

Reading *cinnamon* activates olfactory brain regions

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Some words immediately and automatically remind us of odours, smells and scents, whereas other language items do not evoke such associations. This study investigated, for the first time, the abstract linking of linguistic and odour information using modern neuroimaging techniques (functional MRI). Subjects passively read odour-related words ('garlic', 'cinnamon', 'jasmine') and neutral language items. The odour-related terms elicited activation in the primary olfactory cortex, which include the piriform cortex and the amygdala. Our results suggest the activation of widely distributed cortical cell assemblies in the processing of olfactory words. These distributed neuron populations extend into language areas but also reach some parts of the olfactory system. These distributed neural systems may be the basis of the processing of language elements, their related conceptual and semantic information and the associated sensory information.

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Introduction

A central issue in cognitive neuroscience concerns the way in which words and their meanings are represented and processed in the brain. In the present study, we tested the hypothesis that processing words with strong olfactory associations also activates olfactory regions of the brain. The rationale behind this hypothesis was based on a theoretical perspective according to which words are processed by distributed neural assemblies with cortical topographies that reflect their meaning or, more precisely, aspects of their reference (Braitenberg and Pulvermüller, 1992; Pulvermüller, 2001, 2002, 2005). As words are frequently used together with their referent objects and actions, the cortical neurons processing word- and object-related information frequently fire together and therefore wire together, so that the information about both referent and word is bound

together by cortical networks, or word webs. As referential information is processed in different parts of the cortex, action and object words would materialise as word webs with different cortical distributions.

The neurophysiological properties of such word-related cortical networks could be explained by a few neuroscientific principles (Pulvermüller, 2001). Among these, the Hebbian principle of correlation learning is especially relevant. Donald Hebb postulated that "any two cells or systems of cells that are repeatedly active at the same time will tend to become 'associated', so that activity in one facilitates activity in the other" (Hebb, 1949, p. 70). Therefore, if word forms frequently co-occur with non-linguistic stimuli, such as visual perceptions of objects, sounds, smells or body movements, their neuronal representations will include co-activated neurons involving specific sensory and motor information related to the referent. A consequence of this is that there are distinct neuronal assemblies for different word types, depending on the referential semantic meaning of the words (Hauk et al., 2004; Shtyrov et al., 2004; Moscoso del Prado Martin et al., 2005; Pulvermüller and Hauk, in press).

Evidence for such meaning-related differential topographies was provided by neuropsychological patients and neuroimaging studies of intact brains. For example, the production or comprehension of nouns and verbs or names of animals and tools was differentially affected by brain damage (Damasio and Tranel, 1993; Daniele et al., 1994; Humphreys and Forde, 2001; Miceli et al., 1984, 1988; Warrington and McCarthy, 1983; Warrington and Shallice, 1984). Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies have demonstrated differential activation of brain areas when action- or perceptually related words are being processed (Damasio et al., 1996; Martin et al., 1996; Martin and Chao, 2001; Moore and Price, 1999; Pulvermüller et al., 1999). More fine-grained predictions are confirmed in the case of action words that are semantically related to different parts of the body, such as face-related (e.g., 'to lick'), hand-related ('to pick') or leg-related verbs ('to kick'). Data from neurophysiological/behavioural studies (Pulvermüller et al., 2000, 2001), event-related fMRI

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(Hauk et al., 2004) and transcranial magnetic stimulation (TMS) (Pulvermüller et al., 2005a,b) make it clear that the comprehension of these words automatically activates the motor and premotor cortex in a somatotopic manner.

PET and fMRI studies have served to identify specific brain regions that respond to olfactory stimuli. In a seminal study, Zatorre et al. (1992) demonstrated that smelling odours activated the piriform and orbitofrontal cortices. The primary olfactory cortex (POC) is located within the piriform cortex at the junction of the temporal and frontal lobes. Other neuroimaging studies have confirmed the ability of odourants to increase activity in, or near, the piriform cortex (Bengtsson et al., 2001; Cerf-Ducastel and Murphy, 2004; Dade et al., 1998; Royet et al., 2003; Small et al., 1997; but see also Sobel et al., 1998; Zald and Pardo, 1997) (see Fig. 1).

