The Anatomical Correlates of Abstract and Concrete Words: A meta-analytical review of whole-brain imaging studies

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Abstract

Several studies have investigated how abstract and concrete concepts are processed in the brain, but data are controversial, in particular neuroimaging data contrast with clinical neuropsychological observations. A possible explanation could be that previous meta-analyses considered different types of stimuli (nouns, verbs, literal and figurative sentences).

Using the ALE method, we meta-analyzed 32 brain-activation imaging studies that considered only words (nouns and verbs). Five clusters were associated with concrete words (the left superior occipital, middle temporal, parahippocampal and bilateral posterior cingulate, angular, and precuneus gyri); four clusters were associated with abstract words (left IFG, superior, and middle temporal gyri). When only nouns were considered three left activation clusters were associated with concrete stimuli and only one with abstract nouns (left IFG).

These results confirm that concrete and abstract word processing involves at least partially segregated brain areas, the IFG being relevant for abstract nouns and verbs while more posterior temporo-parieto-occipital regions seem to be crucial for concrete words.

1. Introduction

An advantage for concrete words as compared to abstract words has been demonstrated in a series of psycholinguistic studies. Neurologically unimpaired participants perform better on concrete than abstract words in free recall, cued recall, paired-associate learning and recognition; their reaction times in visual lexical decision are shorter with concrete than abstract words[1].This effect is known as “concreteness effect”, and it increases in aphasic patients. This is especially evident in non-fluent aphasia, for example in patients with agrammatism[2], where it has been found in spontaneous speech[3], reading[4], writing[5], repetition[6], naming[7], and comprehension[8]. Several theories [9–12] have been proposed to explain this advantage of concrete words but all of them share a common feature, namely a quantitative distinction between concrete and abstract concepts, with concrete items more strongly represented than abstract ones, either because they benefit from a verbal and visuo-perceptual representation[10] or thanks to a larger contextual support[12] or a larger number of semantic features[9,11]. However, a reversal of the concreteness effect has been documented in a number of brain-damaged subjects[13,14,23,15–22], and group studies[24–28], who consistently show better performance on abstract as compared to concrete words.

To account for the reversed concreteness effect, it has been proposed that abstract and concrete concepts are distinguished by the manner in which they are acquired, and by the relative weight of sensory-perceptual features in their representation[14]. An alternative explanation by Crutch and Warrington[29], points to a fundamental difference in the architecture of concrete and abstract word representations: the primary organization of concrete concepts is categorical, whereas abstract concepts are predominantly represented by association to other items. In this framework, a reversed concreteness effect might result from selective damage to categorical information (which would selectively affect conceptual representations of concrete words).

The reversal of concreteness effect raises questions on the neural correlates of concrete and abstract concepts. In aphasic patients, an increase of concreteness effects has been associated to vascular damage in the territory of the left middle cerebral artery, involving the dorsolateral prefrontal cortex. Cases of reversed concreteness effects, in contrast, are associated to herpes simplex encephalitis[20,23] and semantic dementia both in single cases[14–16, 19], and group studies[24–26, 28], that typically affect anterior temporal regions. These results have been confirmed in patients after left temporal pole resection[27] and during direct electrical stimulation in awake surgery[30]. All these data seem to suggest a role of the left prefrontal cortex and the anterior temporal lobe, in the representation of abstract and concrete concepts, respectively. Notably, with the exception of Yi et al.’s[28] and Bonner et al.’s[24] studies, the reversal of concreteness effect has been found for nouns but not for verbs.

Neuroimaging data are more controversial and do not match clinical evidence. In a previous meta-analysis[31], based on 19 fMRI and PET studies, abstract concepts compared to concrete ones were found to produce an activation of the left inferior frontal gyrus (IFG) and middle temporal gyrus (MTG), while concrete concepts compared to abstract ones activated the left posterior cingulate, precuneus, fusiform gyrus, parahippocampal cortex. However, Wang et al.[31] took into consideration not only nouns, but also verbs, sentences and fixed expressions, such as idioms.

The present systematic review and meta-analysis aimed at addressing the following research questions: (i) which are the neural correlates of concrete and abstract words, i.e., which regions are consistently activated across experiments that required participants to process abstract and concrete words? (ii) how the results might vary depending on the type of material used (noun or verb stimuli), fMRI recording tasks (e.g., semantic judgments, lexical decision, etc.), and the modality of presentation (visual or auditory). The rationale of this sub-analyses is based on the fMRI literature suggesting that stimulus types, presentation modality, and task could impact on the pattern of activation since minor variations in paradigms can produce large changes in cognitive strategies[32,33].

Accordingly, we did not include studies using complex stimuli as sentences, or short stories since these publications might tap on different cognitive processes such as attention and working memory. Another problem with complex stimuli is the difficulty to properly balance them between the experimental conditions due to the grammatical and syntactical components.

Consequently, our study differs from previous meta-analyses[31,34] in three aspects:

(i) Both, Wang et al.[31] and Binder et al.[34] combined in their studies different types of stimuli, e.g., words, sentences, fixed expressions such as idioms, and short stories without further focusing on the stimulus type. Furthermore, since Binder et al.’s[34] objective was to investigate the semantic processing in general and not concrete and abstract distinction (although they run a sub-analysis on these two categories), the activation peaks meta-analyzed were obtained from different contrasts: concrete and abstract stimuli > baseline, concrete > abstract and abstract > concrete stimuli. This choice is comprehensible given their objective but the results can be biased by the type of contrast applied; indeed, discrepancies in the patterns of cortical activation across studies may be attributable, at least in part, to differences in baseline tasks, and hence, reflect the limits of the subtractive logic.

For these reasons, we did not include the same studies that were included in the previously mentioned meta-analyses.

1. We used a different method, choosing the more popular Activation Likelihood Estimation[35–37] (ALE) as compared to the multilevel kernel density analysis (MKDA)[38] applied by Wang et al.[31]. MKDA and ALE produce similar results, both using the location (xyz-coordinates) of local maxima reported by the individual studies, but MKDA uses a spherical kernel whose radius is determined by the analyst[39] while ALE applies a Gaussian kernel whose FWHM is empirically determined. Moreover, our analyses are conducted on the last version of the GingerAle software, which managed to rectify some of the previous limitations of this instrument, e.g., the frequently used FDR correction is no longer supported[37] and proposes new best-practice ALE recommendations like the cluster-level family-wise error (FWE) corrected threshold of $p < .05$ [40].
2. Our results are an update of the previous reviews, including publications from the last 10 years.

2. Materials And Methods

The present systematic review was conducted under the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[41].

2.1. Studies selection

Our meta-analysis is based on 32 neuroimaging studies exploring the neural basis of concrete and abstract words processing, using either PET or fMRI on adult participants, published between January 1996 and February 2021. Studies were selected using four electronic databases: MEDLINE (accessed by PubMed, https://www.ncbi. nlm.nih.gov/pubmed), PsycARTICLES (via EBSCOHost, https://search.ebscohost.com), PsycINFO (via EBSCOHost) and Web of Science (https://webofknowledge.com/). The search terms used were: (1) *"semantic decision", "semantic judgment"; "abstract words", "concrete words", "abstract concepts", "concrete concepts", "lexical decision"* AND (2) *"imaging", "MRI", "PET"*. Additional sources such as reference lists of included studies and relevant systematic reviews were also checked.

Titles, abstracts, and full-text articles were screened and evaluated for eligibility based on the following criteria:

Inclusion criteria:

- imaging technique: PET or fMRI,
- reported stereotaxic coordinates (in the MNI or Talairach atlases),
- whole-brain voxel-based data analyses,
- more than 5 participants in each study,
- sample population of healthy, adult participants,
- reported concrete > abstract or abstract > concrete contrast,
- word stimuli,
- published in English,

Exclusion criteria:

- region-of-interest analyses,
- multiple single-case analyses,
- sample population of minors,
- sample population of neurological, brain-damaged, cognitively impaired or psychiatric patients,
- only concrete > baseline or abstract > baseline contrasts,
- articles from the gray literature (i.e., literature that is not formally published in sources such as books or journal articles, e.g. unpublished Ph.D. thesis),
- presentations from international meetings with no specific data provided, perspective and opinion publications, case reports, series of cases, previous reviews or meta-analyses,
- studies not published in, or translated into English,
- phrases or sentences stimuli,
- studies without adequate information (e.g., stereotaxic coordinates) to analyze the concrete vs. abstract contrasts and no reply from the authors after asking for the missing data.

