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Investigating the multidimensionality of abstract concepts through a multidisciplinary approach

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1. Introduction

When we think about concrete concepts like *zebra* or *hammer*, a mental image come up easily in mind and almost immediately, as they are generally critically characterized by perceptual and motor features. Conversely, when we think about abstract concepts like *happiness*, *immensity* and *charm*, a mental image hardly come up in mind immediately, as they are not typically referring to clear sensory-motor experiences. More probably, a rich complex of situations and contexts may be evoked, generally ascribed to different kinds of experiences, for example emotions and inner states, spatial and quantitative relations, social situations and events.

In the seminal work reported in 1975, the neuropsychologist Elizabeth Warrington described that abstract and concrete knowledge may be selectively impaired (Warrington, 1975). Patient AB showed a better performance on concrete than on abstract words, while patient EM showed the opposite trend (not significant at statistical level), namely a better performance on abstract words. Despite these representative cases, the majority of subsequent behavioural and neuropsychological studies found a disproportionately worse performance for abstract compared to concrete concepts in both healthy individuals (Miller and Roodenrys, 2009) and patients, including post-stroke patients, the semantic variant of Primary Progressive Aphasia (sv-PPA), and Alzheimer's Disease (AD) (e.g., Franklin et al., 1995; Jefferies et al., 2009; Rissenberg and Glanzer, 1987). This effect has been explained in literature suggesting that the disadvantage for abstract concepts is due to the weaker association of abstract words with contextual cues (Schwanenflugel and Shoben, 1983), or to their exclusive relation with verbal knoweledge, in the absence of links to sensory-perceptual information (Paivio, 1986; 1991). A reversal of the concreteness effect, namely a better performance for abstract over concrete knowledge, has been however also found in a small number of reports, including healthy individuals (Kousta et al., 2011) and in case studies of sv-PPA (Cipolotti and Warrington, 1995; Macoir, 2009; Papagno et al., 2009; Yi and Grossman, 2007; Breedin et al., 1994; Bonner et al., 2009), herpes simplex encephalitis (Sirigu et al., 1991; Warrington and Shallice, 1984), and focal lesions due to stroke (Bachoud-Lévi and Dupoux, 2003; Marshall et al., 1996) or tumors (Warrington, 1981), thus questioning the proposed theories explaining the advantage for concrete concepts. Interestingly, a worse performance for concrete than for abstract knowledge has been found in the case of lesions involving the anterior temporal lobe, particularly of the left hemisphere, suggesting the possible existence of different anatomical substrates for abstract and concrete concepts. Additional evidence supporting this hypothesis comes form a number of neuroimaging studies (for a review see Wang et al., 2010). Despite the interest in this dichotomy, further neuropsychological, neuroimaging, and neurophysiological empirical work on semantic memory has largely focused on the concrete knowledge, permitting to differentiate between different categories, like animals and tools, on the basis of the respective relevant features, sensorial and motor respectively, and exploring the neural substrates involved in their representation. The neglect of the hypothesis of the possible exisence of differences among types of abstract knowledge can be traced, at least in part, in the difficulty in applying to this domain the methodologies traditionally used for the investigation of concrete concepts, such as feature listing (Harpaintner et al., 2018).

Recently, abstract knowledge has become a topic of intense research and debate. A growing body of studies supports the claim of a multidimensionality of the abstract domain, that, similarly to the concrete one, can be differentiated into different types, namely according to the respective relevant dimensions, i.e., social, affective, magnitude related, which should be grounded in the brain areas subserving the corresponding experiences.

The aim of the current thesis is to investigate the heterogeneity of abstract knowledge, trying to individuate the relevant dimensions charactering different kinds of concepts, using a multimodal approach. In Chapter 2, we conducted a systematic literature revision in order to critically evaluate the methodologies adopted for the characterization of abstract concepts, highlighting their respective strengths and limitations. We presented the current state of the art, discussing the results in healthy and clinical populations investigating abstract concepts in behavioural, neuroimaging, electroencephalography and neurostimulation studies. Three different experiments have been consequently developed, all based on the common mechanism, namely the "state dependency". We applied priming and adaptation paradigms, in which the presentation of a stimulus was used to modulate the initial activation state of a target brain region by tuning a subset of neurons coding for the specific features of the stimulus, thus producing an activation imbalance between different neural populations. In this way, we explored the neural representation of different abstract categories constructing ad hoc experiments, namely a functional magnetic resonance adaptation imaging (fMRI-A) in Chapter 3, and a state-dependent transcranial magnetic stimulation (TMS) priming study in Chapter 4, in healthy participants, and a behavioural priming study in patients affected by neurodegenerative diseases, i.e. semantic variant of Primary Progressive Aphasia (sv-PPA) and Cortico-Basal Syndrome (CBS) in Chapter 5. These approaches constituted interrelated and complementary sources of information. While fMRI unveiled the contribution of specific brain regions, TMS and patients' studies shed light to their causal role in representing a specific abstract category. In order to evaluate the consistency of the results, in the TMS experiment we explored the role of superior anterior temporal lobe and intraparietal sulcus in social and quantity-related concepts, subsequently investigating eventual selective impairments of these categories in patients with relatively localized involvement of these two brain regions, i.e. sv-PPA and CBS. Finally, in Chapter 6 the findings are briefly summarized and discussed in terms of their contribution to the issues of the organization of semantic memory.

2. The multidimensionality of abstract concepts: a systematic review

2.1. Introduction

Most studies of semantic memory dealt with concrete concepts. These concepts, e.g., *cat, hammer,* referred to external entities which are perceivable through our senses, and can be easily organized into a taxonomy with a hierarchical structure, from basic (e.g., zebra) to more general (e.g., living entity) levels. According to the embodied cognition theories, brain regions implied in the representation of sensory and motor knowledge have a role in characterizing different types of concepts (Kiefer and Pulvermüller, 2012; Warrington and Shallice, 1984). Some current models extend this consideration, highlighting the importance of finer-grained dimensions, e.g. auditory (Kiefer et al., 2008), colour (Simmons et al., 2007), and odour (Gonzalez et al., 2006) information, for specific types of concepts (e.g., *telephone, taxi, garlic*). Accordingly, category distinctions can arise from complex combinations of attributes, e.g. taste, smell, tactile properties, in turn explaining the impairments in categories, e.g. foods and fruits/vegetables, traditionally not grouped together (Cree and McRae, 2003; Gainotti et al., 2013).

A comprehensive neural model of semantic memory, however, needs also to account for abstract concepts, such as *freedom*, *idea*, which are not directly associated to physical referents in the external world. Abstract concepts are now a central point of debate in the embodied cognition framework. Different approaches have been proposed to account for the neural substrates and organizational principles supporting abstract concepts, applying them to the entire domain. Abstract concepts have been proposed to rely on verbal knowledge (Paivio, 1986; 1991) and associative relations (Crutch and Warrington, 2005), to be represented as metaphors derived from concrete domain (Lakoff, 2014), and to be less readily associated to contextual information (Schwanenflugel and Shoben, 1983). A limitation of these important proposals is that abstract knowledge is considered as a unique class to be differentiated from the concrete domain (Jefferies et al., 2009; see Wang et al., 2010 for a meta-analysis of imaging studies). One of the most critical contribution to the field, during the last twenty years, comes from Barsalou's studies (1999; 2003; 2005; 2016; 2018). This author went beyond the classical dichotomous view of concrete-abstract semantic knowledge, highlighting the relevance of introspection, including representational states, emotions and cognitive operations, as additional kinds of experience, together with situational contexts, in the representation of semantic knowledge. Different kinds of internal experiences and situational information make the abstract domain more heterogeneous (Della Rosa et al., 2018), with fuzzier demarcations of possible categories. These intrinsic characteristics lead to a critical difficulty in characterizing abstract concepts, in delineating the relevant dimensions and their relative contributions to their representation, especially using the methods traditionally applied to the experimental investigation of concrete concepts (Cree and McRae, 2003; McRae et al., 2005; Catricalà et al., 2015). Currently, abstract knowledge has become a topic of intense researches, and the results offer evidence in favour of a multidimensionality in the abstract domain, that, in analogy to the concrete one, can be differentiated into classes or dimensions, grounded in those brain regions engaged by the corresponding experience. Although revisions and meta-analyses investigating abstract and concrete concepts already exist (e.g. Binder et al., 2005; Wang et al., 2010), they did not focus on the different abstract classes/dimensions. An exception is Desai et al. (2018), reporting neuroimaging evidence for different abstract dimensions, i.e. numerical, emotion, morality, theory of mind. Of note, in Desai et al.'s (2018) a very heterogeneous set of stimuli and tasks has been included, i.e. numerical symbols (Arabic numerals, written number words), words and sentences, statements and scenarios, vignettes, stories and scenes, and, in the case of words without differentiating between abstract and concrete ones.

The aim of the current review is to define the types of experience (also labelled dimensions) contributing to the characterization of different abstract concepts (also called in this review categories, types or classes). We start from a critical evaluation of the methodologies that have been adopted in literature in order to characterize abstract concepts, evaluating strengths and limits. We then report a systematic analysis of the studies dealing with categories of abstract concepts. Specifically, we present the results obtained, respectively, in healthy and clinical populations, in behavioural, neuroimaging (i.e., fMRI, MRI, PET, SPECT), EEG, and neurostimulation (i.e., TMS) studies. Finally, in the discussion, we present a general overview of the obtained results, separately for the different abstract dimensions, and of their implications for current models of semantic memory.

2.1.1. Literature review process

An exhaustive literature search has been conducted on the electronic databases of Google Scholar and PubMed, with the last update in February 2020. Different combinations of the following terms, with both extended names and abbreviations, were used: abstract dimensions, abstract concepts, abstract categories, abstract classes, semantic dimensions, social, emotions, mental states, neurodegenerative diseases, Alzheimer's Disease, Semantic Dementia, Primary Progressive Aphasia, Corticobasal syndrome, Posterior Cortical Atrophy, Behavioural Variant Fronto-Temporal Dementia, vascular aphasia, brain lesion, functional Magnetic Resonance Imaging, Positron Emission Tomography, Transcranial Magnetic Stimulation, Electroencephalography, Magnetoencephalography. Starting from the lists of references of the retrieved articles, we further selected papers by manual search, in order to increase the likelihood of including all the relevant studies. This bibliographic search yielded a total of 150 papers.

Papers appearing in peer-reviewed journals and written in English were then selected according to the following criteria. No review studies were included. As main inclusion criterion, the papers had to be focused on the different dimensions or categories of abstract concepts (e.g. emotion, social relations, mental states). For example, we included those papers using emotional valence to characterize a specific abstract category, i.e. usually emotions, without including studies focusing on the exploration of behavioural and/or neural correlates of emotional valence. No papers considering abstract concepts as a unique category compared to concrete concepts were included. We considered only papers dealing with linguistic tasks (i.e. lexico-semantic paradigms, psycholinguistic scales) and yielding results on single words but not on sentence-level processing. We considered those studies analysing nouns, whereas the ones focusing only on other grammatical classes (i.e. verbs, adjectives, and quantifiers) were not included. Studies including both nouns and others grammatical classes in the same category or experimental condition were reported but signalled in the relative sections. We considered both healthy subjects and patients' studies (both single-case and group studies), reporting evidence from behavioural, neuroimaging, electrophysiological and neurostimulation experiments.

The resulting 40 articles were considered for the present review (See Table 1). We use the terms 'dimension', 'information', and 'type of experience' indifferently to indicate the characteristics or features of the semantic representation (as for example the colour feature for concrete knowledge and the social dimension/information/experience for abstract knowledge); the terms 'class', 'type' or 'category' to indicate a set of concepts belonging to the same category (as for example the category of fruits for concrete knowledge and the social category/class/type for abstract knowledge), even in the absence of clear boundaries. Note that a particular dimension/s can be very relevant for a class of concepts, critically contributing to its specific category (colour for fruits, or social dimension/information/experience for the social class/category/type). In addition, to make the results clearer, we have taken into account the different terminology used in the reviewed studies to indicate a dimension or a category and uniformed them in the labels indicated in Table 1. Specifically, the label *emotional* included those concepts indicated as emotion words/concepts (Altarriba et al., 1999; Altarriba and Bauer, 2004; Martin and Fedio, 1983; Hsieh et al., 2012; Moseley et al., 2015; Dreyer et al., 2015; Wilson-Mendenhall et al., 2011; Lebois et al., 2018; Dreyer and Pulvermüller, 2018; Catricalà et al., 2014; Mazzuca et al., 2018), emotional words/concepts (Beauregard et al., 1997; Moseley et al., 2015; Joubert et al., 2017; Giffard et al., 2015), emotion/affective words (Chen et al., 2016), emotionally valenced words, i.e. positive or negative (Kousta et al., 2011; Skipper and Olson, 2014; Vigliocco et al., 2014; Wang et al., 2019; Semenza et al., 1986), and words characterized by emotional experience, manifested as the ease with which the concepts elicit or evoke emotional experience (Newcome et al., 2012; Moffat et al., 2014; Siakaluk et al., 2016). In addition, the label *emotional* was used both when emotions were considered a specific category, and when considering emotional valence, a continuous variable shared by several abstract concepts. The label *social* (Zahn et al., 2007; 2009; 2017; Ross and Olson, 2010; Binney et al., 2016; Rice et al., 2018; Pobric et al., 2016; Wong et al., 2011; Wang et al., 2019; Catricalà et al., 2020) as well as social relations (Catricalà et al., 2014) referred to social words/concepts, variably characterized in terms of behavioural descriptiveness, i.e. how well a specific word described a detailed set of social behaviours of people (Zahn et al, 2007), or association to social situations or interactions among individuals, in terms of inclusion or exclusion (Catricalà et al., 2020; Wang et al., 2019). The label *mental states* included concepts defined as state terms/words (Baron-Cohen et al., 1994; Harris et al., 2006), words with mental/cognitive meaning (Dreyer and Pulvermüller, 2018), defined by a measure of relatedness to mental operations, i.e. something that the mind can do, as well as cognitions (Catricalà et al., 2014), and cognitive states (Setti and Caramelli, 2005). Finally, *magnitude* referred to mathematical words (Wilson-Mendenhall et al. 2013; Bechtold et al., 2019), and quantity-related concepts, i.e. words associated with the quantitative dimension, namely referring to size and numerosity (Catricalà et al., 2020). All the definitions used in each paper indicating the specific class of concepts considered (when available) are reported in Table 1 in Appendix A. The criteria used to identify stimuli for each category are reported in Table 1. A detailed description of the methods chosen by the reviewed studies to describe the dimensions/categories is reported in the respective Results section.

TYPE OF CONCEPTS	reference	Stimuli selection (variables considered)	N. target stimuli (N. comparison stimuli)	Task	Type of study (participants)
Emotional	Altarriba et al. 1999 (Exp. 2)	A priori selection, i.e. words with affective meaning, positive/negative valence and arousal component (frequency, length)	98 nouns, adjectives, verbs (154 abstract, 100 concrete nouns, adjectives, verbs)	free association	Behavioural (55 healthy)
	Altarriba and Bauer, 2004 (Exp. 3)	A priori selection, i.e. words with affective meaning, positive/negative valence and arousal component (concreteness, imageability)	80 nouns, adjectives, verbs (80 abstract nouns, adjectives, verbs)	lexical decision	Behavioural (80 healthy)
	Chen et al. 2016	Positive/negative words produced in association to *happiness, sadness, anger, fear* (familiarity)	Exp.1: 48 nouns, adjective, verbs; Exp.2: 72 nouns, adjective, verbs	lexical decision	Behavioural (100 healthy)
	Kousta et al. 2011 (Exp. 3)	Emotional valence and arousal from Kousta et al. (2009) (concreteness, age of acquisition, imageability, familiarity, number of letters, frequency)	480 words	lexical decision	Behavioural (47 healthy)
	Moffat et al. 2014	From Newcombe et al. 2012	200 nouns (200 concrete nouns)	Exp. 1: semantic categorization; Exp. 2-3: word reading	Behavioural (Exp. 1: 72 healthy; Exp. 2: 25 healthy; Exp. 3: 26 healthy)
	Newcombe et al. 2012	Ratings on the degree of emotional experience (concreteness, imaeability, length, frequency, orthographic distance, number of letters, syllables, phonemes, morphemes, age of acquisition, concreteness, typicality, number of senses; ratings on the degree of body-object interaction)	200 nouns (200 concrete nouns)	Exp. 1: concrete semantic categorization; Exp. 2: abstract semantic categorization	Behavioural (Exp. 1: 30 healthy; Exp. 2: 30 healthy)
	Siakaluk et al. 2016 (Exp. 2)	Ratings on the degree of emotional experience (concreteness, imageability, familiarity, frequency, number of orthographic neighbours, number of letters, syllables, morphemes, age of acquisition, valence, arousal)	150 nouns	lexical decision	Behavioural (50 healthy)
	Mazzuca et al., 2018	From Della Rosa et al. (2010); ratings on emotional value	16 nouns (16 abstract and 16 concrete nouns)	lexical decision; word recognition	Behavioural (Exp.1: 40 healthy; Exp.2: 40 healthy)
	Beauregard et al. 1997	Emotional valence	25 nouns (25 non emotional abstract, 25 concrete nouns)	passive reading	$H_2^{15}O$ PET (10 healthy)
	Vigliocco et al. 2014	Emotional valence and arousal, from Bradley and Lang (1999) (imageability, concreteness, context availability, familiarity, age and mode of acquisition, words and bigrams frequency, number of orthographic neighbours, number of letters, syllables, phonemes, morphemes)	60 nouns (60 concrete nouns)	lexical decision	fMRI (20 healthy)
	Moseley et al. 2012	Rating on emotional valence, arousal, emotional relatedness (imageability, concreteness, length, bigrams and trigrams frequency, number of orthographic neighbours, number of meanings; ratings	20 nouns and verbs (20 concrete emotion, 40 arm-related action, 40 face-related action nouns and verbs, 40 animal nouns)	passive reading	fMRI (18 healthy)

		on sensory-motor features, i.e. action relatedness)			
	Skipper and Olson, 2014	Ratings on emotional valence and arousal (word and bigrams frequency, age of acquisition, number of letters and phonemes, familiarity, number of orthographic neighbours)	41 nouns (41 concrete emotion, 41 concrete neutral, 41 abstract neutral nouns)	thinking about the words and answering questions	fMRI (19 healthy)
	Lebois et al. 2018	From Wilson-Mendenhall et al. (2011)	2 nouns (2 mental states verbs)	word typicality judgement	fMRI (30 healthy)
	Wilson-Mendenhall et al. 2011	A priori selection, i.e. 4 concepts: *fear, anger, plan, observe*	2 nouns (2 mental states verbs)	word typicality judgement	fMRI (20 healthy)
	Martin and Fedio 1983	A priori selection, i.e. emotion-related words	Exp. 1: 9 words (9 concrete objects nouns, 15 actions, 9 adjectives); Exp. 2: 20 words (10 neutral words)	Exp. 1: symbol referent test; Exp. 2; pleasantness rating	Behavioural (14 AD patients, 11 controls)
	Hsieh et al. 2012	Ratings on emotional valence and arousal (concreteness, frequency, number of syllables and letters)	80 nouns, adjectives, verbs	emotion word synonym and emotion word association	Behavioural (8 svPPA. 8 bvFTD, 12 AD, 15 controls)
	Giffard et al. 2015	Ratings on emotional valence (concreteness, imageability, number of letter, frequency)	146 nouns (286 concrete, 144 non emotional abstract nouns)	lexical decision	Behavioural (15 AD, 31 controls)
	Joubert et al. 2017	A priori selection (imageability, frequency)	30 nouns (30 abstract, 30 concrete nouns)	semantic similarity judgment	Behavioural (9 svPPA, 12 AD, 11 controls)
	Moseley et al. 2015	From Moseley et al. (2012)	20 nouns and verbs (40 abstract verbs, 40 animal nouns)	passive reading	fMRI (18 ASD, 18 controls)
	Semenza et al., 1986	A priori selection	15 nouns (5 abstract neutral, 5 power-related nouns, 5 birds name nouns)	Triadic comparison task	Behavioural (13 patients with right brain damage, i.e. 3 frontal, 4 posterior - occipital, parieto-occipital, temporo-occipital-, 6 fronto-parietal, temporo-fronto-parietal lesions; and controls)
	Dreyer et al. 2015	Ratings on the semantic relatedness to emotions and mental processes (number of letters and syllables, lemma, bigram and trigram frequency, number of orthographic neighbours, concreteness, familiarity; ratings on hand/arm, face/mouth, leg/foot actions, visual, olfactory, gustatory, haptic/tactile perceptions)	80 nouns and verbs (240 concrete nouns and verbs)	lexical decision	Behavioural (2 patients with focal brain damages, 21 controls)
Social	Zahn et al. 2007	Ratings on social behaviour descriptiveness (familiarity, frequency, imageability, concreteness)	300 nouns, adjectives (150 animal-functions nouns, adjectives)	semantic similarity judgment	fMRI (21 healthy)
	Ross and Olson 2010	From Zahn et al. (2007)	120 nouns, adjectives (120 animal-functions nouns, adjectives)	semantic similarity judgment	fMRI (15 healthy)
	Binney et al. 2016	From Zahn et al. (2007)	144 nouns, adjectives (144 abstract, 72 animal-functions nouns, adjectives)	two alternative forced-choice semantic decision	fMRI (19 healthy)
	Rice et al. 2018	From Zahn et al. (2007)	144 nouns, adjectives (144 abstract, 72 animal-functions nouns, adjectives)	two alternative forced-choice semantic decision	fMRI (19 healthy)

	Wong et al. 2011	From Zahn et al. (2007)	144 nouns, adjectives (72 animal-functions nouns, adjectives)	two alternative forced-choice semantic decision	rTMS, stimulation at 1Hz (56 healthy)
	Pobric et al. 2016	From Zahn et al. (2007)	147 nouns, adjectives (72 animal-functions nouns, adjectives)	two alternative forced-choice semantic decision	rTMS, stimulation at 1Hz (12 healthy); Behavioral (2 svPPA, 30 controls)
	Zahn et al. 2009	From Zahn et al. (2007)	147 nouns, adjectives (72 animal-functions nouns, adjectives)	two alternative forced-choice semantic decision	FDG-PET, MRI (29 FTLD: svPPA, bvFTD, nfPPA, 18 CBS, 12 controls)
	Zahn et al. 2017	From Zahn et al. (2007)	147 nouns, adjectives (72 animal-functions nouns, adjectives)	two alternative forced-choice semantic decision	MRI, behavioral (19 FTLD: bvFTD, svPPA, mixed PPA, 19 controls)
Mental States	Baron-Cohen et al. 1994	A priori selection, i.e. something that the mind can do	8 nouns and verbs (8 concrete nouns and verbs)	word recognition	Behavioural (15 ASD children, 15 children with mental handicap) SPECT (12 healthy)
Magnitude	Bechtold et al. 2019	A priori selection, i.e. mathematical words, excluding numbers (number of letters, frequency, concreteness, abstractness, valence, familiarity)	31 nouns (31 mental states and emotions nouns)	lexical decision	ERPs (43 healthy)
	Wilson-Mendenhall et al. 2013	A priori selection, i.e. single concept: *arithmetic*	1 noun (1 abstract verb: *convince*, 1 concrete verb: *rolling*, 1 concrete adjective *red*)	concept-scene matching	fMRI (13 healthy)
Emotional, Mental States	Dreyer and Pulvermüller, 2018	Ratings of emotions and mental processes semantic-relatedness (number of letters and syllables, lemma frequency, frequencies of characters, bigrams and trigrams, familiarity, concreteness; ratings on hand/arm-, face/mouth-, leg/foot actions, to visual, olfactory, gustatory, haptic/tactile perceptions)	80 nouns: 40 for each category (80 concrete nouns)	passive reading	fMRI (28 healthy)
Emotional, Social	Wang et al. 2019	Ratings on social and valence scales (frequency, familiarity, concreteness; accuracy and reaction times, from pilot study)	207 nouns: 105 emotional; 102 social (54 abstract, 52 concrete nouns)	two alternative forced-choice semantic decision	fMRI (23 healthy)
Visual, Motor	Harpaintner et al. 2020	High proportion of visual and motor properties, from Harpaintner et al. (2018) (lemma, bigram and trigram frequency, concreteness/abstractness, familiarity, valence, arousal; proportion of acoustic properties)	64 nouns: 32 for each category	lexical decision	fMRI (24 healthy)
Social, Magnitude	Catricalà et al. 2020	Ratings on social and quantity-related scales (familiarity, imageability, emotional valence, number of letters and syllables, written frequency; mean priming effect, from pilot study)	56 nouns: 28 for each category	category priming	TMS state-dependent (36 healthy)
Mental States, Metaphysical	Harris et al. 2006	A priori selection (concreteness, frequency, length)	84 nouns, verbs, adjectives: 42 for each category (42 concrete nouns, verbs, adjectives)	valence judgement	fMRI (14 ASD adults, 22 controls)

Emotional, Mental States, Social, Human Actions, Traits	Catricalà et al. 2014	From pre-existing test of Della Rosa et al. 2014: Wordnet	40 nouns: 8 for each category	sentence completion; multiple choice verbal matching; association	Behavioural (6 svPPA, 14 AD, 20 controls)
Multidimensional	Huth et al. 2016	Words extracted from a story	10470 words	-	fMRI data-driven approach (7 healthy)
	Wang et al. 2018	From Crutch et al. (2013); Troche et al. (2014); Bradley and Lang (1999); Clark and Paivio (2004)	360 nouns, verbs, adjectives, adverbs	-	fMRI data-driven approach (6 healthy)

Table 1. Studies included in the review. Note that we indicated *words* for stimuli type when information on the included grammatical classes was not available, but the authors made examples containing nouns. AD= Alzheimer's Disease, svPPA= semantic variant of Primary Progressive Aphasia, nfPPA= non-fluent variant of Primary Progressive Aphasia, bvFTD= behavioural variant of Fronto-Temporal Dementia, CBS= Cortico-Basal Syndrome, ASD= Autism Spectrum Disorder. See text for further details.

2.2. Methods used for the characterization of abstract concepts

As reported in the introduction, a large variety of different concepts, sometimes difficult to identify, are labelled as "abstract", an aspect that is reflected by the paucity of studies trying to characterize the different types. Three main methods were involved in exploring and characterizing different types of abstract concepts for a total of 16 studies included in this review (see Table 2). Several investigations adopted a featural approach, since this method has provided a useful account of the characteristics of concrete concepts (Hampton, 1981; Cree and McRae, 2003; McRae et al., 2005; Catricalà et al., 2015). Rating procedures, involving both psycholinguistic variables like Concreteness (CNC), Imageability (IMG), Context Availability (CA); and multiple dimensions were also adopted (Altarriba et al., 1999; 2004; Setti and Caramelli, 2005; Dellantonio et al., 2014; Crutch et al., 2013; Troche et al., 2014; 2017; Binder et al., 2016). Finally, existing lexical databases, such as WordNet, grouping words together based on their meanings (Fellbaum, 1998), have been also used to derive distinct types of abstract concepts (Della Rosa et al., 2014).

Task	Variables considered	Advantages	Limitations
FEATURE LISTING			
Feature and definition generation task	-associations (Harpaintner et al., 2018) -definitions (Setti and Caramelli, 2005; Borghi et al., 2016)	-useful to characterize some components of abstract concepts representation	-unspecific features -difficulties in generating features

	-features (Barsalou and Wiemer-Hastings, 2005; Weimer-Hastings and Xu Xu, 200; Roversi et al., 2013; Harpaintner et al., 2018) -relevant contexts/situations (Weimer-Hastings and Xu Xu, 2005; Harpaintner et al., 2018) -examples (Hampton, 1981)		-heterogeneity of taxonomic terms' labels -time consuming -hard scoring -generated features are complex - classification of features post hoc - neglect to mention some features - better suited for concrete concepts
RATING			
Likert scale	Psycholinguistic variables: -imageability (Altarriba et al., 1999; Altarriba and Bauer 2004; Setti and Caramelli, 2005; Dellantonio et al., 2014) -concreteness (Altarriba et al., 1999; Altarriba and Bauer 2004; Setti and Caramelli, 2005; Dellantonio et al., 2014) -context availability (Altarriba et al., 1999; Altarriba and Bauer 2004; Setti and Caramelli, 2005) -abstractness (Setti and Caramelli, 2005)	-easy administration -short task duration -easy scoring -useful to characterize some components of abstract concepts representation	-indirect measure -a priori category selection -heterogeneity in concepts of each class between studies
Likert scale	Semantic dimensions: -polarity, emotion, time, space, quantity, social interaction, morality, thought (Troche et al., 2014; 2017; Crutch et al., 2013) -sensation, action, ease of modifying, ease of teaching (Troche et al., 2014; Crutch et al., 2013) -visual form, auditory, tactile, smell/taste, colour, self-generated motion (Troche et al., 2017) -65 neurobiological-based dimensions (Binder et al., 2016) -body-object-interaction, perceptual modality strength, metacognition, social metacognition, interoception, emotionality, social valence, hand and mouth activation (Villani et al., 2019)	-easy administration -short task duration -easy scoring -useful to characterize several components of abstract concepts representation in a large sample -direct measure	-a priori dimensions' selection - well suited for both abstract and concrete concepts
LEXICAL DATABASES (WordNet)			
None	- domain label (hyperonymy) (Della Rosa et al., 2014)	- based on a large corpus of words - useful to characterize some classes of abstract concepts - easy use of the tool	- contents largely derived from its creators' intuitions - senses of words are not well fine-grained - does not distinguish between abstract and concrete concepts

Table 2. Schematic description of the tests, variables, advantages and limitations of each method employed for the characterization of different types of abstract concepts.

2.2.1. Feature listing

In the feature or definition generation tasks, subjects are asked to produce a list of features or to provide a definition to describe a specific concept, generating anything they feel might be important/relevant/true in describing it (Hampton, 1981; Barsalou and Wiemer-Hastings, 2005;

Weimer-Hastings and Xu Xu, 2005; Setti and Caramelli, 2005; Roversi et al., 2013; Borghi et al., 2016; Harpaintner et al., 2018), as well as relevant contexts associated to each concept (Weimer-Hastings and Xu Xu, 2005). Seven studies were considered, three dealing only with abstract concepts (Hampton, 1981; Borghi et al., 2016; Harpaintner et al., 2018), two comparing abstract vs concrete concepts (Barsalou and Wiemer-Hastings, 2005; Weimer-Hastings and Xu Xu, 2005) and the other two dealing with different classes of abstract and concrete concepts (Setti and Caramelli, 2005; Roversi et al., 2013).

Hampton (1981) observed qualitatively that the abstract concepts description concerns social situations involving 'some kind of act or behavior, together with details of the agent, the motive, the effect, and social meaning of the action'. A more systematic but heterogeneous taxonomy has been used by subsequent studies to classify features produced by subjects for both abstract and concrete items, organized into different domains, namely taxonomic (i.e. synonym) (Barsalou and Wiemer-Hastings, 2005; Wiemer-Hastings and Xu Xu; 2005; Setti and Caramelli, 2005; Roversi et al., 2013; Borghi et al., 2016), entity/attributive/proper/partonomic (i.e. property or quality of an object) (Barsalou and Wiemer-Hastings, 2005; Wiemer-Hastings and Xu Xu; 2005; Setti and Caramelli, 2005; Roversi et al., 2013), setting/event-situations/situational components (i.e. *persons, locations, actions etc.*) (Barsalou and Wiemer-Hastings, 2005; Wiemer-Hastings and Xu Xu; 2005; Borghi et al., 2016), thematic relations (i.e. spatial, temporal, causal relations) (Setti and Caramelli, 2005; Roversi et al., 2013), sensorimotor features (i.e. visual, acoustic, motor-related, tactile, olfactory, gustatory, intereoceptive) (Harpaintner et al., 2018), introspective-subjective-internal experience (e.g. mental state, emotion, cognitive operation) (Barsalou and Wiemer-Hastings, 2005; Wiemer-Hastings and Xu Xu; 2005; Borghi et al., 2016; Harpaintner et al., 2018), social constellation (e.g. *friend* for *sympathy*) (Harpaintner et al., 2018), mental associations (i.e. *project-future*) (Roversi et al., 2013), association (e.g. *sun* for *sympathy*) (Harpaintner et al., 2018), miscellaneous/other (i.e. hesitation, meta-comment) (Wiemer-Hastings and Xu Xu, 2005; Setti and Caramelli, 2005), stereotypes (i.e. conventional associations) (Setti and Caramelli, 2005), examples (Setti and Caramelli, 2005), other abstract concepts (e.g. *karma* for *sympathy*) (Harpaintner et al., 2018), and normative relations (i.e. *signature-attestation*) (Roversi et al., 2013).

While entity/attributive properties were mainly generated for concrete concepts, setting/event-situational properties, involving predominantly social aspects of situation (i.e. *person, social institution*), and introspective properties/subjective experience were typical of abstract concepts (Barsalou and Wiemer-Hastings, 2005; Wiemer-Hastings and Xu Xu, 2005; Roversi et al., 2013; Borghi et al., 2016; Harpaintner et al., 2018), despite some cases without a clear separation between abstract and concrete concepts (Weimer-Hastings and Xu Xu, 2005). Different subjective experiences due to distinct professional expertise may also influence the amount of introspective and types of situational properties generated (Borghi et al., 2016). Finally, different types of thematic relations seem to characterize different types of abstract concepts: causal relations (i.e. *disappointment*-due to unrealized expectations) and evaluative relations (i.e. *anxiety*-deep and strong) were found to be more relevant for emotion concepts (i.e. *fear*), whereas action, function, mean and space relations were found to be more relevant for cognitive processes (i.e. *thought*) (Setti and Caramelli, 2005).

In conclusion, results obtained from the feature listing method have certainly contributed to shed light on the characterization of abstract concepts, highlighting the importance of introspective experience, social contexts and situational information, and emphasizing how these components may be modulated by expertise. However, difficulties are reported in applying this approach for the characterization of abstract concepts (Hampton, 1981), precluding its widespread and systematic use. In fact, abstract concepts, differently from concrete ones, show several highly unspecific properties, e.g. “made by a group of people”, “breaks some moral or social code”, which allows for the representation of a diversity of situations or events, and a “greater freedom for all possible combinations of their features to occur in the real world” (Hampton, 1981). This is reflected by the extreme difficulty reported by some participants in generating properties for abstract items and verbally expressing considerable parts of our conceptual knowledge of abstract entities, maybe due to the unspecific features and the need to construct/remember specific situations (Weimer-Hastings and Xu Xu, 2005). Moreover, abstract concepts, by their nature, lack the taxonomic hierarchical organization and unambiguous contextual properties typical of concrete concepts, leading to a paucity as well as heterogeneity of taxonomic term labels, discrete properties, and other reliable verbal markers that undermine an exhaustive classification of the features produced by subjects. Additional limitations consisted in the complexity of the features produced by participants, sometimes difficult to interpret. This is also associated with the limits of a priori classifications of the features themselves, based on categories and labels which can be more or less detailed and based on experimenters’ knowledge and intuitions. From a practical standpoint, feature listing methods are time consuming and therefore difficult to apply to a large sample of concepts. Indeed, among the studies considered here, only one applied feature listing to a large variety of abstract concepts, namely 296 (Harpaintner et al., 2018). Some idiosyncrasies due to the general limited item samples, as well as the heterogeneity and subtle boundaries typical of abstract knowledge, make this method not adequately suited for its characterization.