Another brain area associated with smelling is the orbitofrontal cortex (OFC), which has been identified as the secondary olfactory region. Lesions in the orbitofrontal cortex lead to deficits in discriminating odours, and this region has shown enhanced levels of activity in most neuroimaging studies of olfaction performed to date (Levy et al., 1997; Royet et al., 2001; Small et al., 1997; Yousem et al., 1997; Zatorre et al., 1992). Stronger activity is usually present in the right orbitofrontal cortex than in the homotopic area on the left, but the reverse laterality has also occasionally been reported (Royet et al., 2001; Zald and Pardo, 1997, 2000). Olfactory-related activity has been consistently reported in the amygdala, especially during aversive stimulation (Zald and Pardo, 1997).

A hypothesis that has not been tested so far concerns the neurobiological basis of words that refer to olfactory sensations. The words ‘garlic’, ‘cinnamon’ and ‘jasmine’ are semantically linked to specific odours, and the cell assemblies processing these words in the human cortex should therefore be distributed over both language areas and olfactory regions of the brain.

We chose to test this hypothesis about the specific cortical distribution of odour word representations in a neuroimaging

experiment. Specifically, we predicted that reading words whose meanings have strong olfactory associations would activate primary and secondary olfactory regions in the piriform, orbitofrontal and insular cortices and in the amygdalae more strongly than matched words with weak or absent olfactory associations. To test this, haemodynamic activity was monitored using functional MRI while subjects passively read words.

Material and methods

Subjects

Twenty-three (four females) right-handed healthy native Spanish speakers took part in the study. Their mean age was 23.7 years (SD 5.2). None of them reported a history of speech or hearing disorders, nor psychiatric, neurological or vision problems.

Stimuli

In order to select appropriate stimulus words, a rating study was first performed to evaluate the semantic properties of a large number of Spanish words. Methods for stimulus evaluation were similar to the standard methods described earlier (Pulvermüller et al., 1999). Eighteen subjects were asked to rate words (nouns and adjectives) according to their olfactory associations – whether the words referred to and reminded them of a smell, or referred to objects with a strong smell – using a scale ranging from 1 (no or very weak olfactory associations) to 7 (very strong olfactory associations).

Two 60-word groups were selected according to their rating scores. One was a group of words with strong olfactory associations (*olfactory* words), and the other group consisted of terms with no or very weak olfactory associations (control words) (mean scores were 6.00 vs. 1.22 respectively; $t(17) = 36.9$, $P < 0.001$) (see Appendix). In order to minimise physical or psycholinguistic differences that could influence the haemodynamic response, both word groups were equated for mean word length (6.2 vs. 6.0 letters; $t(59) = 0.946$, $P = 0.348$) and mean lexical frequency (59.4 vs. 72.1 occurrences per five million from the LEXESP corpus (Sebastián-Gallés et al., 2000); $t(59) = 0.206$, $P = 0.651$).

Cognitive task design for fMRI

During fMRI scanning, subjects had to silently read two 60-word groups presented over 30 s blocks (10 words per block), making six *olfactory* blocks (with olfactory words) and six control blocks (with neutral words) in all. Each word was displayed for 750 ms with a SOA of 3 s. The words within each block were presented in a pseudorandom order alternating olfactory and control blocks. The task was programmed using Presentation software (v. 9.12; Neurobehavioral Systems, Inc), and words were displayed inside the scanner using Visuastim® goggles (Resonance Technologies, Inc.).

Scanning procedure

Imaging data were collected on a 1.5 T Siemens Avanto MRI scanner. Functional images were collected by using a

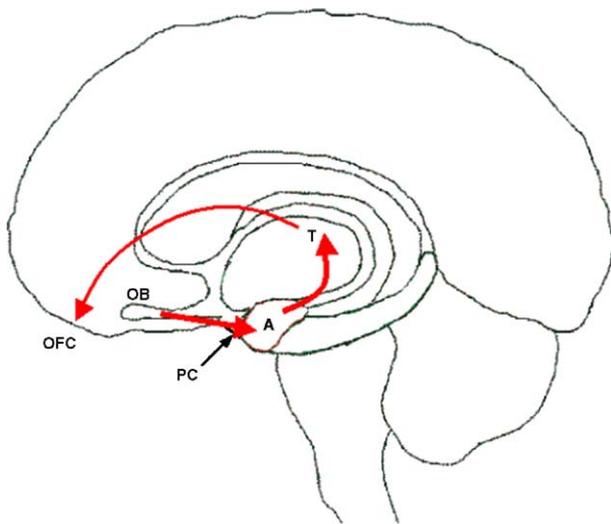


Fig. 1. Schematic drawing of some relevant olfactory pathways. OB: olfactory bulb. PC: piriform cortex. A: amygdala. T: thalamus (medial dorsal nucleus). OFC: orbitofrontal cortex. From the amygdala, diffuse projections emerge to the limbic system.