As previously specified, we looked for publications that reported concrete > abstract words or abstract > concrete words contrast, without analyzing the exact strategies that the authors applied to divide word stimuli into the two categories. Often, the abstractness/concreteness constructs are operationalized in the papers based on two rating methods: (1) asking participants to classify a word as concrete taking into consideration the degree to which it refers to a tangible entity in the world (it has clear references to material objects); (2) or by evaluating its imageability, i.e., the ease with which the word elicits a mental image. Generally speaking, words referring to something that exists in reality and one can have an immediate experience of it through the senses are considered concrete (e.g., animals, tools); while words whose meaning cannot be experienced directly but can be defined by other words, internal sensory experience, and linguistic information, are classified as abstract (e.g., emotions, morality, social interaction, time).

After removing duplicates, research papers which did not satisfy the above criteria were excluded. For example, several studies focused on sentences or phrases[42,43]; or reported only words > baseline contrasts[44]. The more conservative concrete > abstract and abstract > concrete contrast (as opposed to concrete > baseline or abstract > baseline contrasts) was chosen in order to avoid a variety of baselines that could range from resting state, fixation cross[45] to pseudowords[46] and number or letters[47] and could affect the interpretation of the results, since subtractions from different baselines create different activation patterns.

If the same data were reported in different publications, we chose the most recent one and with the highest number of participants[48,49].

Uncertainties regarding some inclusion were solved by the authors through discussion. The PRISMA flow of information diagram was used to track the search process as presented in Fig. 1 and the main characteristics of the studies included in this meta-analysis are reported in Table 1.

Table 1
Descriptive information of the 32 experiments included in the meta-analysis.

	Paper	Technique	Sample size	Age of subjects (years)	Stimuli	Stimuli presentation modality	Experimental task	Design	Random or fixed effect	Contrasts p-value *
1.	D'Esposito, M., Detre, J. A., Aguirre, G. K., Stallcup, M., Alsop, D. C., Tippet, L. J., & Farah, M. J. (1997). A functional MRI study of mental image generation. Neuropsychologia, 35(5), 725–730.	MRI, 1.5 Tesla	7	range 18–37	English nouns (concrete vs abstract)	Auditory	mental image generation (concrete) and passive listening (abstract)	blocks	fixed	p < .001 corrected
2.	Mellet, E., Tzourio, N., Denis, M., & Mazoyer, B. (1998). Cortical anatomy of mental imagery of concrete nouns based on their dictionary definition. Neuroreport, 9(5), 803–808.	PET	8	range 20–25	French nouns (concrete vs abstract)	Auditory	mental image generation (concrete) and passive listening (abstract)	blocks	fixed	p = 0.001 uncorrected
3.	Perani, D., Cappa, S. F., Schnur, T., Tettamanti, M., Collina, S., Rosa, M. M., & Fazio1, F. (1999). The neural correlates of verb and noun processing: A PET study. Brain, 122(12), 2337–2344.	PET	14	range 22–26	Italian words: (i) concrete verbs, (ii) abstract verbs, (iii) concrete nouns, (iv) abstract nouns	Visual	lexical decision (classify stimuli as words or nonwords)	blocks	fixed	p < 0.001 uncorrected
4.	Kiehl, K. A., Liddle, P. F., Smith, A. M., Mendrek, A., Forster and, B. B., & Hare, R. D. (1999). Neural pathways involved in the processing of concrete and abstract words. Human brain mapping, 7(4), 225–233.	MRI, 1.5 Tesla	6	range 22–26	English words: concrete or abstract	Visual	lexical decision (classify stimuli as words or nonwords)	blocks	fixed	p < 0.05 corrected
5.	Jessen, F., Heun, R., Erb, M., Granath, D. O., Klose, U., Papassotiropoulos, A., & Grodd, W. (2000). The concreteness effect: Evidence for dual coding and context availability. Brain and language, 74(1), 103–112.	MRI, 1.5 Tesla	14	range 20–44 (31.5 ± 6.3)	German nouns: concrete or abstract	Visual	memory encoding task	blocks	fixed	p < 0.001 uncorrected
6.	Tyler, L. K., Russell, R., Fadili, J., & Moss, H. E. (2001). The neural representation of nouns and verbs: PET studies. Brain, 124(8), 1619–1634.	PET	9	range 21–34 26 ± 5	English words: concrete or abstract	Visual	lexical decision (classify stimuli as words or nonwords)	block	fixed-effect	p < 0.05 corrected
7.	Grossman, M., Koenig, P., DeVita, C., Glosser, G., Alsop, D., Detre, J., & Gee, J. (2002). The neural basis for category-specific knowledge: an fMRI study. Neuroimage, 15(4), 936–948.	MRI, 1.5 Tesla	16	mean age 23.4	English nouns: animals, implement, abstract	Visual	semantic judgment (pleasant or not)	blocks	fixed	p < 0.05 corrected

	Paper	Technique	Sample size	Age of subjects (years)	Stimuli	Stimuli presentation modality	Experimental task	Design	Random or fixed effect	Contrasts p-value *
8.	Kounios, J., Koenig, P., Glosser, G., DeVita, C., Dennis, K., Moore, P., & Grossman, M. (2003). Category-specific medial temporal lobe activation and the consolidation of semantic memory: evidence from fMRI. Cognitive brain research, 17(2), 484–494.	MRI, 1.5 Tesla	16	mean age 73.9	English nouns: animal, implement, and abstract	visual	semantic judgement (pleasant or not)	block	fixed-effect	$p < 0.05$ corrected
9.	Whatmough, C., Verret, L., Fung, D., & Chertkow, H. (2004). Common and contrasting areas of activation for abstract and concrete concepts: An H215O PET study. Journal of Cognitive Neuroscience, 16(7), 1211–1226.	PET	15	range 69–90 74.3 ± 5.6	English nouns: two pairs (concrete or abstract)	Visual	semantic similarity decision (read aloud if the pairs are similar in meanings)	ns	ns	$p < 0.05$ corrected
10.	Noppeney, U., & Price, C. J. (2004). Retrieval of abstract semantics. Neuroimage, 22(1), 164–170.	MRI, 2 Tesla	15	range 21–46 mean age 30	English (i) abstract concepts, (ii) hand movements, (iii) visual attributes (iv) sounds	Visual	semantic similarity decision	blocks	random	$p < 0.001$ uncorrected
11.	Fiebach, C. J., & Friederici, A. D. (2004). Processing concrete words: fMRI evidence against a specific right-hemisphere involvement. Neuropsychologia, 42(1), 62–70.	MRI, 3 Tesla	12	mean age 25	German nouns: abstract and concrete	Visual	lexical decision (classify stimuli as words or nonwords)	event-related	ns	$p < 0.05$ corrected
12.	Giesbrecht, B., Camblin, C. C., & Swaab, T. Y. (2004). Separable effects of semantic priming and imageability on word processing in human cortex. Cerebral Cortex, 14(5), 521–529.	MRI, 1.5 Tesla	10	ns	English words: high imageable and low imageable	Visual	semantic judgement (words pairs related or unrelated)	event-related	random	$p < .001$, uncorrected
13.	Sabsevitz, D. S., Medler, D. A., Seidenberg, M., & Binder, J. R. (2005). Modulation of the semantic system by word imageability. Neuroimage, 27(1), 188–200.	MRI, 1.5 Tesla	28	range 18–33 22.8 ± 3.6	English nouns: concrete and abstract triads	Visual	semantic similarity decision	event-related	random	$p < .001$, uncorrected

