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Distinct cortical areas associated with native and second languages

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The ability to acquire and use several languages selectively is a unique and essential human capacity. Here we investigate the fundamental question of how multiple languages are represented in a human brain. We applied functional magnetic resonance imaging (fMRI) to determine the spatial relationship between native and second languages in the human cortex, and show that within the frontal-lobe language-sensitive regions (Broca's area)[1-3], second languages acquired in adulthood ('late' bilingual subjects) are spatially separated from native languages. However, when acquired during the early language acquisition stage of development ('early' bilingual subjects), native and second languages tend to be represented in common frontal cortical areas. In both late and early bilingual subjects, the temporal-lobe language-sensitive regions (Wernicke's area)[1-3] also show effectively little or no separation of activity based on the age of language acquisition. This discovery of language-specific regions in Broca's area advances our understanding of the cortical representation that underlies multiple language functions.

Indirect evidence for topographic specialization within the language-dominant hemispheres of multilingual subjects has been provided by clinical reports of selective impairments in one or more of several languages as a result of surgery involving the left perisylvian area[4]. Multilingual patients with complex partial seizure disorders of temporal lobe origin have been reported to shift from a primary to a second language together with ictal progression[5]. Different languages have also been selectively disrupted in polyglots by electrical stimulation of discrete regions of the neocortex of the dominant hemisphere[6,7]. Changes in the topography of background electroencephalogram (EEG) coherence obtained during translation tasks also suggest spatial separation of cortical regions involved in multiple languages[8]. Although these reports are consistent with the existence of spatially separate representations for each language, such functions have not been localized.

Silent, internally expressive linguistic tasks were performed in two languages by subjects who either acquired conversational fluency in their second languages as young adults ('late' bilinguals) or who acquired two languages simultaneously early in their development ('early' bilinguals) (Table 1). As Broca's and Wernicke's areas are known to perform central roles in human language functions[1-3,9-12], we have focused our observations on these cortical areas.

The main findings for a typical 'late' bilingual subject (subject (A)) are shown in Fig. 1. The anterior language area is highlighted by the green box and shown expanded in the inset. Red indicates significant activity during the native language task (English), whereas yellow indicates activity associated with the second language task (French). Two distinct but adjacent centres of activation (+) separated by ∼7.9 mm were evident within the inferior frontal gyrus, suggesting that two specific regions served each of the two languages. In the posterior language area of the same subject (Fig. 2), the same tasks yielded centroids of activity with a centre-to-centre spacing of 1.1 mm, less than the width of a voxel, suggesting that similar or identical cortical regions served both languages in this posterior area.

For all six late bilingual subjects, distinct areas of activation were observed for the native and second languages in Broca's area (Table 2a and Fig. 3). The separation between centroids of activity ranged from ∼4.5 mm to 9.0 mm within one slice, and the number of voxels for each language was similar for each subject. On the other hand, activity in Wernicke's area (Table 2b) showed centre-to-centre distances between the centre-of-mass centroids ranging from 1.1 to 2.8 mm. The mean centroid distance between the anterior
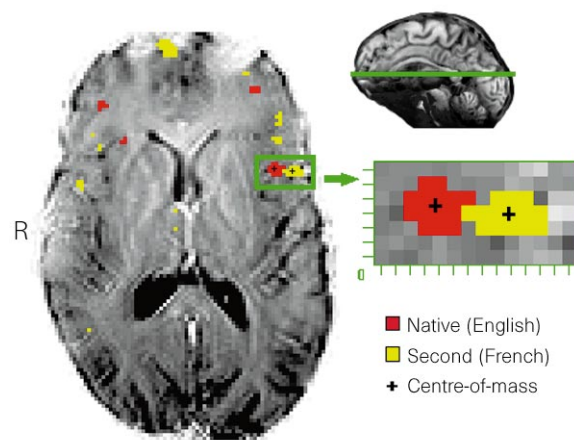
Figure 1 A representative axial slice from a 'late' bilingual subject (A) shows all voxels that pass the multistage statistical criteria at $P \leq 0.0005$ as either red (native language) or yellow (second acquired language). An expanded view of the pattern of activity in the region of interest (inferior frontal gyrus, Brodmann's area 44 (refs 2, 3, 18), corresponding to Broca's area[1-3]) indicates separate centroids (+) of activity for the two languages. Centre-of-mass calculations indicate that the centroids are separated on this plane by 7.9 mm. The green line on the upper right mid-sagittal view indicates the plane location. R indicates the right side of the brain.