2.2.2. Rating methods

Rating methods require participants to evaluate on a Likert scale to what degree a psycholinguistic variable and/or a semantic dimension is relevant for the representation of a specific concept.

2.2.2.1. Psycholinguistic variables

Psycholinguistic variables, like CNC, IMG and CA, widely used in discriminating between abstract and concrete concepts, have been also used to discriminate between different categories of abstract concepts in four studies (Altarriba et al., 1999; Altarriba and Bauer, 2004; Setti and Caramelli, 2005; Dellantonio et al., 2014). All these studies included emotion words (Altarriba et al., 1999; Altarriba and Bauer, 2004; Setti and Caramelli, 2005; Dellantonio et al., 2014) considered alone (Altarriba et al., 1999; 2004) or in comparison with other types of concepts, such as states of the self (e.g. *childhood*), nominal kinds (e.g. *error*), cognitive processes (e.g. *thought*) (Setti and Caramelli, 2005), interoceptive/proprioceptive words (any kind of states based on an internal perception; e.g. *relaxation*) and theoretical terms (e.g. *axiom*) (Dellantonio et al., 2014). The main and most consistent result is that emotion words might represent a separate category (different from abstract and concrete concepts), displaying a peculiar ratings pattern, namely resulting less concrete, but more imageable than the other abstract concepts and less imageable than concrete concepts (Altarriba et al., 1999; Altarriba and Bauer, 2004). The only inconsistence concerns CA, with studies reporting either lower CA (Altarriba et al., 1999), or higher CA (Altarriba and Bauer, 2004) for emotions than for other abstract words, or no difference (Setti and Caramelli, 2005). The pattern of low concreteness and high imageability has been also extended to proprioceptive/interoceptive words, but not to theoretical terms (Dellantonio et al., 2014). This evidence may be accounted for by recent proposal that the imageability construct is related with the ease/difficulty with which a word arouses any kind of sensory experience, including not only external, but also internal, body-related sensations (Dellantonio et al., 2014, see also Paivio, 1986). In addition, emotion and cognitive processes were rated as less concrete and more abstract than states of the self and nominal kind concepts, while cognitive processes were rated as less imageable than states of the self (Setti and Caramelli, 2005).

In conclusion, these studies indicate that the abstract domain can be split into more specific classes of concepts, in particular considering emotion words a separate class of concepts. As discussed above, feature listing studies have also reported the peculiar role of introspective experience in denoting at least some abstract concepts (Barsalou and Wiemer-Hastings, 2005; Weimer-Hastings and Xu Xu, 2005; Roversi et al., 2013; Wiemer-Hastings and Xu Xu, 2005; Borghi et al., 2016). However, psycholinguistic variables provide an indirect measure of different components of experience. For instance, IMG measures the ease/difficulty in arousing any kind of sensory experience, both external and internal. In addition, these studies encompassed a limited number of concepts, ranging from 18 (Setti and Caramelli, 2005) to 155 (Altarriba et al., 1999). The categories used were selected a priori according to different criteria, often not well defined by the authors. This may prevent a systematic comparison among studies and a finer classification of abstract concepts. Classes of concepts may result in an unconstrained composition of concepts, including within the same label (e.g. emotions) different concepts (i.e., moods in Dellantonio et al., 2014) on the basis of the different definition used, based on previous studies (Altarriba et al., 1999; Altarriba and Bauer, 2004; Dellantonio et al., 2004; Setti and Caramelli, 2005), vocabulary definitions (Altarriba et al., 1999; Altarriba and Bauer, 2004), authors' intuitions (Altarriba et al., 1999; Dellantonio et al., 2014; Setti and Caramelli, 2005), only sometimes confirmed by independent judges (Setti and Caramelli, 2005). Furthermore, concepts included in a specific class may be characterized by additional relevant dimensions, which may be not considered by the experimenters, leading to a heterogeneous class composition. For instance, concepts like *jealousy, thankful, grateful* included in the emotion category by Altarriba et al. (1999) are characterized, in addition to an emotional dimension, also by an important social dimension because they involve a relationship between people. In addition, not all studies controlled for potential confounding factors from other psycholinguistic variables, like familiarity, which was found to influence the degree of CA. More familiar words tend to activate more accessible and 'default' contexts than less familiar words (Wiemer-Hastings et al., 2001; Yao et al., 2017), and also different type of working expertise can influence the characterization of abstract words like *risk* and *danger* (Borghi et al., 2016).

2.2.2.2. Dimension rating

This method involves asking participants to rate the importance of particular types of dimensions for the meaning of a given word. In this section, we included only those studies aimed at characterizing different types of abstract concepts, for a total of 5 studies (Troche et al., 2014; 2017; Binder et al., 2016; Crutch et al., 2013; Villani et al., 2019). A variable number of dimensions, ranging from 9 (Villani et al., 2019), 12 (Troche et al., 2014; Crutch et al., 2013) to 65 (Binder et al., 2016), were collected in a large number of participants, ranging from 328 (Troche et al., 2017) to 1743 (Binder et al., 2016). See Table 2 for the dimensions considered.

Villani et al. (2019) investigated 9 dimensions for 425 abstract nouns, namely body-object-interaction, perceptual modality strength, hand and mouth activation, metacognition, social metacognition, interoception, emotionality, and social valence. Four clusters emerged, the first including concepts referring to physical notions and spatial, temporal, and quantitative concepts, the second encompassing concepts referring to psychological characteristics of the self and social situations, the third including philosophical, spiritual concepts, and concepts linked to reasoning, and the last defining concepts associated to emotional and inner states. Troche and collaborators (2014) (see also Crutch et al., 2013) used a sample of 400 nouns (200 abstract and 200 concrete) investigating 12 different dimensions, which were reduced to three latent factors, Affective Association/Social Cognition, Perceptual Salience and Magnitude. A subsequent study on a larger number of nouns (750) with 14 dimensions, adding new variables to better describe the concrete domain (Troche et al., 2017), reported three constructs, namely Endogenous, Exogenous and Magnitude factors. Overall, despite the different labels of the first two factors, the results were similar in both studies (Troche et al., 2014; 2017). A difference emerged only for the Time dimension, grouped into the Perceptual Salience factor in the first study, and together with space and quantity into the Magnitude factor in the second one. This was probably due to the different number and type of words and dimensions considered in the two studies, leading to a better characterization of concrete words. In both studies, the dimensions of thought, emotion, social interaction, and morality were more relevant for abstract concepts. However, concepts with an important affective association also tended to group together regardless of semantic domain: concrete words like *chocolate*, *father*, *baby* were indeed close to abstract words like *love* or *trust*. A comprehensive conceptual representation based on known modalities of neural information processing has been proposed by Binder et al. (2016), collecting ratings of 535 words (335 concrete nouns; 99 abstract nouns) on 65 features, comprising sensory, motor, spatial, temporal, affective, social, and cognitive experiences. Factor analysis reduced the features in 16 latent factors representing visual and tactile attributes, negative emotion associations, social communication, auditory attributes, ingestion, self-related attributes, motion in space, human attributes, surprise, characteristics of large places, upper limb actions, reward experiences, positive associations, time-related attributes, luminance and slow. Abstract entities received higher ratings than the concrete categories on attributes related to temporal, causal, social and emotional experiences. Six abstract entity clusters were also reported: the first two labeled as ‘Beneficial and Neutral’ which comprise a variety of abstract and mental constructs; the third labelled as ‘Causal Entities’ which comprises concepts relating to Consequential and Social attributes; a fourth and fifth cluster including abstract entities with strong emotional meaning or associations, and a final cluster labeled as Time Periods.

In summary, these rating procedures have highlighted that introspective experience, social relations, and the magnitude system are relevant components in the representation of distinct types of abstract concepts. However, differences between studies emerged on the basis of the dimensions considered and because of the a priori selection of concepts. Overcoming the limitation of psycholinguistic variables and of feature listing method, ratings provide a direct measure of different semantic dimensions, distinguishing for instance several aspects of introspection like emotions, thought, morality. Dimension rating methods allowed researchers to collect data for a larger number of stimuli as well as from a larger number of participants, as they are less time consuming than featural approaches. However, as reported above, the choice of the dimensions used is arbitrary and related to empirical and/or theoretical justification, thus potentially biasing the results (Troche et al., 2014; 2017). The selection of dimensions was also influenced by the practicalities of selecting labels which are easily comprehensible and distinguishable for the raters. Notwithstanding these limitations, dimension rating appears to be a useful methodology to characterize different types of abstract concepts.

2.2.3. Lexical databases

Another method for characterizing classes of abstract concepts entails the use of lexical databases. In particular Della Rosa et al. (2014) used WordNet (https://wordnet.princeton.edu/) (Fellbaum, 1998). First developed for English, this corpus has been extended to other languages including Italian (see MultiWordNet: http://multiwordnet.fbk.eu/english/home.php). It is characterized by a hierarchical structure, with concepts organized into a taxonomy, and grouped together based on their meanings. Della Rosa et al. (2014) derived from MultiWordNet 5 distinct classes of abstract concepts (called hyperonymy in WordNet), namely traits (e.g. *weakness*), actions (e.g. *seduction*), emotions (e.g. *fear*), social concepts (e.g. *friendship*), cognitions (e.g. *ideal*). Although the advantage of being applied to a very large corpus of words and the easy and not time-consuming use, WordNet has some limitations. Indeed, contents and the classification into different domains are made a priori and do not take into account the distinction between abstract and concrete concepts, in addition without discriminating between different senses of words. To overcome to these limitations, Della Rosa et al. (2014) additionally rated concreteness, abstractness, and the category membership on a sample of normal subjects.

2.3. Results

Forty papers were included, the majority of which focused on emotions, followed by social concepts, and mental states; only few studies concerned magnitude, and only one each for visuo-motor concepts (Hairpaintner et al., 2020), metaphysical concepts (Harris et al., 2006), violent concepts and communal concepts (Huth et al., 2016) see Figure 1 and the next sections for further details. Of note, results on dimensions investigated in only one paper are reported in the Table 2 in Appendix A, and not considered in the following sections.

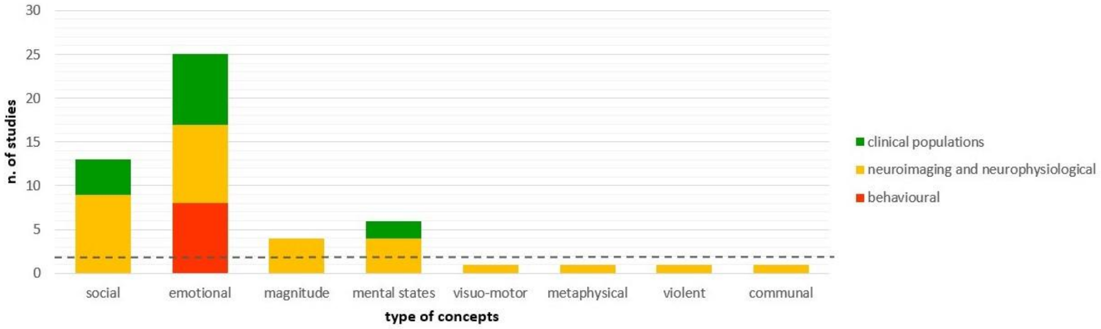

Figure 1. Number of studies investigating each abstract dimension/category, considering the type of study, i.e. behavioral, neuroimaging and neurophysiological and clinical.

2.3.1. Results in healthy subjects: behavioural studies

Eight studies investigated emotional abstract words in healthy participants during behavioural tasks (see Table 1 and Figure 1). Stimulus selection was made a priori (Altarriba et al., 1999; Altarriba and Bauer, 2004), or based on pre-existing databases (Kousta et al., 2011; Moffat et al., 2014; Mazzuca et al., 2018), on ratings of the degree of emotional experience (Siakaluk et al., 2016; Newcombe et al., 2012), or on association with labels denoting emotions (Chen et al., 2016). Both explicit and implicit behavioural tasks, namely lexical decision (Altarriba and Bauer, 2004; Kousta et al., 2011; Chen et al., 2016; Siakaluk et al., 2016; Mazzuca et al., 2018), semantic categorization (Newcombe et al., 2012; Moffat et al., 2014), free association (Altarriba et al., 1999), word recognition (Mazzuca et al., 2018), and word reading tasks (Moffat et al., 2014) have been used.

An advantage in processing emotional abstract words (or words characterized by a higher degree of both emotional valence and emotional experience) over the other abstract or concrete words, speeding up responses, has been reported in all studies (Kousta et al., 2011; Siakaluk et al., 2016; Chen et al., 2016; Altarriba and Bauer, 2004; Newcombe et al., 2012; Moffat et al., 2014; Mazzuca et al., 2018), with the exception of the study of Altarriba et al. (1999) reporting a higher number of associated concepts in respect to both abstract and concrete words, interpreted as a processing disadvantage. In summary all the studies suggested the presence of emotions as specific category of abstract words characterized by emotional/affective information.

2.3.2. Results in healthy subjects: neuroimaging and neurophysiological studies

In investigating the neural basis of abstract concepts' categories in healthy individuals, twenty studies were included (See Figure 1, Figure 2, Table 1; and Table 2 in Appendix A), including only a single category, namely social (Zahn et al., 2007; Ross and Olson, 2010; Wong et al., 2011; Pobric et al., 2016; Binney et al., 2016; Rice et al., 2018), emotional (Beauregard et al., 1997; Moseley et al., 2012; Vigliocco et al., 2014; Skipper and Olson, 2014; Wilson-Mendenhall et al., 2011; Lebois et al., 2018), mental states (Baron-Cohen et al., 1994), magnitude, in these cases mathematical (Bechtold et al., 2019; Wilson-Mendenhall, 2013), or more dimensions together, namely emotional and mental states (Dreyer and Pulvermüller, 2018), mental states and metaphysical (Harris et al., 2006), social and quantity-related (Catricalà et al., 2020), social and emotional (Wang et al., 2019), visual and motor related (Harpaintner et al., 2020) concepts. Stimuli were selected a priori (Wilson-Mendenhall et al., 2011; Harris et al., 2006; Bechtold et al. 2019; Wilson-Mendenhall et al. 2013; Beauregard et al. 1997), from pre-existing studies (Ross and Olson 2010; Binney et al., 2016; Rice et al., 2018; Wong et al., 2011; Pobric et al., 2016; Lebois et al., 2018), from databases providing values of psycholinguistic variables (Vigliocco et al., 2014; Wang et al. 2017), or via dimensions rating (Zahn et al., 2007; Catricalà et al., 2020; Harpaintner et al. 2020; Dreyer and Pulvermüller, 2018; Wang et al. 2019; Moseley et al. 2012; Skipper and Olson, 2014). All the fMRI studies used traditional univariate analyses based on both whole brain and ROI approaches, whereas two studies adopted data-driven methods (Huth et al., 2016; Wang et al., 2018), aimed at investigating the neural correlates subtending a multidimensional semantic space, in line with the rating procedures (Crutch et al., 2013; Troche et al., 2014; Binder et al., 2016). In this section we presented only the results reporting the involvement of a given area in at least the 50% of the studies investigating the area of interest, when the same area was investigated in at least 2 studies. All the results of the studies included in this review, inclusive of those investigating individually a dimension, are reported in the Table 2 of Appendix A.

2.3.2.1. Social concepts

The neural bases of social concepts were investigated in six fMRI (Zahn et al., 2007; Ross and Olson, 2010; Binney et al., 2016; Rice et al., 2018; Wang et al., 2019; Huth et al., 2016) and three TMS studies (Pobric et al., 2016; Wong et al., 2011; Catricalà et al., 2020). Three experimental tasks were used, namely a semantic similarity judgment task (Zahn et al., 2007; Ross and Olson, 2010), a two alternative forced-choice semantic decision task (Wong et al., 2011; Binney et al., 2016; Pobric et al. 2016; Rice et al., 2018; Wang et al., 2019), and a category priming task (Catricalà et al., 2020). In 4 out of the 9 studies, the processing of social concepts was compared with that of a concrete category, namely, animal functions concepts (Zahn et al., 2007; Ross and Olson, 2010; Wong et al., 2011; Pobric et al., 2016), in one to non social abstract concepts (Wang et al., 2019), in two studies to both animal functions and non social abstract concepts (Binney et al., 2016; Rice et al., 2018), and in one to quantity-related abstract concepts (Catricalà et al., 2020).

Eight of the nine studies reported the specific involvement of the superior anterior temporal lobes (sATLs) in social concepts' processing. More in detail, 3 studies found a greater right hemisphere preference (Zahn et al., 2007; Pobric et al., 2016; see also Catricalà et al., 2020 despite the assessment of the only right hemisphere), three found a bilateral involvement (Binney et al., 2016; Huth et al., 2016; Rice et al., 2018), and three a left hemisphere preference (Ross and Olson, 2010; Wang et al., 2019; Wong et al., 2011). Out of 6 studies (note that Wong et al., 2011; Pobric et al., 2016; Catricalà et al., 2020 were not included in the following count since they focused only on a specific region of interest, namely sATL, and IPS), reported additional areas during social concepts processing, although less robustly. Specifically, 3 reported the involvement of the ventral/lateral temporal cortex, i.e. fusiform gyrus (Zahn et al., 2007; Ross and Olson, 2010; Rice et al., 2018), inferior temporal gyrus (Zahn et al., 2007); and 3 of the posterior middle/superior temporal gyrus (Wang et al., 2019; Binney et al., 2016; Rice et al., 2018). In addition, an involvement of fronto-parietal regions has also been found, with 3 studies reporting activation in the inferior frontal gyrus (Zahn et al., 2007; Huth et al., 2016; Rice et al., 2018), and 3 in inferior parietal lobule (Huth et al., 2016; Wang et al., 2019; Binney et al., 2016). An involvement of occipital lobe has been found in 5 studies, encompassing lingual gyri (Binney et al., 2016; Rice et al., 2018) and medial areas, i.e. the medial occipital gyrus (Zahn et al., 2007; Rice et al., 2018), the cuneus (Binney et al., 2016), and the calcarine sulcus (Rice et al., 2018). In summary, a large network of regions, with a prominent role of ATL and additional temporal, occipital and fronto-parietal regions, is implicated in social concepts' representation.

2.3.2.2. Emotional concepts

The neural correlates of emotional concepts have been investigated in one PET study (Beauregard et al., 1997), and eight fMRI studies (Vigliocco et al., 2014; Moseley et al., 2012; Skipper and Olson, 2014; Lebois et al., 2018; Wilson-Mendenhall et al. 2011; Dreyer and Pulvermüller, 2018; Wang et al., 2019; Huth et al., 2016). Five experimental tasks were used, namely passive reading (Beauregard et al., 1997; Moseley et al., 2012; Dreyer and Pulvermüller, 2018), lexical decision (Vigliocco et al., 2014), word typicality judgement (Lebois et al., 2018; Wilson-Mendenhall et al., 2011), thinking about the words and answering questions (Skipper and Olson, 2014), and two-alternative forced-choice semantic decision (Wang et al., 2019) tasks. Emotional abstract words were compared with abstract non emotional (Lebois et al., 2018; Wilson-Mendenhall et al., 2011; Wang et al., 2019) or concrete words (Skipper and Olson, 2014; Vigliocco et al., 2014), or with both (Beauregard et al., 1997; Moseley et al., 2012; Dreyer and Pulvermüller, 2018).

Emotional abstract words' processing involved a widespread brain network. Seven out of 9 studies reported an involvement of frontal areas, and specifically the inferior frontal gyrus (Beauregard et al., 1997; Huth et al., 2016; Skipper and Olson, 2014; Wilson-Mendenhall et al. 2011), and the precentral gyrus (Moseley et al., 2012; Lebois et al., 2018; Wilson-

Mendenhall et al. 2011), in some cases encompassing motor and premotor areas (Dreyer and Pulvermüller, 2018). A bilateral involvement of the anterior temporal cortices was found in 6 out of 9 studies, including temporal pole (Wang et al., 2019; Wilson-Mendenhall et al., 2011; Lebois et al., 2018; Moseley et al., 2012; Skipper and Olson, 2014), and in some cases extending to middle and superior ATL (Huth et al., 2016; Skipper and Olson, 2014). In 5 studies an involvement of mid-posterior superior and middle temporal gyrus was also found (Beauregard et al., 1997; Moseley et al., 2012; Skipper and Olson, 2014; Wilson-Mendenhall et al., 2011; Lebois et al., 2018). In summary, a complex pattern of fronto-temporal regions has been associated to emotional words, in association to further areas, namely cingulate cortex, insula, orbitofrontal cortex and inferior parietal lobule, reported in less than half of the considered studies (see Figure 2 and Table 2 in Appendix A).

2.3.2.3. Mental state concepts

Mental state concepts have been less investigated compared to social and emotional ones; indeed, only four studies were included in this section, namely one SPECT (Baron-Cohen et al., 1994) and three fMRI studies (Dreyer and Pulvermüller, 2018; Harris et al., 2006; Huth et al., 2016). Three tasks were used, i.e. passive reading (Dreyer and Pulvermüller, 2018), word recognition (Baron-Cohen et al., 1994), and valence judgement (Harris et al., 2006). Mental states were compared to concrete words (Baron-Cohen et al., 1994), or to concrete and abstract words, belonging to emotion (Dreyer and Pulvermüller, 2018) and metaphysical (Harris et al., 2006) categories. Two out of 4 studies reported a medial frontal involvement, specifically of the fronto-polar cortex (Baron-Cohen et al., 1994), and of the ventromedial prefrontal cortices (Huth et al., 2016).

2.3.2.4. Magnitude concepts

Quantity, space, time, and mathematical related concepts, here indicated as belonging to the magnitude category, have been rarely investigated. We included four studies, and specifically two with fMRI (Wilson-Mendenhall et al., 2013; Huth et al., 2016), one with TMS (Catricalà et al., 2020), and one with EEG (Bechtold et al., 2019), using concept-scene matching (Wilson-Mendenhall et al., 2013), category priming (Catricalà et al., 2020), and lexical decision (Bechtold et al., 2019) tasks.

These studies included quantity-related (Catricalà et al., 2020), mathematical (Bechtold et al., 2019), numerical, temporal, and locational concepts (Huth et al., 2016), or the single word *arithmetic* (Wilson-Mendenhall et al., 2013). Magnitude-related concepts were compared to abstract words belonging to mental states and emotions (Bechtold et al., 2019), and to the social (Wilson-Mendenhall et al., 2013; Catricalà et al., 2020) category. Two studies reported the involvement of the intraparietal sulcus (Wilson-Mendenhall et al., 2013; Catricalà et al., 2020). Additional frontal lobe activations have also been found in 2 out of 4 studies, encompassing the middle (Wilson-Mendenhall et al., 2013), and the superior (Huth et al., 2016) prefrontal gyrus. In summary, quantity related concepts mostly involve the intraparietal sulcus, and the mid-superior prefrontal gyri.

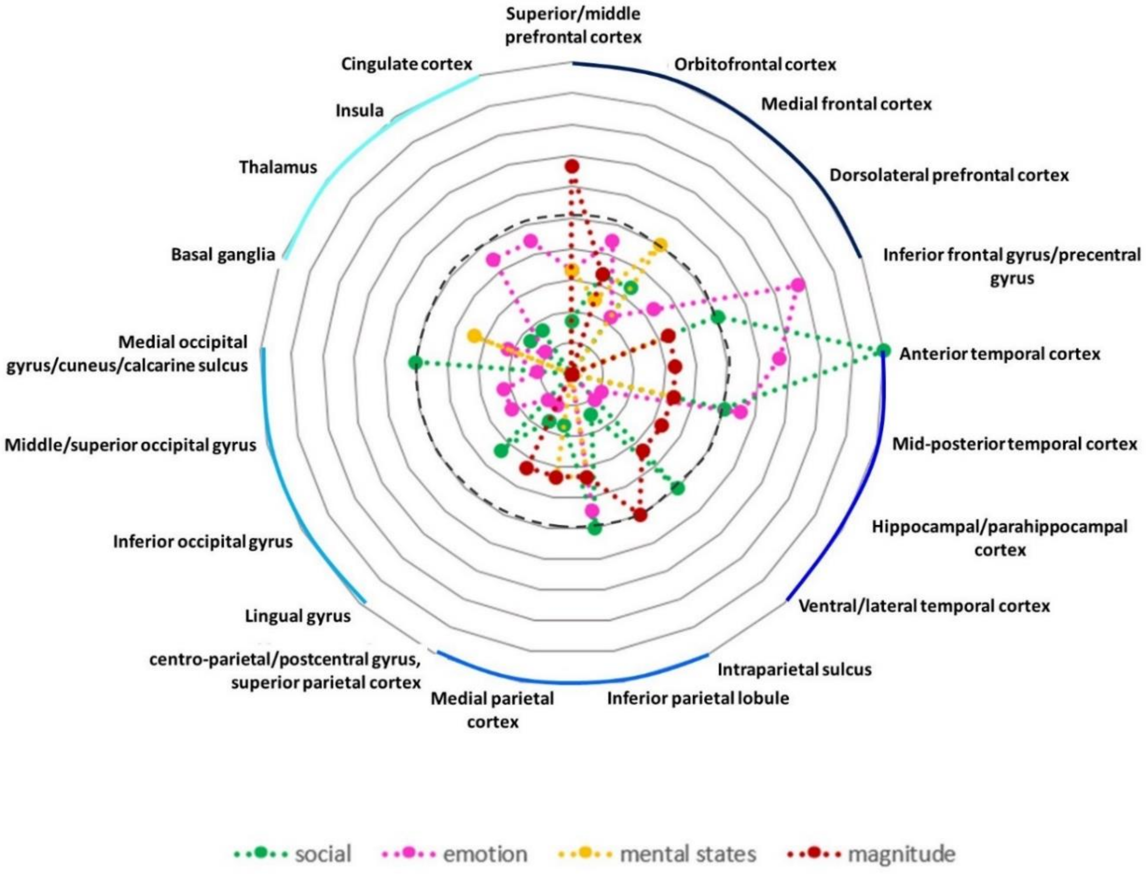

Figure 2. Schematic illustration of the results of neuroimaging and neurophysiological studies in healthy subjects. Concentric lines represent the proportion of studies reporting an area out of the total of studies investigating the same area, separately for each abstract category. Grey dotted line indicates the proportion of 0.5 (i.e. an area found in the 50% of studies). Anterior temporal lobe includes anterior middle, superior, inferior temporal gyri, temporal pole and temporo-polar cortex; mid-posterior temporal cortex includes posterior middle and superior temporal gyri; ventral/lateral temporal cortex includes fusiform and inferior temporal gyri; inferior parietal lobule includes angular and supramarginal gyri; basal ganglia include caudate and putamen.

2.3.3. Results in clinical population

We included 13 studies dealing with data from patients affected by neurodegenerative diseases (i.e. Alzheimer’s Disease, AD; semantic variant of Primary Progressive Aphasia, svPPA; non fluent variant of Primary Progressive Aphasia nfPPA; mixed Primary Progressive Aphasia, mixed PPA; behavioural variant of Fronto-Temporal Dementia, bvFTD; cortico-basal syndrome, CBS) (Martin and Fedio, 1983; Zahn et al., 2009; Hsieh et al., 2012; Catricalà et al., 2014; Giffard et al., 2015; Pobric et al., 2016; Zahn et al., 2017; Joubert et al., 2017), focal brain damage (Dreyer et al., 2015, Semenza et al., 1986), and autism spectrum disorder (ASD) (Baron-Cohen et al., 1994; Moseley et al., 2015; Harris et al., 2006) (see Table 1, Figure 1). Out of 13, 11 are group studies (Martin and Fedio, 1983; Baron-Cohen, 1994; Zahn et al., 2009; 2017; Harris et al., 2006; Hsieh et al., 2012; Catricalà et al., 2014; Giffard et al., 2015; Joubert et al., 2017; Moseley et al., 2015; Semenza et al., 1986), and 2 are single-case studies (Dreyer et al., 2015; Pobric et al., 2016), and in both cases a group of age-matched controls was included. Eleven out of 13 studies investigated only one category of concepts, specifically 6 studies focused on emotions (Martin and Fedio, 1983; Hsieh et al., 2012; Joubert et al., 2017; Dreyer et al., 2015; Moseley et al., 2015; Giffard et al., 2015; Semenza et al., 1986), 3 on social (Pobric et al., 2016; Zahn et al., 2009; 2017), and one on mental states (Baron-Cohen et al., 1994); two studies focused on more categories, namely mental states and metaphysical concepts (Harris et al., 2006), and emotions, mental states, social concepts, human actions, and traits (Catricalà et al., 2014). Stimuli were selected a priori (Martin and Fedio, 1983; Joubert et al., 2017; Baron-Cohen et al., 1994; Harris et al., 2006; Semenza et al., 1986), from previous studies and existing databases (Moseley et al., 2015; Zahn et al., 2009; 2017; Pobric et al., 2016; Catricalà et al., 2014), or via dimension ratings (Dreyer et al., 2015; Hasie et al., 2012; Giffard et al., 2012).

In this section, differently from the previous one, we included all the results, including also those reported in a single clinical condition, given the paucity of the clinical studies and the presence of specific localization of brain damage.

2.3.3.1. Social concepts

Four studies investigated social concepts in clinical populations, two concerning only behavioral data (Pobric et al., 2016; Catricalà et al., 2014), one including also MRI (Zahn et al., 2017) and FDG-PET data (Zahn et al., 2009).

All the studies included patients belonging to one (i.e. svPPA in Pobric et al., 2016) or more (i.e. svPPA and AD in Catricalà et al., 2014; bvFTD, svPPA, and mixed PPA in Zahn et al., 2017; bvFTD, svPPA, nfPPA, CBS in Zahn et al., 2009) neurodegenerative conditions.

Three of them used a two alternatives forced-choice semantic decision task (Pobric et al., 2016; Zahn et al., 2009; 2017), while one used sentence completion, multiple choice verbal matching and association tasks (Catricalà et al., 2014). Social concepts were compared to animal functional concepts in three studies (Pobric et al., 2016; Zahn et al., 2009; 2017), and to other abstract categories, i.e. emotional, mental states, human actions, and traits in one study (Catricalà et al., 2014). An impairment on social concepts is reported in all considered studies, in particular in patients affected by svPPA, when compared to controls (Catricalà et al., 2014; Pobric et al., 2016), and in FTD spectrum, i.e. svPPA, nfPPA, and bvFTD in Zahn et al., 2009, and svPPA, mixed PPA, and bvFTD in Zahn et al., 2017, when compared with CBS patients (Zahn et al., 2009), or with controls (Zahn et al., 2017), a pattern associated with greater right than left ATL atrophy (Pobric et al., 2016), particularly of the right superior ATL portion (Zahn et al., 2009; 2017).

In summary, all the studies consistently show an impairment of social concepts in svPPA, also when grouped with other FTD conditions. A correlation between social concepts deficit and an involvement of the superior ATL has been also reported.

2.3.3.2. Emotional concepts

Emotional abstract concepts were investigated in eight papers, all focusing only on behavioural data (Martin and Fedio, 1983; Hsieh et al., 2012; Catricalà et al., 2014; Giffard et al., 2015; Joubert et al., 2017; Dreyer et al., 2015; Semenza et al., 1986), except one using fMRI (Moseley et al., 2015).

Five out of 8 studies included patients with neurodegenerative diseases, namely AD (Martin and Fedio, 1983; Giffard et al., 2015), svPPA and AD (Catricalà et al., 2014; Joubert et al., 2017), svPPA, bvFTD and AD (Hsieh et al., 2012), whereas two dealt with patients affected by focal brain lesions, including tumors and vascular disease (Dreyer et al., 2015; Semenza et al., 1986), and one with ASD patients (Moseley et al., 2015). Five out of 7 studies used explicit tasks, including symbol referent, word associations, synonym judgment, similarity judgement and association (Martin and Fedio, 1983; Hsieh et al., 2012; Catricalà et al., 2014; Joubert et al., 2017; Semenza et al., 1986); 3 used implicit tasks, including lexical decision (Giffard et al., 2015; Dreyer et al., 2015), and passive reading (Moseley et al., 2015). Emotional concepts were considered alone (Hsieh et al., 2012), or compared to either concrete (Dreyer et al., 2015) and abstract (Catricalà et al., 2014) concepts, or to both (Giffard et al., 2015; Joubert et al., 2017; Moseley et al., 2015; Martin and Fedio, 1983; Semenza et al., 1986).

Three out of the five studies in AD reported a preservation of emotion concepts in both explicit and implicit semantic tasks (Martin and Fedio, 1983; Catricalà et al., 2014; Giffard et al., 2015), whereas the other two, using explicit tasks, did not report a similar pattern (Hsieh et al., 2012; Joubert et al., 2017). For svPPA, results were more heterogeneous, manely reporting respectively no difference (Joubert et al., 2017), a preservation (Catricalà et al., 2014), and an impairment (Hsieh et al., 2012) of emotional concepts compared to either abstract or concrete ones. In bvFTD patients an impairment in emotional concepts was found in a word association but not in a synonym judgments task (Hsieh et al., 2012). Finally, impaired emotional abstract words processing was reported in a patient affected by focal left-hemisphere brain lesions in precentral regions and supplementary motor area during a lexical decision task (Dreyer et al., 2015) and in patients affected by diffuse right-hemispheric brain lesions (Semenza et al., 1986). Diminished brain activity for emotional word processing in bilateral cingulate areas, primary motor and premotor areas, was reported in ASD patients compared to controls (Moseley et al., 2015).

In conclusion, a preservation of emotional concepts was reported in AD and svPPA. An involvement of precentral and motor areas was reported in focal lesions and ASD patients.

2.3.3.3. Mental States concepts

Mental state concepts were investigated in only two studies, specifically one behavioural (Baron-Cohen et al., 1994), and one fMRI study (Harris et al., 2006). Both dealt with ASD, respectively children (Baron-Cohen et al., 1994) and adults (Harris et al., 2006), and the control group was, respectively, a sample of children affected by moderate mental handicap (Baron-Cohen et al., 1994) or healthy subjects (Harris et al., 2006). Two tasks were used, namely a word recognition (Baron-Cohen et al., 1994) and a valence judgment (Harris et al., 2006), and in both studies mental states were compared to concrete concepts.

In both studies, ASD resulted impaired in the processing of mental states concepts. Specifically, only a small percentage of ASD children (26.7 %) were able to recognize mental states concepts (Baron-Cohen et al., 1994), and ASD adults did not show the same pattern of brain activation found in controls during mental states concepts processing, i.e. activations in the left middle temporal gyrus (BA21) and in the right caudate/putamen (Harris et al., 2006).

These findings suggest the presence of deficits and/or neural activation changes in the semantic knowledge of concepts denoting mental states in ASD.

2.4. Discussion

We reviewed behavioural, clinical, neuroimaging and neurophysiological studies of abstract concepts processing, including emotions, mental states, social and magnitude related concepts. In the present section, we discuss the possibility to associate the outlined dimensions of abstract knowledge in the neural systems subserving their respective cognitive functions, namely implied in affective, Theory of Mind, social cognition and magnitude/numerical processing, according to previous studies (Binder et al., 2016; Desai et al., 2018).