	Paper	Technique	Sample size	Age of subjects (years)	Stimuli	Stimuli presentation modality	Experimental task	Design	Random or fixed effect	Contrasts p-value *
14.	Binder, J. R., Westbury, C. F., McKiernan, K. A., Possing, E. T., & Medler, D. A. (2005). Distinct brain systems for processing concrete and abstract concepts. Journal of cognitive neuroscience, 17(6), 905–917.	MRI, 1.5 Tesla	24	range 20–50	English nouns: abstract and concrete	Visual	lexical decision (classify stimuli as words or nonwords)	event-related	random	$p < .005$ uncorrected
15.	Harris, G. J., Chabris, C. F., Clark, J., Urban, T., Aharon, I., Steele, S., ... & Tager-Flusberg, H. (2006). Brain activation during semantic processing in autism spectrum disorders via functional magnetic resonance imaging. Brain and cognition, 61(1), 54–68.	MRI, 1.5 Tesla	20	range 19–50 31 ± 9	English nouns: abstract and concrete	Visual	semantic judgment (positive or negative)	block	random	$p < 0.05$ uncorrected
16.	Fliessbach, K., Weis, S., Klaver, P., Elger, C. E., & Weber, B. (2006). The effect of word concreteness on recognition memory. NeuroImage, 32(3), 1413–1421.	MRI, 1.5 Tesla	21	range 19–43 27.4 ± 6.2	German nouns: abstract and concrete	Visual	recognition task (old/new-decision)	event-related	random	$p < 0.05$ corrected
17.	Rüschemeyer, S. A., Brass, M., & Friederici, A. D. (2007). Comprehending prehending: neural correlates of processing verbs with motor stems. Journal of cognitive neuroscience, 19(5), 855–865.	MRI, 3 Tesla	20	range 22–33 27 ± 3	German verbs: simple, complex, motor, abstract	visual	lexical decision (classify stimuli as words or nonwords)	block	random	$p < .001$, uncorrected
18.	Pexman, P. M., Hargreaves, I. S., Edwards, J. D., Henry, L. C., & Goodyear, B. G. (2007). Neural correlates of concreteness in semantic categorization. Journal of Cognitive Neuroscience, 19(8), 1407–1419.	MRI, 3 Tesla	20	26.5 ± 4.5	English nouns: abstract and concrete	Visual	semantic categorization (consumable or not)	event-related	random	$p < 0.05$ ns
19.	Van Dam, W. O., Rueschemeyer, S. A., & Bekkering, H. (2010). How specifically are action verbs represented in the neural motor system: an fMRI study. Neuroimage, 53(4), 1318–1325.	MRI, 3 Tesla	16	range 18–38 24 ± 4.63	Dutch verbs denoting (i) actions that you perform mostly with your arms/hands/mouth or (ii) abstract events	Visual	semantic categorization task (go – no go)	event-related	random	$p < 0.05$ corrected

	Paper	Technique	Sample size	Age of subjects (years)	Stimuli	Stimuli presentation modality	Experimental task	Design	Random or fixed effect	Contrasts p-value *
20.	Zhuang, J., Randall, B., Stamatakis, E. A., Marslen-Wilson, W. D., & Tyler, L. K. (2011). The interaction of lexical semantics and cohort competition in spoken word recognition: an fMRI study. Journal of Cognitive Neuroscience, 23(12), 3778–3790.	MRI, 3 Tesla	14	range 19–33	British English nouns manipulating (cohort competition and imageability)	Auditory	lexical decision (classify stimuli as words or nonwords)	event-related	random	p < .001, uncorrected
21.	Rodríguez-Ferreiro, J., Gennari, S. P., Davies, R., & Cuetos, F. (2011). Neural correlates of abstract verb processing. Journal of Cognitive Neuroscience, 23(1), 106–118.	MRI, 3 Tesla	14	range 23–35 mean 29	Spanish verbs: concrete and abstract	Visual	passive reading	block	mixed effects	p < .001, uncorrected
22.	van Dam, W. O., van Dijk, M., Bekkering, H., & Rueschemeyer, S. A. (2012). Flexibility in embodied lexical-semantic representations. Human brain mapping, 33(10), 2322–2333.	MRI, 3 Tesla	20	range 18–24 20.5 ± 2.2	Dutch (1) action color (2) action nouns (3) color (4) abstract nouns	Auditory	semantic categorization (action or color characteristics)	block	random	p < 0.005 ns
23.	Wilson-Mendenhall, C. D., Simmons, W. K., Martin, A., & Barsalou, L. W. (2013). Contextual processing of abstract concepts reveals neural representations of nonlinguistic semantic content. Journal of cognitive neuroscience, 25(6), 920–935.	MRI, 3 Tesla	13	range 18–24	English words: two abstract (convince, arithmetic) two concrete (rolling, red)	Visual	semantic task (concept–scene match)	block	random	p < 0.05 corrected
24.	Vigliocco, G., Kousta, S. T., Della Rosa, P. A., Vinson, D. P., Tettamanti, M., Devlin, J. T., & Cappa, S. F. (2013). The neural representation of abstract words: the role of emotion. Cerebral Cortex, 24(7), 1767–1777.	MRI, 3 Tesla	20	range 18–33 21.9 ± 4.4	English nouns: abstract and concrete	Visual	lexical decision (classify stimuli as words or nonwords)	block	random	P < 0.05 FWE-cluster wise
25.	Hayashi, A., Okamoto, Y., Yoshimura, S., Yoshino, A., Toki, S., Yamashita, H., ... & Yamawaki, S. (2014). Visual imagery while reading concrete and abstract Japanese kanji words: An fMRI study. *Neuroscience research*, *79*, 61–66.	MRI, 1.5 Tesla	16	range 20–36 26.1 ± 5.9	Japanese kanji nouns: concrete and abstract	Visual	generate visual imagery	block	random	p < .001, uncorrected
26.	Roxbury, T., McMahon, K., & Copland, D. A. (2014). An fMRI study of concreteness effects in spoken word recognition. Behavioral and Brain Functions, 10(1), 34.	MRI, 3 Tesla	17	27 ± 5.1	English nouns: concrete, abstract and pseudowords	auditory	lexical decision (classify stimuli as words or nonwords)	event-related	random	p < .001, uncorrected

	Paper	Technique	Sample size	Age of subjects (years)	Stimuli	Stimuli presentation modality	Experimental task	Design	Random or fixed effect	Contrasts p-value *
27.	Skipper, L. M., & Olson, I. R. (2014). Semantic memory: Distinct neural representations for abstractness and valence. Brain and Language, 130, 1–10.	MRI, 3 Tesla	19	mean age 23	English nouns: concrete and abstract	Visual	semantic task (answer to question in reference to the 3 words in the block)	block	ns	p < 0.001 corrected
28.	Hoffman, P., Binney, R. J., & Ralph, M. A. L. (2015). Differing contributions of inferior prefrontal and anterior temporal cortex to concrete and abstract conceptual knowledge. *Cortex*, *63*, 250–266.	MRI, 3 Tesla	20	range 20–39 mean: 25	English words: concrete and abstract	Visual	semantic task (synonym judgement)	block	random	p < 0.05 corrected
29.	Kumar, U. (2016). Neural dichotomy of word concreteness: a view from functional neuroimaging. *Cognitive processing*, *17*(1), 39–48.	MRI, 3 Tesla	20	28.3 ± 3.	Hindi nouns: abstract, concrete and non-words	Visual	perceptual task (orthography judgment)	block	fixed	p < 0.05 corrected
30	Wang, X., Wang, B., & Bi, Y. (2019). Close yet independent: Dissociation of social from valence and abstract semantic dimensions in the left anterior temporal lobe. Human brain mapping, 40(16), 4759–4776.	MRI, 3 Tesla	23	range 19–29 mean 22.17	Chinese nouns: abstract, concrete	Visual	semantic task (which of the choices was more semantically related to the probe)	block	ns	P < 0.05 FEW corrected
31	Pauligk, S., Kotz, S. A., & Kanske, P. (2019). Differential impact of emotion on semantic processing of abstract and concrete words: ERP and fMRI evidence. Scientific reports, 9(1), 1–13.	MRI, 3 Tesla	21	23.3 ± 1.9	German nouns: abstract and concrete	Visual	delayed lexical decision task (classify stimuli as words or nonwords)	block	ns	voxelwise p = 0.001
32	Meersmans, K., Bruffaerts, R., Jamoulle, T., Liuzzi, A. G., De Deyne, S., Storms, G., ... & Vandenberghe, R. (2020). Representation of associative and affective semantic similarity of abstract words in the lateral temporal perisylvian language regions. NeuroImage, 217, 116892.	MRI, 3 Tesla	26	range 18–34 22.9 ± 3.7	Dutch nouns: abstract and concrete	visual and auditory	overt repetition task	event-related	random	p < 0.001 uncorrected p < 0.05 FWE-corrected

Abbreviations: ns, not specified

Age is reported in years and when was specified the means and standard deviations are presented

Note

The p values (the statistical threshold for the neuroimaging univariate analysis conducted in the included papers) are reported as they were presented in the original articles; the exact value and the correction procedure was not always specified.