Table 1 Subject information

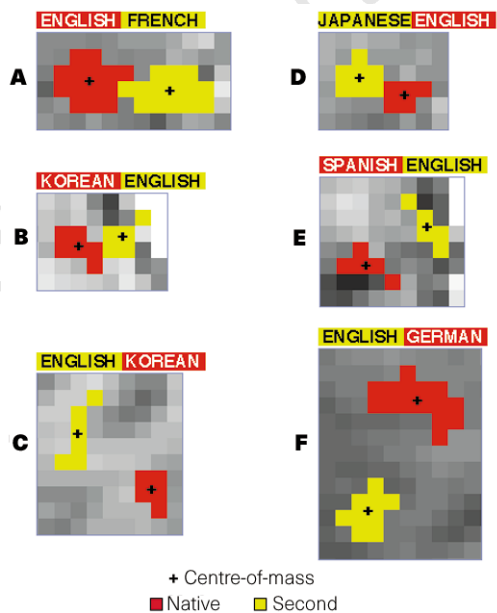| Subject	Age	Gender	Native language(s)	Second language	Handedness	Laterality quotient[24]
A	31	M	English	French	Right	60
B	32	M	Korean	English	Right	100
C	28	M	Korean	English	Right	86
D	26	M	English	Japanese	Ambidextrous	−20
E	27	F	Spanish	English	Right	100
F	32	F	German	English	Right	60
G	38	F	Turkish/English	NA	Ambidextrous	−27
H	27	M	English/Hebrew	NA	Right	85
I	23	M	English/Spanish	NA	Right	100
J	24	F	Croatian/English	NA	Right	89
K	31	M	Italian/German	NA	Right	90
L	32	M	Chinese/English	NA	Ambidextrous	24
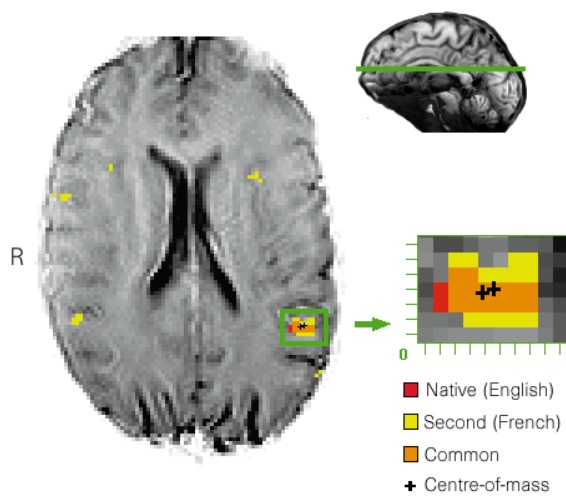
Figure 2 Similar to Fig. 1, an expanded view of the pattern of activity within the superior temporal gyrus (Brodmann's area 22 (refs 2, 3, 18), corresponding to Wernicke's area[1-3]) indicates centroids of activity for the two languages in this posterior language region. Orange indicates that the voxels that passed all statistical criteria during both the native and acquired language tasks. Centre-of-mass calculations indicate that the centroids are separated on this plane by 1.1 mm, less than the diameter of a single voxel.

Figure 3 Expanded views of the activity patterns within Brodman's area 44 (and 46 (refs 2, 3, 18), subject B) for each 'late' bilingual subjects (A–F) indicate the active regions during the native language task (red) and the second acquired language task (yellow). The level of statistical stringency (probability of a false positive result, P) was ≤0.0005 for each subject. The centre-of-mass is indicated by a plus sign for each language; area and centre-to-centre (C–C) distances are listed in Table 2a.

language areas was 6.43 (±1.83) mm and exceeded that of the posterior language areas, which was 1.88 (±0.62) mm, for these subjects ($t = 5.43$, d.f. $= 5$, $P \le 0.004$).

The overall stability of the centre-of-mass centroids with variation in the level of statistical stringency (probability of a false-positive result, P) is illustrated for subject (A) in Fig. 4. In the case of the anterior language area, the centre-to-centre distance between the centroids of activity associated with each language remained within the range of 7.8 to 9.1 mm over statistical stringency levels from $P \le 0.0002$ to $P \le 0.02$. In the case of the posterior language area, the centroids remained within the approximate width of one voxel, 1.6 mm, over the same range of stringency levels. Similar results were obtained for all subjects, confirming that threshold criteria do not account for the centre-to-centre distances between centroids of activity associated with each language task.

