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Supporting Online Material for

Language Control in the Bilingual Brain

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METHODS AND MATERIALS (for supporting online material)

Three different groups of neurologically normal, right handed bilinguals participated in the same experimental protocol with three different scanners.

Subject selection

One group of German-English bilinguals (7/4 M/F, aged between 23 and 62 years, mean 38) was investigated using a SIEMENS/CPS ECAT EXACT HR+ (model 962) PET scanner (Siemens/CTI, Knoxville, TN. USA). A second group of German-English bilinguals (9/5 M/F, aged between 23 and 62 years, mean 33) and a group of Japanese-English bilinguals (7/3 M/F, aged between 21 and 38 years, mean 28) were investigated using Siemens 3T fMRI scanners in London and Kyoto, respectively. The study was approved by the National Hospital for Neurology and Institute of Neurology Medical Ethics Committee in London, and Kyoto University Graduate School and Faculty of Medicine, Ethics Committee in Kyoto.

To ensure proficiency in both languages tested, participants were selected on the basis of a English language assessment using the i) English Vocabulary Test (Vocabulary) *(S1),* ii) New Adult Reading Test (NART) for knowledge of irregularly spelled words and English phonemes *(S2)*, and iii) Graded Naming Test (GNT) for naming vocabulary and knowledge of low frequency words *(S3)*. See Table S1 for a summary of the groups' performance on these tests.

Experimental Paradigm

On each trial, two written names (of objects or animals or one of each) were presented sequentially with a short (250ms) interval between onset times. Participants were instructed to ignore the first word (the prime) and to make a two choice semantic decision on the second word (the target) by responding with a left or right finger press. There were a total of 120 targets and 120 primes. Japanese primes and targets were a mixture of Kanji, Hiragana, and Katakana (as in natural Japanese). Cultural differences between England, Germany, and Japan were taken into account in the selection of primes and targets (see Table S2 for complete list of stimuli in all three languages). Each target word was associated with one of three possible verification questions that focused on the perceptual properties of the object/animal concept: (1) long legs or short legs (e.g. HORSE vs. DUCK); (2) multi-coloured or plain (e.g. WASP vs. WORM); (3) open or closed handles (e.g. SPOON vs. SUITCASE). The question was presented at the start of the scanning block and remained constant within the block. Over the experiment, correct responses were 50% left and 50% right.

A fully balanced 2 × 2 × 2 factorial design manipulated (i) the language of the target word, and whether the prime and target were (ii) semantically related or unrelated, and (iii) written in the same or different languages. This resulted in the following 4 conditions for each target language:

(1) prime and target in same language with unrelated meanings (e.g. ladle–SHOWER; bathtub–SPOON);

(2) prime and target in same language with semantically related meanings (e.g. bathtub–SHOWER; ladle–SPOON);

(3) prime and target in different languages with unrelated meanings (e.g. suppenkelle–SHOWER; badewanne–SPOON);

(4) prime and target in different languages with semantically related meanings (e.g. badewanne–SHOWER; suppenkelle–SPOON);

In addition to these eight conditions (4 for each target language), we included a translation priming condition where the prime and target were the same word presented in two different languages (e.g. dusche–SHOWER; löffel–SPOON). The results pertaining to the translation priming condition are reported below. The eleventh condition was a baseline which required a decision on whether the symbols in a string were the same (ψψψψψ ψ) or different (ψ ϕ ψ ϕ ψ ϕ).

To avoid item-specific confounds, the same prime and target words were used in each condition but in different combinations. For example, the prime "locust" was unrelated to the target (e.g. locust–SALMON) for some subjects but semantically related (e.g. locust–GRASSHOPPER) for other subjects. Across different subjects, each target (e.g. SALMON) was primed by a word that was in the:

(1) same language with an unrelated meaning (e.g. locust);

(2) same language with a semantically related meaning (e.g. trout);

(3) different language with an unrelated meaning (e.g. heuschrecke) ;

(4) different language with a semantically related meaning (e.g. forelle);

(5) different language with the same meaning (e.g. lachs).

The task was held constant for each item and counterbalanced across conditions. To avoid confounds from orthographic and phonological priming, the prime and the target were always orthographically and phonologically dissimilar (e.g. foal–HORSE) and orthographically overlapping items (e.g. brief<u>case</u>–SUIT<u>CASE</u>) were excluded. Note that orthographic priming may also occur when prime and target are both in the same script (e.g. Roman letters or Japanese characters) compared to when prime and target are in different scripts but this was controlled across semantically related and unrelated trials. Likewise, there were differences in the average number of letters or characters across languages (mean = 7.2 letters per German word; 6.1 letters per English word; 3.0 characters per Japanese word), but this was also controlled over the unrelated and semantically related conditions. Finally, response priming (when the prime and target both indicate the same response) was greater for semantically related trials (e.g. foal and HORSE both refer to animals with long legs) than unrelated trials (e.g. foal does not prime the short leg response to DUCK) but this can not explain language-dependent semantic priming effects because, across subjects, identical stimulus pairs were presented in the same language or in different languages.