2.2 Classification of the raw data before clustering analyses

From the selected papers, only the stereotactic coordinates representing the concrete > abstract or abstract > concrete contrasts were extracted. Following this procedure we obtained 295 foci from a total sample of 535 participants. The stereotaxic coordinates reported in terms of the Talairach and Tournoux atlas[50] were transformed into the MNI (Montreal Neurological Institute) stereotaxic space[51] using the tal2icbm transforms implemented in the GingerALE software[35,37,52].

For all the stereotaxic coordinates we extracted the relevant information about the statistical comparisons that generated them. More explicitly, we reported the MNI coordinates (MNI x,y,z), the name of the first author, the journal and the year of publication of the paper, the technique (PET or fMRI) and the stereotactic space used, the age of participants, the type of task, the nature of the contrast from which the peak was extracted, the statistical thresholds, the stimulus type (nouns or verbs) and the presentation modality (auditory or visual).

2.3 Clustering Procedure

Once obtained the set of MNI coordinates, the meta-analyses were carried out using the revised ALE algorithm[35,37] implemented into GingerALE software Version 3.0.2[52] (http://brainmap.org/ale). The ALE algorithm aims to identify areas with a convergence of reported coordinates across experiments that are higher than expected from a random spatial association. The logic behind this approach implies a spatial probability distribution modeled for each activation peak included in the dataset of interest. Reported foci are treated as centers of 3D Gaussian probability distributions capturing the spatial uncertainty associated with each focus[52]. The between-subject variance is weighted by the number of participants per study, since larger sample sizes should provide more reliable approximations of the "true" activation effect. The voxel-by-voxel union of these distributions is used as an activation likelihood map, subsequently tested for statistical significance against randomly generated sets of foci. ALE was proven to be a reliable way of blending evidence from multiple studies[37] and was used successfully in different fields e.g.,[53].

More specifically we used the following procedure:

- anatomical filtering - we applied a first filtering of the coordinates using the most conservative (smallest) mask available in the GingerALE software and 17 foci from the total of 295 fell out of the mask.

- ALE maps (quantify the degree of overlap in peak activation across experiments) were calculated using the modified ALE algorithm and the random-effects model[35,37];

- thresholding procedure – for each ALE calculation described below significance was tested using 1000 permutations with a cluster forming threshold of $p< 0.001$ (uncorrected). In order to increase test sensitivity to false positives significance was corrected with a cluster-level family-wise error threshold of $p< 0.05$ [40] as used by other meta-analytic studies[54].

Unfortunately, ALE cannot deal with multiple independent variables designs, and in this paper we intended to consider the role of different variables like (i) stimulus type (nouns only, verbs only or all the words stimuli), (ii) modality of presentation (visual only, auditory only or both visual and auditory), and (iii) task specificity (e.g., lexical, semantic tasks or all tasks). The ALE strategy we choose in this case was to consider separate sets of foci for each variable and run one meta-analysis for each of these sets when the number of papers was large enough. To this purpose, the overall dataset was divided into several subsets, which automatically implied running meta-analyses on a low number of foci (lowering the power). An important limitation of this approach is that we are not able to statistically assess the interaction between variables like stimuli type and task.

The analyses were based on the following contrasts:

(i) an analysis included the activation peaks associated with **word processing** independently of the stimulus type and task

- *concrete words > abstract words* included 149 stereotactic activation loci from 22 studies, 353 participants (8 foci out of mask)[45,47,62–71,48,72,73,55–61];

- *abstract words > concrete words* included 146 stereotactic activation loci from 25 studies, 415 participants (9 foci out of mask)[45,46,67–69,71,72,74–78,47,79–83,56–58,61–64];

(ii) an analysis with peaks associated with **noun processing** only (because the number of studies including verbs only was too small (4 studies) for a specific analysis on this type of stimuli[64,70,77,78])

- *concrete nouns > abstract nouns* included 107 stereotactic activation loci from 15 studies (5 foci out of mask), 251 subjects;

- *abstract nouns > concrete nouns* included 99 stereotactic activation loci from 18 studies (8 foci out of mask), 324 subjects;

(iii) an analysis included the activation peaks associated with word processing independently of the stimulus type (verbs, names or adjectives), but taking into consideration only **visually presented stimuli**.

- *concrete words > abstract words visual stimuli only* included 121 stereotactic activation loci from 18 studies, 301 participants

- *abstract words > concrete words visual stimuli only* included 135 stereotactic activation loci from 22 studies, 374 participants

Since only 5 studies included auditory stimuli we could not perform a specific analysis for this category [45,48,56,73,84].

(iv) an analysis on peaks associated with **lexical** (words or non-words classification task), or **semantic decision tasks** (e.g., pleasantness decision task, answering a question about the stimuli), excluding all the studies based on: memory tasks (2 studies), perceptual decision task (1 study), mental image generation (3 studies), passive reading (2 studies).

- *concrete > abstract word (only lexical and semantic tasks)* included 114 stereotactic activation loci from 16 studies, 273 participants

- *abstract > concrete word (only lexical and semantic tasks)* included 116 stereotactic activation loci from 17 studies, 289 participants

For anatomical labeling and figures, we capitalized on the Automatic Anatomical Labeling (AAL) template available in the MRIcron visualization Software (https://www.nitrc.org/projects/mricron).

3. Results

Once the appropriate studies were collected, we used activation likelihood estimation (ALE) to meta-analytically remodel available neuroimaging data.

3.1. CONCRETE > ABSTRACT Meta-analysis

The GingerALE procedure run over the concrete words > abstract words set of coordinates identified a total of 5 clusters, with 1 to 4 individual peaks each, from 4 to 11 different studies (Fig. 2). Regions that were consistently activated across experiments were localized in the bilateral middle temporal gyrus and posterior cingulate, the left parahippocampal gyrus, left fusiform gyrus, bilateral precuneus and angular gyri, left superior occipital gyrus and left cerebellum culmen. The peaks distribution for each significant cluster is reported in Table 2.

Table 2

Concrete > Abstract Word Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm^3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score	Contributor cluster	
		Lobe	Gyrus		x	y	z		x	y	z			Nr.	Studi
L	1	Temporal Occipital Parietal	Superior Occipital Middle Temporal Precuneus, Angular Cuneus	BA 39, BA 19	-38.6	-74.2	31.8	4680	-40	-74	34	0.025	5.859	11	Jesse (1); Sabs 2005 Binde (1); H 2006 Dam, (1); Z 2011 Rodrí Ferre (2); v 2012 Roxb 2014 Skipp (5); H 2015
									-44	-78	24	0.020	4.978		
									-40	-70	22	0.015	4.117		
									-38	-72	46	0.014	4.048		
L	2	Cerebellum Anterior Lobe, Limbic Lobe Temporal	Culmen (cerebellum), Parahippocampal Fusiform	BA 35, BA 36	-25.9	-34.3	-19.8	2584	-24	-36	-18	0.021	5.262	7	Sabs 2005 Harris (1); Rodrí Ferre (2); v 2012 Haya 2014 Roxb 2014 (1);H 2015
									-24	-30	-22	0.019	4.928		
									-34	-36	-24	0.013	3.764		
R	3	Parietal Temporal	Inferior Parietal Angular Precuneus, Middle Temporal	BA 39	44.8	-65.6	33.4	1648	44	-68	32	0.017	4.496	4	Sabs 2005 Dam, (1); R 2014 Hoffr 2015
									42	-60	36	0.012	3.640		
									48	-66	44	0.012	3.547		
L	4	Limbic Occipital	Posterior Cingulate Lingual Gyrus Cuneus	BA 30, BA 18	-10.0	-56.1	11.3	1184	-10	-56	12	0.018	4.756	5	Sabs 2005 Binde 2005 Harris 2006 Rüsc 2007 Roxb 2014
R	5	Limbic Lobe	Posterior Cingulate	BA 30	8.5	-54.0	10.0	840	8	-54	10	0.019	4.891	4	Sabs 2005 Harris (1); Rodrí Ferre (1);H 2015

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster; R = right.

A similar activation pattern, except for the right hemisphere involvement, was observed when only studies reporting exclusively noun stimuli were taken into consideration (concrete nouns > abstract nouns). We observed three left activation clusters (Fig. 3, Table 3) situated in the middle temporal gyrus, parahippocampal gyrus, posterior cingulate, precuneus, superior occipital gyrus, and culmen (left cerebellum anterior lobe).