2.4.1. Social concepts

Socially related information has been often reported in the characterization of abstract concepts, in the case of feature listing, e.g. details about behaviors, agents, social meaning of the action, social aspect of a situation (Hampton, 1981; Barsalou and Wiemer-Hastings, 2005; Roversi et al., 2013; Borghi et al., 2016; Harpainter et al., 2018), as well as more directly in dimension rating (Troche et al., 2014; 2017; Binder et al., 2016; Villani et al., 2019). Social concepts recruited the same brain network associated with social cognition processing, involving the interpretation and prediction of others' behaviours, as well as the interaction in social contexts (Frith, 2007). The reviewed studies reported a prominent involvement of temporal regions, with a further extension to inferior frontal gyrus, inferior parietal lobule and occipital areas, i.e. lingual and medial occipital gyri, cuneus and calcarine sulcus. The involvement of the ATL, in particular of its superior portion (sATLs), has been robustly reported in neuroimaging and neurophysiological studies in healthy subjects (Zahn et al., 2007; Ross and Olson, 2010; Pobric et al., 2016; Binney et al., 2016; Huth et al., 2016; Rice et al., 2018; Wang et al., 2019; Catricalà et al., 2020). Consistently, clinical populations studies suggested a deficit in social concepts in FTD, and specifically in svPPA (Catricalà et al., 2014; Pobric et al., 2016; Zahn et al., 2009; 2017), where this impairment is associated with a sATL involvement (Pobric et al., 2016; Zahn et al., 2009; 2017). These findings are compatible with the role of the ATLs in social cognition (Amodio and Frith, 2006), and specifically of the sATLs (Adolfi et al., 2017). Indeed, the ATLs have been proposed to have a crucial role in encoding, retrieving and applying general knowledge about social situations, and in storing abstract person identity representations (Olson et al., 2013; Wang et al., 2017). A recent proposal further suggested that sATL is responsible for storing stable conceptual information of social behaviors and in connecting to other systems, e.g. prefrontal cortices, for the evaluation of long term consequences of these behaviors (Zahn et al., 2017). Several studies reported the involvement of ATL in social cognition tasks, including theory of mind and mentalizing (Ross and Olson, 2010), and during the attribution of social stereotypes (Contreras et al., 2012) and adjectives defining people (Mitchell et al., 2002).

The imaging and clinical studies do not indicate a convergent lateralization in the processing of social concepts. The imaging studies suggested a similar contribution of both ATLs while a lateralization suggesting an ATL right-hemispheric bias, emerged from the clinical data. Accordingly, patients with a right ATL atrophy displayed social and behavioural disturbances, including social disinhibition, depression, aggressive behavior, loss of empathy and personality changes (Mychack et al., 2001; Chan et al., 2009; Thomson et al., 2003), as well as deficits in social cognition tasks (Irish et al., 2014). Similarly, structural alterations of the right uncinate fasciculus, connecting sATL to the amygdala and other regions supporting social cognition and affect, including the lateral orbitofrontal and frontal polar cortices (Catani et al., 2013; Binney et al., 2012), are reported in psychopathy and in antisocial personality disorder (Craig et al., 2009; Motzkin et al., 2011; Sundram et al., 2012), characterized with severe lack of empathy and increased aggressiveness (Blair et al., 2001). Other brain regions are engaged by social concepts processing, including additional temporal regions (posterior middle and superior temporal gyri, ventral/lateral temporal cortex, encompassing fusiform and inferior temporal gyri), the IFG, inferior parietal lobule, and the medial occipital lobe. These areas have been implicated in different aspects related to social cognition. The posterior temporal regions and inferior parietal lobule have been implicated in the attribution of intentions to other individuals, with different contributions. Posterior mid-superior temporal regions, extending to the temporoparietal junction, exerted a role in storing the representations of social perceptual features extracted from multiple cues, e.g. facial expression, gaze, prosody, body postures, and gestures (Allison et al., 2000; Frith, 2001; Moll, 2005; Wurm and Schubotz, 2018). On the other hand, the dorsal areas, encompassing the inferior parietal lobe, and specifically the angular gyrus, have been linked to understanding others' intentions based on covert cues, such as in the false belief task (Schurz et al., 2014; Gobbini et al., 2007). Activations in fusiform and inferior temporal gyri, extending posteriorly to occipital regions, have been reported during theory of mind and empathy tasks (Vollm et al., 2006). In particular, the fusiform gyrus has been involved in processing (Narumoto et al., 2000) as well as learning the positive vs aversive value of individual face stimuli (Petrovic et al., 2008). Activations in medial occipital areas, encompassing the cuneus, have been differently interpreted either as reflecting the involvement of mental imagery or an enhanced salience in response to relevant social stimuli (Sander et al., 2005). Additionally, inferior frontal gyrus has been entailed in making decisions about characteristics of individuals, including judgements about their hierarchal position or classification as friends or enemies (Farrow et al., 2011).

2.4.2. Emotional concepts

Emotional concepts were the first (see for example Martin and Fedio, 1983) and most explored among abstract categories. They were defined by introspective and emotional experience in feature listing (Barsalou and Wiemer-Hastings, 2005; Wiemer-Hastings and Xu Xu; 2005; Borghi et al., 2016; Harpaintner et al., 2018), and on the basis of a social-affective or endogenous factor (Troche et al., 2014; 2017), or as associated with inner states (Villani et al., 2019) in rating studies. In general, they are more imageable than other abstract concepts (Altarriba et al., 1999; Altarriba and Bauer, 2004). An advantage in processing emotional concepts, manifested as decreased reaction times, has been reported in behavioural studies in healthy subjects (Kousta et al., 2011; Siakaluk et al., 2016; Chen et al., 2016; Altarriba and Bauer, 2004; Newcombe et al., 2012; Moffat et al., 2014; Mazzuca et al., 2018).

The reviewed imaging studies of emotional concept processing involved fronto-temporal brain regions, encompassing bilateral anterior temporal cortices, i.e. temporal pole, middle and superior ATL, as well as mid-posterior superior and middle temporal gyrus, inferior frontal gyrus, precentral, motor and premotor cortices. These areas, together with other regions, i.e. cingulate cortex, insula, orbitofrontal cortex and inferior parietal lobule, have been previously associated to various aspect of emotion processing (Lindquist et al., 2012). Both posterior and anterior regions of the temporal lobes, specifically in the superior temporal gyrus, have been involved in integrating visual and auditory emotional cues (Robins et al., 2009) and elaborating emotional contents of stories (Ferstl and von Cramon, 2007). In addition, the temporal pole has been though to exert a role in the modulation and association of visceral responses to perceptual emotional stimuli, e.g. voices, faces (Olson et al., 2007). The temporal pole is strictly connected to regions involved in affect processing, including orbitofrontal cortex and amygdala (Pascual et al., 2013), and damage to these areas lead to Kluver-Bucy syndrome, manifested by blunted affect and social withdrawal (Kluver and Bucy, 1997). The role of frontal cortices in emotional concepts has been revealed both in neuroimaging studies in healthy and in clinical populations, e.g. focal lesions (Dreyer et al., 2015) and ASD (Moseley et al., 2015). Specifically, activation of the inferior frontal gyrus has been associated to valence processing (Kuchinke et al., 2005), and to the perception of emotional prosody (Hoekert et al., 2010) and emotional facial expressions (Jabbi and Keysers, 2008). Moreover, the involvement of motor and premotor cortices has been interpreted as linkage between words' emotional meaning and emotion-expressing action schemas (Moseley et al., 2012; Dreyer and Pulvermüller, 2018). In neurodegenerative diseases the results were not convergent. For instance, in AD a preservation of emotional concepts has been found in both explicit and implicit semantic tasks (Martin and Fedio, 1983; Catricalà et al., 2014; Giffard et al., 2015), but other evidence, using explicit tasks, did not found the same result (Hsieh et al., 2012; Joubert et al., 2017). These contrasting results may reflect the different level of severity of semantic impairment and/or the sensibility of the tests employed. Indeed, emotional concepts were preserved in AD patients who also exhibited semantic deficits in both concrete and abstract categories (Martin and Fedio, 1983; Giffard et al., 2015; Catricalà et al., 2014). On the other hand, the AD patients included in the study by Hsieh et al. (2012) exhibited comparable performance to age-matched controls in concrete, abstract and emotional abstract words' comprehension tasks, whereas in the study of Joubert et al. (2017), the AD patients performed worse than controls, but without difference among concrete, abstract and emotional words. In svPPA, emotional concepts were either preserved (Catricalà et al., 2014), impaired (Hsieh et al., 2012), or not significantly different from abstract or concrete concepts (Joubert et al., 2017). Of note, in Hsieh et al. (2012) stimuli included several emotionally valenced concepts conveying also a social meaning, such as *sympathy*, and as reported above, social concepts are generally degraded in svPPA, possibly biasing the results. It is possible that emotional concepts, engaging a widespread neural correlates in fronto-temporal regions, are less vulnerable to semantic degradation.

The emotional concepts class is heterogeneous. Heterogeneity may be traced both in the characterization of emotional concepts, e.g. in terms of valence as in Vigliocco et al., (2014) or emotional experience as in Newcombe et al. (2012), as well as in the different processes involved in their representation, varying, for example, as a function of situational contexts

(Wilson-Mendenhall et al., 2011; Lebois et al., 2018), as resulting in the reviewed neuroimaging and patients' studies. This variability mirrored the heterogeneity of the processes and of the neural correlates subtending experiencing and perceiving emotions, namely including a complex set of affective, cognitive, motor and interoceptive experiences (Lindquist et al., 2012; Wager et al., 2015).

2.4.3. Mental states concepts

Abstract concepts referring to mental states have been scarcely investigated in literature. The role of introspective-subjective-internal experience, including mental states and cognitive operations, has been highlighted in the characterization of abstract concepts by feature listing approaches (Barsalou and Wiemer-Hastings, 2005; Wiemer-Hastings and Xu Xu; 2005; Borghi et al., 2016; Harpaintner et al., 2018). Mental states have been defined as more abstract than other categories (Setti and Caramelli, 2005), and described as referring to "mental activity, ideas, opinions and judgements" (Troche et al., 2014; 2017). These characteristics may be associated to the general domain of Theory of Mind (ToM) processing, namely the ability to attribute, understand, and infer other people's mental states, encompassing thoughts, desires and intentions (Premack and Woodruff, 1978). It relies on the recognition that others' beliefs may not correspond to ours or to objective facts (Gallagher and Frith, 2003), and it is crucial for the development of adequate social relations, allowing us to predict people's actions. Consequently, the acquisition of mentalizing capabilities appears extremely intertwined with the emerging social competencies since childhood (Hughes and Leekam, 2004).

A consistent result of the reviewed neuroimaging studies in healthy subjects suggested that mental states concepts are represented in medial frontal areas (Baron-Cohen et al., 1994; Huth et al., 2016), in particular ventromedial prefrontal regions, traditionally associated with Theory of Mind processes (Schurz et al., 2014). For instance, ventromedial prefrontal cortex (vmPFC) was activated during thinking about other individuals' mental states (Schurz and Perner, 2015), and reasoning about judgements, intentions, and goals (Van Overwalle and Baetens, 2009). Specifically, vmPFC has been involved in the decoupling mechanism, namely separating others' perspective from the objective state of reality (Gallagher and Frith 2003; Döhnel et al., 2012). Interestingly, vmPFC has been associated with valence and affective aspects of ToM evaluations (Koster-Hale et al., 2017). Patients with lesions extending to vmPFC and orbitofrontal cortex showed severe disturbances in those ToM tasks requiring both cognitive and affective components, namely irony and faux-pas comprehension (Shamay-Tsoory et al.

2005). Additionally, in the reviewed studies, patients with autism spectrum disorder, known to be impaired in understanding others' mental states, intentions or beliefs (Baron-Cohen, 2000), and displaying abnormal connectivity in frontal cortex (Courchesne and Pierce, 2005), also exhibited disturbances in the processing of mental states concepts (Baron-Cohen et al., 1994; Harris et al., 2006).

2.4.4. Magnitude concepts

Dimension rating studies have suggested that quantity, space, and time related concepts may be grouped together in a magnitude factor (Troche et al., 2014; 2017; Villani et al., 2019). The reviewed neuroimaging and neurophysiological evidence in healthy subjects revealed the involvement of intraparietal sulcus (IPS) (Wilson-Mendenhall et al., 2013; Catricalà et al., 2020), and of the middle (Wilson-Mendenhall et al., 2013) and superior (Huth et al., 2016) prefrontal gyrus during the elaboration of magnitude concepts, encompassing quantity, space and time related concepts, and also numerical stimulus processing. These regions are known to be part of the neural network subtending numbers and magnitude cognition (Amalric and Deheane, 2017), also responsible for the representation of quantifiers, namely noun phrases which bear quantitative properties and assign them to nouns (Clark and Grossman, 2007). For instance, the involvement of IPS is found in a sentence-picture matching task involving quantifiers, with activations also extending to prefrontal cortices, in turn thought to reflect the recruitment of executive resources, e.g. working memory (Mc Millan et al., 2005; Troiani et al., 2009). Deficits in quantifiers' processing are found in cortico-basal syndrome, affecting parietal cortices (Troiani et al., 2011), and in bvFTD, characterized by frontal atrophy and executive dysfunctions (Morgan et al., 2011; Ash et al., 2016), but not in other neurodegenerative conditions, e.g. svPPA (Cappelletti et al., 2006; Ash et al., 2016). IPS activity was also found during both production and comprehension of quantifiers and numbers, as well as during arithmetical operations in an electrocorticographic study in epileptic patients (Dastjerdi et al., 2013).

According to the Theory of Magnitude, a peculiar role is assigned to parietal cortices, considered responsible for performing magnitude related estimations involving quantity, time, and space (Walsh, 2003; Bueti and Walsh, 2009). Activations in parietal areas have been found during numerositiy estimation, temporal discriminations and length/spatial judgements tasks (Dormal et al., 2012A; Dormal et al., 2012B; Skagerlund et al., 2016), and common developmental trajectory of a magnitude estimation system subserving those processes has been proposed (Lourenco and Aulet, 2019). Moreover, patients affected by parietal lesions displayed deficits in numerosity tasks (Koss et al., 2010), time perception (Harrington et al., 1998) and in the processing of spatial prepositions, e.g., *above, behind, inside* (Shebani et al., 2017).

2.5. Conclusion

In this systematic review, we have considered multiple sources of potential evidence for the organization of abstract semantic knowledge. A substantial number of behavioural, imaging and clinical studies have investigated emotional and social concepts; less evidence is available for mental state- and magnitude-related concepts. Notwithstanding the huge methodological differences, a relatively converging pattern of results supports the existence of a categorical organization. In particular, partially non overlapping cerebral correlates of brain activity during imaging tasks, and category-related patterns of impairment in pathological conditions are compatible with an embodied model of cerebral organization, in which categorical conceptual representations involve brain systems engaged by the corresponding perceptual experiences in the case of both concrete and abstract entities.

3. In search of different categories of abstract concepts: a fMRI adaptation study

3.1. Introduction

The storage and processing of word meanings is underpinned by neural systems subserving the representation of conceptual knowledge and the control of its access, use and manipulation (Lambon Ralph et al., 2017). According to “embodied” theories, concrete concepts involve distributed neural networks coding perceptual and motor information, differently contributing in characterizing specific categories, e.g. animals, tools (Kiefer and Pulvermüller, 2012).

If and how this framework apply to abstract concepts is debated. Despite their characterization is complex due to the presence of fuzzy demarcations among categories (Della Rosa et al., 2018), recent proposals suggested that different abstract categories may be grounded in brain regions representing specific semantic dimensions (Catricalà et al., 2014).

The hypothesis is that, in analogy to concrete knowledge, different types of semantic dimensions, e.g. emotional-, social-, cognitive-, quantity-related, may support specific categories of abstract representations (Desai et al., 2018). Recent evidence suggested that a few dimensions characterize different categories of concepts, engaging the brain networks involved in affect (Vigliocco et al., 2014), social and numerical processing (Catricalà et al., 2020). The neural correlates of social and quantity-related categories are consistent, involving, respectively, the anterior temporal lobe and the intraparietal sulcus (Wilson-Mendenhall et al., 2013; Catricalà et al., 2020), whereas for emotion-related concepts the results are more complex. Activations were reported in inferior frontal, motor/premotor areas (Dreyer and Pulvermüller, 2018), rostral cingulate cortex (Vigliocco et al., 2014), anterior (Huth et al., 2016; Wang et al., 2019), and mid-posterior temporal gyri (Skipper and Olson, 2014; see for a review Conca et al., submitted).

We aimed to investigate the neural correlates of different abstract categories, including some never investigated, namely attitudes, human actions and cognitions. We firstly developed a novel approach, combining literature review and BrainMap database to select the brain regions supporting semantic cognition, namely areas responsible for the representation of semantic contents and for controlling their usage. Some evidence suggested indeed that abstract concepts have a high variability in meaning and appear in a broad range of contexts and situations (Hoffman et al., 2013; Saffran, 2000), leading to the assumption that abstract, compared to concrete concepts pose higher demands on control functions (Hoffman et al., 2015), revealed by a greater activation of the left inferior frontal gyrus (Wang et al., 2010).

We used a functional magnetic resonance adaptation (fMRI-A) paradigm, presenting words pairs belonging to different concrete and abstract categories in a passive reading task. fMRI-A allows the exploration of the functional properties of a neural population, making use of the property displayed by some neurons of reducing their response to a repeatedly presented stimulus (Krekelberg et al. 2006; Orban and Kourtzi, 2009). The underlying assumption is that, if the brain area remains adapted to the second stimulus, this indicates that its neural population is coding the attributes shared between the two stimuli (Grill-Spector and Malach, 2001). This method was largely and successfully used with concrete stimuli like pictures of animals and faces (Chouinard and Goodale, 2012; Pourtois et al. 2008), but never with abstract concepts.

We expect that presenting two concrete exemplars of the same category, e.g. two biological entities, will lead to activation suppression within the ventral visual areas tuned to concrete words (Wang et al., 2010), resulting in a reduced fMRI signal. If the neurons within the voxel are domain-sensitive, differences should emerge only for concrete and not for abstract items. Abstract concepts should adapt regions generally activated by these stimuli, e.g., mid-superior anterior temporal and/or rostral cingulate cortex for emotion-related words (Skipper and Olson, 2014; Vigliocco et al., 2014). The observation of specific adaptation effects for additional abstract categories could give new insights into the organization of abstract knowledge. Since we adopted a passive reading task without explicit control demands, we do not expect to find adaptation in control-related regions for abstract or concrete categories.

3.2. Materials and Methods

3.2.1. Participants

36 healthy right-handed Italian subjects (mean age= 21.3±2.5 years; 12 males) with normal hearing and vision, no history of neurological or psychiatric illness, and no early exposure to a second language participated. All provided written informed consent. The study complied with all provisions of the Declaration of Helsinki and was approved by the San Raffaele Hospital Ethics Committee.

3.2.2. Stimuli

Ninety-six abstract and 96 concrete nouns were selected from the Della Rosa et al. (2010). Abstract nouns belonged to 4 categories: emotions (EM), cognitions (COG), attitudes (ATT), human actions (ACT) according to MultiWordNet Domain and number of senses in MultiWordNet (http://multiwordnet.fbk.eu), including 24 stimuli for each category. Concrete nouns belonged to biological entities (BIOL) (e.g., animal, vegetable) and artefacts (ART) (e.g., furniture, tool), including 48 stimuli each (see MultiWordNet for classification: http://multiwordnet.fbk.eu/english/home.php). See Table 1 and Table 2 in Appendix B for the list of stimuli and variables taken into account.

Within each domain, word pairs were created, with half of the stimuli (n= 48) used as a prime and half as a target (i.e., first and second word in the pair). Prime and target were never switched in terms of order of presentation within each pair and were matched between categories, considering separately abstract (all p-values > .055) and concrete domains (all p-values > .056), for concreteness, imageability, familiarity, age of acquisition, context availability, abstractness, mode of acquisition, number of letters, written and spoken frequency (respectively from COLFIS and BADIP), distance from the median value of MoA of the specific category, frequency of senses in WordNet, number of senses and N-Synset in MultiWordNet.

For each domain, prime and target were combined into two conditions, Same Category, e.g. BIOL-BIOL or ACT-ACT, and Different Category, e.g. BIOL-ART or EM-ACT. Abstract and concrete nouns were never combined in a pair.

To account for the semantic relatedness of the word pairs, Gloss Vector measure was considered. It combines the structure and content of WordNet with co–occurrence information derived from raw text and determines the relatedness of two concepts as the cosine of the angle between their gloss vectors (Patwardhan and Pedersen, 2006). For abstract and concrete domains, pairs in the Same Category condition were equally related (p at least .967), while pairs of the Different Category condition were equally unrelated (p=.1).

The number of pairs for each condition and the respective combinations, and the number of lists, pairs for each list and participants to whom the lists were administered are described in Appendix B.

Twelve nouns (6 abstract; 6 concrete), not included in the previous sample, formed a Same Word semantic adaptation baseline condition, in which the same word was displayed as prime and target (e.g., sole-SOLE, see Appendix B, Table 4). This condition was introduced in order to tease apart effects related to repetition of semantic information from perceptual information related to the word form (Wheatley et al., 2005). See Appendix B for the variables considered for matching the stimuli between Same Word and Same Category conditions.

As repeated stimuli usually share also low-level visual properties, such as shape and orientation, we reduced stimulus durations to minimize the effects derived from early visual cortices (Feuerriegel, 2016), and displayed prime and target respectively in lower and upper case, to minimize their perceptual similarity (Copland et al., 2003).

The presence of semantic adaptation was measured by comparing the activation elicited by words belonging to the same category to the effect induced by the repetition of the same word.

3.2.3. Passive Reading Task

The task was a passive reading task where subjects were presented with abstract or concrete word pairs, consisting of two words belonging to the Same or Different Category conditions. On each trial a fixcross was presented for 1 second preceding the prime written in lower case (500 ms), followed by a blank screen (400 ms), and a target written in upper case (500 ms) (Figure 3). Each trial was followed by a 3, 5 or 7 second jittered inter-trial interval (mean =5.021ms) (Dale et al., 1999).

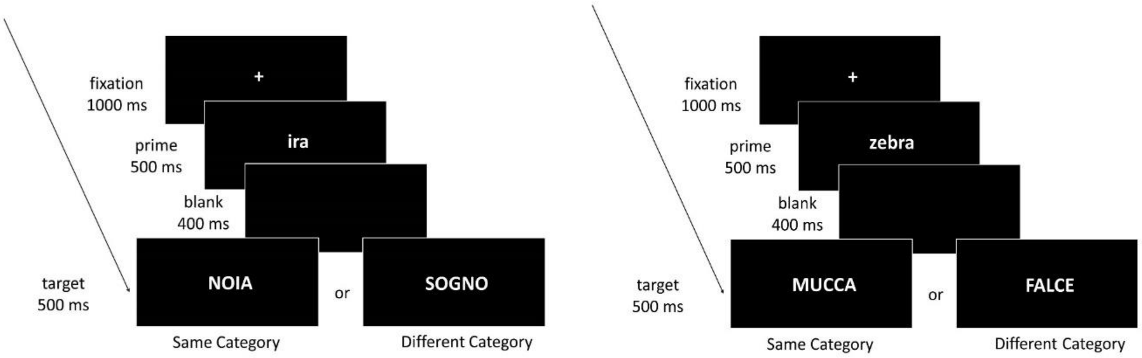

Figure 3. Timeline of an experimental trial, for abstract (left) and concrete (right) domains. See text for details.

The experiment was divided into two runs, each one including 54 trials: 24 Same Category, 24 Different Category and 6 Same Word pairs, half abstract and half concrete.

Stimuli were presented with Presentation software (NeuroBehavioral Systems Inc.) via a PC outside the scanner room and delivered on a translucent screen at the foot of the magnet bore.

Participants viewed the screen through a mirror system attached to the top of the head coil. They were instructed to silently read the words without moving their lips or tongue.

Prior to fMRI scanning, participants read the instructions and performed a training session, consisting in 10 trials not included in the experiment to familiarize with the task.

3.2.4. fMRI data acquisition

An fMRI event-related technique was adopted (3T Intera Philips body scanner, Philips Medical Systems, Best, NL, 8 channels-sense head coil, sense reduction factor= 2, TE =30 ms, TR= 2000 ms, FOV= 240x240, matrix size= 96x96, 38 axial slices per volume, 191 volumes for each run, slice thickness= 3 mm).

Optimal EPI parameters at 3T were chosen to gain BOLD sensitivity in temporal and frontal regions (Weiskopf et al., 2006) and slice tilt was set to 20° on the (RL) tangent to minimize susceptibility induced artefacts and signal dropouts. The phase encoding gradient polarity was chosen to be negative with the phase encoding direction going from the anterior part to the posterior part of the brain (Della Rosa et al., 2018).

Each run was anticipated by five dummy scans, discarded before analysing the data to optimize EPI image signal. For each participant, a high-resolution structural image was acquired (MPRAGE, 150 slice T1-weighted image TR= 8.03 ms, TE= 4.1 ms; flip angle= 8°, TA= 4.8 min, resolution= 1x1x1 mm) in the axial plane for coregistration, segmentation, spatial normalization of the EPI scans.

3.2.5. fMRI Data Preprocessing and Analysis

Image preprocessing was performed using SPM8 (http://www.fil.ion.ucl.ac.uk/spm). Data preprocessing for each subject included: 1) EPI time-series diagnostics using tsdiffana (Matthew Brett, MRC CBU, http://imaging.mri-cbu.cam.ac.uk/imaging/DataDiagnostics), 2) alignment and orientation of structural images to improve segmentation accuracy, 3) co-registration of EPI scans to the structural volume, 4) T1-weighted image tissue segmentation using the 'new segment' tool in SPM8 and generation of deskulled bias-corrected T1 images, 5) study-specific template creation using diffeomorphic image registration (DARTEL) in SPM8 and subject-specific flow fields generation containing the spatial deformations to normalize the EPI images into a common MNI coordinate space, 6) co-registered EPI time-series noise filtering (ArtRepair toolbox:

http://cibsr.stanford.edu/tools/ArtRepair/ArtRepair.htm), motion and distortion correction using subject-specific field-map parameters (realign and unwarp) and suppression of residual motion effects with Art Repair toolbox, 7) creation of a deskulled mean functional mask to remove nonbrain tissue from co-registered, noise-, motion-, and distortion-corrected EPI time-series in order to increase sharpness and avoid mismatch between alignment of the EPI data to the T1 image, 8) affine normalization of EPI data to MNI space with DARTEL flow fields, according to smooth deformations for each subject's native space gray, 9) spatial smoothing, with Gaussian kernel of 6 mm.

At the first single-subject level, the 10 experimental conditions were used as separate regressors according to 6 pseudo-randomized lists resulting from the combinations of Same and Different Category conditions in ABS and CNC domains, and Same Word conditions. The conditions were modelled by convolving a delta function of each event type with a "canonical" hemodynamic response as the basis function to create regressors of interest. Low frequency signal drifts were removed with a high-pass filter (128s) and AR1 correction for serial autocorrelation was applied. Second level group analyses using participants as a random effect were performed on contrast images for Same Category minus Same Word and Different Category minus Same Word conditions for all categories in the ABS and CNC domains derived from 1st level analyses (n= 36 participants).

3.2.6. Regions of Interest selection

We created a map of brain regions underlying semantic knowledge representation and cognitive control. We used two different approaches, based on literature (LB) and BrainMap database (BM), and their combination, to create five indexes for the selection of the ROIs, see Figure 4.

Literature based approach. We performed a literature search using Google Scholar and PubMed databases, selecting those studies investigating the domains of semantics (e.g., concrete and abstract domains of knowledge) and cognitive control (i.e. domain-general and semantic-specific). Exclusion criteria were: a) clusters of activations in brain regions not reported in MNI or Talairach reference space (coordinates in Talairach space were converted into MNI space using Tal2MNI function in Matlab) b) resting state fMRI based studies, c) connectivity based brain parcellations, d) studies not reporting specific contrasts related to cognitive control or semantic abstract/concrete domains of knowledge. 38 papers were included: 31 original research papers and 7 meta-analyses. fMRI was used in all included studies, alone (n=27) or in combination with other methods (e.g. PET: n= 6; TMS: n=1). Among the original research papers, the majority included healthy subjects (n=30) and only one dealt with patients; the mean number of participants per study was 16.13 subjects (range:3-32). The stimuli used were only words (n=24), only pictures (n=5), both words and pictures (n=4), and other types of stimuli (e.g., arrows in the Flanker task) (n=5).

For each region we calculated two indexes, a *correction level index* and *Semantics/control sensitivity index.*

Correction level index. For each paper, we considered only one contrast relative to semantics or control and one x, y, z coordinate per region. However, if activation cluster coordinates for two or more contrasts had a distance greater than 10 mms, they were included. Among the included contrasts (n=195), most (n=122) were thresholded at p-values corrected for multiple comparisons, including false discovery rate correction (n=60), family-wise error correction (n=28), or combined different methods for multiple-comparison correction (n=34); 56 contrasts were uncorrected (n=33 with p<.001; n=10 with p<.005; n=10 with p<.05; n=3 with p<.01); and for 17 contrasts such information was not available. A mean value was calculated for multiple coordinates. For each region a single value ranging from -1 to 1 was assigned and coded as *correction level index*. The level of correction for false-positives was coded as “1” for voxel-level corrections, “0.5” for cluster-level corrections and “-1” for uncorrected p-values.

Semantics/control sensitivity index. A mean value for each region ranging from -1 (i.e. Control) to 1 (i.e. Semantics) was calculated and coded as *semantics/control sensitivity index*. Contrasts were coded as “1” for the well-known specific concrete semantic categories according to the previous literature (e.g., , naming tools > naming animals); “0.5” for other possible semantic abstract categories, e.g., social, morality, characterized by more fuzzy and blurred boundaries (e.g., social > non-social words); and “-1” for control (e.g., incongruent > congruent trials). For instance, a brain area with a corresponding *semantics/control sensitivity index* of -1 displayed a high sensitivity for control over semantics and viceversa.

The median coordinate x-, y- and z- values resulting from the different contrasts for each region were then calculated. We mapped these median coordinates in the human Brainnetome Atlas (http://atlas.brainnetome.org) (Fan et al., 2016), which includes 210 cortical and 36 subcortical brain areas, characterized in terms of connectivity, anatomical and cytoarchitectonic features. Median coordinates derived from different contrasts in different papers corresponding to the same region in the Atlas were collapsed, thus a total of *48 regions* was considered for the mapping procedures.

BrainMap database approach. A functional description of the behavioural domains and the types of paradigms' classes associated to each of the 48 areas was also defined on the basis of BrainMap databases (http://www.brainmap.org/taxonomy).

Domain specificity. Cognitive domains included the macro-domains of Action, Cognition, Emotion, Interoception and Perception, with possible micro-domains (e.g., Orthography; Phonology; Semantics; Speech; Syntax for language). For each domain, to individuate the heterogeneity of domains involved for each region, we calculated the value *W*, taking into account the number of both micro and macro-domains. The formula was as follows:

$$W = \frac{\frac{n.\ of\ micro-domains\ of\ the\ region}{total\ n.\ of\ micro-domains} + \frac{n.\ of\ macro-domains\ of\ the\ region}{total\ n.\ of\ macro-domains}}{total\ \ n.\ of\ domains\ of\ the\ region}$$

We then computed the *domain specificity index*, as the product of the value *W* for the likelihood *P* of observing activations in a brain region given a specific cognitive domain (i.e., *Domain specificity= WxP*), for each domain of each brain region.

Control type mean. We categorized paradigms classifying the type of control involved in each (i.e. *control-type*), assigning the values of "1" for more semantic paradigms (e.g., Semantic Monitor/Discrimination), "0.5" for mixed domain-general/language-specific (e.g., Phonological Discrimination), and "-1" for control (e.g., Flanker Task) paradigms. A *control-type mean* value for each region was then calculated.

Combination of LB and BM approaches. We combined LB and BM information to select brain regions underlying semantics or control processing. In order to calculate the concordance between the two approaches we computed for each region the Semantic-Control differential measure (i.e., *[LB: semantics/control sensitivity index] – [BM: Control Type mean]*). A value of zero indicates a perfect concordance.

Regions were selected based on *control-type mean* values lower than -0.6 to be included in control regions or higher than 0.6 for semantics regions, and had also to display highest values of *domain specificity*, lowest values of Semantic-Control differential measure, and values of *semantic-control sensitivity* specific for semantic or control. This procedure lead to the inclusion of 15 semantic and 11 control regions for a total of 26 ROIs (see Figure 4 below and Table 5 in Appendix B).

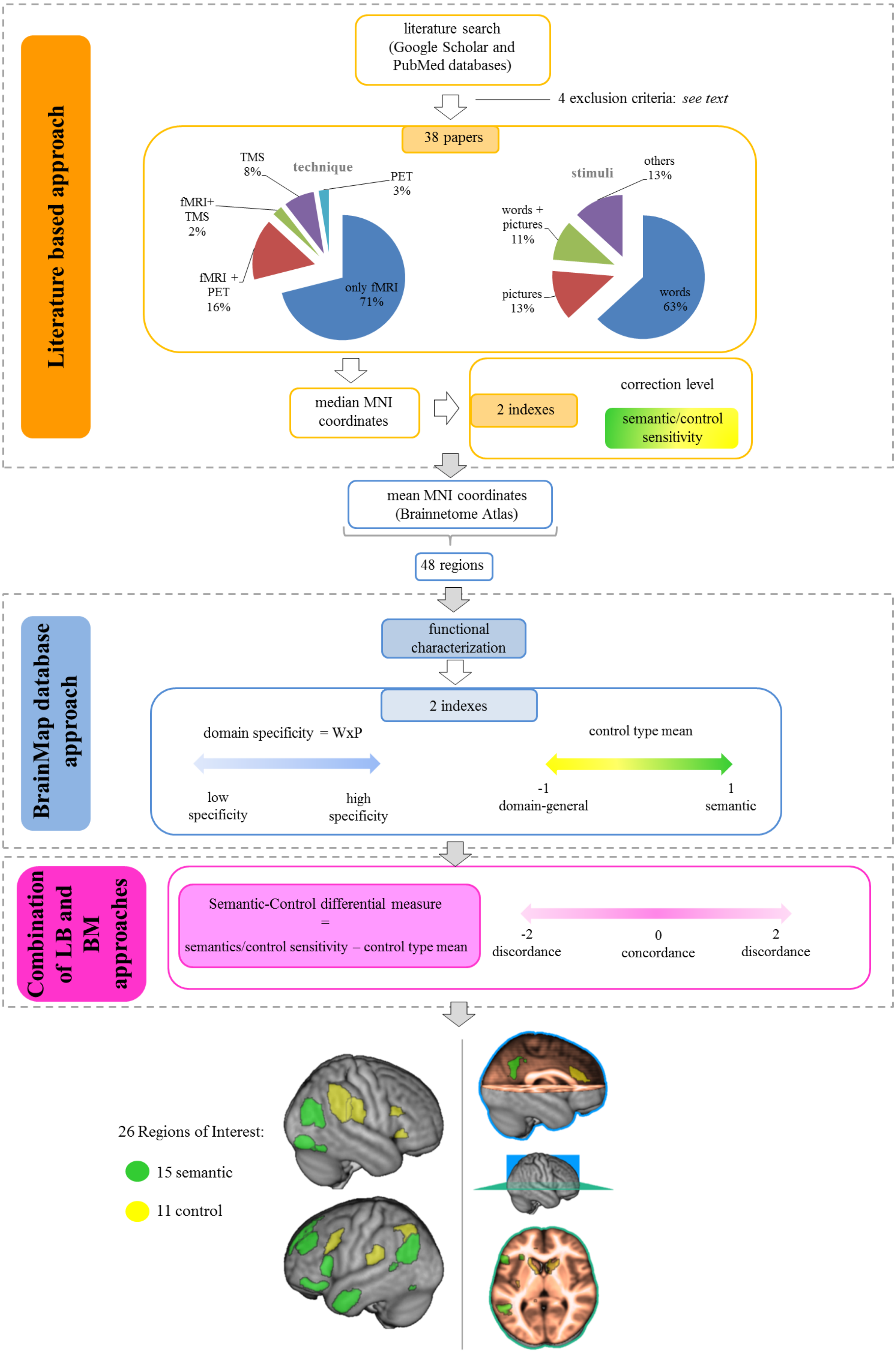

Figure 4. Schematic illustration of ROIs' selection process.