single-shot echo-planar imaging (EPI) sequence (64×64 matrix, FOV = 24 cm; TE = 50; TR = 3000; flip angle 90° ; slice thickness = 5; interslice gap = 1 mm; voxel size $3.94 \times 3.94 \times 6$ mm) with 29 slices acquired parallel to the inter-commissural line. Sagittal T1-weighted structural images (256×224 matrix; FOV 24×26 cm; TE = 4.9; TR = 11; voxel size $1 \times 1 \times 1$ mm) were acquired for each participant.

fMRI analysis

MRI images were processed using the SPM2 software (Wellcome Department of Cognitive Neurology, London). The first two volumes were excluded from analysis in order to avoid a T1 saturation effect. After realignment and co-registration using 12-parameter affine transformations, images were spatially normalised ($3 \times 3 \times 6$ mm) (Montreal Neurology Institute, MNI coordinates) and smoothed with a Gaussian kernel (FWHM $9 \times 9 \times 18$ mm). The data for each participant were modelled using a boxcar design convolved with the haemodynamic response function and time derivative (1 s). Motion correction parameters from realignment were included as regressors of non-interest at this first level, and a high pass filter with a cutoff period of 256 s was applied. A two-level random-effect analysis was performed. Group activations were considered if 10 or more adjacent voxels all passed the threshold of $P < 0.001$ (uncorrected). Stereotaxic coordinates for voxels with maximal z values within activation clusters are reported in the Montreal Neurological Institute standard space.

To test the hypothesis that activation produced by olfactory words should activate primary olfactory processing areas, a region-of-interest (ROI) analysis with small volume (SV) correction (Worsley et al., 1996) was therefore carried out. Central coordinates for SVC were based on previous local maxima of primary and secondary olfactory cortex obtained in response to valence-independent odour activations (Gottfried et al., 2002). This SVC analysis was done for a radius of 10 mm. Specifically, central coordinates were defined bilaterally for the piriform cortex in its temporal and frontal portion (temporal x ,

$y, z = -26, 2, -26$ (left)/ $24, 0, -24$ (right); frontal $x, y, z = -32, 4, -20$); bilateral amygdala (left: $x, y, z = -14, -10, -18$; right: $x, y, z = 24, -8, -18$); and bilateral OFC (left: $x, y, z = -24, 34, -16$; right: $x, y, z = 20, 30, -20$). Additionally, we estimated effect size of each ROI applied for SV correction using the Marsbar software utility (Brett et al., 2002).

Results

Comparisons between the reading of olfaction-related words and that of the matched control words revealed activations in the left occipito-temporal cortex, left inferior frontal gyrus, basal ganglia, thalamus, cingulate gyrus, insula, amygdala and piriform cortex (see Table 1 and Fig. 2). There were no areas where control words produced stronger activation than olfaction words. Specific hypotheses were tested using SV correction analyses, and results appear on Table 2. The reading of olfaction-related words has yielded significant activations in the bilateral piriform area and the right amygdala, whereas activations for the OFC and left amygdala were not significant.

Discussion

The results of the present study suggest that reading words with strong olfactory associations in their meaning activates olfactory regions of the brain. In particular, comparison of the olfactory words to the baseline (control words) revealed bilateral activation in primary olfactory areas (i.e., the piriform cortex) and the right amygdala, but not in the orbitofrontal cortex (i.e., the secondary olfactory area). Activation of primary olfactory areas by words with olfactory semantic associations supports the idea that perceptual information associated with the reference of a word is important for its neural representation. Using a different task, naming, Martin et al. (1995) found that generation of colour words activated a region near the area involved in perception of colour. Colour words were elicited by achromatic line drawings of objects in one experiment and by the written names of objects in a second experiment, which meant that the subjects were at no time submitted to sensorial stimulation by the colour named. In the present experiment, the subjects read words such as *canela* ('cinnamon'), *ajo* ('garlic'), *fétido* ('fetid'), etc., but, obviously, they were not exposed to any olfactory stimulation during the neuroimaging session.