Table 3
Concrete > Abstract Nouns Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score	Contributors cluster	
		Lobe	Gyrus		x	Y	z		x	y	z			No.	Studie
L	1	Occipital, Parietal, Temporal	Superior Occipital, Precuneus, Middle Temporal, Angular	BA 39, BA 19	-37.1	-73.8	35.2	3376	-34	-68	36	0.019	5.112	8	Jesse 2000 Sabse 2005 Binde 2005 Harris 2006 Zhuar 2011 van D 2012 Roxbu 2014 Skipp 2014 **
									-38	-74	32	0.019	5.051		
									-34	-78	38	0.017	4.784		
									-46	-76	28	0.015	4.320		
									-38	-72	46	0.014	4.240		
L	2	Anterior, Limbic	Culmen, Parahippocampal	BA 36, BA 35	-23.7	-34.2	-18.3	1432	-24	-36	-18	0.015	4.392	4	Hayas 2004 Sabse 2005 Harris 2006 Roxbu 2014 **
L	3	Limbic, Occipital	Posterior Cingulate, Cuneus	BA 30, BA 29	-9.5	-55.7	12.5	1040	-10	-56	12	0.017	4.745	4	Sabse 2005 Binde 2005 Harris 2006 Roxbu 2014 **
									-8	-46	14	0.009	3.338		

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster

The ALE procedure run over the concrete words > abstract words, visual stimuli only set of coordinates, identified a total of 5 clusters, with 1 to 6 individual peaks each, from 4 to 8 different studies (Fig. 4). Regions that were consistently activated across experiments were localized in the left middle temporal gyrus, bilateral posterior cingulate, and parahippocampal gyrus, left fusiform gyrus, bilateral precuneus and angular gyri, left superior occipital gyrus and left cerebellum culmen. The peaks distribution for each significant cluster is reported in Table 4.

Table 4
Concrete > Abstract Words - Visual stimuli- Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score	Contribut cluster	
		Lobe	Gyrus		x	y	z		x	y	z			No.	St
L	1	Temporal, Occipital, Parietal	Superior Occipital, Middle Temporal, Precuneus, Angular	BA 19, BA 39	-38.5	-74.6	31.9	4360	-40	-76	34	0.0212	5.3445	8	Sa 20 Bi (3) 20 Da (1) 20 Ro Fe (2) 20 Ho 20
									-44	-78	24	0.0174	4.7222		
									-36	-78	38	0.0172	4.6952		
									-34	-68	36	0.0169	4.6447		
									-40	-70	22	0.0145	4.1705		
									-38	-72	46	0.0143	4.1460		
L	2	Limbic Lobe, Anterior, Temporal	Parahippocampal, Culmen, Fusiform	BA 35, BA 36	-25	-33.2	-19.5	1752	-24	-30	-22	0.0180	4.8145	4	Sa 20 Ha (1) 20 Ho 20
									-26	-38	-16	0.0169	4.6525		
R	3	Parietal	Inferior Parietal, Angular, Precuneus	BA 39	45.9	-65.9	35	1336	46	-68	34	0.0151	4.2998	4	Je (1) Sa 20 Da (1) 20
									48	-66	44	0.0118	3.6536		
									42	-60	36	0.0116	3.6238		
R	4	Limbic	Posterior Cingulate, Parahippocampal	BA 30, BA 29	8.7	-54	10	992	8	-54	10	0.0192	5.0153	4	Sa 20 Ha (1) Ro Fe (1) 20
L	5	Limbic, Occipital	Posterior Cingulate, Lingual	BA 30, BA 18	-11	-55.6	12.8	888	-12	-56	14	0.0164	4.5739	4	Sa 20 Bi (1) 20 Rü 20

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster; R = right

A comparable activation pattern was observed when only studies based on lexical and semantic tasks were taken into consideration. The analysis indicated 4 activation clusters correlated with concrete words > abstract words - lexical and semantic tasks: bilateral middle temporal gyrus, left posterior cingulate and the left parahippocampal gyri, bilateral precuneus, left angular, left superior occipital gyrus and left cerebellum culmen (Fig. 5, Table 5).

Table 5
Concrete > Abstract Words – semantic and lexical tasks only- Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score
		Lobe	Gyrus		x	y	z		x	y	z		
L	1	Occipital,Temporal, Parietal	Superior Occipital, Middle Temporal, Precuneus, Angular	BA 19, BA 39	-38.6	-73.9	31.3	3856	-40	-74	34	0.0247	5.91
									-46	-78	26	0.0183	4.87
									-40	-70	22	0.0144	4.15
L	2	Limbic Lobe, Anterior lobe, Temporal	Parahippocampal, Culmen	BA 35, BA 36	-24.9	-33.8	-18.6	1792	-24	-38	-16	0.0193	5.03
									-24	-28	-22	0.0156	4.41
R	3	Temporal, Parietal	Middle Temporal, Precuneus	BA 39	44.3	-65.6	31.4	1696	44	-68	32	0.0167	4.62
									42	-60	36	0.0122	3.73
									40	-56	24	0.0091	3.19
L	4	Limbic Lobe, Occipital	Posterior Cingulate, Lingual	BA 30, BA 18	-10.1	-55.9	11.4	1392	-10	-56	12	0.0184	4.88
									-8	-46	14	0.0095	3.26

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster; R = right

3.2. ABSTRACT > CONCRETE Meta-analysis

The revised ALE algorithm discriminated four clusters that correlated with abstract word processing in a healthy population (Fig. 6), from four to 12 different papers (Table 6). Our analyses identified a robust neural pattern of activity in the left frontal and temporal lobes, specifically, the inferior frontal gyrus, the superior and middle temporal gyri and left inferior parietal.

Table 6
Abstract > Concrete Word Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score	Contributors to cluster	
		Lobe	Gyrus		x	y	z		x	y	z			Nr.	Studies
L	1	Frontal, Temporal	Inferior Frontal, Superior Temporal	BA 45, BA 47, BA 44	-50.8	21.7	-3.4	6680	-52	24	4	0.029	6.369	12	Perani, 1999 (2); Fiebach, 2004 (1); Sabsevitz, 2005 (3); Binder, 2005 (5); Fliessbach, 2006 (2); Pexman, 2007 (1); Rodríguez-Ferreiro, 2011 (2); Hayashi, 2014 (1); Hoffman, 2015 (3); Skipper, 2014 (2); Wang, 2019 (1); Pauligk, 2019 (2) **
									-48	20	-10	0.025	5.835		
									-54	8	-18	0.016	4.346		
L	2	Temporal	Middle Temporal	BA 22, BA 21	-60.5	-44.4	-1.6	1048	-60	-42	-6	0.016	4.369	5	Noppeney, 2004 (1); Sabsevitz, 2005 (1); Pexman, 2007 (2); Rodríguez-Ferreiro, 2011 (2); Wang, 2019 (1)**
									-60	-48	4	0.015	4.219		
L	3	Temporal Parietal	Superior Temporal Inferior Parietal,	BA 13, BA 40	-53.5	-42.9	24.1	960	-54	-42	24	0.021	5.112	4	Hayashi, 2014 (1); Hoffman, 2015 (2); Wang, 2019 (1); Meersmans, 2020 (1)**
L	4	Temporal	Superior and Middle Temporal	BA 22, BA 21	-49.5	-27.5	-2.6	840	-50	-28	-4	0.016	4.350	4	Sabsevitz, 2005 (1); Hoffman, 2015 (2); Kumar, 2016 (1); Wang, 2019 (1)**

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster

When only abstract nouns (abstract nouns > concrete nouns) were analyzed, the results indicated a single cluster with two peaks, from 9 studies, in the left inferior frontal gyrus (Fig. 7, Table 7).

Table 7
Abstract > Concrete Nouns Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score	Contributors to cluster	
		Lobe	Gyrus		X	Y	z		x	y	z			Nr.	Studies
L	1	Frontal	Inferior Frontal, Precentral	BA 47, BA 45, BA 44	-50.1	23.4	-1.3	4520	-52	22	6	0.0253	6.118	9	Fiebach, 2004 (1); Sabsevitz, 2005 (2); Binder, 2005 (3); Fliessbach, 2006 (2); Pexman, 2007 (1); Hayashi, 2004 (1); Skipper, 2014 (2); Wang, 2019 (1); Pauligk, 2019 (2) **
									-48	22	-10	0.0227	5.712		

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster

We identified three clusters associated with abstract words processing in a healthy population when only studies reporting abstract visual stimuli were included (Fig. 8), from 4 to 12 different papers (Table 8). Our analyses revealed a robust neural pattern of activity in the frontal and temporal lobes, specifically, the inferior frontal gyrus and the superior and middle temporal gyri.