Data acquisition and analysis

In the PET study, there were 12 scanning blocks with one scan for each of the 10 semantic conditions and two scans for the baseline with the order of conditions counterbalanced between subjects. Within each scan, twelve pairs of stimuli of the same type were presented sequentially at a rate of 1750 while a 20s intra-venous bolus of $H_2{}^{15}O$ was injected at a concentration of 55 Mbq/ml and a flow rate of 10 ml/min through a forearm cannula. The effective dose equivalent was <5.0mSv. Correction for attenuation was made by a transmission scan with an exposed $^{68}Ge/^{68}Ga$ external source. Images with 2.05 × 2.05 × 2mm voxels were reconstructed by filtered back projection (Hanning filter, cut-off frequency 0.5 Hz)

The fMRI studies acquired T_2*-weighted echoplanar images with BOLD contrast. There were 20 activation blocks which alternated with 20 blocks of baseline task. Within each block, 6 stimuli of the same type were presented at a rate of 1750 with two blocks for each activation condition counterbalanced across subjects. Therefore, the PET and fMRI experiments presented the same number of activation stimuli but there were twice as many baseline stimuli in fMRI. Each echoplanar image comprised 40 axial slices of 2 mm thickness with 1 mm slice interval and 3 × 3 mm in-plane resolution. The repetition time (TR) was 2.6seconds. A total of 476 volumes were acquired in one session and the first 6 (dummy) images of each run were discarded to allow for T_1 equilibration effects. Exactly the same scanning protocol was used in London and Kyoto.

Both PET and fMRI data were analyzed using Statistical Parametric Mapping as implemented in SPM2 software (Wellcome Department of Imaging Neuroscience, London, UK). All volumes from each subject were realigned using the first as reference and resliced with sinc interpolation. The functional images were spatially normalized (Friston et al., 1995a) to a standard MNI-305 template and smoothed with a 8 mm full width at half maximum isotropic Gaussian kernel in PET and 6mm in fMRI. Statistical analysis of the PET data involved analysis of covariance (ANCOVA) with subject effects and global activity included as subject-specific covariates. For the fMRI data, first level analyses were performed in a subject-specific fashion. Low-frequency drifts were removed with high-pass filtering and a cutoff period of 128 seconds. Each experimental condition was then modelled independently, by convolving the onset times with a synthetic hemodynamic response function. The parameter estimates were calculated for each subject in all brain voxels using the general linear model. These subject-specific contrast images were then entered into a second level ANOVA modelling 20 conditions (10 for German bilinguals and 10 for Japanese bilinguals). One Japanese subject was excluded because of right lateralized activations for semantic decisions relative to the baseline. The final analysis therefore included 14 German and 9 Japanese fMRI subjects and 11German PET subjects.

Second level statistical contrasts, in both the PET and fMRI analyses, identified the main effects of (1) target language, (2) unrelated vs. semantically related word pairs over all language pairs, when primes and targets were in same language and when primes and targets were in different languages, and (3) the interaction of semantic priming with same or different language pairs. Language-dependent semantic priming was identified as the difference between unrelated and semantically related word pairs when prime and target were in the same language compared to a different language. For all contrasts, the *t*-images were transformed into statistical parametric maps of the *Z* statistic.

Statistical threshold

Semantic priming effects are notoriously small and difficult to detect in a whole brain un-directed search that needs to account for the number of comparisons being made. We therefore adopted a two stage procedure which started with a whole brain search using a liberal statistical threshold ($p<0.001$ uncorrected) on effects from a second level fMRI analysis that included both the German and Japanese data sets. To exclude the possibility of false positive results, we then focus on effects that replicated across both fMRI subject groups as well as the PET study and used a small volume correction (6mm radius) for independent replication of the PET and fMRI data.

Behavioural measures (response times and accuracies) were quantified using factorial analyses of variance. The effects of interest were the same as those in the imaging analysis and are reported at $p<0.05$, two tailed. Responses that were longer than 2 seconds were excluded from the reaction time analysis. The behavioural data from one of the subjects in the German fMRI group were lost. The behavioural analyses are therefore based on 33 subjects but the imaging analyses are based on a total of 34 subjects.