3.3. Analysis of BOLD signal

3.3.1. Extraction of BOLD signal

We used REX toolbox (https://www.nitrc.org/projects/rex/) to extract the BOLD signal from the 26 ROIs for 1) beta images relative to the 10 conditions of interest at the 1st subject-level, and 2) contrast images (i.e. linear combination of beta images) coding comparisons between Same Category and Different Category conditions with Same Word condition at the 2nd group level, thus obtaining a subjects X regions matrix including BOLD signal estimates extracted for all betas relative to all conditions of interest at the 1st and 2nd level. For each region, we extracted the eigenvariate values (first component, corresponding to the values that summarized signal across voxels by means of Singular Value Decomposition), with a within-ROI scaling procedure.
No subjects or ROIs were identified as outliers (see Appendix B for details).

3.3.2. ROIs data analyses

Analyses were performed with SPSS software (IBM SPSS Statistics 20) on the extracted eigenvariate values on BOLD estimates extracted from the 26 ROIs from contrast images testing for Same Category–Same Word and Different Category–Same Word differences. Lower differences of the BOLD signal in a ROI between the same (or different) category condition and the same word condition (the adaptation baseline), indicates greater adaptation effects.

Our main aim was to unveil whether state-dependent effects (i.e., adaptation or enhancement) (Krekelberg et al., 2006) were detectable at the semantic level (i.e. net of repetition of perceptual information related to word form: Same Word condition) and whether these effects were different for abstract versus concrete domains.

We first entered contrast BOLD eigenvalues in a Linear Mixed Effect Model, which allows controlling for subject variability, with CONDITION (i.e., Same Category-Same Word, Different Category–Same Word), DOMAIN (i.e., ABS; CNC), and ROI (n=26) (Table 5 in Appendix B) as within-subjects factors. Participant was used as random factor. The model was tested using repeated-measures analysis of variance (rANOVA). To explore possible two-way (i.e. CONDITION x ROI) or three-way interactions (i.e. CONDITION x DOMAIN x ROI) in specific ROIs, paired-sample t-tests or ANOVA models, Bonferroni-correced, were used to compare contrast estimate means for significant ROIs.

3.4. Results

3.4.1. Abstract and Concrete domains effects

The participant random effect was not significant (Wald Z= 1.568, p= .117) and the amount of overall data variance due to between-subjects variability (i.e. intraclass correlation coefficient) was 0.006 (0.6%), indicating that the inter-subjects variability did not affect the results.

The CONDITION x ROI interaction revealed a significant effect in two semantic-related regions, namely the Left Middle Temporal Gyrus (L-MTG, rostral Brodmann Area 21, MNI coordinates: -53, 2, -30) (mean difference= 1268.81, F(1,3708)= 3.993, p= .046) and the Left Fusiform Gyrus (L FG, rostro-ventral Brodmann Area 20, MNI coordinates: -33, -16, -32) (mean difference= 1430.57, F(1,3708)= 5.076, p= .024). In the DOMAIN x ROI interaction significant differences were reported between ABS and CNC domains in L-MTG (mean difference= 1403.28, F(1,3708)= 4.88, p= .027) and L Fusiform Gyrus (mean difference= 1904.59, F(1,3708)= 8.99, p= .003).

In the three-way CONDITION x DOMAIN x ROI interaction, significant effects were found for the Same Category condition between the ABS and CNC domain in L-MTG and L-FG. In L-MTG the BOLD signal change from the adaptation baseline (i.e. Same Word Condition) was significantly lower in the ABS domain (mean difference= -2754.63, F(1,3708)= 9.41, p= .002), while in the L-FG the BOLD signal change from the adaptation baseline (i.e. Same Word Condition) was significantly lower in the CNC domain (mean difference= -3407.68, F(1,3708)= 14.40, p< .001). No comparable effects were found in the Different Category condition (Figure 5A, 5B and Table 6 in Appendix B for the results in all the ROIs).

3.4.2. Abstract and Concrete categories effects

We explored the dissociation found in the Same Category condition between abstract and concrete domains testing whether significant differences existed between categories for the abstract domain in L-MTG, and in the L-FG for the concrete domain, running, respectively, an ANOVA and a t-test on the BOLD contrast eigenvariate values (Same Category-Same Word).

For the ABS domain in L-MTG, we found a main effect of Category (F(3)= 109.366; p <.001). Post hoc Bonferroni-corrected tests revealed that emotions and attitudes did not differ between each other (mean difference= 49.078, p= 1), but they significantly differ with cognitions (EM: mean difference= -1082.339, p< .001; ATT: mean difference= -1033.261, p< .001) and human actions (EM: mean difference= -630.369, p< .001; ATT: mean difference= -581.292, p< .001); cognition showed the greatest difference compared to all abstract categories (all p< .001). Specifically, whereas emotions and attitudes displayed the lowest BOLD signal change from the adaptation baseline, i.e. index of adaptation effects, cognitions showed the greatest difference (Figure 5C).

For the CNC domain in L-FG we found a trend towards significance (t(35)= -1.882; p=.068), namely a lower and negative BOLD signal change from the adaptation baseline for biological compared to artefacts categories (Figure 5D).

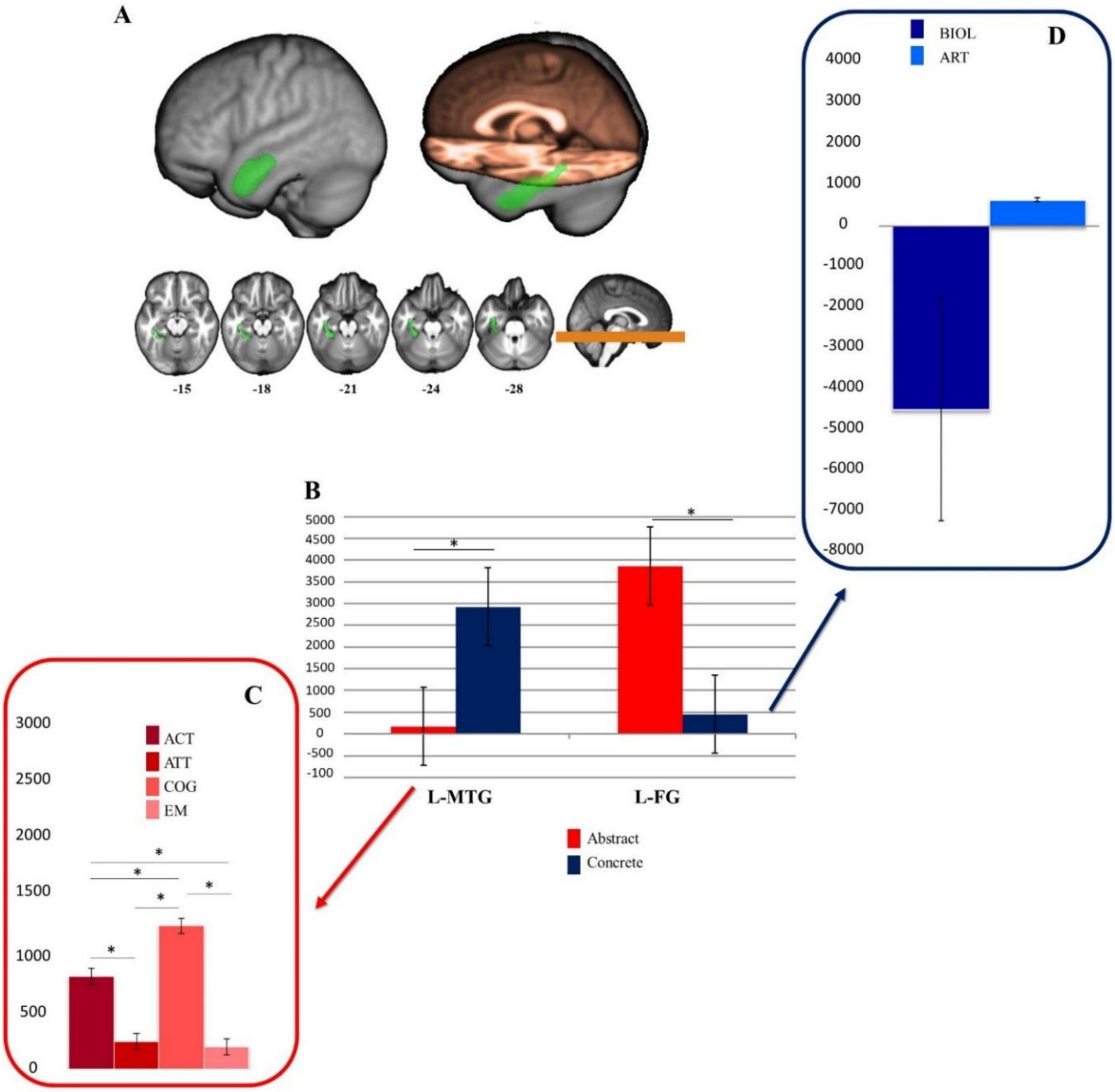

Figure 5. Anatomical location of L-MTG and L-FG (**A**) and plots with the mean eigenvariate values of Same Category–Same Word, for abstract and concrete domains (**B**) of abstract categories in L-MTG (**C**) and concrete categories in L-FG (**D**). Error bars indicate standard errors; * significant, bonferroni-corrected. See text for details. L-MTG= left Middle Temporal Gyrus; L-FG= left Fusiform Gyrus; BIOL= biological entities; ART= artefacts; ACT= human actions; ATT= attitudes; COG= cognitions; EM= emotions.

3.5. Discussion

15 semantic representation- and 11 semantic control-related regions were selected, and used to investigate the neural correlates of different kinds of abstract compared to concrete concepts, using an fMRI-A paradigm. We found that the neural response associated to abstract and

concrete concepts significantly differed in two semantic representation regions of the left ATL. The presentation of two concrete exemplars of biological entities and artefacts categories adapted the rostral L-FG, whereas two abstract exemplars of emotions or attitudes categories adapted the anterior L-MTG.

We showed distinct neural correlates for different semantic categories. Anterior fusiform gyrus was adapted by the concrete domain, with a trend for biological entities (e.g., *apple, zebra*) when compared to artefacts (e.g., *knife, airplane*). This result confirms a role of the anterior fusiform in representating concrete in comparison to abstract concepts (Price et al., 2003), given its contribution in high level visual features processing (Wang et al., 2010), including the retrieval of colour (Simmons et al., 2007), verification of physical properties (Kan et al., 2003), and mental generation of features (Ganis et al., 2004). The repetition of semantically-related biological exemplars led to negative BOLD values compared to repeating the same word, inducing a stronger adaptation effect in comparison to artefacts, similar to the findings of Wheatley et al., (2005) in frontal, occipital and postcentral areas. This result is compatible with the role of the anterior fusiform gyrus in differentiating an item from similar competitors sharing visual and semantic features, specifically in the case of biological items (Price et al., 2003; Catricalà et al., 2015). Biological entities share indeed numerous highly correlated common properties, including shape and parts (Garrard et al., 2001).

Conversly, in the abstract domain, we found a selective adaptation in the left aMTG for emotions (e.g., *fear, happiness*) and attitudes (e.g., *dishonesty, tolerance*). Activations of left aMTG have been found during the retrieval of information regarding individuals, e.g., name, face identity, occupation, personality traits (Tsukiura et al., 2008), the attribution of adjectives defining people to a person name, using words close to ours (e.g., *assertive*) (Mitchell et al., 2002), and in the representation of emotional-valenced social pictures and words (Sakaki et al., 2012). Our results are in accordance with an aMTG involvement in the processing of emotion concepts (Huth et al., 2016; Skipper and Olson, 2014). The left aMTG, in some cases extending to the aSTG, is thought to contribute to socio-emotional contents, which may constitute important dimensions in representing the meaning of attitudes- and emotions-related abstract concepts.

These results posit important issues to the hub-and-spoke model, which suggested a graded specialization of ATL according to the differential connections to sensory, motor and limbic regions (Lambon Ralph et al., 2017). The superior and ventromedial ATL have been mostly involved, respectively, in processing abstract and concrete concepts, given their differential association to auditory/verbal and visual areas (Hoffman et al., 2015). The selectivity of the middle ATL is less clear, since this region responded equally to verbal and visual inputs and to abstract and concrete concepts (Visser et al., 2012). The ventro-lateral ATL, corresponding to anterior fusiform gyrus, has been instead considered the heteromodal representational hub, where all information converges, representing all types of concepts equally (Shimotake et al., 2016). Our results suggest a stringent specialization of ATL, as only two categories of abstract concepts adapted the middle ATL, without any adaptation in the superior portion. Additionally, the anterior fusiform gyrus was selectively tuned for concrete and not for abstract concepts, in contrast with its role as semantic hub (Shimotake et al., 2016).

No adaptation effects were instead reported for human actions (e.g., *authorisation, punishment*) and cognitions (e.g., *mystery, logic*), abstract categories less investigated. Concepts referring to cognition include words like *dream*, *reason*, *intellect*, and have been associated with orbitofrontal cortex (Baron-Cohen et al., 1994), face-related motor area (Dreyer and Pulvermüller, 2018), and angular gyrus (Huth et al., 2016). Both categories may include heterogenous concepts, composed by different dimensions, probably preventing the involvement of specific regions. Accordingly, on the basis of feature listing studies, cognitions have been characterized by a greater variability than other abstract concepts, eliciting information linked to the different events and situations in which they can occur (Setti and Caramelli, 2005).

Finally, we found no adaptation in control-related regions, either for concrete or abstract concepts. Previous findings of a greater involvement of control-related areas for abstract compared to concrete concepts emerged from a variety of tasks, including lexical decision (Binder et al., 2005), recognition memory (Fliessbach et al., 2006), synonym (Hoffman et al., 2015) and semantic similarity judgement tasks (Noppeney and Price, 2004). All these tasks can be expected to engage control demands to a different degree, contrary to our task with minimal processing requirements.

In conclusion, our results are in line with the framework positing a cerebral distribution of semantic dimensions characterizing different categories of abstract concepts according to their content. Future studies are needed to explore additional abstract dimensions/categories, including for example morality- (Desai et al., 2018), theoretical- (Dellantonio et al., 2014), and quantity-related (Catricalà et al., 2020), information and their interactions.

4. State-Dependent TMS reveals the differential contribution of ATL and IPS to the representation of abstract concepts related to social and quantity knowledge

4.1. Introduction

One of the most fascinating challenges in cognitive neuroscience is to understand how our knowledge of the world is represented in our brains. Many models, based on concrete concepts, suggest that distinct and distributed brain regions are involved in the representation of sensory and motor information, which differently contributes to the meaning of specific classes of concepts (Martin, 2007; Kiefer and Pulvermüller, 2012; Catricalà et al., 2015). Patients showing category-specific deficits after localized brain damage provided the first direct evidence that object knowledge depends on specific, and distinguishable, brain regions (Warrington and McCarthy, 1983; 1987; Warrington and Shallice, 1984; Gainotti et al., 1995; see also Capitani et al., 2003 for a review). Imaging studies in normal subjects have provided additional crucial evidence (Perani et al., 1995; Chao et al., 1999; Chao and Martin, 2000; Marques et al., 2008; Cappa, 2008). While early theories were based only on two types of features (functional and sensorial) (Warrington and McCarthy, 1983; 1987; Warrington and Shallice, 1984), current multimodal approaches imply that a combination of more specific kinds of features (colour, taste, etc.) may contribute in the meaning of different, more fine-grained classes of concrete concepts (Cree and McRae, 2003; Goldberg et al., 2006; Binder et al., 2016). The representation of abstract concepts is a considerable challenge of these “embodied” approaches to knowledge representation. While sensory-motor knowledge is crucial for concrete concepts, a constituent link between abstract concepts and language has been for a long time the most popular framework for the representation of these concepts (Paivio, 1986; 1991). Specifically, according to Paivio’s Dual Coding Theory, concrete concepts are represented by perceptual as well as verbal information, whereas abstract concepts rely only on verbal knowledge. On the other hand, the Context Availability theory posits that both the quantity and availability of contextual cues differentiate concrete and abstract concepts, with the latter associated with less available information (Schwanenflugel and Shoben, 1983).

An important issue is whether, similarly to concrete knowledge, also abstract concepts may be differentiated in distinct classes, grounded on the brain regions involved in the processing of selective relevant dimensions (Barsalou, 1999). Several different aspects of experience may support specific abstract semantic representations (Binder et al., 2016; Crutch et al., 2013; Troche et al., 2014). For instance, affective and social aspects are relevant dimensions for some abstract concepts like, respectively, *anger* and *friendship* (Troche et al., 2014; 2017). While emotional words have been associated with the anterior cingulate cortex (Vigliocco et al., 2014), socially related concepts, referring to social relations and interactions among people, seem to be related to the right superior anterior temporal lobe (sATL) (Zahn et al., 2007; Pobric et al., 2016), i.e., brain regions involved, respectively, in emotional processing and in social cognition. Studies of patients with neurodegenerative diseases showing deficits for selective classes of abstract concepts support this evidence. Patients with the semantic variant of the Primary Progressive Aphasia (svPPA), also known as semantic dementia (SD), associated to focal atrophy of the anterior temporal lobe, showed a selective impairment in social, but not in other abstract concepts (Catricalà et al., 2014). On the other hand, patients with Alzheimer's disease can show a selective preservation of emotion words (Martin and Fedio, 1983; Catricalà et al., 2014; Giffard et al., 2015).

Quantity-related concepts, defined in relation to size, amount, or scope, and included in the more general domain of magnitude (Troche et al., 2014; 2017) are another important class of abstract concepts, whose neural correlates have been seldom investigated. Some cues derive from studies of patients affected by the cortico-basal syndrome, associated with atrophy of the parietal cortex, who, differently from patients with SD (Cappelletti et al., 2006; Ash et al., 2016), Alzheimer's disease and Frontotemporal dementia (Mc Millan et al., 2006), showed a selective deficit on quantifiers (Morgan et al., 2011; Troiani et al., 2009; 2011), like *some, any*, i.e., a class of words denoting quantity. Some of these studies suggested that the quantifiers comprehension depends on number knowledge (Mc Millan et al., 2006), known to be associated with a network including the right intraparietal sulcus (IPS) (Amalric and Deheane, 2017; Desai et al., 2018). The right IPS was activated in a fMRI study during the comprehension of the concept *arithmetic* (Wilson-Mendenhall et al., 2013), suggesting a possible grounding for quantity- related concepts.

One of the most influent current theories of neural semantic representation, the "hub-and-spoke" model (Patterson et al., 2007), posits that all conceptual representations depend on a single hub, located in the bilateral ATL, with a graded specialisation of different subregions, arising from differential connectivity and proximity to input sources (Lambon-Ralph et al., 2017; Rice et al., 2015). Ventromedial areas are more engaged by concrete concepts, because of their connectivity with brain areas involved in visual processing; superior areas (sATL) are particularly involved in abstract concepts, given their close association with regions involved in auditory-verbal information (Hoffmann et al., 2015). In particular, the dorsal polar ATL appears to be linked to a specific class of abstract concepts, namely the social ones, due to the connections to networks devoted to social and affective processing (Lambon-Ralph et al., 2017). It remains an open question whether other classes of abstract concepts are related to additional, specific subsectors of the superior ATL (Lambon Ralph et al., 2017; Binney et al., 2016; Pobric et al., 2016; Hoffman et al., 2015). The fact that social concepts showed a greater activation in the superior and in the dorsal polar ATL when compared to other abstract concepts matched for psycholinguistic variables (Binney et al., 2016) weakens the hypothesis of a specialization of the sATL for all the abstract concepts. Crucially, it is unknown if other categories of abstract concepts may reside in different brain regions, located outside the auditory-verbal network.

This study focused on the neural correlates of two different kinds of abstract concepts, namely social and quantity-related concepts. Namely, we aimed at investigating the causal role of the right sATL and of the right IPS in representing, respectively, social and quantity-related abstract concepts, by means of a state-dependent transcranial magnetic stimulation (TMS)-priming paradigm in healthy participants.

State-dependent TMS enables the conjoint exploration of both the causal role played by a specific brain region in a given process and of the functional selectivity exhibited by a neural population within this region. Adaptation or priming paradigms are generally employed to induce a modulation of the initial activation of the target area (Silvanto et al., 2008; Silvanto and Pascual-Leone, 2008). The presentation of a stimulus is used to produce an activation imbalance between different neuronal populations, by tuning a subset of cells encoding the specific attributes of the stimulus and making them a selective target for TMS. The subsequent TMS application interacts with the manipulated state of activation and consequently produces an effect only if the neural population is selectively responding to the target attributes. State-dependent TMS-priming paradigms have been used in the study of several processes, but only rarely in language domain (e.g., Cattaneo et al., 2010).

In the current experiment, participants were primed either with the “quantity” or “social” category label, followed by a target word, namely one exemplar of one of these two categories. The subjects were required to produce a semantic categorization of the target. Participants were expected to be faster in responding when the target belonged to the primed, compared to unprimed, category. When TMS is applied after priming, if the cortical area is involved in target processing, we expect a slowing of reaction times to unprimed targets relative to primed targets, thus abolishing the priming effect. Different set of predictions were tested for the role of IPS and sATL. TMS on the right IPS should abolish the priming effect for the quantity category only. If the right sATL acts as a single hub for all abstract concepts, as proposed by the 'hub-and-spoke' model, then a TMS application over this site should interact with the priming effect of both social- and quantity-related concepts. In contrast, if the right sATL contains a representation of the social, but not of the quantity-related concepts, exemplars of the latter class should not be affected by TMS, and only the priming effect of the social category should be abolished.

4.2. Materials and Methods

4.2.1. Stimuli

A rating procedure was conducted on a large sample of nouns (N= 567). Participants had to rate each word for familiarity and imageability on a 7-points Likert scale (1= low, 7= high), and for emotional valence on a 9-points Likert scale (1= positive, 9= negative), following Della Rosa et al., (2010). In addition, they had to rate each word for the social (i.e., indicating how much a word is linked to a social situation or to an interaction among people, both in terms of inclusion and exclusion) and the quantity dimensions (i.e., indicating how much a word is associated with the quantitative dimension, namely referring to size and numerosity) on a 7-points Likert scale (1= not social or not quantitative, 7= social or quantitative).

Each word was evaluated by at least 10 healthy participants, for a total of 35 subjects (17 female; mean age 26 years, sd= 3.5; mean education= 17 years, sd= 1.7).

4.2.2. Behavioural pilot study

A behavioural pilot study was conducted before the main experiment in order to evaluate the efficacy of the automatic category priming task and to select the most suitable stimuli for the TMS experiment.

Six healthy right-handed participants were tested (4 females; mean age 25.3 years, sd= .5; mean education= 17 years, sd= 2); none of them had participated in the other experimental sessions.

A hundred and twelve stimuli for each category were selected from the results of the rating procedures (56 quantity nouns with a value of at least 4.25 on the respective scale and 56 social nouns with a value of at least 4.50 on the respective scale). On each trial (see Figure 6) participants were primed by one category label, i.e., “QUANTITÀ’’ (quantity) or “SOCIALE” (social) (200 ms), followed by a blank screen (50 ms) and then by the target word (i.e., an exemplar of one of the two categories, namely a quantity or a social concept). Two experimental conditions were created, namely congruent (i.e., QUANTITY label-quantity target and SOCIAL label - social target) and incongruent (i.e., QUANTITY label - social target and SOCIAL label - quantity target) conditions. We created two blocks, displayed in a single session in a counterbalanced order among participants, each block including 112 trials (56 congruent and 56 incongruent) presented in a randomized order among participants. Participants had to indicate by a button press whether the target belonged to the quantity or to the social category. Response buttons were “M” and “N” and participants were instructed to respond as accurately and quickly as possible, with their right hand.

Incorrect trials and trials in which response time (RT) was shorter than 100 ms were excluded. For each participant and condition, outliers were defined as RTs above or below three sd from the condition’s mean and were replaced by the condition’s mean. All subjects displayed a priming effect (i.e., faster RTs for congruent compared to incongruent trials) for the Quantity category, and five out of six subjects for the social category. Paired sample t-tests between congruent versus incongruent trials revealed significant priming effects for both categories (quantity: mean= -60 ms, sd= 185; social: mean= -40 ms, sd= 164; both p< .001). We calculated the mean priming effect associated to each word, and used these values to select the final sample of 56 nouns (28 quantity and 28 social) for the main TMS experiment, namely the words displaying greater priming effects, balanced between categories.

In order to evaluate the nature of the priming effect, a behavioural control experiment was performed to disentangle positive (i.e., speeding up of RTs for primed targets) and negative (i.e., slowing down RTs for unprimed targets) priming (see Appendix C for details). The results showed the presence of positive priming for both categories.

4.2.3. TMS Experiment

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

Experimental task, anonymised raw data, and randomization order are available at https://data.mendeley.com/datasets/ydp4zjrknh/2.

No part of the study procedures or analyses was pre registered in a time-stamped, institutional registry prior to the research being conducted.
Sample size was estimated with G*Power software (Faul et al., 2007; 2009), by means of two-tailed paired samples t-test (statistical power β= 0.80; significance level α= 0.05).

4.2.3.1. Subjects

Thirty-six healthy Italian participants (18 females, mean age 23.8 years, sd= 3.3; mean education 13.6 years, sd= 1.7), with normal or corrected-to-normal vision, took part to the TMS experiment. All participants were right-handed (mean score= .64, sd= .2) according to the Edinburgh Inventory scale (Oldfield, 1971).

The study was approved by the local ethical committee, and all participants gave written informed consent to participate. The subjects were paid € 10 for their participation.

4.2.3.2. Stimuli selection

Fifty-six nouns were included in the TMS experiment (for the list of experimental stimuli see Table 1 in Appendix C): 28 for the social (e.g., *sociability*) and 28 for the quantity (e.g., *immensity*) categories. Social and quantity words have a value greater than 4.25 in the corresponding scale, see Table 3. The two categories differed significantly in the quantity and social scales (p at least < .001), reflecting the specificity of the quantity and social dimensions for the respective categories, see Table 3.

Paired sample t-tests revealed that the two categories were matched for written form frequency (values from COLFIS database, see http://www.istc.cnr.it/material/database/colfis/index_eng.shtml), letters and syllables number, familiarity, imageability and emotional valence. Quantity and social concepts were matched for mean priming effect, obtained from the behavioural pilot study (see section 4.2.2 for details).

	Quantity			**social**			**t-test**	
Variable	***mean***	***min***	***Max***	***mean***	***min***	***max***	**t**	**p**
Number of letters	8.678	4.000	13.000	8.750	5.000	14.000	-.104	.918
Number of syllables	3.607	2.000	5.000	3.678	2.000	6.000	-.263	.795
Written frequency	1.145	.000	2.250	1.266	.300	2.410	-.63	.532
Familiarity	4.591	3.000	6.500	4.620	1.900	7.000	-.283	.779
Imageability	3.074	1.750	4.800	2.954	1.000	4.800	.467	.644
Emotional valence	5.072	3.500	8.250	5.183	2.500	8.000	-.369	.715
Social scale	1.878	1.000	3.600	5.750	4.500	6.700	-25.231	< **.001**
Quantity scale	5.672	4.250	7.000	1.559	1.100	2.400	25.835	< **.001**
Mean priming effect (ms)	-63	-162	17	-70	-266	104	.369	.715

Table 3. Mean, minimum (min) and maximum (max) values of number of letters and syllables, written frequency, familiarity, imageability, emotional valence, social and quantity scales, and mean priming effect, for quantity and social words. T and p-values of paired sample t-tests between quantity and social categories are reported.

4.2.3.3. Category priming task

The task was the same as the one described in the pilot study (see Figure 6). Participants were primed by one category label, i.e., “QUANTITY” or “SOCIAL” (200 ms), followed by a blank screen (50 ms) and then by the target word (i.e., an exemplar of one of the two categories, i.e., a Quantity or social concept). Congruent (i.e., QUANTITY label - quantity target and SOCIAL label - social target) and incongruent (i.e., QUANTITY label - social target and SOCIAL label - quantity target) conditions were created. Participants had to indicate as accurate and quickly as possible, by a button press with their right hand, whether the target represented a quantity or a social concept. Response buttons were “N” and “M” (i.e., “N” for social target and “M” for quantity target for half of the participants, and the opposite, i.e., “M” for social target and “N” for quantity target, for the other half of participants).

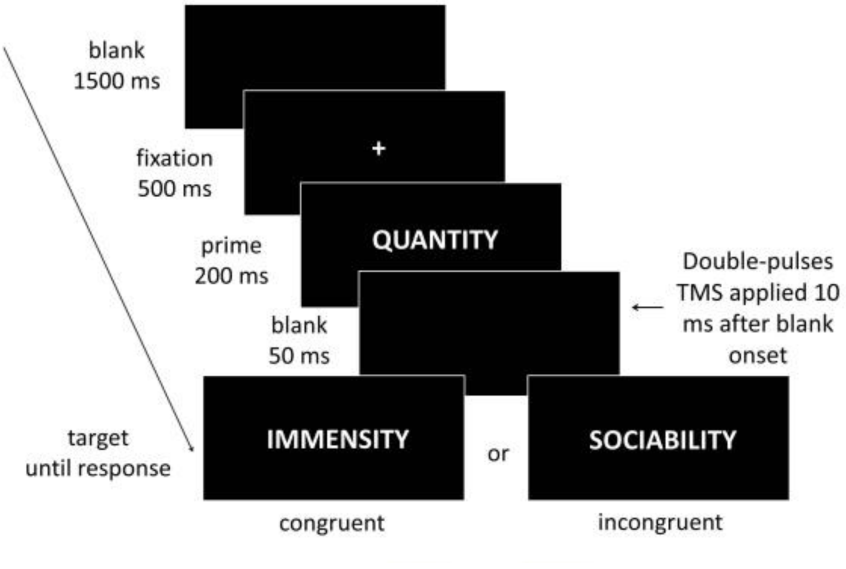

Figure 6. Timeline of an experimental trial. See section 4.2.3.3 for further details.

A single block, including 112 trials (56 congruent and 56 incongruent) presented in randomized order, was created. The same block was repeated for each of the three TMS sites (right sATL, right IPS, and Vertex as control site). TMS sites' order was counterbalanced among participants.

Before the experiment, in order to familiarize with the stimuli, participants had to read the list of items and to report whether the meaning of any of the words was unknown to them. Stimuli were delivered via Presentation software (Neurobehavioral Systems, http://www.neurobs.com) and presented in the centre of the screen, in white letters on a black background on a computer monitor at a viewing distance of approximately 50 cm.

In order to evaluate the stability of the priming effect in three consecutive sessions, a behavioural study was conducted on ten healthy right-handed participants (6 females; mean age 23.2 years, sd= 1.5; mean education= 15.5 years, sd= 2.5).

Data on reaction times were analysed following the same procedures used for the previous pilot study and for the main experiment (see section 4.3). Separate analyses were performed for quantity and social categories. For the quantity category, all participants showed a significant priming effect (i.e., congruent vs incongruent trials) in all the three sessions (p at least < .002). A repeated measure ANOVA on the mean priming effect with session (session 1, 2, and 3) as a within factor showed a non significant effect of session (session 1: mean= -69, sd= 32; session

2: mean= -86, sd= 54; session 3: mean= -57, sd= 32; F= 1.058, p= .368), revealing the stability of the priming effect across the three sessions. For the social category, one participant did not show a priming effect in the first session and was excluded from the analyses. In the remaining 9 participants, a significant priming effect (i.e., congruent vs incongruent trials) was found in all three sessions (p at least < .004). A repeated measure ANOVA on the mean priming effect with session (session 1, 2, and 3) as within factor showed a nonsignificant effect of session (session 1: mean= -50, sd= 35; session 2: mean= -82, sd= 55; session 3: mean= -66, sd= 44; F= 1.416, p= .271).

4.2.3.4. Transcranial magnetic stimulation

TMS was delivered by means of a Magstim Super Rapid machine (Magstim Company, Whitland, UK), via a custom 50 mm figure-of-eight coil (Alpha B. I.), using neuro-navigated TMS with Softaxic navigator system software (SofTaxic, EMS, Bologna, Italy). The Talairach coordinates of right sATL and right IPS were taken from previous studies, namely the sATL from Pobric et al. (2016) (coordinates: 52.5; 7.2; -11.3) and the IPS from Wilson-Mendenhall et al. (2013) (coordinates: 42; -44; 51) (see Figure 7A). Coil orientation for right IPS was medial-to lateral, 70° from the midline (see Mazzoni et al., 2017). For ATL stimulation, the coil was placed parallel to the scalp, roughly orthogonal to the midline (Pobric et al., 2007). The orientation of the coil was slightly adjusted to avoid covering the ear of the participants. Participants received also a sham-control stimulation block, using a spacer tool made of compact wood, which prevented the induced electric currents to reach the brain and was positioned on the Vertex, corresponding to the CZ point in the 10-20 reference system. The spacer was made of the same shape and colour as the 50 mm coil, and attached to the real coil by Velcro strips. It managed to reproduce both the same acoustic sensation and the visual impact of the real TMS (Rossi et al., 2007).

Before the main experiment, three practice blocks, lasting approximately 1 minute each, were run, one for each stimulation site, to familiarize the subjects with TMS sensations. Double-pulses TMS were applied after prime, before target onset, at 25 Hz. The first pulse was applied 10 ms after the blank that followed the prime word. TMS was applied at 100% of the individual, visually assessed resting motor threshold, corresponding to the stimulator's intensity necessary to produce a visible twitch in the contralateral hand muscles in 50% of trials in a series of at least ten consecutive pulses (Rossini et al., 1994; Jackson et al., 2015). The intensity was diminished if participants reported any uncomfortable sensations after a practice block of TMS stimulation at the right sATL site (see Jackson et al., 2015 for a similar procedure). The mean stimulation intensity was 49.9%, sd= 7.3 (range= 39-60%). The same intensity was used for the three sites in each subject. During the experiment and the practice blocks, participants listened to a white noise delivered by means of earphones, individually adjusted in order to attenuate the acoustic sensation of the TMS stimulation.