Figure 5 illustrates the main findings for a typical 'early' bilingual subject (subject (G)) for whom the centre-to-centre distance between the activity centroids (+) of the two activity patterns was 2.3 mm, less than 1.5 voxels (Table 2a). This represents the general pattern for all six early bilingual subjects, where the mean separation

was 1.53 (±0.78) mm. In the case of the posterior language area, Wernicke's area, the mean separation for all early bilingual subjects was 1.58 (±0.79) mm, similar to the anterior area.

Our findings are summarized by an analysis of variance (Table 3) in which language area (Broca's and Wernicke's) was compared with bilingual type (early and late) with respect to the centre-to-centre distance in millimetres between the two language centroids. Significant main effects for language area ($P \le 0.000059$) and bilingual type ($P \le 0.000084$) with an interaction effect ($P \le 0.000067$) show that activation sites for the two different languages tend to be spatially distinct in Broca's area when the second language was obtained late in life and not when acquired in early childhood; and

Table 3 ANOVA

Source of variation	SS	d.f.	MS	F	P
A (language area)	52.01	1	52.01	25.70	0.000059
B (bilingual type)	48.80	1	48.80	24.11	0.000084
AB	50.79	1	50.79	25.10	0.000067
Within cell	40.47	20	2.02		

Table 2 Areas of activation

(a) Anterior language area

Subject	Bilingual type	Hemisphere	Gyrus	Brodmann's area	X	Y	Z	Area L1† (mm²)	Area L2† (mm²)	C–C distance‡ (mm)	Common voxels L1 and L2† (%)
A	Late	Left	Inferior frontal	44	d	D	12	34.2	34.2	7.9	0
B	Late	Left	Inferior frontal	44, 46	c	D, C	12	14.6	12.2	4.5	0
C	Late	Left	Inferior frontal	44	c	D	12	12.2	14.6	9.0	0
C′	Late	Left	Inferior frontal	44	c	D	12	15.4	24.2	7.5	0
D	Late	Left	Inferior frontal	44	c	B	1	12.2	17.1	4.7	0
E	Late	Left	Inferior frontal	44	c	D	12	12.2	12.2	7.0	0
F	Late	Left	Inferior frontal	44	c	D	12	33.1	19.8	11.2	0
G	Early	Left	Interior frontal	44	c	D	12	107.4	75.7	2.3	50
H	Early	Left	Interior frontal	44	c	D	12	12.2	7.3	0.5	60
I	Early	Left	Interior frontal	44	c	B	1	41.9	28.6	0.7	46
J	Early	Left	Interior frontal	44	c	D	12	8.8	4.4	1.7	20
K	Early	Left	Interior frontal	44	c	D	12	123.4	154.2	2.2	45
L	Early	Left	Interior frontal	44	c	D	12	44.1	17.6	1.8	22

(b) Posterior language area

| Subject	Bilingual type	Hemisphere	Gyrus	Brodmann's area	X	Y	Z	Area L1† (mm²)	Area L2† (mm²)	C–C distance‡ (mm)	Common voxels L1 and L2† (%)
A	Late	Left	Superior temporal	22	d	G	20	39.1	65.9	1.1	48
B	Late	Left	Superior temporal	22	d	G	20	9.8	19.5	1.5	33
C	Late	Left	Superior temporal	22	d	F	8	31.7	34.2	2.2	35
C′	Late	Left	Superior temporal	22	d	G	20	19.8	33.1	3.3	26
D	Late	Left	Superior temporal	22	d	E	1	43.9	19.5	2.2	30
E	Late	Left	Superior temporal	22	d	F	8	22.0	9.8	1.5	18
F	Late	Left	Superior temporal	22	d	G	16	83.7	46.3	1.0	18
G	Early	Left	Superior temporal	22	d	G	16	4.9	31.7	1.7	15
H	Early	Left	Superior temporal	22	d	G	16	56.2	39.1	1.5	56
I	Early	Left	Superior temporal	22	d	E	4	94.7	22.0	3.0	23
J	Early	Left	Superior temporal	22	d	G	16	15.4	125.6	1.4	12
K	Early	Left	Superior temporal	22	d	G	20	121.2	96.9	1.3	62
L	Early	Left	Superior temporal	22	d	F	12	48.5	88.1	0.6	48

C′ is a replication of C after 16 months on a different scanner. All observations of area and distance are made at a common level of significants ($P \leq 0.0005$).
* See ref. 18 where the three-dimensional proportional grid system is described. Columns X, Y and Z indicate coordinates of an orthogonal parallelogram, the dimensions of which vary with the principal axes of the brain. Each of these volumes is defined by its three dimensions indicated by a capital letter (Y), a lower-case letter (X), and a number (Z).
† L1 and L2 refer to the native and second acquired languages for late bilingual subjects, respectively, and the two languages acquired during the early developmental period for the early bilingual subjects in the respective order as listed on Table 1.
‡ C–C distance refers to the centre-to-centre spacing between the centre-of-mass centroids of significant voxels associated with the two languages.

that Wernicke's area showed little or no separation of activity regardless of age of acquisition.