Table 8
Abstract > Concrete Words - visual stimuli- Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score	Contributors to cluster	
		Lobe	Gyrus		x	y	z		x	y	z			No.	Studies
L	1	Frontal, Temporal	Inferior Frontal, Superior Temporal	BA 47, BA 45, BA 38	-50.7	21.7	-3.5	6992	-52	24	4	0.029	6.440	12	Perani, 1999 (2); Fiebach, 2004 (1); Sabsevitz, 2005 (3); Binder, 2005 (5); Fliessbach, 2006 (2); Pexman, 2007 (1); Rodríguez-Ferreiro, 2011 (2); Hayashi, 2014 (1); Hoffman, 2015 (3); Skipper, 2014 (2); Wang, 2019 (1); Pauligk, 2019 (2)**
									-48	20	-10	0.025	5.900		
									-54	8	-18	0.016	4.403		
L	2	Temporal	Middle Temporal	BA 22, BA 21	-60.4	-44.5	-1.7	1160	-60	-42	-6	0.016	4.425	5	Noppeney, 2004 (1); Sabsevitz, 2005 (1); Pexman, 2007 (2); Rodríguez-Ferreiro, 2011 (2); Wang, 2019 (1) **
									-60	-48	4	0.015	4.273		
L	3	Temporal	Superior Temporal	BA 22, BA 21	-49.5	-27.5	-2.6	904	-50	-28	-4	0.016	4.407	4	Sabsevitz, 2005 (1); Hoffman, 2015 (2); Kumar, 2016 (1); Wang, 2019 (1) **

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster

When only foci from lexical and semantic tasks were analyzed, the results indicated 2 clusters (with 1 to 4 individual peaks each, from 3 to 9 different studies), in the left inferior frontal gyrus, superior and middle temporal gyrus (Fig. 9 and Table 9).

Table 9
Abstract > Concrete Words – semantic and lexical task only- Clusters

H	Cluster	Macroanatomical Location		Cytoarchitectonic Label	Weighted Center (MNI; mm)			Vol. (mm3)	Peaks: MNI Coordinates (mm)			ALE score	Z Score	Contributors to cluster	
		Lobe	Gyrus		x	y	z		x	y	z			Nr.	Studies
L	1	Frontal, Temporal	Inferior Frontal, Superior Temporal	BA 47, BA 38	-50.3	20.7	-6.7	6080	-48	20	-10	0.025	6.014	9	Perani, 1999 (2); Fiebach, 2004 (1); Sabsevitz, 2005 (3); Binder, 2005 (4); Pexman, 2007 (1); Hoffman, 2015 (3); Skipper, 2014 (2); Wang, 2019 (1); Pauligk, 2019 (2) **
									-48	30	-4	0.017	4.737		
									-54	8	-18	0.016	4.497		
									-52	24	6	0.016	4.484		
L	2	Temporal	Superior Temporal, Middle Temporal	BA 22, BA 21	-50	-29.2	-2.6	688	-50	-28	-4	0.015	4.340	3	Sabsevitz, 2005 (1); Hoffman, 2015 (2); Wang, 2019 (1) **

Note

All the values and labels were extracted from the GingerALE output files. Clusters are ordered for decreasing volume size. Coordinates (x, y, z) are in the MNI space.

Abbreviations

H = Hemisphere; ALE = activation likelihood estimation; Nr. = number of studies that contributed to each cluster; L = left; BA = Brodmann area; ** = between brackets are the number of foci from each study that contributed to that specific cluster

As previously specified, due to the very small number of studies we could not conduct sub-analysis based on the (i) verbs only, (ii) other types of tasks present in the included publications like mental image generation, memory tasks, or perceptual decision task only; (iii) auditory stimuli only.

4. Discussion

As we pointed out in the introduction, neuropsychological studies suggest a role of the lateral prefrontal cortex in processing abstract words and of the left anterior temporal lobe in processing concrete ones. We then run a meta-analysis to assess whether imaging data confirm this segregation.

Thirty-two imaging studies were included, which evaluated the activation patterns in response to concrete and abstract concepts in order to evaluate whether their processing recruits separate brain circuits, and, if so, where those specific areas are located in the brain. All the data included in the ALEanalysis are based on general linear model, GLM.

We also looked for studies that used the more modern multivariate pattern analysis, i.e., a set of methods that analyze neural responses as patterns of activity[85], in order to have a separate dataset with this type of methods. Unfortunately, we found a very small number of publications preventing a further meta-analytic procedure[42,86,87].

The results of this meta-analysis, consistent with those of previous research[31,34], confirmed that concrete and abstract words processing relies, at least in part, on different brain regions. The ALE procedure was completely data-driven, without a prior theoretical basis, and the results are constrained only by the nature of our data (e.g. the limited temporal resolution of the neuroimaging techniques, the correlational nature of the data), and by our inclusion/exclusion criteria.

As previously mentioned, experiments testing for greater activation for concrete than abstract words (concrete words > abstract words) converge in the temporo-parieto-occipital regions; namely, the left middle temporal gyrus, left fusiform, left parahippocampal and lingual gyri, bilateral angular gyrus and precuneus, bilateral posterior cingulate, left superior occipital gyrus and left culmen in the cerebellum. The neuroimaging evidence indicates that concrete concept representations are at least partly associated to the perceptual system, and also rely on mental imagery (precuneus, superior occipital gyrus).

Binder et al.[34] found significant overlapping for concrete stimuli in the angular gyrus bilaterally, left mid-fusiform gyrus, left posterior cingulate, and left dorsomedial prefrontal cortex (DMPFC). With the exception of DMPFC that might be related to the stimuli complexity and/or different baselines, all the other regions are confirmed by our data. At variance with Wang et al.'s meta-analysis[31] we found a bilateral involvement of the posterior cingulate cortex, angular and precuneus gyri. Binder et al.[34] found that the angular gyrus was the most reliably activated area across the 120 studies (included in their meta-analysis) and interpreted these data as an indicator of its involvement in concrete concepts semantic representation. Another area activated for concrete > abstract concepts was the bilateral posterior cingulate cortex (PCC). Although involved in many semantic-based tasks, the function of the PCC in semantic cognition is still debated. The following hypothesis are proposed. (i) this region could act as a supramodal convergence zone[34], (ii) PCC activation could reflect the greater engagement of an imagery-based perceptual system for concrete stimuli, or (iii) PCC might be an interface between semantic knowledge and episodic memory[86]. The precuneus also seams associated with visuospatial imagery, a hypothesis supported by experiments conducted on episodic memory retrieval and linguistic tasks which required the processing of high imagery words or mental image generation[78].

The same regions were found when only nouns were considered (concrete nouns > abstract nouns contrast) with the difference that the right hemisphere activation disappeared. The two right hemisphere clusters might be specifically correlated with action verbs but this result could also be a consequence of the lack of power due to the limited number of studies (15 studies in the nouns dataset vs. 22 in the noun-and-verb database).

The results on abstract words replicated those reported by Wang and colleagues[31] and Binder et al.[34]; higher activation for abstract compared to concrete words conditions (abstract words > concrete words) is more frequently reported in a left lateralized network, encompassing the inferior frontal gyrus (IFG, Brodmann areas 45, 47), a very small portion of the precentral gyrus, the superior and middle temporal gyri, and inferior parietal.

Concerning the left IFG, it has been suggested that the ventrolateral prefrontal cortex (VLPFC) implements semantic control in two steps[88]. Step 1 constitutes controlled access to stored representations when bottom-up input is not sufficient. Step 2 operates at post-retrieval and is thought to bias competition among representations that have been activated during Step 1. According to Badre and Wagner[89], both steps recruit VLPFC, though different parts of it, with BA 45 involved in Step 2. In other words, rather than abstract knowledge representation, IFG activation could reflect a higher level of semantic control processes (additional resources) since abstract stimuli might require semantic selection, irrelevant cues inhibition, effortful integration, top-down control and working-memory related processes[90], in agreement with the context availability theory[91]. In line with this hypothesis, this region showed greater activation for abstract words when a judgment task was made following irrelevant cues and reduced activation when semantic decisions were made with contextual help, supporting the idea that this area responds more strongly to abstract words because their meanings are inherently more variable and require more control during linguistic processing as compared to the concrete ones [47,92]. An alternative explanation is offered by Della Rosa[93] using a lexical decision task, they found that the left IFG was particularly active during presentation of words characterized by low imageability and low context availability. The authors' interpretation was that this area could be a functional convergence zone between imageability and context availability, differentiating abstract from concrete concepts.