4.3. Analyses and Results

Two participants were excluded from the analyses because of low overall accuracy (< 50%). In addition, in line with previous studies (Cattaneo et al., 2010), the presence of the priming effect (i.e., faster reaction times for congruent versus incongruent trials) in the control condition was used as inclusion criterion for the following analyses, leading to the exclusion of three subjects. Data from the remaining thirty-one subjects revealed that 20 and 22 participants showed a priming effect, respectively for the quantity and for the social category. Eleven participants showed priming effects for both categories. The overall mean accuracy as well as the accuracy for each condition and TMS site are reported in Table 4. Analysis of the accuracy results is reported in Appendix C. Incorrect trials and trials in which RT was lower than 100 ms were excluded. For each participant, RTs above or below three sd from the condition's mean were defined as outliers and replaced by the condition's mean. The exclusion of those trials did not change the results.

	overall	**Vertex**					**sATL**					**IPS**				
		QQ	**SQ**	**SS**	**QS**	**overall**	**QQ**	**SQ**	**SS**	**QS**	**overall**	**QQ**	**SQ**	**SS**	**QS**	**overall**
mean (%)	92.8	90.5	89.9	95.8	97.1	93.3	85.2	90.7	98.4	97.9	93.0	87.5	86.3	96.9	97.7	92.1
sd	7.6	7.6	7.2	4.8	3.8	6.7	8.8	6.8	1.8	3.6	7.9	7.7	9.0	3.2	3.6	8.1

Table 4. Mean (%) and standard deviation (sd) of the overall accuracy, and of the accuracy for each sites (i.e., sATL= superior Anterior Temporal lobe and IPS= Intraparietal sulcus) and for each condition (i.e., QQ= congruent condition, quantity label – quantity target; SQ= incongruent condition, social label - quantity target; SS= congruent condition, social label - social target; QS= incongruent condition, quantity label – social target).

To investigate whether TMS interfered with the priming effect, the difference between congruent and incongruent trials was compared among the three TMS sites. A repeated measure ANOVA on the priming effect, with TMS site (Vertex, sATL, IPS) as within subject factor was performed separately for quantity and social categories. For the quantity category, a statistically significant effect of TMS site (F(2,38)= 6.763, p= .003, η=.262; error(38)= 4396.048) was reported. Holm-Bonferroni corrected (Holm, 1979) pairwise comparisons (control site vs IPS and control site vs sATL), revealed that IPS stimulation, but not sATL stimulation, abolished the priming effect present in Vertex. In fact, a statistically significant difference emerged between Vertex and IPS sites (t(19)= -4.080, p= .001, corrected-p= .002, corrected-α= .025, Cohen's d= .912), but not between Vertex and sATL sites (t(19)= -1.909, p= .071, corrected-p= .071, corrected-α= .05, Cohen's d= .427), see Figure 7B. For the social category, the TMS site was also statistically significant (F(2,42)= 6.074, p= .005, η=.224; error(42)= 4003.902). Pairwise comparisons with Holm-Bonferroni correction revealed that both the sATL and IPS stimulations abolished the priming effect reported in Vertex. In fact, differences emerged between Vertex and sATL (t(21)= -3.227, p= .004, corrected-p= .008, corrected-α= .025, Cohen's d= .689) and between Vertex and IPS (t(21)= -2.806, p= .011, corrected-p= .011, corrected-α= .05, Cohen's d= .598), see Figure 7B.

We performed the same analyses on the entire participants' sample, using the presence of the priming effect as a between factor. The results are reported in the Appendix C.

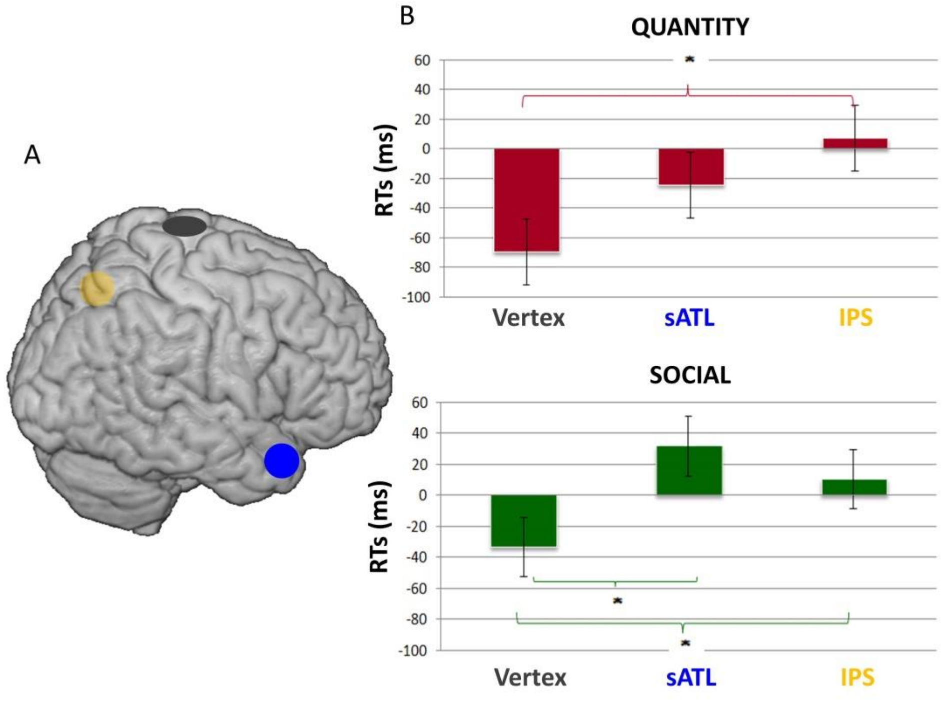

Figure 7. A: Anatomical location of the TMS sites: right IPS (yellow circle), right sATL (blue circle) and control site (Vertex) (black circle). **B**: Mean priming effect (RT congruent – RT incongruent trials) for quantity (red, above) and social (green, below) related concepts. Bars indicate the standard error. * = statistically significant, see text. IPS= Intraparietal Sulcus, sATL= superior Anterior Temporal Lobe.

In order to unveil the way in which TMS affects the priming effect, i.e., modulating differently congruent or incongruent trials, a repeated measure ANOVA, with prime congruency (congruent and incongruent conditions) and TMS site (sATL, IPS, Vertex) as within factors was carried out separately for the quantity and the social categories.

For the quantity category, a significant main effect of congruency (F(1,19)= 5.918, p= .025, η= .238; error(19)= 4297.714), and a significant interaction site x congruency (F(2,38)= 6.763, p= .003, η= .262; error(38)= 2198.024) were found. The main effect of site was not significant (F(2,38)= 1.542, p= .227, η= .075; error(38)= 11042). Pairwise comparisons with Holm-Bonferroni correction revealed that only the IPS site stimulation, when compared to the control site, significantly diminished RTs in the incongruent trials (t(19)= 3.231, p= .004, corrected-p= .008, corrected-α= .025, Cohen's d= .722), but not in the congruent ones (t(19)= -.582, p= .568, corrected-p= .568, corrected-α= .05, Cohen's d= .130). No differences were detected for the sATL site stimulation in any condition (congruent: t(19)= -1.369, p= .187, Cohen's d= .306; incongruent: t(19)= .328, p= .746, Cohen's d= .073).

For the social category, the main effect of site (F(2,42)= 4.628, p= .015, η= .181; error(42)= 7200.648), and the interaction site x congruency (F(2,42)= 6.074, p= .005, η= .224; error(42)= 2001.951) were significant. The main effect of congruency was not significant (F(1,21)= .122, p= .730, η= .006; error(21)= 2015.751). Pairwise comparisons with Holm-Bonferroni correction revealed that IPS stimulation (t(21)= 3.647, p= .002, corrected-p= .004, corrected-α= .025, Cohen's d= .778), and sATL stimulation (t(21)= 2.119, p= .046, corrected p= .046, corrected-α= .05, Cohen's d= .452), compared to the control site stimulation, significantly diminished RTs only in incongruent trials, see Figure 8.

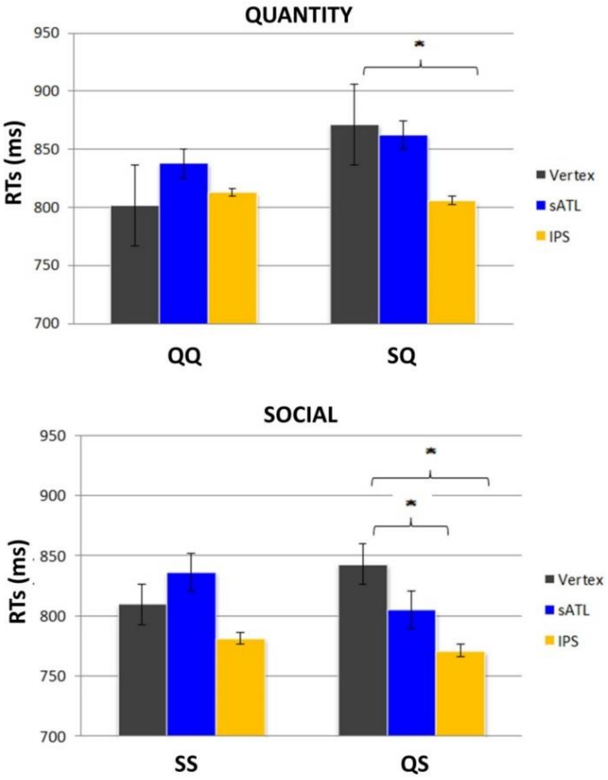

Figure 8. Mean RTs for the congruent and incongruent conditions for the quantity (above) and social (below) targets. Bars indicate the standard error. * = p-statistically significant, see text. IPS= Intraparietal Sulcus, sATL= superior Anterior Temporal Lobe; QQ= congruent condition, quantity label – quantity target; SQ= incongruent condition, social label - quantity target; SS= congruent condition, social label - social target; QS= incongruent condition, quantity label – social target.

4.4. Discussion

In this study, we investigated the neural correlates of two different classes of abstract concepts, namely social and quantity-related concepts. Using a priming paradigm with a state dependent TMS approach, we showed that the right sATL contains neuronal representations tuned to social concepts, while the right IPS is tuned to both social and quantity-related concepts. TMS over the right sATL, in fact, selectively abolished the priming effect for the social category observed in the sham Vertex condition; in contrast, TMS over the right IPS abolished the priming effects for both social and quantity concepts. The priming effects found in the sham condition are due to a facilitation of primed target stimuli (i.e., congruent trials), rather than to an interference for unprimed stimuli. Consistent with previous evidence (Campana et al., 2002; Cattaneo et al, 2008; Cattaneo et al., 2010), TMS acts by facilitating the processing of unprimed targets for both ATL and IPS sites. In neurophysiological terms this can be depicted as if the neural population with a higher activation threshold at baseline, such as in the case of unprimed trials, is more susceptible to facilitatory effect by TMS. Conversely the increased neural activity at baseline in the primed trials, leads to a lack of TMS facilitatory effects.

In line with our predictions, TMS over sATL abolished the priming effect selectively for social concepts. The ATLs are in fact part of the extended network underlying social cognition processing, in addition to the orbitofrontal cortex, the dorsal anterior cingulate cortex, the anterior frontal poles and the temporo-parietal junction (Amodio and Frith, 2006). Several studies reported an involvement of the ATL in social cognitive tasks involving theory of mind, mentalizing, or deception understanding (Frith and Frith, 2003; Olson et al., 2007; Ross and Olson, 2010), with, in some cases, a prevalent contribution of the right over the left ATL (Olson et al., 2007). The role of the sATL in processing social related concepts has been consistently reported in neuroimaging studies (Zahn et al., 2007; Ross and Olson, 2010; Binney et al., 2016; Rice et al., 2018). An increase of the right, but not of the left, ATL functional activity was for example associated with the richness of details conveyed by social stimuli (Zahn et al., 2007). Additional evidence comes from brain stimulation and patient studies (Pobric et al., 2016). The impairment in processing social concepts reported in patients with SD was more severe in presence of a greater atrophy and hypometabolism in the right compared to the left ATL (Zahn et al., 2009; Pobric et al., 2016). Patients with severe right ATL involvement display severe disturbances in social behaviour, loss of empathy, and personality changes (Thompson et al., 2003), as well as an impairment at social cognition tasks (Irish et al., 2014). The impairment in face and voice recognition reported in SD patients with a greater involvement of the right than the left ATL (Snowden et al., 2004; Gainotti, 2011; Luzzi et al., 2017) is in line with a major role of this area in social cognition (Olson et al., 2007; 2013; but see Gainotti et al. 2011; 2015 for a different interpretation).

Quantity-related abstract concepts involved specifically the right IPS and not the right ATL. It is well known that the right IPS has a crucial role in the processing and representation of numerical and magnitude knowledge, regardless of whether they are expressed by Arabic digits or dots patterns (Piazza et al., 2007; Amalric and Deheane, 2017). Indeed, in contrast to the left IPS, which has been reported as crucial for coding numbers and performing exact calculations (Andres et al., 2005; Lemer et al., 2003; Sandrini et al., 2004; Zago e al., 2001; Rosseli and Ardila, 1989), the right IPS is involved in approximating quantities and estimating numerical magnitude (Langdon and Warrington, 1997; Dehaene and Cohen, 1991; Stanescu-Cosson et al., 2000). Right IPS, but not left IPS, is activated in both length and numerosity comparisons tasks (Dormal and Pesenti, 2009), and has been proposed to be the neural substrate mediating the acquisition of magnitude estimations abilities during development (Holloway and Ansari, 2010). The brain regions engaged by number and magnitude processing are also involved by language tasks related to the same domains. The right IPS is involved in the processing of quantifiers, defined as noun phrases (e.g., *a few, many, at least five*) which bear quantitative properties, and assign them to nouns (Clark and Grossman, 2007). fMRI data showed an activation of the right IPS during a sentence-picture matching task containing quantifiers (Troiani et al., 2009). A recent study using electrocorticography in patients with epilepsy revealed the contribution of the right IPS in both production and comprehension of numerals, ordinals and quantifiers when they were combined with quantities or numbers in everyday conversations, as well as in arithmetical calculations (Dastjerdi et al., 2013). The selective IPS activation during the comprehension of the concept *arithmetic* (Wilson-Mendenhall et al., 2013) and a count localizer task, where subjects were asked to count the number of independent entities in a scene, further strengthens the evidence for the recruitment of IPS for words and concepts reliant on magnitude processing. Additional relevant evidence derives from the investigation of normal subjects' rating of quantity-related abstract concepts (nouns), asking how a word is related to size, amount or scope (Troche et al., 2014; 2017). Quantity-related nouns merged in a more general domain of "magnitude" knowledge, together with concepts about time (i.e., words related to time, order, or duration) and space (i.e., words related to position, place, or direction) (Troche et al., 2017). These results are in line with the Theory of Magnitude, proposing a single system accounting for different kinds of magnitude estimation, involving quantity, space, time, and ascribing a peculiar and central role to the right IPS for magnitude processing (Walsh, 2003; Bueti and Walsh, 2009). The Theory of Magnitude proposal received support from studies adopting non-linguistic tasks in healthy subjects, i.e., estimations of dot numerosity, line length and temporal durations (Dormal et al., 2012a,b; Skagerlund et al., 2016). Lesions involving regions of the parietal lobes may result in deficits for estimating and appreciating many magnitude distinctions, including numerosity, time durations as well as spatial prepositions (e.g., *above, behind*) (Koss et al., 2010; Harrington et al., 1998; Shebani et al., 2017). Further studies are needed to investigate whether different classes of magnitude-related concepts, including besides quantity, space and time related concepts, share the same neural substrates, and specifically the involvement of the right IPS.

Differently from our predictions, TMS over IPS interfered also with the priming effect for social concepts, suggesting that their grounding involves a brain network extending beyond the temporal lobe. Up to date, there is evidence of a right IPS contribution in perceiving social relevant stimuli, such as eye gaze (Hoffman and Haxby, 2000; Narumoto et al., 2001; Ramsey et al., 2011), and in person-related knowledge (Mitchell et al., 2002; Sugiura et al., 2009). For instance, an activation of the right IPS has been reported when participants associated a social trait (e.g., *assertive, nervous*) to a person name (Mitchell et al., 2002), using items similar to those employed in our experiment. Further studies have indicated that right IPS coded serial order information in working memory for various stimuli types, including faces, numbers, pseudo-words, and letters (Marshuetz et al., 2000; Majerus et al., 2007; 2010; Attout et al., 2014). These results suggest that the right IPS has a role in representing abstract sequential and ordinal relations among items on a continuum reference framework (Abrahamse et al., 2014). In line with this perspective, the right IPS is reported to contribute to the semantic representation of all the concepts that can be graduated in magnitude, including social concepts and emotions (e.g., “irritated < angry < infuriated” as in Troche et al., 2014). Furthermore, recent work has argued that social hierarchies are represented as a magnitude and are processed by the same cognitive system as physical magnitudes (Chiao, 2010; Thomsen et al., 2011). A shared neural substrate in the IPS has been reported for magnitude comparisons of social status and numbers (Chiao et al., 2009), but not for animals (Thioux et al., 2005). The IPS is sensitive also to the perception of social status even in the absence of a request for explicit comparison (Cloutier et al., 2012), suggesting an involvement in the spontaneous assessment of the status of others in comparison to our own. The IPS may thus have a critical role in a “person perception” network (Cloutier and Gyurovski, 2013). Further studies are needed comparing the brain correlates of social status compared to other forms of person-specific conceptual knowledge (Koski et al., 2015). It cannot be excluded that the stimulation of the right IPS may have an aspecific effect, encouraging the participants to go for the "other" condition, regardless of what it is. The adoption of a deliberate strategy is however unlikely in the case of an automatic priming paradigm.

Our results constitute novel findings, with implications for current models of semantic memory. In the revised “hub-and-spoke” model, Lambon Ralph and co-workers (2017) do not explicitly consider the representation of different classes of abstract words, with the exception of the social ones. On the basis of previous studies, the model posits that the superior portion of ATL is specialized in the processing of the abstract concepts (Hoffman et al., 2015) and the dorsal polar ATL for social concepts (Ross and Olson, 2010; Zhan et al., 2007). The MNI coordinates for the superior and polar ATL reported in these studies are however very similar (in Hoffman et al., 2015 coordinates= -54, 10, -18 and 54, 14, -20; in Zahn et al. 2007: 51, 15, -12 and 57, 12, 0). In addition, the few subsequent studies assessing the predictions of the model do not allow a clear definition of those anatomical correlates (Pobric et al., 2016; Binney et al., 2016; Rice et al., 2018). In fact, both the ROIs reported by Pobric et al. (2016), centred at 53, 8, -13 (and labelled as sATL), and by Rice et al. (2018), centred at 51, 16, -27 (and labelled as superior temporal gyrus), were found to be specifically involved in the processing of social concepts. In addition, Binney et al. (2016) reported that both the superior (coordinates: 57, 9, -18) and the dorsal polar (coordinates: -51, 16, -27) ATL were more involved in the processing of social concepts than other abstract concepts. The absence of consistency among studies prevents a clear characterization of the functional specialization of the superior and polar portions of ATL. It is probable that the superior part of the temporal lobe, extending to the polar tip, is involved in the processing of social concepts, in line with the studies that independently showed that both portions may contribute to social concepts elaboration (Skipper et al., 2011).

As we consider only the right ATL, we cannot rule out that the left sATL may contribute to both social and non-social abstract concepts. This possibility is also problematic for the “graded hub and spoke” theory, which, despite admitting a grade of specialization of the two hemispheres, claims for a similar role of both ATLs. Further studies are needed investigating the connectivity between right and left ATLs (and their subcomponents) and the brain networks underlying the processing of the different dimensions relevant for specific classes of abstract concepts, as in the case of quantity information.

In conclusion, our results are in line with the ongoing literature emphasising the possibility that, like concrete concepts, abstract concepts are grounded in a distributed brain network devoted to the representation of specific semantic content, including non-linguistic information (Desai et al., 2018; Wilson-Mendenhall et al., 2013; Binder et al., 2016; Catricalà et al., 2014). While some specific dimensions can better characterize some classes of abstract concepts, a multimodal approach is warranted, given that different dimensions are involved in the representation of both abstract and concrete concepts. While similarities with the organization of concrete knowledge exist, abstract knowledge needs a separate consideration, because of more fuzzy boundaries among different types of concepts, its occurrence in many different contexts, the presence of an interplay of multiple brain regions and of higher demands on brain areas integrating both external (e.g., context) and internal (e.g., experience) factors (Della Rosa et al., 2018).

5. Different types of abstract concepts: evidence from neurodegenerative patients

5.1. Introduction

How abstract concepts are represented and organized in our brains is a controversial topic in cognitive neuroscience. Important evidence comes from patients with neurological diseases. Category-specific semantic disorders following localized brain damage offer direct evidence that conceptual knowledge relies on distinct brain substrates (see Capitani et al., 2003 for a review), subserving the processing of category-relevant features. For instance, patients with selective impairments for living and non-living concepts usually have lesions localized in, respectively, inferior temporal cortices or fronto-parietal areas, according to the differential role of these brain regions in processing visual and action-related features (Gainotti et al., 1995). These findings have played a crucial role in the development of “embodied” models of semantic representation for concrete concepts (Kiefer and Pulvermüller, 2012).

Whether abstract concepts, e.g. *scarcity*, *seduction*, *joy*, in analogy to concrete ones, are organized into different categories and represented in the brain networks supporting the associated experience is a controversial issue. According to recent proposals, different categories of abstract knowledge may rely on affective, social, and magnitude dimensions, processed in the neural systems subserving, respectively, emotion processing, social cognition, and the elaboration of numerical and magnitude information (Desai et al., 2018; Catricalà et al., 2020; for a review see Conca et al., submitted).

Evidence from neurodegenerative diseases involving different, and relatively selective, neural substrates, represents an additional source of information about the existence of specific abstract categories and their neural substrates. For example, patients with the semantic variant of the Primary Progressive Aphasia (sv-PPA), associated to focal atrophy of the anterior temporal lobes, display severe and progressive loss of semantic memory, manifested as difficulties in recognize, comprehend, and name single objects and words (Gorno-Tempini et al., 2011). The loss of semantic memory is usually general, namely involving all types of concepts, and only rarely a category-specific effect has been found in the concrete domain, e.g. worse performance for living entities compared to artefacts (Lambon Ralph et al., 2003). In the case of abstract knowledge, sv-PPA patients may show a selective impairment in social concepts, i.e. those words indicating relations and interactions among individuals and groups, but not in other abstract categories, as revealed by performance in semantic association

(Catricalà et al., 2014) and forced-choice semantic decision tasks (Pobric et al., 2016). These concepts have been associated to a network implied in social cognition by imaging studies reporting an involvement of the anterior temporal lobes (ATLs) (Huth et al., 2016), with either a right (Zahn et al., 2007) or a left (Ross and Olson, 2010) hemispheric prevalence.

Patients affected by the Cortico-Basal Syndrome (CBS), involving the parietal cortices and mid-superior frontal gyri (Albrecht et al., 2017), display relatively preserved objects knowledge, but compromised calculation skills and numbers knowledge (Ash et al., 2006; Spotorno et al., 2014). Interestingly, recent studies in CBS patients reported also an impairment in quantifiers (words bearing quantitative properties, such as *many*, *some*, *all)*, in sentence verification, sentence-picture matching, and picture description task, when compared to sv-PPA (Cappelletti et al., 2006; Ash et al., 2016), Fronto-Temporal Dementia (FTD) and Alzheimer's Disease (AD) (Mc Millan et al., 2006) patients. The neural representation of quantifiers is thought to involve the neural system responsible for numbers knowledge, including the intraparietal sulcus (Amalric and Deheane, 2017). Of note, a recent neurostimulation study in healthy participants suggested a role of parietal cortices in processing quantity related concepts (Catricalà et al., 2020).

In the present study, we explored the processing of different categories of abstract (emotion, social, quantity) and concrete (animals, tools) concepts in two patients affected by, respectively, sv-PPA and CBS, by means of an implicit task, namely a semantic priming lexical decision task. This paradigm offers a direct and automatic measure of semantic memory, minimizing the intervention of potential confounding factors, e.g. control processes for the retrieval of conceptual knowledge (Giffard et al., 2015). The priming effect is manifested as faster reaction times when the target word is preceded by a semantically related prime word, as result of the spreading of activation between related nodes (i.e. concepts) in the semantic network (Collins and Loftus, 1975).

Given the different pattern of prevalent brain involvement in sv-PPA and CBS (respectively, anterior temporal and parietal lobe), we expected a selective impairment, manifested as absence of the priming effect, for social concepts in the former and of quantity related abstract concept in the latter condition.

5.2. Materials and methods

5.2.1. Participants

Two patients were tested, CV and EM. At the time of the present investigation, CV was a 66 years old, right-handed man with 13 years of education, working as insurer, with a diagnosis of sv-PPA according to consensus criteria (Gorno-Tempini et al., 2011). He was tested at IRCCS Istituto Centro San Giovanni di Dio Fatebenefratelli, Brescia (Italy). Profound disturbances were present in semantic memory and language (see Table 5). Significant impairments were observed in picture naming (Catricalà et al., 2013), with anomia, semantic errors, and frequent circumlocutions, including specific or general descriptions. For example, in response to the picture of a hat the patient said "this must be put on the head", and to the picture of an orange "it is eaten…I eat that one too". An impaired performance was also found for single word comprehension (Catricalà et al., 2013), reporting, out of 8, 6 errors for living (4 animals and 2 vegetables) and 2 for non living items (1 tool, 1 clothing piece). In particular, in this task CV performed worse for animals compared to tools items, although the difference did not reach statistical significance (Pearson Chi-Square= .554; p= .439). A reduced but non-pathological performance was found in the DeCAbs association task (Della Rosa et al., 2014) assessing abstract concepts knowledge. Specifically, CV's response accuracy was of 75% for words referring to human actions, cognitions, traits, and of 50% for social-related concepts and emotions. Additionally, the patient was impaired in memory tests assessing the immediate and delayed recall of verbal material, i.e. list of words, and in delayed recall of non-verbal material, i.e. Rey figure. Letter and category fluency was also impaired.

ME was a 69 years old, right-handed female with 5 years of education, a retired typographer, with a diagnosis of CBS according to current criteria (Armstrong et al., 2013). She underwent the neuropsychological evaluation at IRCCS Fondazione Mondino, Pavia (Italy). On formal assessment, ME displayed normal performance in global cognitive functioning, as well as normal scores in memory and language tests (see Table 5). Spontaneous speech showed articulation impairment, but was otherwise normal for fluency and content. Semantic knowledge for concrete and abstract concepts, as assessed by CaGi (Catricalà et al., 2013) and DeCAbs association (Della Rosa et al., 2014) tests was normal. In CaGi naming task, she failed 2 items, namely a vegetable and an element of furniture. The patient complained of deficits in the coordination of the left upper limb associated with progressive difficulties in performing precise movements. Accordingly, ideomotor apraxia was present, and affected the left more than the right hand. Constructional apraxia was also observed. Performance on Attentional Matrices and Frontal Assessment Battery (Spinnler and Tognoni, 1987; Apollonio et al., 2005), evaluating executive functioning, was also impaired.

		CV (svPPA)		**ME (CBS)**	
clinical scales		*score*	*normal/ pathological*	*score*	*normal/ pathological*
Clinical scale for anxiety and depression (HADS) (Zigmond et al., 1983)		n.a.	n.a.	axiety: 1/21 depression: 1/21	normal
Geriatric Depression Scale (GDS) (Galeoto et al., 2008)		5	normal	n.a.	n.a.
STAY-trait (Spielberg et al., 1983)		35 (40th percentile)	normal	n.a.	n.a.
STAY-state (Spielberg et al., 1983)		31 (22th percentile)	normal	n.a.	n.a.
neuropsychological tests		*corrected score*	*equivalent score*	*corrected score*	*equivalent score*
Global Cognitive Efficacy	Mini Mental State Examination (Magni et al., 1996)	19.2	deficit	26.9	normal
Visuo-constructive	Rey figure (copy) (Caffarra et al., 2002)	29.75	1	n.a.	n.a.
Memory	Digit span (Monaco et al., 2013)	6.02	4	4.39	1
	Corsi span (Monaco et al., 2013)	7	4	4.44	2
	Rey list (immediate recall) (Carlesimo et al., 1996)	15.3	0	50.1	4
	Rey list (delayed recall) (Carlesimo et al., 1996)	1.6	0	12.8	4
	Rey figure (delayed recall) (Caffarra et al., 2002)	5.5	0	n.a.	n.a.
	Story (immediate recall) (Carlesimo et al., 2002)	n.a.	n.a.	5.4	3
	Story (delayed recall) (Carlesimo et al., 2002)	n.a.	n.a.	4.1	2
Language	Letter fluency (Novelli et al. 1986 for CV; Carlesimo et al., 1996 for ME)	7	0	29.9	3
	Category fluency (Novelli et al., 1986)	4	0	38	3
	DeCAbs (association task) (Della Rosa et al., 2014)	25.9	1	40	4

	CaGi (naming task) (Catricalà et al., 2013)	0	0	46.05	3
	CaGi (comprehension task) (Catricalà et al., 2013)	39.979	0	48	4
	Verbal span (repetition of disyllabic words) (Spinnler and Tognoni, 1987)	n.a.	n.a.	3.25	1
	AAT token test (Luzzatti et al., 1996)	raw score:26	deficit (severity index:5/9)	n.a.	n.a.
	AAT repetition (Luzzatti et al., 1996)	raw score:142	deficit (severity index: 8/9)	n.a.	n.a.
	AAT naming (Luzzatti et al., 1996)	raw score:25	deficit (severity index: 3/9)	n.a.	n.a.
	AAT written language (Luzzatti et al., 1996)	raw score:87	normal (severity index: 9/9)	n.a.	n.a.
	AAT comprehension (Luzzatti et al., 1996)	raw score:70	deficit (severity index: 4/9)	n.a.	n.a.
Executive functions	Raven Matrices (Basso et al., 1987 for CV; Carlesimo et al., 1996 for ME)	25.5	2	19.9	1
	Attentive Matrices (Spinnler and Tognoni, 1987)	n.a.	n.a.	26	0
	Stroop test: interference effect (errors) (Caffarra et al., 2002)	n.a.	n.a.	-2.25	4
	Stroop test: interference effect (time) (Caffarra et al., 2002)	n.a.	n.a.	22.49	3
	Trial Making test (TMT): part A (Giovagnoli et al., 1996)	30	4	n.a.	n.a.
	Trial Making test (TMT): part B (Giovagnoli et al., 1996)	155	2	n.a.	n.a.
	Trial Making test (TMT): part B-A (Giovagnoli et al., 1996)	125	1	n.a.	n.a.
	Digit span backward (Monaco et al., 2013)	5.94	4	n.a.	n.a.
	Frontal Assessment Battery (FAB) (Apollonio et al., 2005)	n.a.	n.a.	11	0
Praxic abilities	Constructional praxia (Spinnler and Tognoni, 1987)	n.a.	n.a.	7.25	0
	Ideomotor praxia (De Renzi et al., 1980)	n.a.	n.a.	right hand: 56/72 left hand: 26/72	uncertain present

Table 5. Results of the neuropsychological tests and clinical scales administered to patients CV and ME, reporting corrected scores for age and education and equivalent scores, ranging from 0 to 4, with 0 indicating a pathological performance; in AAT test, a severity index of 1 indicate a severe deficit, whereas a value of 9 indicate a normal performance; n.a.= test not performed.

Eight right-handed healthy control participants (3 males, age-range: 60-80 years, education-range: 5-13 years; normal performance on the Mini Mental State Examination, mean: 28.65±1.64), without cognitive complains and history of neurological and/or psychiatric diseases, were tested in the experimental task.

The study followed the provisions of the Helsinki Declaration and was approved by the ethics committee of the centers. Written informed consent was obtained from the participants.

5.2.2. Lexical decision task

5.2.2.1. Stimuli

Word-word pairs. A rating procedure was conducted on a large sample of nouns (N= 567) and nouns-pairs (N= 552) created for a previous study (Catricalà et al., 2020). Each word and pair was evaluated by at least 10 healthy Italian participants. Participants were asked to rate each word for imageability and familiarity on a 7-points Likert scale (1= low, 7= high) and had to rate the semantic similarity of word-pairs on a 9-points Likert scale (1= not similar, 7= very similar) (Catricalà et al., 2020; Casasanto, 2008).

One hundred and twenty nouns were selected, 48 belonging to the concrete categories of animals (ANI) and tools (TOL), and 72 to the abstract categories of emotions (EM), social (SOC) and quantity (QU). See Appendix D for the list of the stimuli.

One hundred and twenty pairs were created with half of the stimuli used as a prime and half as a target i.e., first and second word in the pair. Prime and target were never switched for presentation order within each pair. 60 of the pairs belonged to the Same Category condition, and specifically, 12 for each of the following combinations: ANI-ANI, TOL-TOL, EM-EM, SOC-SOC, QU-QU; 60 pairs belonged to the Different Category condition, namely 12 for each of the following combinations: X-ANI (i.e. with X indicating TOL, EM, SOC, QU categories, thus forming the following pairs: TOL-ANI, EM-ANI, SOC-ANI, QU-ANI), X-TOL (i.e. with X indicating ANI, EM, SOC, QU categories), X-EM (i.e. with X indicating ANI, TOL, SOC, QU categories), X-SOC (i.e. with X indicating ANI, TOL, EM, QU categories), X-QU (i.e. with X indicating ANI, TOL, SOC, EM categories). Each word appeared twice, once in the

Same Category condition and once in the Different Category condition. Pairs in the Same Category condition were equally semantically related among categories (p= .165), and pairs of the Different Category condition were equally semantically unrelated among categories (p= .393).

Prime and target words were matched among categories for written frequency (values from COLFIS database, see http://www.istc.cnr.it/material/database/colfis/index_eng.shtml), number of letters, number of syllables, frequency of initial, medial and final bigrams and for familiarity (all p > .06) and, separately for concrete and abstract categories, they were matched for imageability (p= .1).

Separately for each category, prime and target words of the Same Category condition were matched for written frequency, number of letters, number of syllables, frequency of initial, medial and final bigrams, familiarity and imageability (all p > .18), whereas prime and target words in the Different Category condition were matched for written frequency, number of letters, number of syllables, frequency of medial bigrams, and familiarity (all p > .09).

Word-pseudoword pairs. Word-pseudoword pairs were presented in 50% of trials, i.e. 60 trials (Neely, 1991).