The observation that the anatomical separation of the two languages in Broca's area varies with the time at which the second language was acquired, suggests that age of language acquisition may be a significant factor in determining the functional organization of this area in human brain. Human infants, initially capable of discriminating all phonetically 'relevant' differences, may eventually modify the perceptual acoustic space, based on early and repeated exposure to their native languages[13]. It is possible that representations of languages in Broca's area that are developed by exposure early in life are not subsequently modified. This could necessitate the utilization of adjacent cortical areas for the second language learned as an adult.

The difference between the results of this investigation and a positron emission tomography (PET) study in which multiple languages were found to generate overlapping regions of activation within the inferior frontal gyrus[14] may be reconciled in part by the higher effective resolution of this fMRI technique. The intrinsic resolution of the PET $H_2^{15}O$ cerebral-blood-flow technique was $5 \times 5 \times 6\,mm^3$ and the results from several subjects were combined and averaged. Individual variability in both the locations of the language areas and the diversity of brain shapes and gyral patterns of the subjects averaged together further reduce the effective resolution of this approach[9,15], which could account for the discrepancy. However, on the basis of our findings, the distinction between native and second languages may be less for younger ages of exposure to a second language. The average age of initial exposure to the second language in the PET study was 7.3 years, younger than that of the late bilingual subjects in our study, and could therefore be consistent with our observation for early bilinguals.

To render our findings independent of particular languages or cultural background, our study made use of simple expressive tasks with similar semantic content across multiple languages and
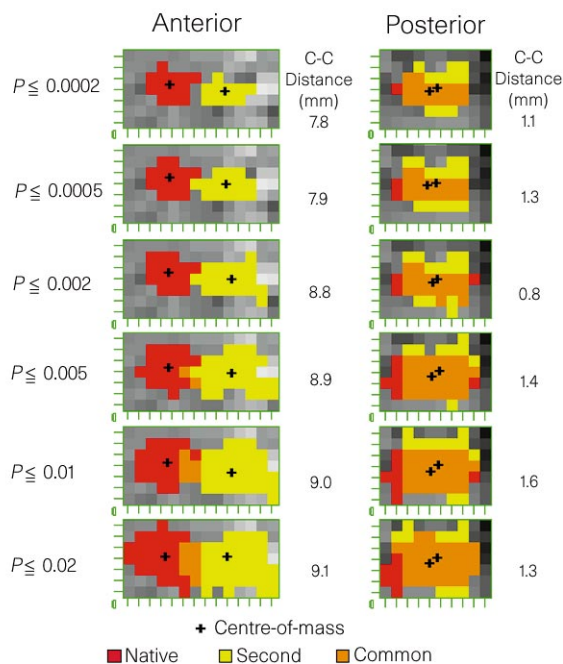
Figure 4 All voxels that pass the statistical criteria during the native (red) and acquired (yellow) language tasks (subject (A)) are shown for the anterior region of interest, left, and the posterior region of interest, right, over approximately 3 orders of statistical stringency ($P \leq 0.0002$ to $P \leq 0.02$). The centre-to-centre (C–C) distance between the centroids of activity in the anterior area (based on the centre-of-mass, +), ranges from 7.8 mm at $P \leq 0.0002$ to 9.1 mm at $P \leq 0.02$, suggesting that the centroid is nearly independent of cluster size (radial expansion). Similarly, for the posterior language area, the C–C distance ranges from 1.1 to 1.3 mm (less than the width of a single voxel) over the same level of statistical stringency.
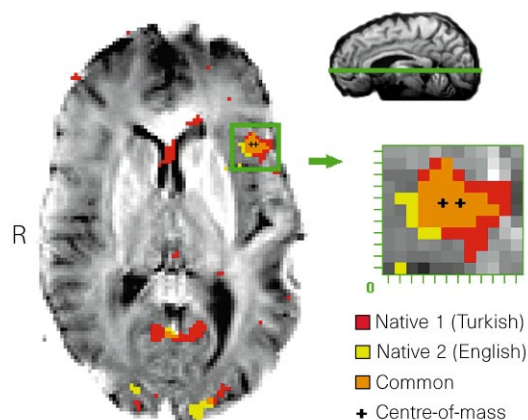
Figure 5 A representative axial slice from an 'early' bilingual subject (G) who learned English and Turkish simultaneously during early childhood shows all voxels that pass the multistage statistical criteria at $P \leq 0.0005$. Red indicates the Turkish language task and yellow indicates the English language task. An expanded view of the region of interest (Broca's area[1-3]) indicates multiple common voxels between the two language areas. The geometric centres-of-mass indicate that the centroids are within 1.5 voxels. R indicates the right side of the brain.