According to Pulvermüller (2005, p. 580), "The cortical systems that process information about the referential meaning of a word seem to determine the cortical distribution of the neuronal network that the word activates". Evidence for this theoretical perspective has been obtained in recent years, especially from action words semantically related to different parts of body. Data provided by different techniques (Hauk et al., 2004; Hauk et al., 2004; Pulvermüller et al., 2001, 2005) suggested that the comprehension of these words activates the motor and premotor cortex in a somatotopic manner. That is, reading for example a leg-related verb such as 'to kick' activates classical language areas as well as motor regions involved in leg/foot movement. Processing of mouth (e.g., 'to kiss')- and hand-related ('to pick') words activates – along with the language areas – regions of the primary motor cortex

Table 1
Local maximas for each cluster of activation after whole volume analysis

Area	BA	Hemisphere	X	Y	Z	Z score	Cluster size
Inferior frontal gyrus/piriform/ claustrum	47	L	-39	21	0	4.53	37
Middle occipital gyrus/lingual gyrus	18	L	-24	-87	0	4.32	158
Insula	13	R	27	-27	24	4.04	18
Cingulate gyrus	32	L	-9	15	48	3.94	22
Putamen/Piriform/ Amygdala/ Claustrum		R	27	0	-6	3.78	48
Cerebellum		R	15	-60	-18	3.68	14
Cerebellum		L	-12	-60	-18	3.67	15
Thalamus/Caudate		L	-12	-21	6	3.61	24

Areas included in each cluster of more than 10 voxels of continuous activation (one-sample t test; $P < 0.001$ uncorrected) are named. L, left hemisphere; R, right hemisphere.

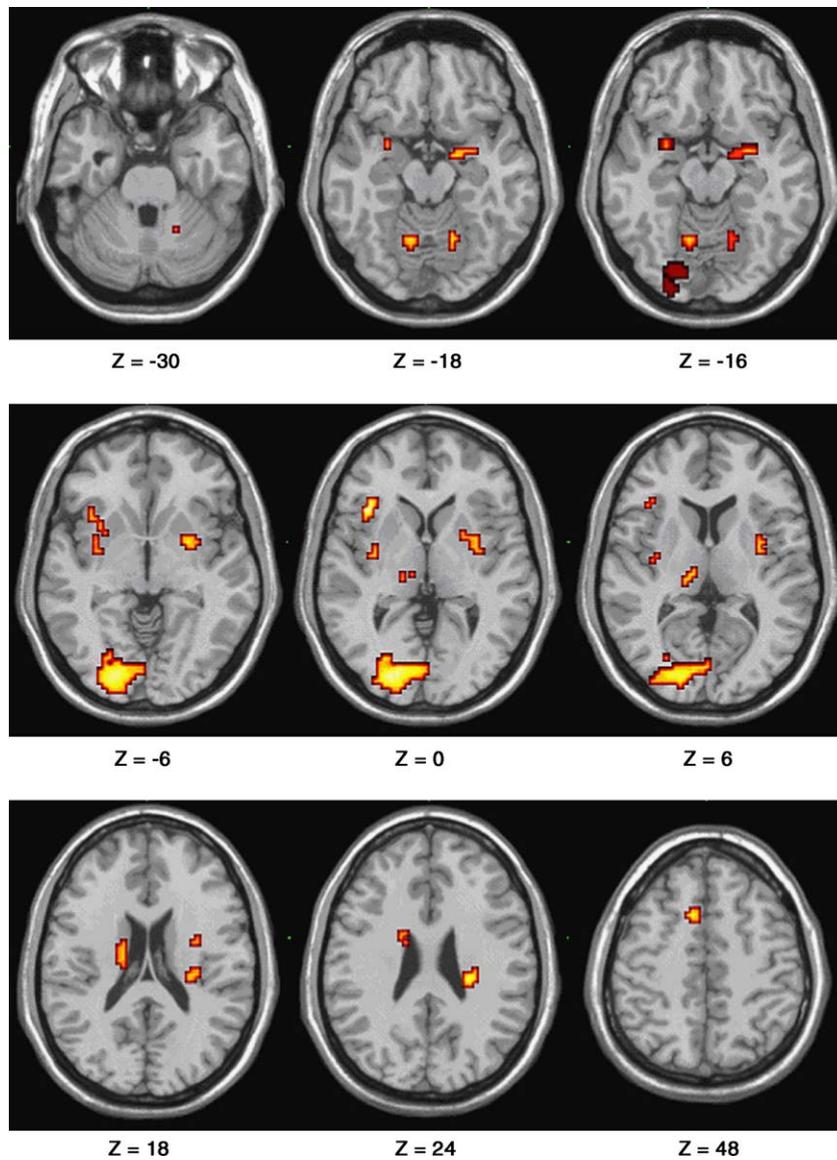


Fig. 2. Brain activation for whole volume analysis at each referred Z coordinate in Table 1.

