorusso, M. et al. (2000). A cultural
effect on brain function. *Nature Neuroscience*, *3*, 91–96.
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O.,
Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V. et al. (2011). Scikit-
learn: Machine learning in python. *the Journal of Machine Learning Re-*
570 *search*, *12*, 2825–2830.

- Poeppel, D., Emmorey, K., Hickok, G., & Pylkkänen, L. (2012). Towards a new neurobiology of language. *Journal of Neuroscience*, *32*, 14125–14131.
- Rothstein, S. (2017). *Semantics for counting and measuring*. Cambridge: Cambridge University Press.
- 575 Rullmann, H. (2002). Bound-variable pronouns and the semantics of number. In *Proceedings of the western conference on linguistics: Wecol* (pp. 243–254). volume 14.
- Rullmann, H., & You, A. (2006). General number and the semantics and pragmatics of indefinite bare nouns in mandarin chinese. *Where Semantics meets*
580 *Pragmatics*, (pp. 175–196).
- de Saint-Exupéry, A. (1946). *Le petit prince [The little prince]*. Paris: Gallimard.
- de Swart, H., & Farkas, D. (2010). The semantics and pragmatics of plurals. *Semantics and Pragmatics*, *3*, 6–1.
- Van Rooy, R. (2004). Signalling games select horn strategies. *Linguistics and*
585 *Philosophy*, *27*, 493–527.
- Varga, D., Halácsy, P., Kornai, A., Nagy, V., Németh, L., & Trón, V. (2007). Parallel corpora for medium density languages. *Amsterdam Studies In The Theory And History Of Linguistic Science Series 4*, *292*, 247.
- Yang, R. (2001). *Common nouns, classifiers, and quantification in Chinese*.
590 Ph.D. thesis Rutgers University.