included subjects with various combinations of languages (Table 1). Our findings are consistent with distinct roles for the anterior and posterior language areas in the processing of human language, and raise further questions regarding the role of Broca's area in processing the phonetic structures of different languages. □

Methods

Imaging. A 1.5-tesla magnetic resonance scanner (General Electric) retrofitted (advanced NMR Instascan) for echo–planar imaging and subsequently upgraded to the GE echo–planar system was used to obtain T2*-weighted images with a gradient echo pulse sequence (echo time, 60 ms; repetition time, 3,000 ms; flip angle, 30°) which is sensitive to magnetic resonance signal changes caused by alteration in the proportion of deoxyhaemoglobin in the local vasculature accompanying neuronal activation[16]. Either a volume-optimized 5×5-mesh dome resonator[17] or a General Electric head coil was employed. The in-plane resolution was 1.6 mm by 1.6 mm. Slice thickness was 4.5–4.7 mm and 16 contiguous slices of brain were obtained parallel to a reference line through the superior edge of the anterior commissure and the inferior edge of the posterior commissure[18,19]. These slices covered the inferior frontal gyrus (the anterior language region, 'Broca's' area including Brodmann's areas 44 and 46) and the posterior superior temporal gyrus (the posterior language region, 'Wernicke's' area including Brodmann's area 22)[1-3,18,19]. Thirty images were taken, one every 3 s; thus, an entire run lasted 90 s. The first 10 images (30 s) were acquired during a baseline period, followed by a stimulation or task period of 10 images (30 s), and a final (30 s) baseline period also consisting of 10 images. A fixation cross-hair was provided during the baseline epochs to help the subject to maintain a stable head position.

Analysis. Two identical runs were performed in each language. Before statistical analysis, all brain images were computationally aligned to allow direct spatial comparisons between different language tasks for individual subjects[20], and a two-dimensional gaussian filter (approximately 3 volume elements, voxels, at half-height) was applied to the data. Significant signal changes were identified by a multistage statistical analysis which compared average baseline and stimulation signal intensities and required significant signal changes on two runs (coincidence)[21,22]. The rate of false-positive voxels, p, was empirically determined from images of a copper sulphate solution-filled spherical phantom (General Electric standard) and found to be less than 0.0005. The centroid of a cluster of language-activated voxels was determined as the two-dimensional centre of mass, and the centre-to-centre distance between centroids was taken as the separation (mm) between language-specific activity.

Task. The sentence-generation task was performed silently (internal speech) to minimize head movement and was similar to tasks previously employed in neuroimaging language studies[23]. The subject was instructed to "describe" events that occurred during a specified period of the previous day (morning, afternoon, night); this task was practised before the imaging sessions. Immediately before each run, the subject was instructed which language he/she was to imagine speaking, and graphical cues signalling morning, afternoon, and night were displayed in various orders for 10 s during the 30-s task period. These graphics provided common non-linguistic cues for the task and the unpredictable order of presentation presumably reduced the tendency to rehearse mentally before the cue. The languages were alternated during the imaging session to prevent habituation and a potentially time-dependent bias.

Subjects. Twelve healthy multilingual volunteers, 9 males and 3 females, were recruited according to institutional informed consent procedures. Subjects were either right-handed or ambidextrous, as assessed by the Edinburgh handedness inventory[24] (Table 1). The mean age of subjects was 29.3 (± 4.2) years. Six subjects ('early' bilinguals) were exposed to two languages during infancy, and six subjects ('late' bilinguals) were exposed to a second language in early adulthood. The mean age of initial exposure to the second language was 11.2 (± 1.5) years and the mean age that conversational fluency was achieved was 19.2 (± 4.1) years. Each of the 'late' bilingual subjects had lived in the country of the second language, which assured a high standard for fluency. Each of the early bilinguals was raised in a home where either the parents spoke one language and siblings and friends spoke another, or the parents spoke two languages. Ten languages were represented as indicated on Table 1, and all subjects reported approximately equal fluency and frequent usage in each language at the time of testing.

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