involved in mouth and hand movements respectively. These and other data suggested that word meaning is not confined to just meaning-specific brain regions in some left perisylvian areas; rather, it seems likely that semantic representations are distributed in a systematic way throughout the entire brain (Hauk et al., 2004). Additional cortical areas critically involved

in processing perceptual and motor information of the semantic reference possibly contribute to the processing of word meaning. Activation of olfactory brain regions when a subject processes words with olfactory semantic attributes is consistent with this viewpoint. It seems that olfactory activation may be interwoven with the neuronal representation of such *olfactory* words. A tentative explanation comes from the cell assembly model, in which distributed functional networks bind information about word forms and the referents to which they are semantically linked. Neuronal assemblies for odour words could include neuron populations in the primary olfactory cortex and the amygdala.

On the basis of the present data, we may suggest that odour words automatically and immediately activate their semantic networks in the olfactory cortices. Such an immediate process of ignition of semantic networks, which reflects the psycholinguistic process of lexico-semantic access, is suggested by recent MEG data. These data showed fast spreading (within 200 ms) of neuronal activity from language areas to specific sensorimo-

Table 2
Coordinates and statistics for significant activation peaks after small volume correction ($P < 0.05$) using ROIs based on Gottfried et al. (2002)

ROI	Hemisphere	Effect size	x	y	z	Z	P
Piriform	L (temporal)	0.11 ($P = 0.002$)	-27	0	-18	3.30	0.02
	L (frontal)	0.12 ($P = 0.002$)	-30	0	-12	3.38	0.009
	R (temporal)	0.08 ($P = 0.004$)	21	-6	-18	3.49	0.009
Amygdala	R	0.09 ($P = 0.009$)	18	-6	-18	3.64	0.005
	R		27	-3	-12	3.58	

Effect sizes are also estimated for the each ROI independently.
L, left hemisphere; R, right hemisphere.

tor areas when action words semantically related to different parts of body are being perceived (Pulvermüller et al., 2005a,b). However, mental imagery of odours as a late secondary process following the initial lexico-semantic processing of odour words constitutes a second possible interpretation of our present data. Neurophysiological experiments will be necessary to reveal the time course of brain activation in odour word processing and to decide whether specific olfactory areas are activated automatically and immediately (within 200 ms) or after an additional delay (400–500 ms) as a result of additional cognitive activity. This question could be addressed, for example, by using high-resolution neurophysiology imaging with MEG or EEG (Pulvermüller, 2005; Pulvermüller et al., 2005a,b). Furthermore, activation of the sensorimotor cortex should not require people to attend to language stimuli but should instead be automatic (Pulvermüller, 2005). To further investigate this possibility, new experiments could be necessary, in which participants were actively distracted while odour words were being presented (Pulvermüller et al., 2005a,b; Shtyrov et al., 2004).

Experimental stimuli selected in the present study were words with strong olfactory associations, regardless of their hedonic odour valence (i.e., their being pleasant vs. unpleasant). For example, both *rosa* ('rose') and *heces* ('faeces') have olfactory associations, but it is obvious that their hedonic valence is quite different. It is probable that both types of words activate different brain regions beyond the primary olfactory areas. Our data show that *olfactory* words activate the right amygdala. Studies using electrophysiological and lesion techniques suggested that the amygdala played a crucial role in emotional processing in animals (Kier, 1977; Takagasi, 1991).

In humans, data are scarcer but point to the implication of the amygdala in emotional processing and, particularly, in the hedonic or emotional processing associated with smelling. There is evidence of amygdala activation during aversive olfactory stimulation. In a PET study, Zald and Pardo (1997) reported that exposure to a highly aversive odourant produced strong rCBF increases in both amygdalae. In an fMRI study of emotional responses to odours, Royet et al. (2003) found that the amygdala was activated more for unpleasant than for pleasant odours. It would be interesting to know whether the brain response to *olfactory* words parallels the neural response to actual odours.