A result, which is totally in contrast with the neuropsychological literature, is the activation of the anterior part of the superior and middle temporal gyri. In fact, apart from the main single cases of herpes simplex encephalitis and semantic dementia, with a reversal of concreteness effect in the presence of bilateral anterior temporal lobe damage, there are now several group studies confirming the evidence of a concrete word impairment after anterior temporal lobe atrophy. In particular, a study comparing the behavioral variant of frontotemporal dementia (FTD), in which there is a predominant prefrontal atrophy, to the semantic variant, with an anterior temporal atrophy showed that while the former group of patients had an increase of the concreteness effect, the reversal was found in the semantic variant group. Similarly, patients with left Anterior Temporal Lobe (ATL) resection show the same pattern of reversal concreteness effect[27]. One possibility is the type of task used; the selected studies used very different tasks (pleasantness judgment, memory tasks, lexical decision, etc.) while, in general, the reversal of concreteness effect in patients is mainly found in naming and comprehension tasks and, when tested, in semantic judgments. Orena et al.[30], for example, using direct electrical stimulation (DES) for brain mapping during awake surgery found no behavioral differences between BA 44 and BA 38 stimulation while patients performed a lexical decision task, but they registered a dissociation between abstract and concrete words during a concreteness judgment task; in particular, abstracts words were impaired during stimulation of BA 44 and concrete words during BA 38 stimulation. However, it has to be underlined that, when only abstract nouns (and not verbs) were considered, the clusters in the left superior and middle temporal lobe lost significance, supporting the idea that the cerebral networks deputed to noun and verb processing might be slightly different. It is important to mention that, even when only nouns were taken into account, selected stimuli to represent abstract or concrete items greatly varied among studies encompassing emotions, mind states, living and nonliving things, of different frequency of use, age of acquisition and imageability. In addition, many studies use interchangeably the concreteness and imageability terms, which are in fact two distinct properties that can differently affect naming and recall[94–96].

Neuroimaging studies are often hard to compare and many variables could influence the reported results as the duration of the stimuli presentation and the stimuli number. For example, in the same type of experiment a large number of stimuli [e.g., 164 nouns in [68]] were presented while in others, only four words were repeated for more than 140 trials[72]. Another relevant element is the participants' age since aging can modify neural organization due to neuroplasticity[97]. With two exceptions[63,71] in which the participants' mean age was > 70, all the other studies included a young population with a mean age < 30 (see Table 1). Neuropsychological studies (on patients) involve a different population ranging from 55 to 75.

We also controlled for presentation modality. When only visually presented words were included in the analysis no relevant differences were observed between auditory and visual stimuli combined, and only visually presented words (see Fig. 5 and Fig. 9). This can be partially due to the very small number of studies using auditory information (only 5 studies out of 32 used auditory stimuli).

According to Eickhoff et al.[40], the statistical power of the current meta-analysis to detect not only large, but also small- and medium-size effects can be considered acceptable. Nevertheless, meta-analytic power is intrinsically limited by the number of currently available data especially for two sub-analyses: (i) concrete nouns > abstract nouns, only 15 independent experiments, and (ii) lexical and semantical task - concrete words > abstract words, 16 studies. Another limitation is related to the sample size of the included experiments that ranged from 6 to 28 participants. This presumably limited the publications power to detect small- and medium-size effects.

Considering the main question of our meta-analysis, we can confirm that concrete and abstract words processing involve at least partially segregated brain, the IFG being relevant for abstract nouns and verbs, but we could not find evidence of the ATL role for concrete items. Our data indicate a more posterior activation for concrete words in regions that are often correlated with mental imagery processes, updating (adding more studies and controlling for possible confounding factors) and partially confirming the results of the previous reviews on the same topic. The discrepancy between clinical neuropsychological and neuroimaging data deserves further investigation, for example by means of balanced groups of healthy and clinical participants, combining different techniques in the same experiment as TMS-EEG, or TMS and fMRI.

Declarations

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Figures

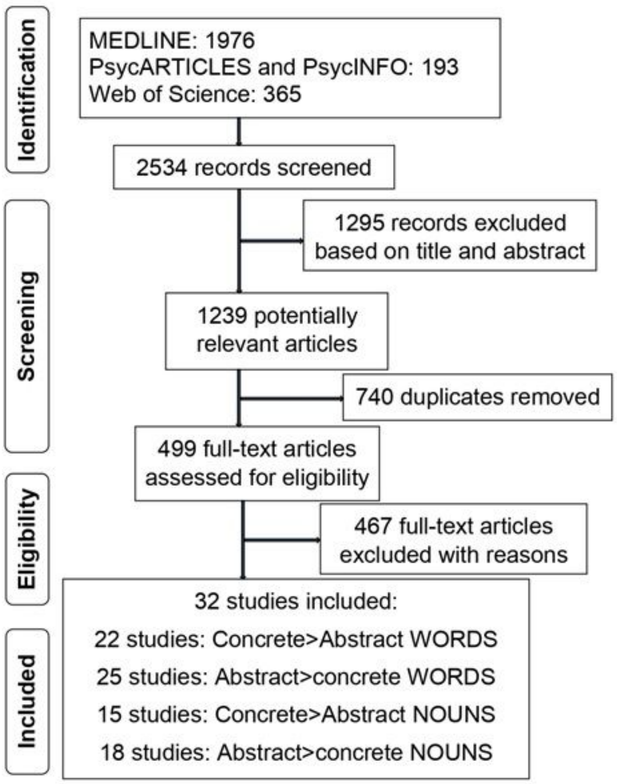

Figure 1

PRISMA flowchart of the selection process for included articles.

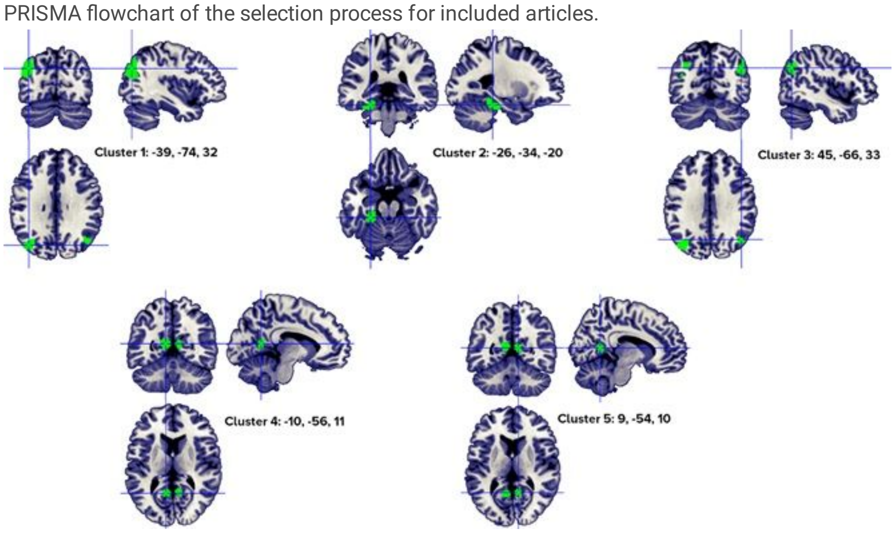

Figure 2

Clusters activated by the concrete > abstract words contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 2. The images are presented in neurological convention.

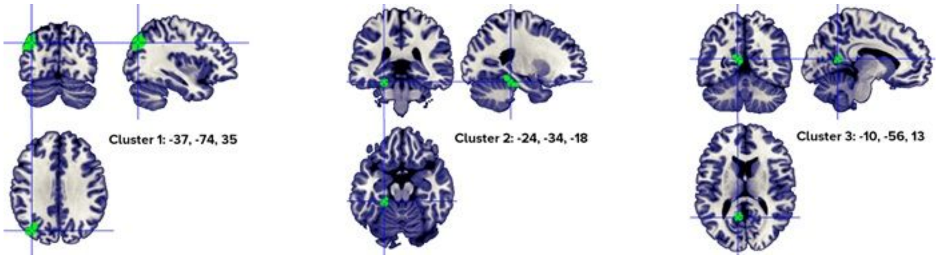

Figure 3

Clusters activated by the concrete > abstract nouns contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 3. The images are presented in neurological convention.