Translation priming results

In all three groups, behavioural responses were faster when the target was preceded by a translation prime than an unrelated prime. The size of this effect was 78ms in the German PET group, 89ms in the German fMRI group and 30ms in the Japanese fMRI group. Over groups, the effect was highly significant ($F(1,33)=16.1$, $p<0.001$). In terms of brain activation, the largest effect of unrelated - translation priming was observed in the calcarine sulcus in both the PET (MNI x,y,z co-ordinates= 0, -70 14, Z score = 4.0, 714 voxels at $p<0.05$) and fMRI analyses (MNI x,y,z co-ordinates= 0 -72 12, Z score = 2.6, 502 voxels at $p<0.05$). As activation in the calcarine sulcus has been associated with visual imagery (S4), the effect of lexical priming suggests less visual imagery when the prime and target are related to the same object than when they referred to two different objects.

In the caudate, where we found greater activation for unrelated - semantically related primes in the same language, we note that activation for the translation priming conditions was the same as the unrelated conditions ($p>0.1$ uncorrected) but greater than semantic priming within language (Z=2.3 for German PET group, Z=1.9 for German fMRI group and Z=1.2 for Japanese fMRI group). This is entirely consistent with our proposal that caudate responses increase when there is a change in semantics ***or*** a change in language (the translation condition involved a change in language but not semantics).

References

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S2. Nelson, H. E. (1982) *The national adult reading test*. Windsor: NFER-Nelson Publishing.

S3. McKenna, P. and Warrington, E. K. *Graded Naming Test.* NFER-Nelson Publishing.

S4. Lambert S, Sampaio E, Scheiber C, Mauss Y. (2002) Neural substrates of animal mental imagery: calcarine sulcus and dorsal pathway involvement-an fMRI study. *Brain Res.* 924(2):176-83.

Table S1: Group English language performance data

The table displays mean scores and standard deviations (SD) of the subject groups. We performed independent t-tests for each variable, and significance was set at P<0.05 (two tailed).The German PET and fMRI groups were significantly better than the Japanese group on all 3 tests (Vocabulary: p=0.018, SE: 7.4; p=0.005, SE: 6.7; GNT: p=0.005, SE: 1.9; p=0.003, SE: 1.7; NART: p=0.014, SE: 2.7; p=0.001, SE: 2.1, respectively). There was no difference between the 2 German groups on the same tests. There was no difference between the 3 groups on the age of English acquisition (AOA).

Group	Vocabulary		GNT[1]		NART[1]		AOA	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
German PET (n=11)	80.5[2]	20.9	19[3]	5.2	40.3[3]	7.7	11.3	4.5
German fMRI(n=11[4])	82.5	19.0	18.7	4.4	41	5.5	7.7	7
Japanese fMRI (n=9[5])	61.2	7.3	12.8	2.8	32.8	3.1	10.9	3.4
Maximum Score	*100*		*30*		*50*		*Years*	

[1] The GNT and NART have only been standardized on English monolingual subjects.

[2] One subject did not complete this test

[3] One subject did not complete these tests as they were already familiar with them.

[4] Three subjects did not complete the behavioural tests.

[5] One subject was later excluded from the fMRI analysis so their data are not included here.

Table S2: Experimental stimuli

The complete list of stimuli. Items in *italics* were those that were adapted for the Japanese subjects. Note that (i) the list of semantic and unrelated primes are the same but their pairing with the target differed and (ii) the same sets of unrelated and semantically related stimuli are presented in each language combination (e.g. English-English, German-German, English-German, German-English).