Sixty nouns, 38 concrete and 22 abstract, different from the previously described set of stimuli, were selected from the database (N= 567, see above) and used as primes in the word-pseudoword pairs. Sixty pronounceable pseudowords were created, maintaining the same orthographic structure as the targets of word-word pairs, i.e. replacing either a vowel or consonant in each syllable. Initial, medial and final bigram frequency of the pseudowords ranged between the corresponding minimal and maximal frequencies of the targets of word-word pairs. Additionally, 10 healthy participants were asked to indicate if the pseudowords were related to any real word. The selected 60 pseudowords were not associated with any real words by more than half of the participants and were not constantly associated to the same real word in more than 2 participants.

Each prime and each target appeared twice, but in different word-pseudoword pairs.

Primes of word-pseudoword pairs, targets of word-pseudoword pairs, primes of word-word pairs and targets of word-word pairs were matched for number of letters (p=.875) and syllables (p=.985); whereas primes of word-pseudoword pairs, and primes and targets of word-word pairs were matched for frequency (p=.532).

5.2.2.2. Task

On each trial participants were presented with the prime (200 ms), followed by a blank screen (50 ms) and by the target, that stayed on the screen until response. Target could be a real word, either of the Same Category or of the Different Category, or a pseudoword (See Figure 9). Two blocks were created and presented in a single session in a counterbalanced order among participants. Each block included 120 trials (60 word-word trials and 60 word-pseudoword trials), delivered in a pseudorandomized order among participants. No more than three word-word trials or three word-pseudoword trials were consecutively displayed (see Giffard et al., 2015). Two pseudorandomized orders were created and presented in a counterbalanced order among participants.

Participants had to indicate by a button press whether the target was a word or a pseudoword, and were instructed to respond with their right hand as accurately and quickly as possible. Before the two experimental blocks, a short training session, lasting about one minute, was administered to familiarize with the task.

Stimuli were delivered with Presentation software (Neurobehavioral Systems, http://www.neurobs.com), and displayed in the centre of the screen in white letters on a black background on a computer monitor at a distance of approximately 50 cm.

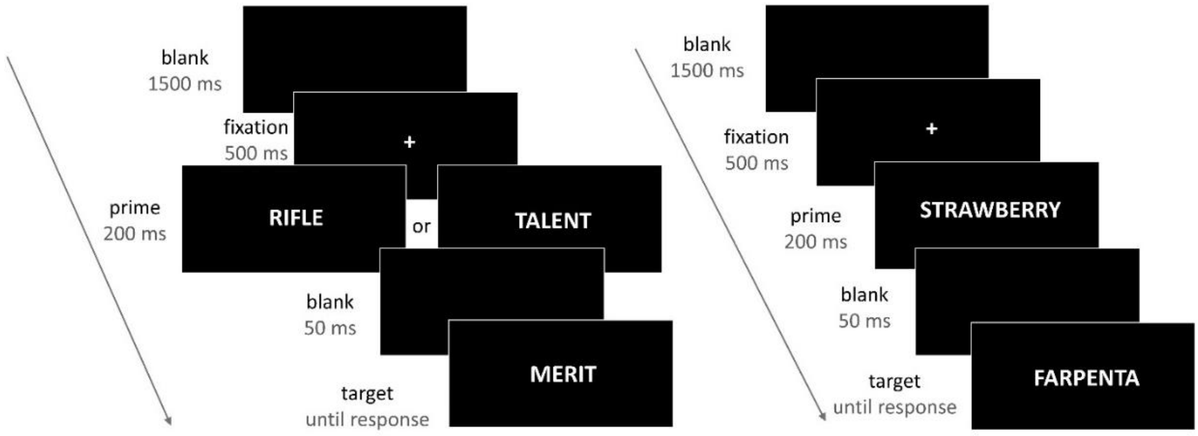

Figure 9. Timeline of an experimental word-word trial (left) and word-pseudoword trial (right). See text for details.

5.3. Analysis and results

Incorrect trials and trials in which reaction times (RT) was below 100 ms were excluded from the analyses. RTs above or below three standard deviations (SD) from the condition's mean were classified as outliers and replaced by the condition's mean.

For the two patients, the priming effect, calculated as difference in RTs between the Same and Different Category conditions, was compared to that of controls, separately for each category (Crawford and Garthwaite, 2011).

Controls showed a priming effect for all categories, namely faster reaction times for the Same compared to Different category condition (see Table 6 and Figure 10).

Compared to controls, CV showed an abolished priming for social concepts (t= 3.484, p= .010), whereas ME showed an abolished priming only for quantity-related concepts (t= 2.408, p= .047). An increased priming effect (hyperpriming effect) was found for the animal category in CV (t = -2.561, p= .038), with a similar trend in ME (t = -2.351, p = .051). No other differences were significant.

	Animals	**Tools**	**Emotions**	**Quantity**	**Social**
controls (mean ± SD)	-26.11 ± 81.90	-62.77 ± 127.95	-64.11 ± 94.63	-99.20 ± 74.06	-44.24 ± 46.91
CV	-245.99	61.32	-40.38	-18.93	126.07
ME	-228.77	31.18	-211.60	90.17	-93.87

Table 6. Mean and standard deviation (SD) of the priming effect (RTs Same Category – RTs Different Category) of controls and mean of the priming effect of patients for each category.

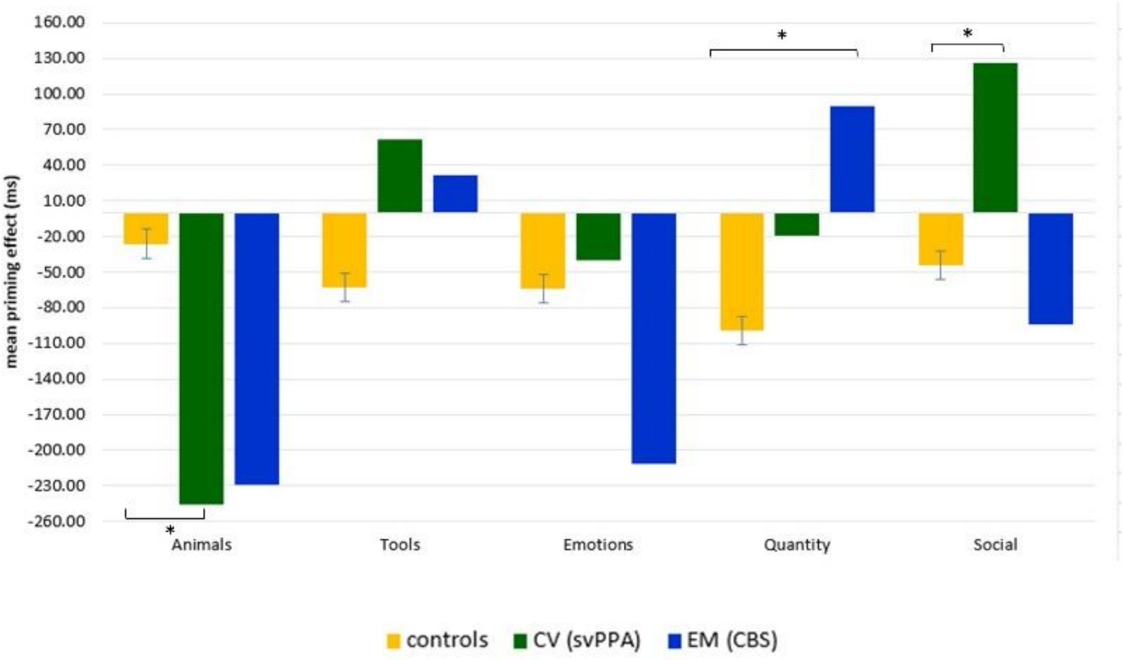

Figure 10. Mean priming effect in ms of controls, CV and EM for each category; error bars indicate the standard error; *= significant.

5.4. Discussion

In this study we described two patients, ME and CV, respectively affected by CBS and sv-PPA, showing a double dissociation on social and quantity related abstract concepts, using a priming paradigm. Both patients have been administered a neuropsychological assessment including an explicit semantic memory evaluation, considering both abstract and concrete concepts. For concrete knowledge, living, e.g. animals, vegetables, and non living, e.g. tools, kitchen items, furniture, clothing pieces, were included, whereas for abstract knowledge we considered concepts related to emotions, cognitions, human actions, social and traits. In the experimental implicit task, we used two concrete categories, namely animals and tools, and three abstract categories, namely emotions, social and quantity related concepts.

Impairments in explicit tests assessing semantic memory, i.e. picture naming or association tasks, have traditionally been attributed either to a degradation of semantic representations or to a failure in retrieving this knowledge (Rogers and Friedman, 2008). Conversely, implicit tasks, such as priming, are defined as automatic processes, namely proceeding without intention or strategic elaboration, thus better tailored to assess the integrity of semantic representations of different conceptual categories (McNamara and Holbrook, 2003). Notably, if conceptual representations are not degraded but rather they are not accessible, priming effect will not be different from the performance of control participants. Conversely, if conceptual representations are degraded, priming effect should not be present.

All the categories that we explored in the implicit task were also investigated in the explicit task, with the exception of the quantity related abstract concepts, thus preventing a systematic comparison.

ME reported no semantic memory deficits at the explicit tasks of the neuropsychological assessment. However, she showed a selective abolishment of the priming effect for the abstract category of quantity related concepts, e.g. *thickness*, *reduction*, *enormity*. To the best of our knowledge, the current study represented the first direct exploration of quantity related abstract concepts in neurological patients. Indeed, as reported in the introduction, previous investigations have been mainly focused on quantifiers, and found a selective deficit in CBS (Cappelletti et al., 2006; Mc Millan et al., 2006; Ash et al., 2016). Interestingly, patients affected by parietal lesions caused by heterogeneous diseases, e.g. CBS, Posterior Cortical Atrophy, or stroke, manifested deficits in different tasks requiring magnitude-related judgements including numerosity (Koss et al., 2010), time perception tasks (Harrington et al., 1998) and in the elaboration of spatial prepositions, e.g., beyond, under, inside (Shebani et al., 2017). Studies in healthy participants suggested that the processing of mathematical (Bechtold et al., 2019), numerical, temporal, locational concepts (Huth et al., 2016), the word arithmetic (Wilson-Mendenhall et al., 2013), and specifically quantity-related (Catricalà et al., 2020) words, engaged the parietal regions, in particular the intraparietal sulcus, with in some cases additional contributions of mid-superior prefrontal cortices (Huth et al., 2016), i.e. areas traditionally involved in the representation of numerical and magnitude knowledge (Amalric and Deheane, 2017). Accordingly, dimension rating studies described quantity-related concepts as words related to size, amount and scope, grouped together with concepts referring to time and space in a magnitude factor (Villani et al., 2019; Troche et al., 2017). The Theory of Magnitude proposed a role of the parietal cortices in performing magnitude related estimations encompassing quantity, time, and space (Bueti and Walsh, 2009). Further studies are necessary in order to explore if different categories of magnitude-related concepts, including not only quantity, but also space- and time- related concepts, are also impaired in CBS, sharing the same neural substrates, and specifically the involvement of the parietal regions.

CV, according to the literature, showed a severe deficit in the explicit tasks assessing semantic memory. A floor effect was indeed reported in the picture naming task, confirming a greater difficulty in production. Although no significant differences were reported in the word picture matching test between different categories, we found a trend toward a worse performance for living, in particular for animals, compared to non living items. In the DeCAbs association test, we found that CV had a performance at chance for social related words. Consistently, we found an abolition of the priming effect for social concepts, i.e. *charm*, *talent*, *glory*, and a hyperpriming in the animal category.

An impairment in social concepts processing has been already reported in sv-PPA patients, usually adopting explicit tasks (Catricalà et al., 2014; Pobric et al., 2016; Zahn et al., 2009; 2017). Accordingly, marked disturbances in different domains of social cognition have been found in sv-PPA, including emotion recognition, empathy as well as Theory of Mind deficits, appearing early in the disease progression and alongside behavioral disturbances (Fittipaldi et al., 2019). These impairments are compatible with the involvement in sv-PPA of the anterior temporal lobe and of the underlying connections (Bisenius et al., 2016; Galantucci et al., 2011), which have been previously implied in the representation of social concepts in healthy participants (Rice et al., 2018), plausibly due to their association to various aspects of social cognition (Amodio and Frith, 2006). Accordingly, anterior temporal lobe, together with a more widespread network, including for instance fusiform and inferior temporal gyri, have been involved in retrieving and applying social knowledge (Olson et al., 2013; Wang et al., 2017), mentalizing (Ross and Olson, 2010; Vollm et al., 2006), and assigning adjectives and stereotypes (Mitchell et al., 2002; Contreras et al., 2012). Similarly, connections between anterior temporal lobe and orbitofrontal cortices and amygdala have been implied in affect processing and social cognition (Binney et al., 2012).

The hyperpriming effect, i.e. a greater priming compared to controls, has been interpreted as the result of a gradual and progressive loss of semantic features. Specifically, it has been suggested that shared features, i.e. common properties between exemplars of the same category, are preserved for longer time, while distinctive ones, i.e. unique features distinguishing among exemplars, are more vulnerable to deterioration (Catricalà et al., 2015). The loss of distinctive features progressively causes the concepts to be represented solely by shared properties and to be merged together, allowing only the use of prototypical information (Hodges et al., 1995). Despite the fact that several authors reported a generalized impairment of semantic memory, namely a similar performance on all semantic categories of concepts and all kinds of features, in sv-PPA, some studies described a more severe decline for visuo-perceptual compared to functional features (how the item is used and its function)/not sensorial (Tyler and Moss, 1998; Merck et al., 2014; Catricalà et al., 2015). The loss of sensory/visual distinctive features is compatible with the spreading of the disease from the anterior temporal lobe, implied in differentiating an item from similar exemplars (Rogers et al., 2006), along the ventral pathway including the fusiform gyrus, elaborating visual features (Hoffman et al., 2015). As visual features are particularly relevant for representing living items (Martin, 2007), these evidence are compatible with the few studies reporting a selective loss of living items (Lambon Ralph et al., 2003). For instance, when a zebra loses its distinctive attributes, i.e. stripes, it is not distinguishable from other four-legs animals, e.g. horse. Previous semantic priming studies in sv-PPA are in line with the result of the current experiment and revealed an hyperpriming effect in the category coordinate condition, e.g. *tiger-lion, elephant-crocodile,* taken as evidence of the blurring between the boundaries of the concepts belonging to the same category (Laisney et al., 2011). With the subsequent and more extensive deterioration of semantic knowledge, the loss further spreads to the shared features, and the priming effect is no longer detectable (Rogers and Friedman, 2008). A similar time-course pattern has also been found in Alzheimer’s Disease (Giffard et al., 2002).

In conclusion, the results of the implicit lexical decision task indicated an impaired knowledge of quantity-related concepts in CBS patient and of animals and social concepts in svPPA, suggesting a crucial role of the brain areas involved in the two pathologies, namely the parietal regions and the anterior temporal lobes, in the representation of specific categories of abstract and concrete knowledge.

6. General discussion

Returning to some of the words cited in the Introduction to intoduce the different types of abstract concepts, i.e. *happiness*, *immensity* and *charm*, the results outlined in the current thesis suggested that they may be referred to as concepts belonging to different abstract categories. In particular, we showed that they are respectively characterized in terms of emotional-affective, quantity and social related semantic dimensions, and represented in the neural systems involved in affect processing, magnitude estimation, and social cognition.

We explored different abstract categories, namely emotions, cognition, attitudes, human actions, social, and quantity-related concepts. We derived these stimuli using dimension ratings and the taxonomy of existing lexical database, i.e. WordNet, allowing a precise characterization of abstract concepts, on the basis of the results of the systematic revision (Chapter 2). The different methods that have been used are not always well suited to characterize abstract concepts. For example, in characterizing the word *charm* and in claiming its membership to the social category, information may be derived from listing the features evoked by the concept, e.g. event and situational properties. The generation and the classification of the produced features are however time-consuming and not always easy to analyse. Similarly, characterizing the word *charm* on the basis of psycholinguistic properties, e.g. imageability or context availability, did not offer a direct measure for the evaluation of the prevalent underlying social dimension.

The results of the three experiments suggest that relatively specific brain networks are supporting the processing of different abstract categories. Indeed, we found that emotions and attitudes induced an adaptation effect in the anterior middle temporal gyrus, known to be involved in affect processing and in the representation of personality traits, while concrete items adapted the fusiform gyrus, implied in the elaboration of high-level visual features (Chapter 3). We also reported a selective abolition of the priming effect for quantity-related concepts after the stimulation of right intraparietal sulcus (IPS), in line with its involvement in numerical and magnitude information, and for social concepts after stimulating right intraparietal sulcus and right superior anterior temporal lobe, considered parts of the network implied in person-related knowledge and social cognition (Chapter 4). Finally, as revealed by a lexical decision task in two single-cases, an impaired processing of quantity related concepts was found in Cortico-Basal Syndrome, affecting parietal regions, whereas an impairment for animals and social concepts was found in semantic variant of Primary Progressive Aphasia, involving anterior temporal lobe (Chapter 5).

Our findings open important questions for the current models of semantic memory. For instance, according to the influent “hub-and-spoke” theory, anterior temporal lobes function as a highly interconnected hub, receiving and integrating input from multiple modality-specific brain regions, and displaying graded specialization according to connectivity profiles (Lambon Ralph et al., 2017). While the ventrolateral section, i.e. corresponding to anterior fusiform gyrus, has been described as the heteromodal hub (Shimotake et al., 2016), ventromedial and superior sections have been considered parts of the networks implied, respectively, in concrete and abstract knowledge, given the respective connections to brain regions devoted to visual and auditory-verbal processing (Hoffman et al., 2015). The evidence of a specialization of superior ATL for social concepts has weakened its proposed contribution for all abstract concepts (Binney et al., 2016), and it still remains uncertain whether other abstract categories recruit specific portions of the anterior temporal lobe. The “hub-and-spoke” theory, with the exception of social related concepts, does not explicitly take into account other potential categories in the abstract domain, which is treated as a unique class. Crucially, our data speak in favor of a graded specialization of the anterior temporal lobe, with different portions manifesting a preferential response for different categories of abstract and concrete concepts. Indeed, we found a contribution of the middle portion to emotions and attitudes, of the superior portion to social concepts, and of the anterior fusiform gyrus to concrete ones, whereas no regions of the ATL were involved in quantity-related concepts. In the fMRI-A experiment we did not find adaptation for concepts referring to cognition and human actions, plausibly because both categories included heterogeneous words, characterized by multiple dimensions, preventing the recruitment of specific regions. We can conclude that large-scale brain networks, not limited to the anterior temporal lobes, encompassing, for instance the parietal regions and in particular the intraparietal sulcus, are involved in the processing and representation of abstract concepts. While the TMS experiment suggested a role of IPS for both social and quantity related concepts, CBS patient showed impairment only in quantitative concepts. Conversely, the spared anterior temporal lobe allowed CBS patient to show intact priming for social concepts.

In conclusion, our data are compatible with an embodied brain organization of conceptual knowledge, in which categorical representations are supported by brain systems involved in the corresponding experiences in the case of both concrete and abstract knowledge. Taken together, our results highlight the variety and richness of abstract concepts and provide constraints to the classical theories of conceptual representation, i.e. Context Availability and Dual Coding Theory, which describe abstract concepts as a unique class, qualitatively different from the concrete one. These promising initial steps point to the need to explore other abstract categories, which received little or no attention in literature, including for instance those concepts relying on theoretical, morality, and quantity-related information.

Additionally, we have to take into account that multiple dimensions may be relevant in representing a specific abstract concept. For example, the word *closeness* may assume different meanings according to the ongoing situation or context, one associated to magnitude and in particular to a spatial-related dimension, and another linked to an affective/social relation among individuals. Future studies are needed to elucidate the mechanisms mediating the interplay between the different facets of abstract concepts, as well as the role of the contextual contraints in determining the relevance of one dimension over the other(s).

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Appendices

Appendix A

dimension	references	definition of the category
Emotional	Altarriba et al. 1999 (Exp. 2)	words whose meanings are affective and have pleasantness or unpleasantness and arousal components
	Altarriba and Bauer, 2004 (Exp. 3)	words whose meanings are affective and have pleasantness or unpleasantness and arousal components
	Chen et al. 2016	emotionally valenced words produced in association to *happiness, sadness, anger, fear*
	Kousta et al. 2011 (Exp. 3)	words characterized by emotional valence and arousal
	Moffat et al. 2014	from Newcombe et al. 2012
	Newcombe et al. 2012	words that easily elicit or evoke an emotional experience
	Siakaluk et al. 2016 (Exp. 2)	words with high degree of emotional experience
	Mazzuca et al., 2018	emotionally valenced words
	Beauregard et al. 1997	words with positive or negative emotional salience
	Vigliocco et al. 2014	emotionally valenced words
	Moseley et al. 2012	words with high relatedness to emotions, namely usually used to speak about emotions
	Skipper and Olson, 2014	emotionally valenced words
	Lebois et al. 2018	from Wilson-Mendenhall et al. 2011
	Wilson-Mendenhall et al. 2011	n.a.
	Martin and Fedio 1983	n.a.
	Hsieh et al. 2012	emotionally valenced words
	Giffard et al. 2015	emotionally valenced words
	Joubert et al. 2017	emotionally valenced words
	Moseley et al. 2015	from Moseley et al. 2012
	Semenza et al., 1986	n.a.
	Dreyer et al. 2015	words with high relatedness to emotions processes
Social	Zahn et al. 2007	words describing a detailed set of social behaviours of people, i.e. behavioural descriptiveness
	Ross and Olson 2010	from Zahn et al. 2007
	Binney et al. 2016	from Zahn et al. 2007
	Rice et al. 2018	from Zahn et al. 2007
	Wong et al. 2011	from Zahn et al. 2007
	Pobric et al. 2016	from Zahn et al. 2007
	Zahn et al. 2009	from Zahn et al. 2007
	Zahn et al. 2017	from Zahn et al. 2007
Mental States	Baron-Cohen et al. 1994	words referring to something that the mind can do
Magnitude	Bechtold et al. 2019	mathematical words, not indicating numbers
	Wilson-Mendenhall et al. 2013	n.a.

Emotional, Mental States	Dreyer and Pulvermüller, 2018	emotional: words with high relatedness to emotions; mental states: words with high relatedness to mental processes
Emotional, Social	Wang et al. 2019	social: words whose meaning involves an interaction between people; emotional: valenced words
Visual, Motor	Harpaintner et al. 2020	visual: words with high proportion of visual related properties; motor: words with high proportion of motor related properties
Social, Magnitude	Catricalà et al. 2020	quantity-related: words associated with the quantitative dimension, namely referring to size and numerosity; social: words linked to a social situation or to an interaction among people, both in terms of inclusion and exclusion
Mental States, Metaphysical	Harris et al. 2006	n.a.
Emotional, Mental States, Social, Human Actions, Traits	Catricalà et al. 2014	from Della Rosa et al. 2014
Multidimensional	Huth et al. 2016	n.a.
	Wang et al. 2018	n.a.

Table 1. Summary of how the different abstract categories have been defined in the 40 included papers. See text for additional details. n.a.= information not available in the paper.

dimension	**references**	**contrast/analysis/ condition**	**brain regions**					**conversion to MNI (tal2MNI matlab)**			**Brainnetome atlas (Fan et al. 2016)**				
			region	x	y	z	coord. system	x	y	z	n.	Gyrus	Gyrus_name	Laterality	Anatomical and modified Cyto-architectonic descriptions
social	Catricalà et al., 2020	social: stimulation vs CZ-placebo abolished priming effect	R IPS	42	-44	51	Tal	42.42	-47.93	52.98	140	IPL	Inferior Parietal Lobule	R	A40rd, rostrodorsal area 40(PFt)
			R superior ATL	52.5	7.2	-11		53.03	7.98	-12.65	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
	Pobric et al., 2016	social > animal functions: pre-post stimulation worsened performance	R superior ATL	53	8	-13	MNI	53	8	-13	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
		social and animal functions: pre-post stimulation worsened performance	L superior ATL	-53	8	-13		-53	8	-13	79	STG	Superior Temporal Gyrus	L	A22r, rostral area 22
	Wong et al., 2011	social and animal functions: stimulation vs controls decreased RTs	L ATL	n.a.			n.a.	n.a.			n.a.	STG*	Superior Temporal Gyrus	L	n.a.
		social vs animal functions	n.s.								n.a.	n.a.	n.a.	n.a.	n.a.
	Huth et al., 2016	social (cluster)	lateral parietal cortex (angular gyrus)	-43	-67	24	MNI	-43	-67	24	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-51	-57	23		-51	-57	23	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-47	-63	34		-47	-63	34	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-53	-54	36		-53	-54	36	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)
				52	-53	28		52	-53	28	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
				48	-58	25		48	-58	25	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
			medial parietal cortex	-5	-55	26		-5	-55	26	153	Pcun	Precuneus	L	A31, area 31 (Lc1)
				-9	-47	34		-9	-47	34	175	CG	Cingulate Gyrus	L	A23d, dorsal area 23
				-5	-59	37		-5	-59	37	153	Pcun	Precuneus	L	A31, area 31 (Lc1)
				5	-52	33		5	-52	33	154	Pcun	Precuneus	R	A31, area 31 (Lc1)
				9	-60	27		9	-60	27	154	Pcun	Precuneus	R	A31, area 31 (Lc1)
			superior prefrontal cortex	-37	20	42		-37	20	42	23	MFG	Middle Frontal Gyrus	L	A8vl, ventrolateral area 8
				-34	19	48		-34	19	48	23	MFG	Middle Frontal Gyrus	L	A8vl, ventrolateral area 9

				38	16	38		38	16	38	18	MFG	Middle Frontal Gyrus	R	IFJ, inferior frontal junction
				37	27	36		37	27	36	24	MFG	Middle Frontal Gyrus	R	A8vl, ventrolateral area 8
				39	18	48		39	18	48	24	MFG	Middle Frontal Gyrus	R	A8vl, ventrolateral area 8
				-8	10	65		-8	10	65	7	SFG	Superior Frontal Gyrus	L	A6dl, dorsolateral area 6
				-9	26	57		-9	26	57	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-6	40	46		-6	40	46	11	SFG	Superior Frontal Gyrus	L	A9m,medial area 9
				-5	54	33		-5	54	33	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-8	47	18		-8	47	18	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
				-6	56	18		-6	56	18	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
				12	25	57		12	25	57	2	SFG	Superior Frontal Gyrus	R	A8m, medial area 8
				24	29	44		24	29	44	4	SFG	Superior Frontal Gyrus	R	A8dl, dorsolateral area 8
				17	40	47		17	40	47	6	SFG	Superior Frontal Gyrus	R	A9l, lateral area 9
				9	57	17		9	57	17	14	SFG	Superior Frontal Gyrus	R	A10m, medial area 10
				7	45	40		7	45	40	12	SFG	Superior Frontal Gyrus	R	A9m,medial area 9
				28	58	7		28	58	7	20	MFG	Middle Frontal Gyrus	R	A46, area 46
				20	52	31		20	52	31	20	MFG	Middle Frontal Gyrus	R	A46, area 47
			anterior lateral temporal cortex	-51	3	-21		-51	3	-21	79	STG	Superior Temporal Gyrus	L	A22r, rostral area 22
				-56	-45	3		-56	-45	3	121	pSTS	posterior Superior Temporal Sulcus	L	rpSTS, rostroposterior superior temporal sulcus
				57	-23	-6		57	-23	-6	88	MTG	Middle Temporal Gyrus	R	aSTS, anterior superior temporal sulcus
				51	11	-21		51	11	-21	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
				53	-27	1		53	-27	1	80	STG	Superior Temporal Gyrus	R	A22r, rostral area 22
				47	7	-35		47	7	-35	84	MTG	Middle Temporal Gyrus	R	A21r, rostral area 21
			inferior prefrontal cortex (opercularis/triangularis)	-45	37	-7		-45	37	-7	35	IFG	Inferior Frontal Gyrus	L	A45r, rostral area 45
				49	35	-1		49	35	-1	36	IFG	Inferior Frontal Gyrus	R	A45r, rostral area 45
				52	25	13		52	25	13	34	IFG	Inferior Frontal Gyrus	R	A45c, caudal area 45
	Zahn et al., 2007	social concepts > animals function (whole brain)	R lateral orbitofrontal/anterior temporal	48	21	-9	MNI	48	21	-9	52	OrG	Orbital Gyrus	R	A12/47l, lateral area 12/47
			R anterior superior temporal gyrus	57	12	0		57	12	0	62	PrG	Precentral Gyrus	R	A4tl, area 4(tongue and larynx region)

			R lateral orbitofrontal/inferior frontal gyrus	54	33	6		54	33	6	36	IFG	Inferior Frontal Gyrus	R	A45r, rostral area 45
			dorsomedial prefrontal cortex	-6	21	54		-6	21	54	1	SFG	Superior Frontal Gyrus	L	A8m, medial area 8
			L middle frontal gyrus	-36	33	24		-36	33	24	21	MFG	Middle Frontal Gyrus	L	A9/46v, ventral area 9/46
			L inferior frontal gyrus	-48	15	9		-48	15	9	33	IFG	Inferior Frontal Gyrus	L	A45c, caudal area 45
			L parieto-temporal junction	-57	-45	30		-57	-45	30	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)
			L lateral inferior temporal gyrus	-63	-39	-12		-63	-39	-12	99	ITG	Inferior Temporal Gyrus	L	A20cl, caudolateral of area 20
			L lateral fusiform gyrus	-42	-51	-30		-42	-51	-30	107	FuG	Fusiform Gyrus	L	A37lv, lateroventral area37
			L medial occipital gyrus	-33	-84	12		-33	-84	12	199	LOcC	lateral Occipital Cortex	L	mOccG, middle occipital gyrus
			L subthalamic nucleus	-12	-15	-3		-12	-15	-3	245	Tha	Thalamus	L	lPFtha, lateral pre-frontal thalamus
		social > animals function and correlated with social behavior/meaning relatedness (whole brain)	R superior anterior temporal cortex	51	15	-12		51	15	-12	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
		social concepts > animals function (ROI analysis)	R superior anterior temporal cortex	51	18	-12		51	18	-12	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
			R anterior middle temporal cortex	57	-3	-21		57	-3	-21	88	MTG	Middle Temporal Gyrus	R	aSTS, anterior superior temporal sulcus
	Wang et al., 2019	social > emotional (whole brain)	L MTG/STG	-58	-4	-16	MNI	-58	-4	-16	87	MTG	Middle Temporal Gyrus	L	aSTS, anterior superior temporal sulcus
			L angular gyrus/middle occipital gyrus/MTG	-44	-72	28		-44	-72	28	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
			L MTG	-54	-42	0		-54	-42	0	121	pSTS	posterior Superior Temporal Sulcus	L	rpSTS, rostroposterior superior temporal sulcus
	Binney et al., 2016	social > animals function (whole brain)	L ventrolateral temporopolar cortex	-48	9	-39	MNI	-48	9	-39	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
			L anterior STG	-57	9	-12		-57	9	-12	79	STG	Superior Temporal Gyrus	L	A22r, rostral area 22
			L basal temporopolar cortex	-39	3	-48		-39	3	-48	93	ITG	Inferior Temporal Gyrus	L	A20r, rostral area 20
			L medial lingual gyrus	-15	-87	-9		-15	-87	-9	205	LOcC	lateral Occipital Cortex	L	iOccG, inferior occipital gyrus
			R medial lingual gyrus	3	-84	-6		3	-84	-6	190	MVOcC	MedioVentral Occipital Cortex	R	cLinG, caudal lingual gyrus
			L lateral lingual gyrus	-33	-72	-9		-33	-72	-9	105	FuG	Fusiform Gyrus	L	A37mv, medioventral area37
			L superior cuneus	-12	-78	24		-12	-78	24	197	MVOcC	MedioVentral Occipital Cortex	L	vmPOS,ventromedial parietooccipital sulcus
				-27	-78	24		-27	-78	24	135	IPL	Inferior Parietal Lobule	L	A39c, caudal area 39(PGp)
				-15	-87	30		-15	-87	30	107	FuG	Fusiform Gyrus	L	A37lv, lateroventral area37

			L supramarginal gyrus	-54	-39	21		-54	-39	21	71	STG	Superior Temporal Gyrus	L	A41/42, area 41/42
			L posterior insular cortex	-48	-24	18		-48	-24	18	145	IPL	Inferior Parietal Lobule	L	A40rv, rostroventral area 40(PFop)
			L opercular inferior parietal lobule	-60	-21	18		-60	-21	18	145	IPL	Inferior Parietal Lobule	L	A40rv, rostroventral area 40(PFop)
		social > abstract non-social (SVC)	R anterior STS/STG	57	9	-18		57	9	-18	80	STG	Superior Temporal Gyrus	R	A22r, rostral area 22
			L anterior MTG/temporopolar cortex	-54	9	-33		-54	9	-33	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
		social > animals function (SVC)	L ventrolateral temporopolar cortex	-48	9	-39		-48	9	-39	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
		social > abstract non social, animals function (ROIs)	L posteriolateral temporal cortex (ventral superior, dorsal MTG, STS)	-66	-42	3		-66	-42	3	81	MTG	Middle Temporal Gyrus	L	A21c, caudal area 21
	Ross and Olson, 2010	social > animals function (whole brain)	R anterior temporal lobe	60	-9	-17	Tal	60.6	-8.39	-20.75	88	MTG	Middle Temporal Gyrus	R	aSTS, anterior superior temporal sulcus
			L anterior temporal lobe	-48	16	-20		-48.49	15.5	-22.83	77	STG	Superior Temporal Gyrus	L	A38l, lateral area 38
			L fusiform gyrus	-31	-72	-17		-31.21	-73.26	-24.5	105	FuG	Fusiform Gyrus	L	A37mv, medioventral area37
	Rice et al., 2018	social > abstract non social (whole brain)	R anterior middle temporal gyrus	57	9	-15	MNI	57	9	-15	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
			orbitofrontal cortex	21	45	-18		21	45	-18	46	OrG	Orbital Gyrus	R	A11l, lateral area 11
				42	33	-18		42	33	-18	44	OrG	Orbital Gyrus	R	A12/47o, orbital area 12/47
				36	51	-18		36	51	-18	44	OrG	Orbital Gyrus	R	A12/47o, orbital area 12/47
			L anterior inferior temporal gyrus	-54	9	-33		-54	9	-33	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
				-60	-3	-33		-60	-3	-33	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
				-51	-3	-36		-51	-3	-36	95	ITG	Inferior Temporal Gyrus	L	A20il, intermediate lateral area 20
			L medial frontal cortex	-36	51	24		-36	51	24	15	MFG	Middle Frontal Gyrus	L	A9/46d, dorsal area 9/46
			L lingual gyrus	-12	-78	-12		-12	-78	-12	189	MVOcC	MedioVentral Occipital Cortex	L	cLinG, caudal lingual gyrus
			L posterior superior temporal gyrus	-57	-42	15		-57	-42	15	71	STG	Superior Temporal Gyrus	L	A41/42, area 41/42
			L medial occipital gyrus	-18	-93	6		-18	-93	6	203	LOcC	lateral Occipital Cortex	L	OPC, occipital polar cortex
			L posterior middle temporal gyrus	-60	-39	0		-60	-39	0	87	MTG	Middle Temporal Gyrus	L	aSTS, anterior superior temporal sulcus
			L middle temporal gyrus	-45	-27	-9		-45	-27	-9	87	MTG	Middle Temporal Gyrus	L	aSTS, anterior superior temporal sulcus
			R posterior fusiform gyrus	24	-78	-33		24	-78	-33	106	FuG	Fusiform Gyrus	R	A37mv, medioventral area37
			R post-central gyrus	27	-33	60		27	-33	60	162	PoG	Postcentral Gyrus	R	A1/2/3tru, area1/2/3(trunk region)
			R calcarine sulcus	15	-87	3		15	-87	3	194	MVOcC	MedioVentral Occipital Cortex	R	cCunG, caudal cuneus gyrus
				12	-78	0		12	-78	0	192	MVOcC	MedioVentral Occipital Cortex	R	rCunG, rostral cuneus gyrus