In short, our results suggest that reading odour-related words elicits activation of olfactory brain regions. This fact is compatible with a theoretical framework according to which words are processed by distributed cortical systems involving information about the referential meaning. A critical question for future research is the need to determine the point in time when olfactory activation arises, and whether this activation occurs automatically and immediately as part of the semantic processing. In addition to this, further refinement in the stimulus selection will allow the role of the hedonic valence to be defined.

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Appendix A

Experimental items: Spanish words with strong olfactory associations (mean rating = 6.00 on a 1–7 scale) and their English translations Control items: Spanish

Aguarrás	(Turpentine)	Fétido	(Fetid)	Perfume	(Perfume)
Ajo	(Garlic)	Flor	(Flower)	Peste	(Foul smell)
Alcanfor	(Camphor)	Halitosis	(Halitosis)	Pies	(Feet)
Amoniaco	(Ammonia)	Heces	(Faeces)	Pintura	(Painting)
Anís	(Anise)	Hedor	(Stink)	Podrido	(Rotten)
Aroma	(Aroma)	Incienso	(Incense)	Pólvora	(Gunpowder)
Azahar	(Orange blossom)	Jabón	(Soap)	Pútrido	(Putrid)
Barniz	(Varnish)	Jazmín	(Jasmine)	Rancio	(Rancid)
Basura	(Rubbish)	Lavanda	(Lavender)	Resina	(Resin)
Betún	(Bitumen)	Lejía	(Bleach)	Retrete	(Bathroom)
Caca	(Poo)	Letrina	(Latrine)	Romero	(Rosemary)
Café	(Coffee)	Limón	(Lemon)	Rosa	(Rose)
Canela	(Cinnamon)	Maloliente	(Stinking)	Sándalo	(Sandal)
Clavel	(Carnation)	Menta	(Mint)	Sardina	(Sardine)
Cloaca	(Sewer)	Mentol	(Menthol)	Sobaco	(Armpit)
Colonia	(Cologne)	Mierda	(Shit)	Sudor	(Sweat)
Establo	(Cowshed)	Orégano	(Oregano)	Tufo	(Fug)
Eucalipto	(Eucalyptus)	Orina	(Urine)	Vainilla	(Vanilla)
Excremento	(Excrement)	Pachulí	(Patchouli)	Vinagre	(Vinegar)
Fecal	(Faecal)	Pedo	(Fart)	Vómito	(Vomit)

Control items: Spanish words without or very weak olfactory associations (mean rating = 1.22 on a 1–7 scale) and their English translations

Abrigo	(Coat)	Corto	(Short)	Pinza	(Hairgrip)
Aguja	(Needle)	Croquis	(Sketch)	Póquer	(Poker)
Ascuá	(Ember)	Curso	(Course)	Rima	(Rhyme)
Avión	(Plane)	Estropicio	(Breakage)	Ruleta	(Roulette)
Bastón	(Stick)	Gafas	(Glasses)	Saeta	(Dart)

Appendix A (continued)

Bayoneta	(Bayonet)	Granate	(Deep red)	Salto	(Jump)
Bingo	(Bingo)	Gris	(Grey)	Secador	(Drier)
Botón	(Button)	Guitarra	(Guitar)	Sierra	(Saw)
Bribón	(Rascal)	Jota	(Letter J)	Silbato	(Whistle)
Brújula	(Compass)	Látigo	(Whip)	Silla	(Chair)
Campana	(Bell)	Letra	(Letter)	Sinfonía	(Symphony)
Canción	(Song)	Llave	(Key)	Sota	(Jack)
Cartaginés	(Cartaginian)	Lote	(Lot)	Tablón	(Plank)
Chaflán	(Corner)	Mago	(Wizard)	Tambor	(Drum)
Chamán	(Shaman)	Metrónomo	(Metronome)	Tarzán	(Tarzan)
Círculo	(Circle)	Montón	(Heap)	Tendón	(Tendon)
Copa	(Glass)	Nube	(Cloud)	Tijeras	(Scissors)
Córner	(Corner)	Patada	(Kick)	Tratado	(Treaty)
Correo	(Post)	Peonza	(Spinning top)	Trato	(Deal)
Cortejo	(Entourage)	Piano	(Piano)	Yonqui	(Junkie)

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