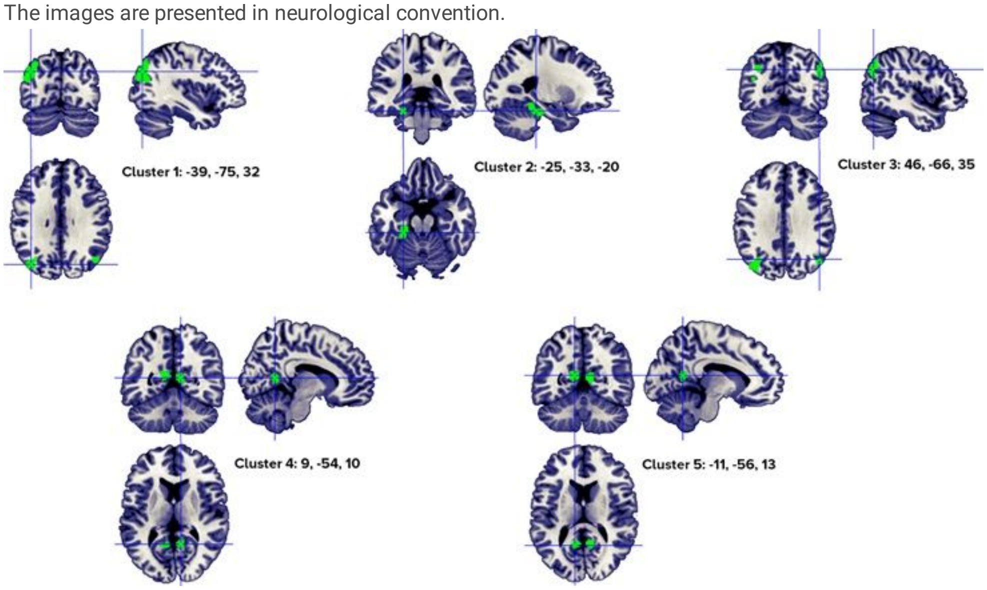

Figure 4

Clusters activated by the concrete > abstract words - visual stimuli – contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 4. The images are presented in neurological convention.

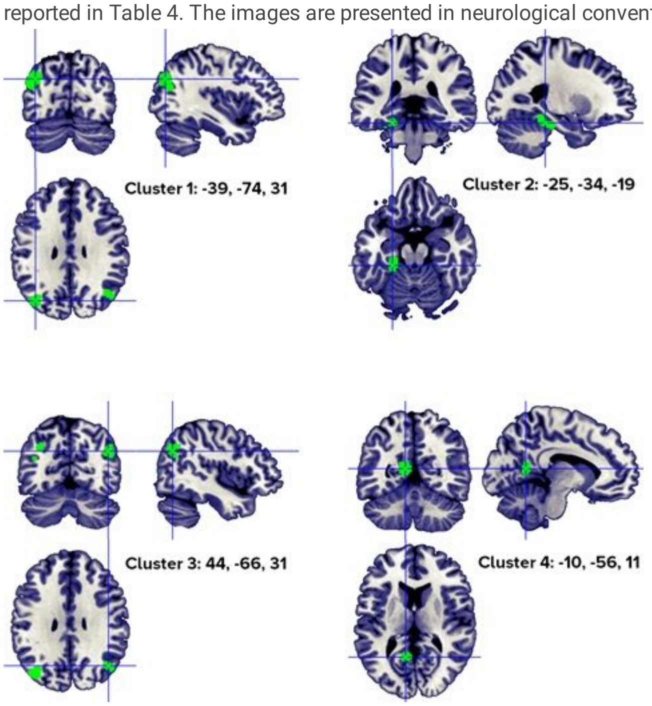

Figure 5

Clusters activated by the concrete > abstract words -semantic and lexical tasks – contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 5. The images are presented in neurological convention.

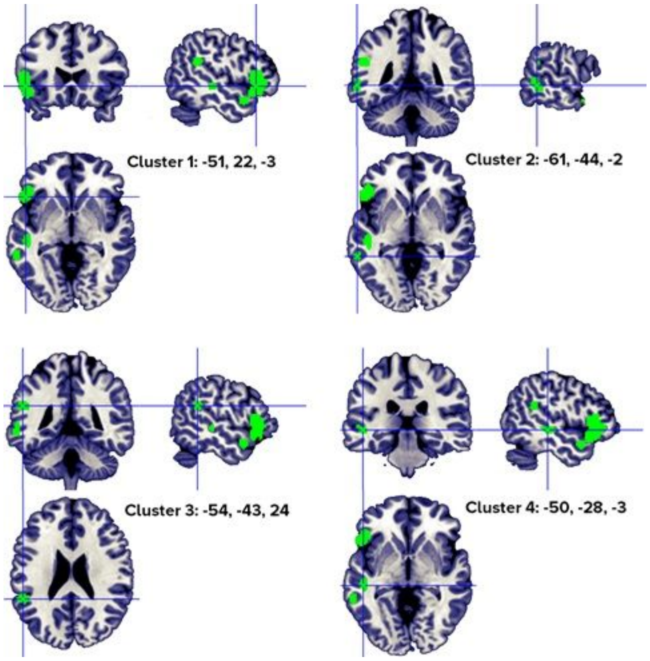

Figure 6

Clusters activated by the abstract > concrete words contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 6. The images are presented in neurological convention.

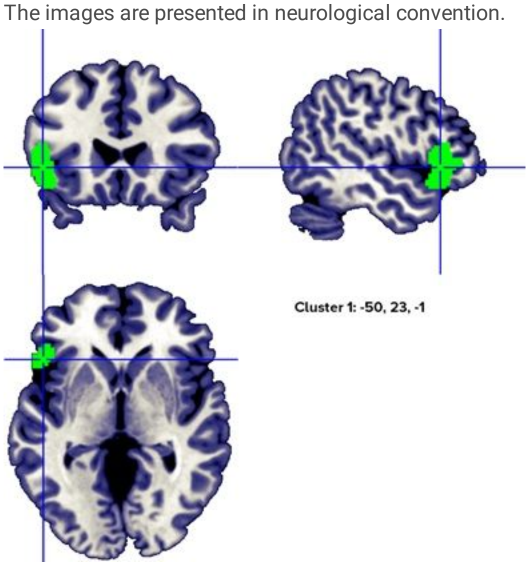

Figure 7

Clusters activated by the abstract > concrete nouns contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 7. The images are presented in neurological convention.

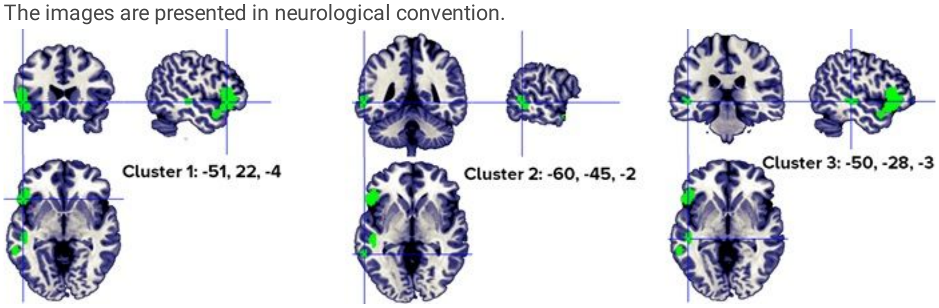

Figure 8

Clusters activated by the abstract > concrete words - visual stimuli – contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 8. The images are presented in neurological convention.

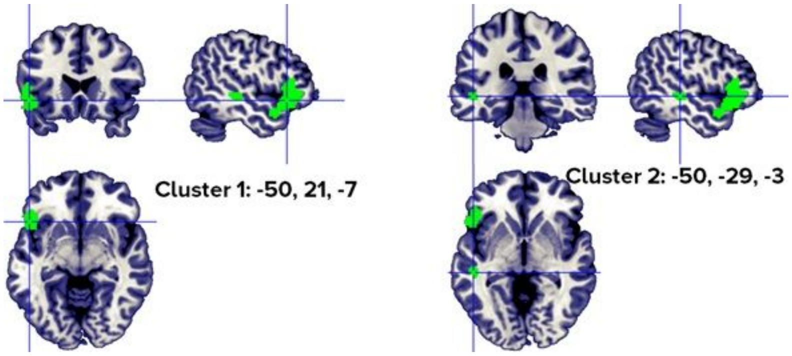

Figure 9

Clusters activated by the abstract > concrete words -semantic and lexical task- contrast. The crosses are centered in the areas correspond to stereotactic coordinates reported in Table 9. The images are presented in neurological convention.