			L superior medial frontal cortex	-9	48	27		-9	48	27	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
				-12	60	24		-12	60	24	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
			L inferior frontal gyrus (orbitalis)	-36	30	-21		-36	30	-21	43	OrG	Orbital Gyrus	L	A12/47o, orbital area 12/47
				-27	33	-21		-27	33	-21	45	OrG	Orbital Gyrus	L	A11l, lateral area 11
			L posterior fusiform gyrus	-36	-54	-18		-36	-54	-18	105	FuG	Fusiform Gyrus	L	A37mv, medioventral area37
				-30	-45	-21		-30	-45	-21	105	FuG	Fusiform Gyrus	L	A37mv, medioventral area37
			gyrus rectus	3	45	-18		3	45	-18	48	OrG	Orbital Gyrus	R	A11m, medial area 11
		social > abstract non social (ROI analysis)	R aSTG	51	16	-27		51	16	-27	84	MTG	Middle Temporal Gyrus	R	A21r, rostral area 21
			R aMTG	61	-1	-16		61	-1	-16	88	MTG	Middle Temporal Gyrus	R	aSTS, anterior superior temporal sulcus
emotional	Beauregard et al., 1997	emotional > concrete	L middle temporal gyrus	-59	-42	2	Tal	-59.6	-43.35	-0.12	121	pSTS	posterior Superior Temporal Sulcus	L	rpSTS, rostroposterior superior temporal sulcus
			medial frontal gyrus	0	55	11		0	56.06	14.93	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
			L medial frontal gyrus	-5	49	29		-5.05	48.96	34.14	11	SFG	Superior Frontal Gyrus	L	A9m,medial area 9
			orbital frontal gyrus	0	27	-24		0	29.04	-26.93	47	OrG	Orbital Gyrus	L	A11m, medial area 11
			R superior frontal gyrus	17	6	68		17.17	2.67	74.15	8	SFG	Superior Frontal Gyrus	R	A6dl, dorsolateral area 6
			R inferior frontal gyrus	40	22	-17		40.4	52.53	-18.9	44	OrG	Orbital Gyrus	R	A12/47o, orbital area 12/47
			L inferior frontal gyrus	-29	20	-20		-29.29	21.62	-22.59	45	OrG	Orbital Gyrus	L	A11l, lateral area 11
				-36	20	-18		-36.36	21.52	-20.21	43	OrG	Orbital Gyrus	L	A12/47o, orbital area 12/47
				-44	30	-3		-44.44	31.04	-1.78	37	IFG	Inferior Frontal Gyrus	L	A44op, opercular area 44
			L anterior cingulate gyrus	-8	42	-8		-8.08	43.66	-7.01	187	CG	Cingulate Gyrus	L	A32sg, subgenual area 32
	Huth et al., 2016	emotional (cluster)	lateral parietal cortex (angular gyrus)	-47	-63	34	MNI	-47	-63	34	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-43	-67	24		-43	-67	24	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-51	-57	23		-51	-57	23	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-53	-54	36		-53	-54	36	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)
				41	-45	42		41	-45	42	140	IPL	Inferior Parietal Lobule	R	A40rd, rostrodorsal area 40(PFt)
			superior prefrontal cortex	-34	19	48		-34	19	48	23	MFG	Middle Frontal Gyrus	L	A8vl, ventrolateral area 10
				-37	20	42		-37	20	42	23	MFG	Middle Frontal Gyrus	L	A8vl, ventrolateral area 11
				-8	10	65		-8	10	65	7	SFG	Superior Frontal Gyrus	L	A6dl, dorsolateral area 7
				-9	26	57		-9	26	57	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9

				-6	40	46		-6	40	46	11	SFG	Superior Frontal Gyrus	L	A9m,medial area 9
				-5	54	33		-5	54	33	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-8	47	18		-8	47	18	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
				-6	56	18		-6	56	18	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
				12	25	57		12	25	57	2	SFG	Superior Frontal Gyrus	R	A8m, medial area 9
				7	45	40		7	45	40	12	SFG	Superior Frontal Gyrus	R	A9m,medial area 9
				20	52	31		20	52	31	20	MFG	Middle Frontal Gyrus	R	A46, area 48
			anterior lateral temporal cortex	-51	3	-21		-51	3	-21	79	STG	Superior Temporal Gyrus	L	A22r, rostral area 22
				-56	-45	3		-56	-45	3	121	pSTS	posterior Superior Temporal Sulcus	L	rpSTS, rostroposterior superior temporal sulcus
				57	-23	-6		57	-23	-6	88	MTG	Middle Temporal Gyrus	R	aSTS, anterior superior temporal sulcus
				51	11	-21		51	11	-21	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
				53	-27	1		53	-27	1	80	STG	Superior Temporal Gyrus	R	A22r, rostral area 22
				47	7	-35		47	7	-35	84	MTG	Middle Temporal Gyrus	R	A21r, rostral area 21
			inferior prefrontal cortex (opercularis/triangularis)	-45	37	-7		-45	37	-7	35	IFG	Inferior Frontal Gyrus	L	A45r, rostral area 45
				49	35	-1		49	35	-1	36	IFG	Inferior Frontal Gyrus	R	A45r, rostral area 45
				52	25	13		52	25	13	34	IFG	Inferior Frontal Gyrus	R	A45c, caudal area 45
			frontal opercolum/anterior insula	n.a.	n.a.	n.a.		n.a.	n.a.	n.a.	n.a.	INS*	Insular Gyrus	n.a.	n.a.
	Wang et al., 2019	emotional > social (whole brain)	L middle occipital gyrus	-40	-92	2	MNI	-40	-92	2	199	LOcC	lateral Occipital Cortex	L	mOccG, middle occipital gyrus
			L temporal pole/superior temporal gyrus	-44	8	-20		-44	8	-20	77	STG	Superior Temporal Gyrus	L	A38l, lateral area 38
			R IOG	32	-98	-8		32	-98	-8	204	LOcC	lateral Occipital Cortex	R	OPC, occipital polar cortex
			R temporal pole/superior temporal gyrus	42	4	-18		42	4	-18	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
	Dreyer and Pulvermüller, 2018	emotional (comparison between ROIs)	L face-related motor area	-62	-14	38	MNI	-62	-14	38	159	PoG	Postcentral Gyrus	L	A2, area 2
			L hand-related motor area	-34	-22	52		-34	-22	52	53	PrG	Precentral Gyrus	L	A4hf, area 4(head and face region)
		emotional > hashmark baseline (whole brain)	L dorsal/ventral precentral and rolandic motor areas	-40	-2	14		-40	-2	14	61	PrG	Precentral Gyrus	L	A4tl, area 4(tongue and larynx region)
				-44	-8	8		-44	-8	8	61	PrG	Precentral Gyrus	L	A4tl, area 4(tongue and larynx region)
				-40	-20	54		-40	-20	54	53	PrG	Precentral Gyrus	L	A4hf, area 4(head and face region)
				-38	-8	60		-38	-8	60	55	PrG	Precentral Gyrus	L	A6cdl, caudal dorsolateral area 6

				-38	-14	54		-38	-14	54	53	PrG	Precentral Gyrus	L	A4hf, area 4(head and face region)
	Vigliocco et al., 2014	modulation effect of emotional valence for abstract words	rostral anterior cingulate cortex	0	42	6	MNI	0	42	6	187	CG	Cingulate Gyrus	L	A32sg, subgenual area 32
	Moseley et al., 2012	emotional > hashmark baseline (whole brain)	L precentral gyrus	-56	4	24	MNI	-56	4	24	53	PrG	Precentral Gyrus	L	A4hf, area 4(head and face region)
				-48	-12	40		-48	-12	40	53	PrG	Precentral Gyrus	L	A4hf, area 4(head and face region)
				-56	-8	44		-56	-8	44	155	PoG	Postcentral Gyrus	L	A1/2/3ulhf, area 1/2/3(upper limb, head and face region)
			R precentral gyrus	56	0	40		56	0	40	54	PrG	Precentral Gyrus	R	A4hf, area 4(head and face region)
			R postcentral gyrus	60	2	24		60	2	24	54	PrG	Precentral Gyrus	R	A4hf, area 4(head and face region)
			L frontopolar cortex	-10	56	12		-10	56	12	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
			R frontopolar cortex	8	52	8		8	52	8	14	SFG	Superior Frontal Gyrus	R	A10m, medial area 10
			L middle temporal gyrus	-60	-34	2		-60	-34	2	121	pSTS	posterior Superior Temporal Sulcus	L	rpSTS, rostroposterior superior temporal sulcus
			L fusiform gyrus	-40	-40	-14		-40	-40	-14	107	FuG	Fusiform Gyrus	L	A37lv, lateroventral area37
			L inferior occipital cortex	-44	-74	-8		-44	-74	-8	201	LOcC	lateral Occipital Cortex	L	V5/MT+, area V5/MT+
			L superior temporal pole	-48	16	-26		-48	16	-26	77	STG	Superior Temporal Gyrus	L	A38l, lateral area 38
			R superior temporal gyrus	50	-32	24		50	-32	24	146	IPL	Inferior Parietal Lobule	R	A40rv, rostroventral area 40(PFop)
			R fusiform gyrus	36	-64	2		36	-64	2	202	LOcC	lateral Occipital Cortex	R	V5/MT+, area V5/MT+
			R superior parietal cortex	16	-50	64		16	-50	64	126	SPL	Superior Parietal Lobule	R	A7r, rostral area 7
			R basal ganglia	28	24	6		28	24	6	168	INS	Insular Gyrus	R	dIa, dorsal agranular insula
			R insula	34	-16	22		34	-16	22	172	INS	Insular Gyrus	R	dIg, dorsal granular insula
		emotional > action words (ROI analysis)	L orbitofrontal cortex	-62	23	15		-62	23	15	33	IFG	Inferior Frontal Gyrus	L	A45c, caudal area 45
			L dorsolateral prefrontal cortex	-44	33	-3		-44	33	-3	35	IFG	Inferior Frontal Gyrus	L	A45r, rostral area 45
	Skipper and Olson, 2014	abstract > non words (whole brain)	L anterior middle temporal gyrus	-56	-6	-20	MNI	-56	-6	-20	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
			L temporal pole	-50	12	-30		-50	12	-30	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
			L posterior middle temporal gyrus	-50	-66	20		-50	-66	20	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
			L pars orbitalis	-46	30	-16		-46	30	-16	51	OrG	Orbital Gyrus	L	A12/47l, lateral area 12/47
			L inferior parietal gyrus	-38	-60	18		-38	-60	18	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
			L parahippocampal gyrus	-36	6	-32		-36	6	-32	93	ITG	Inferior Temporal Gyrus	L	A20r, rostral area 20

			L calcarine sulcus	-32	-50	2		-32	-50	2	191	MVOcC	MedioVentral Occipital Cortex	L	rCunG, rostral cuneus gyrus
			L middle occipital gyrus	-14	-102	14		-14	-102	14	203	LOcC	lateral Occipital Cortex	L	OPC, occipital polar cortex
			L lingual gyrus	-10	-84	-10		-10	-84	-10	189	MVOcC	MedioVentral Occipital Cortex	L	cLinG, caudal lingual gyrus
			L medial orbitofrontal gyrus	-6	22	-20		-6	22	-20	49	OrG	Orbital Gyrus	L	A13, area 13
			L anterior cingulate	-6	50	-12		-6	50	-12	41	OrG	Orbital Gyrus	L	A14m, medial area 14
			R putamen	2	12	-12		2	12	-12	50	OrG	Orbital Gyrus	R	A13, area 13
			R lingual gyrus	2	-90	-10		2	-90	-10	190	MVOcC	MedioVentral Occipital Cortex	R	cLinG, caudal lingual gyrus
			R anterior cingulate	4	52	-8		4	52	-8	42	OrG	Orbital Gyrus	R	A14m, medial area 14
			R cuneus	10	-92	18		10	-92	18	194	MVOcC	MedioVentral Occipital Cortex	R	cCunG, caudal cuneus gyrus
			R superior temporal pole	42	8	-28		42	8	-28	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
			R anterior superior temporal sulcus	42	-2	-20		42	-2	-20	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
			R middle superior temporal sulcus	44	-12	-10		44	-12	-10	80	STG	Superior Temporal Gyrus	R	A22r, rostral area 22
			R posterior superior temporal gyrus	54	-28	14		54	-28	14	146	IPL	Inferior Parietal Lobule	R	A40rv, rostroventral area 40(PFop)
		valenced words > non words (whole brain)	L posterior superior temporal sulcus	-56	-56	18		-56	-56	18	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
			L anterior middle temporal gyrus	-56	-6	-22		-56	-6	-22	83	MTG	Middle Temporal Gyrus	L	A21r, rostral area 21
			L anterior inferior frontal gyrus	-46	30	-16		-46	30	-16	51	OrG	Orbital Gyrus	L	A12/47l, lateral area 12/47
			L inferior parietal gyrus	-48	-66	20		-48	-66	20	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
			L medial temporal pole	-32	6	-32		-32	6	-32	69	STG	Superior Temporal Gyrus	L	A38m, medial area 38
			L posterior parahippocampal gyrus	-16	-54	2		-16	-54	2	181	CG	Cingulate Gyrus	L	A23v, ventral area 23
			L posterior cingulate gyrus	-16	-42	42		-16	-42	42	185	CG	Cingulate Gyrus	L	A23c, caudal area 23
			L superior frontal gyrus	-10	52	34		-10	52	34	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
			L superior occipital gyrus	10	-100	16		10	-100	16	204	LOcC	lateral Occipital Cortex	R	OPC, occipital polar cortex
			L inferior posterior cingulate	-6	-56	12		-6	-56	12	151	Pcun	Precuneus	L	dmPOS, dorsomedial parietooccipital sulcus(PEr)
			L anterior cingulate	-6	48	-16		-6	48	-16	41	OrG	Orbital Gyrus	L	A14m, medial area 14
			R anterior cingulate	6	52	-10		6	52	-10	42	OrG	Orbital Gyrus	R	A14m, medial area 14
			R inferior posterior cingulate	6	54	4		6	54	4	14	SFG	Superior Frontal Gyrus	R	A10m, medial area 10
			R middle occipital gyrus	14	-92	20		14	-92	20	204	LOcC	lateral Occipital Cortex	R	OPC, occipital polar cortex

			R medial orbitofrontal cortex	4	16	-16		4	16	-16	50	OrG	Orbital Gyrus	R	A13, area 13
			R medial temporal pole	38	8	-30		38	8	-30	84	MTG	Middle Temporal Gyrus	R	A21r, rostral area 21
			R middle superior temporal sulcus	42	-14	-10		42	-14	-10	74	STG	Superior Temporal Gyrus	R	TE1.0 and TE1.2
			R posterior superior temporal gyrus	60	-26	16		60	-26	16	72	STG	Superior Temporal Gyrus	R	A41/42, area 41/42
		valenced words > neutral words (whole brain)	L posterior cingulate	-2	-52	26		-2	-52	26	175	CG	Cingulate Gyrus	L	A23d, dorsal area 23
		valenced words > neutral words (ROI analysis)	rostral anterior cingulate cortex	12	45	12		12	45	12	14	SFG	Superior Frontal Gyrus	R	A10m, medial area 10
	Lebois et al., 2018	anger in physical and social situation (whole brain)	L mid-temporal	-49	-45	8	Tal	-49.5	-46.75	6.24	123	pSTS	posterior Superior Temporal Sulcus	L	cpSTS, caudoposterior superior temporal sulcus
			L mid-cingulate	-25	-29	24		-25.25	-31.1	24.48	15	MFG	Middle Frontal Gyrus	L	A9/46d, dorsal area 9/46
			L STG	-49	-3	-6		-49.5	-2.78	-7.31	73	STG	Superior Temporal Gyrus	L	TE1.0 and TE1.2
			R temporal pole	51	15	-10		51.51	15.96	-11	78	STG	Superior Temporal Gyrus	R	A38l, lateral area 38
			R insula	43	-15	-6		43.43	-15.44	-0.89	164	INS	Insular Gyrus	R	G, hypergranular insula
			R dlPFC	43	17	28		43.43	16.06	31.32	18	MFG	Middle Frontal Gyrus	R	IFJ, inferior frontal junction
		fear in physical and social situation (whole brain)	R mid-temporal	43	-23	-4		43.43	-23.48	-6.12	88	MTG	Middle Temporal Gyrus	R	aSTS, anterior superior temporal sulcus
			R mid-frontal eye field	31	1	42		31.31	-1.13	45.65	56	PreC	Precentral Gyrus	R	A6cdl, caudal dorsolateral area 6
			L mid-temporal	-47	-31	4		-47.48	-32.12	2.66	121	pSTS	posterior Superior Temporal Sulcus	L	rpSTS, rostroposterior superior temporal sulcus
			L cingulate gyrus	-23	-15	32		-23.23	-17.09	33.92	185	CG	Cingulate Gyrus	L	A23c, caudal area 23
			R insula	47	-23	16		47.48	-24.5	16.12	146	IPL	Inferior Parietal Lobule	R	A40rv, rostroventral area 40(PFop)
			L precentral gyrus	-59	-7	12		-59.6	-7.82	12.65	157	PoG	Postcentral Gyrus	L	A1/2/3tonIa, area 1/2/3(tongue and larynx region)
			R thalamus	13	-25	-4		13.13	-25.53	-6.24	246	Tha	Thalamus	R	lPFtha, lateral pre-frontal thalamus
			L anterior cingulate cortex	-19	31	4		-19.19	31.71	6.02	227	BG	Basal Ganglia	L	dCa, dorsal caudate
			R dlPFC	47	17	30		47.48	15.96	33.49	18	MFG	Middle Frontal Gyrus	R	IFJ, inferior frontal junction
			R supramarginal gyrus	55	-47	18		55.55	-49.32	16.99	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
			L insula	-47	-33	20		-47.47	-35.01	19.92	145	IPL	Inferior Parietal Lobule	L	A40rv, rostroventral area 40(PFop)
	Wilson-Mendenhall et al., 2011	anger, fear in physical, social situation (activation in at	L OFC	-47	23	-1	Tal	-47.48	23.73	0.16	37	IFG	Inferior Frontal Gyrus	L	A44op, opercular area 44
			L IFG	-52	15	8		-52.52	15.03	9.44	39	IFG	Inferior Frontal Gyrus	L	A44v, ventral area 44

		least one condition, whole brain)		-49	26	10		-49.5	26.26	12.27	33	IFG	Inferior Frontal Gyrus	L	A45c, caudal area 45
			L dlPFC	-52	27	12		-52.52	27.18	14.49	31	IFG	Inferior Frontal Gyrus	L	IFS, inferior frontal sulcus
				-58	14	28		-58.59	12.97	31.16	63	PrG	Precentral Gyrus	L	A6cvl, caudal ventrolateral area 6
			LTemporal Pole	-44	14	-18		-44.44	15.34	-20.57	77	STG	Superior Temporal Gyrus	L	A38l, lateral area 38
			L STG	-43	-22	10		-43.43	-23.17	9.66	73	STG	Superior Temporal Gyrus	L	TE1.0 and TE1.2
				-55	-15	10		-55.56	-15.96	10.04	157	PoG	Postcentral Gyrus	L	A1/2/3tonIa, area 1/2/3(tongue and larynx region)
				-56	-7	7		-56.57	-7.58	7.22	73	STG	Superior Temporal Gyrus	L	TE1.0 and TE1.2
			L insula	-43	-20	11		-43.43	-21.16	10.86	73	STG	Superior Temporal Gyrus	L	TE1.0 and TE1.2
			L inferior parietal	-54	-40	38		-54.55	-43.14	39.08	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)
			R STG	57	-18	8		57.58	-18.95	7.71	72	STG	Superior Temporal Gyrus	R	A41/42, area 41/42
				60	-22	10		60.61	-23.17	9.66	72	STG	Superior Temporal Gyrus	R	A41/42, area 41/42
				50	-16	6		50.51	-16.78	5.64	72	STG	Superior Temporal Gyrus	R	A41/42, area 41/42
			R Insula	47	-15	7		47.47	-15.81	6.78	74	STG	Superior Temporal Gyrus	R	TE1.0 and TE1.2
			R inferior parietal	58	-50	30		58.59	-53.03	29.85	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
mental states	Baron-Cohen et al., 1994	mental states > concrete (ROI analysis)	R orbitofrontal cortex	n.a.			n.a.	n.a.			n.a.	OrG*	Orbital Gyrus	R	n.a.
		mental states < concrete (ROI analysis)	L fronto-polar cortex								n.a.	MFG*	Middle Frontal Gyrus	L	n.a.
	Harris et al., 2006	mental states vs metaphysical (whole brain)	n.s.	n.s.			MNI	n.s.			n.a.	n.a.	n.a.	n.a.	n.a.
		mental states and metaphysical > concrete (whole brain)	L middle temporal gyrus	-45	-42	-3		-45	-42	-3	121	pSTS	posterior Superior Temporal Sulcus	L	rpSTS, rostroposterior superior temporal sulcus
			R caudate/putamen	15	15	0		15	15	0	220	Str	Basal Ganglia	R	vCa, ventral caudate
	Huth et al., 2016	mental states (cluster)	lateral parietal cortex (angular gyrus)	-51	-57	23	MNI	-51	-57	23	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-47	-63	34		-47	-63	34	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-53	-54	36		-53	-54	36	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)
				52	-53	28		52	-53	28	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
				48	-58	25		48	-58	25	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
			medial parietal cortex	-5	-55	26		-5	-55	26	153	Pcun	Precuneus	L	A31, area 31 (Lc1)

				-9	-47	34		-9	-47	34	175	CG	Cingulate Gyrus	L	A23d, dorsal area 23
				-5	-59	37		-5	-59	37	153	Pcun	Precuneus	L	A31, area 31 (Lc1)
				5	-52	33		5	-52	33	154	Pcun	Precuneus	R	A31, area 31 (Lc1)
				9	-60	27		9	-60	27	154	Pcun	Precuneus	R	A31, area 31 (Lc1)
				-10	-69	31		-10	-69	31	151	Pcun	Precuneus	L	dmPOS, dorsomedial parietooccipital sulcus(PEr)
				12	-69	36		12	-69	36	152	Pcun	Precuneus	R	dmPOS, dorsomedial parietooccipital sulcus(PEr)
			superior prefrontal cortex	-8	10	65		-8	10	65	7	SFG	Superior Frontal Gyrus	L	A6dl, dorsolateral area 8
				-9	26	57		-9	26	57	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-6	40	46		-6	40	46	11	SFG	Superior Frontal Gyrus	L	A9m,medial area 9
				-5	54	33		-5	54	33	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-17	53	29		-17	53	29	15	MFG	Middle Frontal Gyrus	L	A9/46d, dorsal area 9/46
				20	52	31		20	52	31	20	MFG	Middle Frontal Gyrus	R	A46, area 49
				12	25	57		12	25	57	2	SFG	Superior Frontal Gyrus	R	A8m, medial area 10
			ventromedial cortex	-7	51	0		-7	51	0	187	CG	Cingulate Gyrus	L	A32sg, subgenual area 32
				8	48	-4		8	48	-4	42	OrG	Orbital Gyrus	R	A14m, medial area 14
	Dreyer and Pulvermüller, 2018	mental states (comparison between ROIs)	L face-related motor area	-62	-14	38	MNI	-62	-14	38	159	PoG	Postcentral Gyrus	L	A2, area 2
		mental states > hashmark baseline (whole brain)	L ventral rolandic and precentral areas	-54	4	8		-54	4	8	61	PrG	Precentral Gyrus	L	A4tl, area 4(tongue and larynx region)
				-52	2	44		-52	2	44	63	PrG	Precentral Gyrus	L	A6cvl, caudal ventrolateral area 6
				-34	-6	62		-34	-6	62	55	PrG	Precentral Gyrus	L	A6cdl, caudal dorsolateral area 6
magnitude	Catricalà et al., 2020	quantity: stimulation vs CZ-placebo abolished priming effect	R IPS	42	-44	51	Tal	42.42	-47.93	52.98	140	IPL	Inferior Parietal Lobule	R	A40rd, rostrodorsal area 40(PFt)
	Wilson-Mendenhall et al., 2013	arithmetic > convince (ROI analysis based on functional localizer: count > thought)	L IPS/Superior Parietal	-31	-47	37	Tal	-31.31	-50.3	37.61	129	SPL	Superior Parietal Lobule	L	A5l, lateral area 5
			R Middle Frontal Gyrus (dlPFC)	34	34	35		34.34	33.2	39.84	15	MFG	Middle Frontal Gyrus	L	A9/46d, dorsal area 9/46
			R IPS	42	-44	51		42.42	-47.93	52.98	139	IPL	Inferior Parietal Lobule	L	A40rd, rostrodorsal area 40(PFt)
	Huth et al., 2016	locational (cluster)	lateral parietal cortex (angular gyrus)	-36	-78	32	MNI	-36	-78	32	135	IPL	Inferior Parietal Lobule	L	A39c, caudal area 39(PGp)
				-30	-75	37		-30	-75	37	135	IPL	Inferior Parietal Lobule	L	A39c, caudal area 39(PGp)

				45	-68	26		45	-68	26	136	IPL	Inferior Parietal Lobule	R	A39c, caudal area 39(PGp)
				36	-70	39		36	-70	39	138	IPL	Inferior Parietal Lobule	R	A39rd, rostrodorsal area 39(Hip3)
			ventral medial parietal cortex	-9	-62	20		-9	-62	20	151	Pcun	Precuneus	L	dmPOS, dorsomedial parietooccipital sulcus(PEr)
				-8	-55	12		-8	-55	12	181	CG	Cingulate Gyrus	L	A23v, ventral area 23
				-6	-45	9		-6	-45	9	181	CG	Cingulate Gyrus	L	A23v, ventral area 23
				11	-57	17		11	-57	17	152	Pcun	Precuneus	R	dmPOS, dorsomedial parietooccipital sulcus(PEr)
			parahippocampal gyrus	-33	-23	-22		-33	-23	-22	217	Hipp	Hippocampus	R	msOccG, medial superior occipital gyrus
				-29	-39	-13		-29	-39	-13	113	PhG	Parahippocampal Gyrus	L	TL, area TL (lateral PPHC, posterior parahippocampal gyrus)
				30	-25	-21		30	-25	-21	114	PhG	Parahippocampal Gyrus	R	TL, area TL (lateral PPHC, posterior parahippocampal gyrus)
			orbitofrontal cortex	-35	39	-14		-35	39	-14	43	OrG	Orbital Gyrus	L	A12/47o, orbital area 12/47
				31	41	-14		31	41	-14	46	OrG	Orbital Gyrus	R	A11l, lateral area 11
		temporal (cluster)	lateral parietal cortex (angular gyrus)	52	-53	28		52	-53	28	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
				48	-58	25		48	-58	25	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
				-52	-49	45		-52	-49	45	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)
				50	-52	42		50	-52	42	142	IPL	Inferior Parietal Lobule	R	A40c, caudal area 40(PFm)
			R posterior middle temporal gyrus	57	-51	-1		57	-51	-1	86	MTG	Middle Temporal Gyrus	R	A37dl, dorsolateral area37
			ventral medial parietal cortex	-9	-62	20		-9	-62	20	151	Pcun	Precuneus	L	dmPOS, dorsomedial parietooccipital sulcus(PEr)
				-8	-55	12		-8	-55	12	181	CG	Cingulate Gyrus	L	A23v, ventral area 23
				-6	-45	9		-6	-45	9	181	CG	Cingulate Gyrus	L	A23v, ventral area 23
				11	-57	17		11	-57	17	152	Pcun	Precuneus	R	dmPOS, dorsomedial parietooccipital sulcus(PEr)
			R superior prefrontal cortex	12	25	57		12	25	57	2	SFG	Superior Frontal Gyrus	R	A8m, medial area 11
				24	29	44		24	29	44	4	SFG	Superior Frontal Gyrus	R	A8dl, dorsolateral area 8
				20	52	31		20	52	31	20	MFG	Middle Frontal Gyrus	R	A46, area 50
				28	58	7		28	58	7	20	MFG	Middle Frontal Gyrus	R	A46, area 51

		numeric (cluster)	R posterior middle temporal gyrus	57	-51	-1		57	-51	-1	86	MTG	Middle Temporal Gyrus	R	A37dl, dorsolateral area37
			lateral temporal cortex	-57	-56	-1		-57	-56	-1	85	MTG	Middle Temporal Gyrus	L	A37dl, dorsolateral area37
				-48	-64	1		-48	-64	1	97	ITG	Inferior Temporal Gyrus	L	A37vl, ventrolateral area 37
				-54	-59	-9		-54	-59	-9	97	ITG	Inferior Temporal Gyrus	L	A37vl, ventrolateral area 37
				55	-57	-6		55	-57	-6	98	ITG	Inferior Temporal Gyrus	R	A37vl, ventrolateral area 37
			ventral temporal cortex	-43	-48	-14		-43	-48	-14	107	FuG	Fusiform Gyrus	L	A37lv, lateroventral area37
				-50	-55	-14		-50	-55	-14	91	ITG	Inferior Temporal Gyrus	L	A37elv, extreme lateroventral area37
				-45	-59	-11		-45	-59	-11	107	FuG	Fusiform Gyrus	L	A37lv, lateroventral area37
			lateral parietal cortex (angular gyrus)	-52	-49	45		-52	-49	45	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)
				50	-52	42		50	-52	42	142	IPL	Inferior Parietal Lobule	R	A40c, caudal area 40(PFm)
				-25	-72	34		-25	-72	34	209	LOcC	lateral Occipital Cortex	L	lsOccG, lateral superior occipital gyrus
				-31	-65	45		-31	-65	45	137	IPL	Inferior Parietal Lobule	L	A39rd, rostrodorsal area 39(Hip3)
				-30	-75	37		-30	-75	37	135	IPL	Inferior Parietal Lobule	L	A39c, caudal area 39(PGp)
				41	-45	42		41	-45	42	140	IPL	Inferior Parietal Lobule	R	A40rd, rostrodorsal area 40(PFt)
				31	-64	44		31	-64	44	138	IPL	Inferior Parietal Lobule	R	A39rd, rostrodorsal area 39(Hip3)
			superior prefrontal cortex	-19	12	61		-19	12	61	3	SFG	Superior Frontal Gyrus	L	A8dl, dorsolateral area 8
				-27	8	52		-27	8	52	23	MFG	Middle Frontal Gyrus	L	A8vl, ventrolateral area 12
				-22	23	46		-22	23	46	3	SFG	Superior Frontal Gyrus	L	A8dl, dorsolateral area 8
				33	8	52		33	8	52	26	MFG	Middle Frontal Gyrus	R	A6vl, ventrolateral area 6
				28	35	38		28	35	38	16	MFG	Middle Frontal Gyrus	R	A9/46d, dorsal area 9/46
				23	18	50		23	18	50	4	SFG	Superior Frontal Gyrus	R	A8dl, dorsolateral area 8
			orbitofrontal cortex	-35	39	-14		-35	39	-14	43	OrG	Orbital Gyrus	L	A12/47o, orbital area 12/47
				31	41	-14		31	41	-14	46	OrG	Orbital Gyrus	R	A11l, lateral area 11
			inferior prefrontal cortex (inferior precentral/frontal sulcus)	-42	3	40		-42	3	40	63	PrG	Precentral Gyrus	L	A6cvl, caudal ventrolateral area 6
				-46	7	22		-46	7	22	29	IFG	Inferior Frontal Gyrus	L	A44d,dorsal area 44
				-43	8	31		-43	8	31	63	PrG	Precentral Gyrus	L	A6cvl, caudal ventrolateral area 6
				42	11	31		42	11	31	18	MFG	Middle Frontal Gyrus	R	IFJ, inferior frontal junction

				-45	28	19		-45	28	19	31	IFG	Inferior Frontal Gyrus	L	IFS, inferior frontal sulcus
				-44	38	14		-44	38	14	21	MFG	Middle Frontal Gyrus	L	A9/46v, ventral area 9/46
				-41	35	26		-41	35	26	21	MFG	Middle Frontal Gyrus	L	A9/46v, ventral area 9/46
				-41	42	4		-41	42	4	21	MFG	Middle Frontal Gyrus	L	A9/46v, ventral area 9/46
				45	36	15		45	36	15	32	IFG	Inferior Frontal Gyrus	R	IFS, inferior frontal sulcus
	Bechtold et al., 2019	mathematical > mental states/emotions in experts vs non experts	centro-parietal	n.a.			n.a.	n.a.			n.a.	IPL*	Inferior Parietal Lobule	n.a.	n.a.
visual, motor	Harpaintner et al., 2020	motor > visual (whole brain)	L precentral gyrus	-26	-24	66	MNI	-26	-24	66	57	PrG	Precentral Gyrus	L	A4ul, area 4(upper limb region)
			R precentral gyrus	16	-26	66		16	-26	66	60	PrG	Precentral Gyrus	R	A4t, area 4(trunk region)
			R precentral gyrus	26	-24	72		26	-24	72	58	PrG	Precentral Gyrus	R	A4ul, area 4(upper limb region)
			R precentral gyrus	22	-36	70		22	-36	70	162	PoG	Postcentral Gyrus	R	A1/2/3tru, area1/2/3(trunk region)
			L precuneus	-16	-36	68		-16	-36	68	161	PoG	Postcentral Gyrus	L	A1/2/3tru, area1/2/3(trunk region)
			L postcentral gyrus	-42	-12	50		-42	-12	50	53	PrG	Precentral Gyrus	L	A4hf, area 4(head and face region)
			L posterior cingulate cortex	-12	-40	14		-12	-40	14	181	CG	Cingulate Gyrus	L	A23v, ventral area 23
			L thalamus	-18	-28	10		-18	-28	10	239	Tha	Thalamus	L	PPtha, posterior parietal thalamus
		visual > motor (whole brain)	L temporal pole	-36	12	-18		-36	12	-18	43	OrG	Orbital Gyrus	L	A12/47o, orbital area 12/47
			R opercular inferior frontal gyrus	30	4	30		30	4	30	18	MFG	Middle Frontal Gyrus	R	IFJ, inferior frontal junction
			R insula	30	14	-14		30	14	-14	166	INS	Insular Gyrus	R	vIa, ventral agranular insula
			R fusiform gyrus	30	-62	-6		30	-62	-6	106	FuG	Fusiform Gyrus	R	A37mv, medioventral area37
			L lingual gyrus	-20	-44	-8		-20	-44	-8	195	MVOcC	MedioVentral Occipital Cortex	L	rLinG, rostral lingual gyrus
			L fusiform gyrus	-26	-42	-14		-26	-42	-14	103	FuG	Fusiform Gyrus	L	A20rv, rostroventral area 20
			R parahippocampal gyrus	26	-26	-18		26	-26	-18	114	PhG	Parahippocampal Gyrus	R	TL, area TL (lateral PPHC, posterior parahippocampal gyrus)
			R superior temporal gyrus	46	-42	16		46	-42	16	124	pSTS	posterior Superior Temporal Sulcus	R	cpSTS, caudoposterior superior temporal sulcus
violent	Huth et al., 2016	violent (cluster)	lateral parietal cortex (angular gyrus)	-51	-57	23	MNI	-51	-57	23	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-47	-63	34		-47	-63	34	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-53	-54	36		-53	-54	36	141	IPL	Inferior Parietal Lobule	L	A40c, caudal area 40(PFm)

				52	-53	28		52	-53	28	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
				48	-58	25		48	-58	25	144	IPL	Inferior Parietal Lobule	R	A39rv, rostroventral area 39(PGa)
			superior prefrontal cortex	-8	10	65		-8	10	65	7	SFG	Superior Frontal Gyrus	L	A6dl, dorsolateral area 8
				-6	40	46		-6	40	46	11	SFG	Superior Frontal Gyrus	L	A9m,medial area 9
				-9	26	57		-9	26	57	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-5	54	33		-5	54	33	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-6	56	18		-6	56	18	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
				-17	53	29		-17	53	29	15	MFG	Middle Frontal Gyrus	L	A9/46d, dorsal area 9/46
				-8	47	18		-8	47	18	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
				12	25	57		12	25	57	2	SFG	Superior Frontal Gyrus	R	A8m, medial area 11
				7	45	40		7	45	40	12	SFG	Superior Frontal Gyrus	R	A9m,medial area 9
				20	52	31		20	52	31	20	MFG	Middle Frontal Gyrus	R	A46, area 50
			inferior prefrontal cortex (opercularis/triangularis)	-45	37	-7		-45	37	-7	35	IFG	Inferior Frontal Gyrus	L	A45r, rostral area 45
				49	35	-1		49	35	-1	36	IFG	Inferior Frontal Gyrus	R	A45r, rostral area 45
				52	25	13		52	25	13	34	IFG	Inferior Frontal Gyrus	R	A45c, caudal area 45
communal	Huth et al., 2016	communal (cluster)	L lateral parietal cortex (angular gyrus)	-43	-67	24	MNI	-43	-67	24	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-51	-57	23		-51	-57	23	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
				-47	-63	34		-47	-63	34	143	IPL	Inferior Parietal Lobule	L	A39rv, rostroventral area 39(PGa)
			L superior prefrontal cortex	-34	19	48		-34	19	48	23	MFG	Middle Frontal Gyrus	L	A8vl, ventrolateral area 10
				-37	20	42		-37	20	42	23	MFG	Middle Frontal Gyrus	L	A8vl, ventrolateral area 11
				-6	40	46		-6	40	46	11	SFG	Superior Frontal Gyrus	L	A9m,medial area 9
				-9	26	57		-9	26	57	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-5	54	33		-5	54	33	5	SFG	Superior Frontal Gyrus	L	A9l, lateral area 9
				-17	53	29		-17	53	29	15	MFG	Middle Frontal Gyrus	L	A9/46d, dorsal area 9/46
				-6	56	18		-6	56	18	13	SFG	Superior Frontal Gyrus	L	A10m, medial area 10
			frontal opercolum/anterior insula	n.a.	n.a.	n.a.		n.a.	n.a.	n.a.	n.a.	INS*	Insular Gyrus	n.a.	n.a.