	Unrelated Prime	Semantic Prime	TARGET		Unrelated Prime	Semantic Prime	TARGET
1.	mite	foal / *pony*	HORSE	61.	walking stick	trunk	CONTAINER
2.	rabbit	woodpecker	PIGEON	62.	groceries	knob	DOOR HANDLE
3.	locust	cow	BULL	63.	spear	box	CRATE / *PACKET*
4.	cow	locust	GRASSHOPPER	64.	box	groceries	TROLLEY / *SHOPPING CART*
5.	woodpecker	rabbit	GUINEA PIG	65.	knob	spear	DART
6.	foal / *pony*	mite	LICE	66.	trunk	walking stick	UMBRELLA
7.	seahorse	tree	SQUIRREL	67.	church	dirt	DUSTPAN
8.	deer / *sheepdog*	drake / *pelican*	DUCK	68.	bottle opener	knife	FORK
9.	cockerel / *rooster*	lamb	SHEEP	69.	mug	biro / *ballpoint*	FOUNTAIN PEN
10.	lamb	cockerel / *rooster*	CHICKEN	70.	biro / *ballpoint*	mug	CUP
11.	drake	deer / *sheepdog*	ELK / *DOBERMAN*	71.	knife	bottle opener	CORKSCREW
12.	tree	seahorse	PRAWN / EEL	72.	dirt	church	BELL
13.	piglet	lizard	SNAKE	73.	rod	clothes	IRON
14.	wasp	beef	CATTLE	74.	crayon	garbage	DUSTBIN
15.	crane	knight	DRAGON	75.	stick	baking tray	FRYING PAN
16.	knight	crane	HERON / *FLAMINGO*	76.	clothes	stick	BATON
17.	lizard	piglet	HOG	77.	garbage	crayon	PENCIL
18.	beef	wasp	BEE	78.	baking tray	rod	CANE
19.	hummingbird	mule	DONKEY	79.	pram / *buggy*	water	JUG
20.	stag / *terrier*	cuckoo	MAGPIE / *DOVE*	80.	drill	brush	COMB
21.	web	rodent	MOUSE	81.	kettle	mobile	PHONE
22.	rodent	web	SPIDER	82.	mobile	kettle	TEAPOT
23.	cuckoo	stag / *terrier*	REINDEER / *HUSKY*	83.	brush	drill	SCREWDRIVER
24.	mule	hummingbird	BLACKBIRD	84.	water	pram / *buggy*	WHEELCHAIR
25.	owl	millipede	CATERPILLAR	85.	mallet	wallet	PURSE
26.	octopus	fairy	UNICORN	86.	grater / *mixer*	shovel	SPADE
27.	goblin	dog	FOX	87.	sink	mop	BROOM
28.	dog	goblin	DWARF	88.	mop	sink	WATER TAP
29.	millipede	octopus	STARFISH	89.	shovel	grater / *mixer*	SIEVE / *JUICER*
30.	fairy	owl	BAT	90.	wallet	mallet	AXE

	Unrelated Prime	Semantic Prime	TARGET
31.	bird	mare / *poodle*	STALLION / *BULLDOG*
32.	child	cheetah	LION
33.	kestrel / *dolphin*	baboon	MONKEY
34.	baboon	kestrel / *dolphin*	VULTURE / *ORCA*
35.	cheetah	child	ADULT
36.	mare / *poodle*	bird	OSTRICH
37.	hawk	vole / *rat*	MOLE
38.	snail	sparrow	ROBIN
39.	partridge / *skylark*	bug	LADYBIRD
40.	sparrow	snail	WORM
41.	bug	partridge / *skylark*	PHEASANT / *NIGHTINGALE*
42.	vole / rat	hawk	EAGLE
43.	flea	cockroach	BEETLE
44.	poultry	canary	PARROT
45.	moth	shark	WHALE
46.	shark	moth	BUTTERFLY
47.	canary	poultry	TURKEY
48.	cockroach	flea	LEECH / *MOSQUITO*
49.	toad	trout	SALMON
50.	goose	seagull	SEAL
51.	gnat / *cicada*	plaice / *tuna*	COD
52.	plaice / *tuna*	gnat	DRAGONFLY
53.	trout	goose	SWAN
54.	seagull	toad	FROG
55.	skunk / *wolf*	ant	FLY
56.	crab	skunk / *wolf*	BADGER / *RACCOON*
57.	raven	rhinoceros	HIPPOPOTAMUS
58.	rhinoceros	porcupine / *panda*	HEDGEHOG / *BEAR*
59.	porcupine / *panda*	raven	CROW
60.	ant	crab	LOBSTER

	Unrelated Prime	Semantic Prime	TARGET
91.	dagger	satchel / *bag*	SUITCASE
92.	bathtub	ladle	SPOON
93.	bucket	pliers	TWEEZERS
94.	pliers	bucket	BASKET
95.	ladle	bathtub	SHOWER
96.	satchel / *bag*	dagger	SWORD
97.	harpsichord	safe	LOCKER
98.	cradle / *futon*	kitchen	SINK
99.	escalator	nightdress	PYJAMAS
100.	nightdress	escalator	BANISTER / *ELEVATOR*
101.	kitchen	cradle / *futon*	COT / *MATTRESS*
102.	safe	harpsichord	PIANO
103.	wall	oven	STOVE
104.	wardrobe	settee / *couch*	ARMCHAIR
105.	overall	hammock	BUNKBED
106.	hammock	overalls	TROUSERS
107.	settee / *couch*	wardrobe	CUPBOARD
108.	oven	wall	FENCE
109.	stilts / *hammer*	toy	DOLL
110.	library	paintbrush	EASEL
111.	bench	skirt	TIGHTS
112.	skirt	bench	TABLE
113.	paintbrush	library	BOOKCASE
114.	toy	stilts / *hammer*	CRUTCHES / *NAIL*
115.	freezer	office	DESK
116.	chair	freezer	FRIDGE
117.	pillow	chair	STOOL
118.	crockery / *plate*	pillow	BED
119.	office	staircase	LADDER
120.	staircase	crockery / plate	DISHWASHER