Table 2. Neuroimaging and neurophysiological studies with healthy participants, divided for abstract dimension. Conversion from Talairach to MNI coordinates was made with tal2MNI Matlab script. x,y,z MNI coordinates are mapped in the human Brainnetome Atlas (http://atlas.brainnetome.org) (Fan et al., 2016). n.a.= information not available; n.s.= not significant; Tal= coordinates in Talairach reference space; MNI= coordinates in Montreal Neurological Institute reference space; * studies not reporting the coordinates (in this case only the gyrus name was indicated). See the main text for further details.

Appendix B

ABS category	prime (Italian)	prime (English)	target (Italian)	target (English)
Human Actions (ACT)	abbandono	neglect	difesa	defense
	approvazione	authorisation	educazione	education
	assoluzione	absolution	fallimento	default
	carriera	career	inganno	deception
	conflitto	conflict	peccato	sin
	dovere	duty	preghiera	pray
	preparazione	preparation	responsabilità	responsibility
	punizione	punishment	rimedio	remedy
	riduzione	reduction	scoperta	discovery
	salvezza	salvation	seduzione	seduction
	scherzo	joke	tradimento	betrayal
	torto	wrong	vendetta	revenge
Attitudes (ATT)	avarizia	avarice	bellezza	beauty
	differenza	difference	calma	quietness
	disonestà	dishonesty	fascino	charm
	follia	madness	gentilezza	kindness
	forza	strength	importanza	importance
	giustizia	justice	innocenza	innocence
	immortalità	immortality	lealtà	loyalty
	insolenza	insolence	onore	honour
	insufficienza	deficiency	originalità	originality
	mediocrità	mediocrity	pazienza	patience
	merito	merit	stile	style
	virtù	virtue	tolleranza	tolerance
Cognitions (COG)	concetto	concept	curiosità	curiosity
	dimenticanza	forgetfulness	fantasma	ghost
	esitazione	hesitation	fiducia	trust
	filosofia	philosophy	illusione	illusion
	giudizio	judgement	inesperienza	inexperience
	ideale	ideal	invenzione	creation
	incertezza	uncertanty	istinto	instinct
	incredulità	disbelief	mistero	mystery
	logica	logic	scopo	purpose
	principio	principle	sogno	dream
	saggezza	wisdom	sospetto	suspicion
	schema	scheme	talento	talent
Emotions (EM)	disprezzo	disdain	agonia	agony
	fervore	fervour	amarezza	bitterness
	furia	rage	amore	love
	gioia	happiness	entusiasmo	eagerness
	inquietudine	inquietude	esasperazione	exasperation
	ira	anger	invidia	envy
	panico	panic	noia	boredom
	paura	fear	odio	hate
	risentimento	resentment	passione	passion
	simpatia	sympathy	soddisfazione	satisfaction
	sollievo	relief	tristezza	sadness
	tormento	anguish	vergogna	shame

CNC category	prime (Italian)	prime (English)	target (Italian)	target (English)
Biological Entities (BIOL)	alghe	seaweed	albicocca	apricot
	asino	donkey	arancia	orange
	asparago	asparagus	banana	banana
	braccio	arm	cammello	camel
	cane	dog	carota	carrot
	carciofo	artichoke	cavallo	horse
	ciliegie	cherries	cuore	heart
	cipolla	onion	elefante	elephant
	gallina	hen	erba	grass
	gallo	rooster	fragola	strawberry
	giraffa	giraffe	fungo	mushroom
	insalata	salad	gufo	owl
	limone	lemon	insetto	bug
	naso	nose	leone	lion
	noce	walnut	maiale	pig
	oca	goose	mela	apple
	palma	palm	melanzana	aubergine
	pappagallo	parakeet	mucca	cow
	pera	pear	muscolo	muscle
	piccione	pigeon	orso	bear
	pomodoro	tomato	pecora	sheep
	topo	mouse	peperone	pepper
	zebra	zebra	quercia	oak
	zucca	pumpkin	uva	grape
Artefacts (ART)	aereo	airplane	automobile	car
	argento	silver	bicicletta	bicycle
	calzino	sock	cappello	hat
	canoa	canoe	cenere	ash
	casco	helmet	cera	wax
	cemento	cement	cravatta	tie
	coltello	knife	diamante	diamond
	cristallo	crystal	elicottero	helicopter
	cucchiaio	spoon	falce	sickle
	divano	couch	ferro	iron
	forbici	scissors	forchetta	fork
	lampada	bulb	ghiaccio	ice
	martello	hammer	giacca	blazer
	ombrello	umbrella	letto	bed
	pantaloni	trousers	libreria	bookstore
	perla	pearl	matita	pencil
	pistola	gun	pennello	brush
	polvere	dust	poltrona	armchair
	scrivania	desk	sabbia	sand
	sedia	chair	scarpa	shoe
	stivale	boot	scopa	broom
	trattore	tractor	specchio	mirror
	uniforme	uniform	tavolo	table
	veleno	poison	trapano	drill

Table 1. List of the experimental stimuli.

Concrete vs abstract nouns	**t-test**	
Variable	**t**	**p**
Written frequency (from COLFIS database)	1.637	.103
Number order of the sense (from Multi Word Net)	0.451	.652
Concreteness (CNC) (from Della Rosa et al., 2010)	-65.879	**< .001**
Imageability (IMG) (from Della Rosa et al., 2010)	-40.735	**< .001**
Abstractness (ABS) (from Della Rosa et al., 2010)	-54.543	**< .001**
Context availability (CA) (from Della Rosa et al., 2010)	-25.555	**< .001**
Age of acquisition (AoA) (from Della Rosa et al., 2010)	-17.331	**< .001**
Mode of acquisition (MoA) (from Della Rosa et al., 2010)	23.148	**< .001**

Table 2. Variables used in the selection of the experimental stimuli, and results of the independent samples t-tests comparing abstract and concrete nouns.

Experimental stimuli conditions and lists

In the abstract domain, the Same Category condition included 48 pairs (i.e., 12 EM-EM, 12 ACT-ACT, 12 ATT-ATT, 12 COG-COG) and the Different Category condition included a total of 144 pairs (i.e. 36 X-EM, 36 X-ACT, 36 X-ATT, 36 X-COG) resulting from the combination of each target category with the other three remaining prime categories (i.e. 12 ATT-EM, 12 ACT-EM, 12 COG-EM; 12 EM-ACT, 12 ATT-ACT, 12 COG-ACT; 12 EM-ATT, 12 ACT-ATT, 12 COG-ATT; 12 EM-COG, 12 ACT-COG,12 ATT-COG). The category membership conditions were organized in six lists, each one presented to 6 participants, and divided into two experimental sessions in a counterbalanced way. Each list contained 24 word pairs of the Same Category condition and 24 word pairs of the Different Category condition. Within each list, the Same and Different conditions included word pairs belonging only to two categories, with categories never overlapping between the two conditions (i.e. SAME: 12 pairs EM-EM and 12 pairs COG-COG; DIFFERENT: 12 pairs ACT-ATT and 12 pairs ATT-ACT). The full rotation of combinations of categories in the SAME or DIFFERENT conditions is reported in Table 3.

In the concrete domain, the Same Category and Different Category conditions included 48 pairs each (i.e., Same Category: 24 BIOL-BIOL and 24 ART-ART; Different Category: 24 ART-BIOL and 24 BIOL-ART). Same and Different Category conditions in the concrete domain were organized in two pseudorandomised lists in the sense that if a prime preceded a target of the same category in one list, it appeared before a different category target in the other list (e.g., *pera-GUFO* in list 1, *pera-SCARPA* in list 2). Each list contained 24 pairs of the Same Category (i.e., 12 BIOL-BIOL and 12 ART-ART) and 24 pairs of the Different Category condition (i.e., 12 ART-BIOL and 12 BIOL-ART). The two lists were presented to half of the participants (n=18) and each list was divided between two experimental sessions in a counterbalanced way.

List number	***Same***	***Different***
list 1	COG-COG	ACT-ATT
	EM-EM	ATT-ACT
list 2	ATT-ATT	EM-COG
	ACT-ACT	COG-EM
list 3	ATT-ATT	ACT-COG
	EM-EM	COG-ACT
list 4	ATT-ATT	EM-ACT
	COG-COG	ACT-EM
list 5	ACT-ACT	EM-ATT
	COG-COG	ATT-EM
list 6	ACT-ACT	ATT-COG
	EM-EM	COG-ATT

Table 3. Lists with the full rotation of combinations of abstract categories.

We matched the 12 words used in the Same Word Condition (listed in Table 4 below) with both prime and target words belonging to the 6 categories in the Same Category condition for number of letters (prime: all p-values > .884; target: p-values= 1) and frequency (prime: all p-values= 1; target: p-values > .151), as in Wheatley et al., 2005.

Domain	***word (Italian)***	***word (English)***
Abstract	Legge	law
	Stupore	astonishment
	Funzione	function
	Preferenza	preference
	Suggestione	suggestion
	Indifferenza	indifference
Concrete	Sole	sun
	latte	milk
	barba	beard
	scuola	school
	pescatore	fisherman
	labirinto	maze

Table 4. List of the stimuli used in the Same Word Condition.

LB Regions	corr. level	semantic / control sensitivity	BM Regions	Behavioural Domain			control type mean	LB - BM
				Label	P (activation|domain)	domain specificity		
semantic regions								
L anterior fusiform gyrus	0.92	1.00	FuG_L_3_1	Cognition.Language.Semantics Cognition.Language.Speech Cognition.Memory.Explicit	3.08 1.98 1.95	1.51 0.97 0.80	1.00	0.00
L posterior MTG	0.33	0.13	pSTS_L_2_2	Cognition.Language.Speech Cognition.Language.Orthography Cognition.Language.Semantics Cognition.Language.Syntax Perception.Audition	4.32 2.84 2.51 2.38 1.68	3.33 2.19 1.94 1.84 0.17	1.00	-0.86
L pars opercularis/ triangularis (BA44/45)	0.43	0.06	IFG_L_6_3	Cognition.Memory.Explicit Cognition.Language.Semantics Cognition.Language.Syntax Cognition.Language.Speech	3.84 3.55 2.20 1.65	1.77 2.52 1.56 1.17	1.00	-0.94
L pars orbitalis (IFG, BA47)	-0.70	0.83	OrG_L_6_6	Emotion Cognition.Language.Semantics Cognition.Memory.Explicit	1.90 1.46 1.44	na 0.32 0.44	1.00	-0.17
R angular gyrus	0.33	0.33	IPL_R_6_1	Cognition.SocialCognition Perception.Vision.Shape Perception.Vision.Motion Cognition.Space	2.55 2.29 2.18 2.07	0.13 1.37 1.31 0.11	1.00	-0.67
L middle frontal gyrus	0.22	-0.11	MFG_L_7_1	Action.Inhibition Cognition.SocialCognition	2.68 2.13	0.19 0.06	1.00	-1.11
L anterior hippocampus	0.50	0.50	Hipp_L_2_1	Emotion.Sadness Perception.Gustation Emotion.Disgust Emotion.Happiness Emotion Emotion.Fear Perception.Olfaction Cognition.Memory.Explicit	4.88 4.49 3.51 3.32 3.17 2.75 2.34 1.50	2.11 0.30 1.51 1.16 na 1.19 0.16 0.40	0.83	-0.33
L angular gyrus	0.17	0.00	IPL_L_6_5	Emotion Cognition.Language Cognition Cognition.Memory.Explicit Cognition.SocialCognition	3.47 2.69 1.87 1.46 1.36	na 0.73 na 0.52 0.14	0.83	-0.83
L posterior-lateral fusiform gyrus, L ITG	0.50	0.89	FuG_L_3_3	Cognition.Language.Speech Cognition.Language Cognition.Language.Orthography Cognition.Language.Phonology Cognition.Language.Semantics Perception.Vision.Shape	2.89 2.56 2.56 2.24 2.06 1.51	2.79 2.47 2.47 2.16 1.99 0.45	0.80	0.09
R lateral occipital area	1.00	1.00	OcG_R_4_4	Perception.Vision.Shape Perception.Vision Cognition.Space Cognition.Language.Orthography	3.20 2.76 2.25 1.72	1.92 1.66 0.12 0.38	0.75	0.25
R anterior fusiform gyrus	1.00	1.00	FuG_R_3_3	Cognition.Language.Orthography Emotion.Anger Interoception.Sexuality Cognition.Language Action.Observation Cognition.Space Perception.Vision Cognition.Language.Semantics Emotion.Fear Perception.Vision.Shape	3.91 3.57 2.75 2.32 2.23 2.11 1.94 1.93 1.83 1.58	2.12 0.88 0.05 1.26 0.06 0.09 1.05 1.05 0.45 0.85	0.75	0.25
R posterior-medial fusiform gyrus	0.00	0.75	FuG_R_3_2	Perception.Vision Cognition.Language Emotion.Fear Perception.Vision.Shape Action.MotorLearning	3.86 2.82 2.47 2.46 1.86	2.12 0.51 0.31 1.35 0.07	0.75	0.00
L middle ATL	-0.33	0.83	MTG_L_4_2	Cognition.SocialCognition Cognition.Language	10.97 4.92	1.15 1.34	0.67	0.16
R precuneus	0.00	0.60	Pcun_R_4_4	Cognition.SocialCognition Cognition.Memory.Explicit	3.11 2.45	0.33 0.87	0.67	-0.07

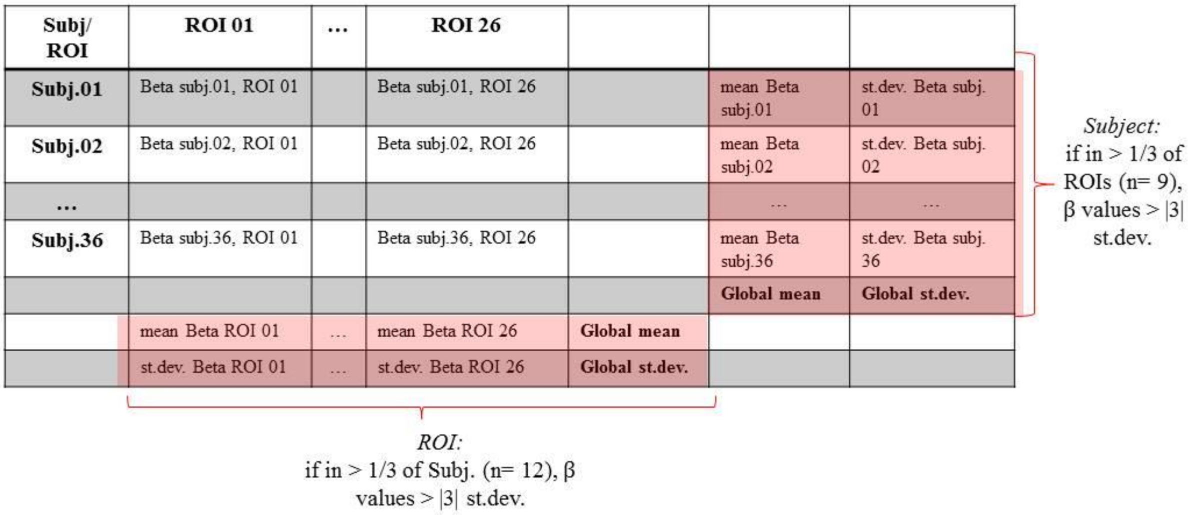
L superior frontal gyrus	-0.10	0.10	SFG_L_7_3	Cognition.Memory.Explicit Emotion Cognition.SocialCognition	4.97 2.24 2.14	1.50 na 0.11	0.67	-0.57
control regions								
L dorsolateral PFC	0.17	0.00	MFG_L_7_2	Cognition.Language.Phonology Cognition.Language.Semantics Cognition.Memory.Explicit Cognition.Memory.Working	1.82 1.80 1.63 1.45	0.99 0.98 1.16 1.03	-0.60	0.60
R posterior superior temporal gyrus	1.00	1.00	IPL_R_6_6	Action.Execution Perception.Somesthesis Perception.Somesthesis.Pain	3.89 3.27 2.05	2.22 3.60 2.26	-1.00	2.00
L supramarginal gyrus	0.00	0.42	IPL_L_6_6	Action.Execution Perception.Audition Perception.Somesthesis Perception.Somesthesis.Pain	3.20 2.63 1.68 2.18	1.83 0.39 1.93 2.51	-1.00	1.42
R pars opercularis/ triangularis (BA44/45)	0.33	1.00	IFG_R_6_1	Cognition.Reasoning Cognition.Attention	2.35 1.52	0.25 0.16	-1.00	2.00
R caudate nuclues	0.50	1.00	Str_R_6_1	Cognition Perception.Gustation Emotion	3.36 2.86 2.51	na 0.10 na	-1.00	2.00
L dorsomedial PFC	0.75	0.50	SFG_L_7_6	Cognition.Memory.Explicit	1.71	0.52	-1.00	1.50
anterior cingulate cortex	0.11	-0.22	CG_L_7_3	Perception.Gustation Emotion.Sadness Perception.Somesthesis.Pain Cognition Emotion	2.95 2.45 2.19 1.86 1.83	0.20 0.37 1.24 na na	-1.00	0.78
R pars triangularis (IFG, BA45)	0.00	-1.00	IFG_R_6_5	Cognition.Time Perception.Somesthesis.Pain	3.28 2.14	0.09 1.18	-1.00	0.00
R supramarginal gyrus	1.00	-1.00	IPL_R_6_4	Interoception.Bladder Cognition.Attention Perception.Vision.Motion Action.Execution Perception.Somesthesis.Pain Action.Inhibition	2.99 2.46 2.10 1.98 1.43 1.37	na 0.03 0.63 1.13 0.86 0.10	-1.00	0.00
L dorsal angular gyrus	1.00	-1.00	IPL_L_6_2	Cognition.Space Cognition.Reasoning Cognition.Memory.Working	2.29 2.06 1.88	0.36 0.33 0.77	-1.00	0.00
L caudate nuclues	-1.00	-1.00	Str_L_6_5	Cognition Emotion	1.91 1.78	na na	-1.00	0.00

Table 5. Characterization of the 15 semantic and 11 control regions by means of the Literature-Based (LB) approach (columns in orange), the information in the BrainMap (BM) databases (columns in blue), and the Semantic-Control differential measure (LB-BM columns in pink).
For example, consider the left anterior fusiform gyrus. According to LB information, it had a correction level index of 0.92, indicating that activity in this region mostly survived voxel level correction and a semantics/control sensitivity index value of 1, thus suggesting the region's involvement in semantics. In BM database, the region, named 'FuG_L_3_1', is mainly involved in Cognition and Language, and had a control type mean of 1, indicting a high specificity in semantic paradigms. The region displayed a Semantic control differential value of 0, which indicated the concordance between LB and BM information.

Outliers screening

Outliers screening was divided into two steps. First, we calculated the mean BOLD signal in beta images (n= 20: 10 beta images x 2 sessions) in each ROI (n= 26) (columns) for each subject (n= 36) (rows), thus obtaining a subjects (row) (n=36) X region (columns) (n= 26) matrix including BOLD signal estimates extracted for all betas relative to all conditions of interest (n= 20 x subject).

Second, we calculated 1) the mean (e.g., mean Beta s1) and standard deviation (e.g., st.dev. Beta s1) for each subject across all the ROIs; 2) the mean and standard deviation for each ROI across all subjects. Third we calculated the global mean and standard deviation relative to 1) all subjects (n= 36) and 2) ROIs (n= 26). Subjects were excluded if beta values were above or below 3 standard deviations from the global mean in more than 1/3 of the ROIs (n> 9). ROIs were excluded if beta values were above or below 3 standard deviations from the global mean in more than 1/3 of the subjects (n> 12). See Figure 1 below.



Subj/ ROI	**ROI 01**	**…**	**ROI 26**			
Subj.01	Beta subj.01, ROI 01		Beta subj.01, ROI 26		mean Beta subj.01	st.dev. Beta subj. 01
Subj.02	Beta subj.02, ROI 01		Beta subj.02, ROI 26		mean Beta subj.02	st.dev. Beta subj. 02
…					…	…
Subj.36	Beta subj.36, ROI 01		Beta subj.36, ROI 26		mean Beta subj.36	st.dev. Beta subj. 36
					Global mean	**Global st.dev.**
	mean Beta ROI 01	…	mean Beta ROI 26	**Global mean**		
	st.dev. Beta ROI 01	…	st.dev. Beta ROI 26	**Global st.dev.**		

Subject:
if in > 1/3 of ROIs (n= 9), β values > |3| st.dev.

ROI:
if in > 1/3 of Subj. (n= 12), β values > |3| st.dev.

Figure 1. Illustration of the outliers screening procedure.

			Same Category- Same Word			**Different Category- Same Word**		
ROI			*mean difference*	*standard error*	*p-value*	*mean difference*	*standard error*	*p-value*
SFG_L_7_3	ABS	CNC	-22.786	897.982	0.98	-40.655	897.982	0.964
	CNC	ABS	22.786	897.982	0.98	40.655	897.982	0.964
SFG_L_7_6	ABS	CNC	-0.233	897.982	1.00	-114.932	897.982	0.898
	CNC	ABS	0.233	897.982	1.00	114.932	897.982	0.898
MFG_L_7_1	ABS	CNC	298.686	897.982	0.739	-234.317	897.982	0.794
	CNC	ABS	-298.686	897.982	0.739	234.317	897.982	0.794
MFG_L_7_2	ABS	CNC	-3.355	897.982	0.997	3.277	897.982	0.997
	CNC	ABS	3.355	897.982	0.997	-3.277	897.982	0.997
IFG_R_6_1	ABS	CNC	2.253	897.982	0.998	3.09	897.982	0.997
	CNC	ABS	-2.253	897.982	0.998	-3.09	897.982	0.997

IFG_L_6_3	ABS	CNC	66.122	897.982	0.941	-5.995	897.982	0.995
	CNC	ABS	-66.122	897.982	0.941	5.995	897.982	0.995
IFG_R_6_5	ABS	CNC	210.594	897.982	0.815	58.042	897.982	0.948
	CNC	ABS	-210.594	897.982	0.815	-58.042	897.982	0.948
OrG_L_6_6	ABS	CNC	67.078	897.982	0.94	16.808	897.982	0.985
	CNC	ABS	-67.078	897.982	0.94	-16.808	897.982	0.985
MTG_L_4_2	ABS	CNC	-2754.627	897.982	0.002*	-51.927	897.982	0.954
	CNC	ABS	2754.627	897.982	0.002*	51.927	897.982	0.954
FuG_L_3_1	ABS	CNC	3407.684	897.982	<0.001*	401.489	897.982	0.655
	CNC	ABS	-3407.684	897.982	<0.001*	-401.489	897.982	0.655
FuG_R_3_2	ABS	CNC	37.17	897.982	0.967	-323.383	897.982	0.719
	CNC	ABS	-37.17	897.982	0.967	323.383	897.982	0.719
FuG_L_3_3	ABS	CNC	419.941	897.982	0.64	-403.912	897.982	0.653
	CNC	ABS	-419.941	897.982	0.64	403.912	897.982	0.653
FuG_R_3_3	ABS	CNC	-40.831	897.982	0.964	180.978	897.982	0.84
	CNC	ABS	40.831	897.982	0.964	-180.978	897.982	0.84
pSTS_L_2_2	ABS	CNC	-29.169	897.982	0.974	-17.303	897.982	0.985
	CNC	ABS	29.169	897.982	0.974	17.303	897.982	0.985
IPL_R_6_1	ABS	CNC	297.478	897.982	0.740	-48.172	897.982	0.957
	CNC	ABS	-297.478	897.982	0.740	48.172	897.982	0.957
IPL_L_6_2	ABS	CNC	-4.755	897.982	0.996	-3.96	897.982	0.996
	CNC	ABS	4.755	897.982	0.996	3.96	897.982	0.996
IPL_R_6_4	ABS	CNC	-4.958	897.982	0.996	8.645	897.982	0.992
	CNC	ABS	4.958	897.982	0.996	-8.645	897.982	0.992
IPL_L_6_5	ABS	CNC	-40.492	897.982	0.964	69.074	897.982	0.939
	CNC	ABS	40.492	897.982	0.964	-69.074	897.982	0.939
IPL_L_6_6	ABS	CNC	-167.557	897.982	0.852	-953.385	897.982	0.288
	CNC	ABS	167.557	897.982	0.852	953.385	897.982	0.288
IPL_R_6_6	ABS	CNC	-236.99	897.982	0.792	20.236	897.982	0.982
	CNC	ABS	236.99	897.982	0.792	-20.236	897.982	0.982
Pcun_R_4_4	ABS	CNC	-18.801	897.982	0.983	-3.09	897.982	0.997
	CNC	ABS	18.801	897.982	0.983	3.09	897.982	0.997
CG_L_7_3	ABS	CNC	21.512	897.982	0.981	-111.517	897.982	0.901
	CNC	ABS	-21.512	897.982	0.981	111.517	897.982	0.901
OcG_R_4_4	ABS	CNC	-206.962	897.982	0.818	227.183	897.982	0.8
	CNC	ABS	206.962	897.982	0.818	-227.183	897.982	0.8
Hipp_L_2_1	ABS	CNC	60.173	897.982	0.947	6.519	897.982	0.994
	CNC	ABS	-60.173	897.982	0.947	-6.519	897.982	0.994
Str_R_6_1	ABS	CNC	-49.651	897.982	0.956	170.946	897.982	0.849
	CNC	ABS	49.651	897.982	0.956	-170.946	897.982	0.849
Str_L_6_5	ABS	CNC	-1507.982	897.982	0.093	78.113	897.982	0.931
	CNC	ABS	1507.982	897.982	0.093	-78.113	897.982	0.931

Table 6. Results of the three-way CONDITION x DOMAIN x ROI interaction. * = significant effects, bonferroni-corrected.

Appendix C

Quantità	**Quantity**	**Sociale**	**Social**
accrescimento	growth	alleanza	alliance
accumulo	accumulation	altruismo	altruism
addizione	addition	competizione	competition
allargamento	widening	complotto	plot
carenza	lack	cospirazione	conspiracy
carico	burden	diffamazione	defamation/slander
catasta	stack	dispetto	prank
cumulo	heap	dissenso	dissent
decremento	decrease	emarginazione	marginalization
dilatazione	dilatation	etnia	ethnicity
diminuzione	drop	fascino	charm
enormità	hugeness	gentilezza	kindness
espansione	expansion	infamia	infamy
estensione	extension	lusinga	flattery
frazione	fraction	nomea	reputation
grandezza	size	notorietà	notoriety
grossezza	thickness	offesa	offence
immensità	immensity	patto	pact
incremento	increase	plebe	mob/plebs
ingrandimento	enlargement	relazione	relation
massa	mass	rivalità	rivalry
mole	amount	scherzo	joke
penuria	paucity	servitù	slavery
porzione	section/portion	sfacciataggine	cheek
quintale	quintal	socievolezza	sociability
riduzione	reduction	sudditanza	subjection
stazza	breadth	tradizione	tradition
tonnellata	ton/tonne	venerazione	veneration

Table 1. List of the experimental stimuli

Behavioural control experiment

The aim of this behavioural control experiment was to evaluate the nature of the priming effect. Priming effects found in the control condition of the TMS experiment (faster congruent vs incongruent conditions), could in fact derive either from a positive priming, namely a facilitation of RTs for primed targets (i.e., congruent trials), or from a negative priming, namely slowing down RTs for unprimed targets (i.e., incongruent trials). Thus, a neutral condition in which the prime had no semantic meaning and consisted of the symbol “#” was included in the experiment.

The 56 quantity and 56 social words of the Behavioural Pilot Study were used (see the main text for details). In total we created 112 trials for each of the three conditions, namely 112 congruent (i.e., QUANTITY label - quantity target and SOCIAL label - social target), 112 incongruent (i.e., QUANTITY label - social target and SOCIAL label - quantity target) and 112 neutral (i.e., neutral prime (#) - quantity target and neutral prime (#) - social target) conditions. On half of the neutral trials, the number of symbols was the same as the number of letters of the Italian word “quantità” (i.e., the prime, namely eight symbols); on the other half, it was the same as the number of letters of the Italian word “sociale” (i.e., seven symbols).

Trials were presented in a randomized order among participants and the timeline of the experimental trial, as well as the task, were identical to the main TMS experiment.

Six healthy right-handed participants were tested (3 females; mean age 30.3 years, sd= 6.8; mean education= 17.5 years, sd= 3); none of them had participated in the other experimental sessions.

The inclusion criterion for data analysis was the presence of the priming effect, i.e. faster reaction times for congruent compared to incongruent trials. For quantity and social categories five and six subjects, respectively, showed this pattern and were consequently included. Data on reaction times were analysed following the same procedures used for the pilot studies and for the main TMS experiment (see main text for details). Separate analyses were performed for quantity and social categories.

For quantity target stimuli, the mean RTs in the three conditions were: congruent condition: 746 ms (sd= 124); incongruent condition: 781 ms (sd=132); neutral condition: 782 ms (sd= 145). A repeated measure ANOVA, with prime congruency (congruent, incongruent and neutral conditions) as within factor was carried out and revealed a significant main effect (F= 5.091, p= .037). Pairwise comparisons indicated a facilitation of RTs in congruent compared to neutral condition (t= -3.496, p= .025). On the contrary, no difference was found between incongruent and neutral conditions (t= -.048, p= .964). Taken together, these results supported the presence of positive priming effect for quantity category.

For social target stimuli, the mean RTs in the three conditions were: congruent condition: 765 ms (sd= 127); incongruent condition: 815 ms (sd=158); neutral condition: 810 ms (sd= 164). A repeated measure ANOVA, with prime congruency (congruent, incongruent and neutral conditions) as within factor was carried out and revealed a significant main effect (F= 6.300, p= .017). Pairwise comparisons indicated a facilitation of RTs in the congruent compared to the neutral condition (t= -2.651, p= .045). On the contrary, no difference was found between incongruent and neutral conditions (t= .450, p= .672). As reported for the quantity category, also for the social category the presence of positive priming effect emerged.

In summary, these results converged in indicating that, for both categories, the priming effect was explained by a positive priming, namely a facilitation for exemplars of the primed category, rather than by a negative priming, namely an interference for exemplars of the unprimed category.

Accuracy results

Table 2 reports the mean accuracy values, separately for each condition and stimulation sites. A ceiling effect is present for the social, but not for the quantity category.

	quantity			social		
	Vertex	sATL	IPS	Vertex	sATL	IPS
mean (%)	90.18	87.95	86.88	96.43	98.13	97.32
st.dev.	6.84	7.12	7.78	2.92	2.17	2.90

Table 2. Mean (%) and standard deviation (sd) of the two categories for each site.

A repeated measures ANOVA was applied on the mean accuracy values, separately for social and quantity categories, with stimulation site as within factor, and considering only the subjects displaying priming effect in the control condition. For the social category, the main effect of site was not significant (F(2)= 2.848, p= .069, η=.119). In contrast, a significant main effect of site was present for the quantity category (F(2,38)= 3.645, p= .036, η=.161). Pairwise comparisons with Holm-Bonferroni-correction revealed significant difference between Vertex and IPS (i.e., lower accuracy during IPS stimulation) (t(19)= 2.829, p= .011, corrected-p= .022, corrected-α= .025), but not between Vertex and ATL (t(19)= 1.732, p= .099, corrected-p= .099, corrected-α= .05).

For the social category, the effects of TMS were found only on RTs, but not on accuracy. The lack of significant results on accuracy is probably due to the presence of a ceiling effect.

The TMS modulation of accuracy found in the case of IPS site stimulation for quantity is in line with RTs results. The overall lower accuracy for the quantity category, when compared to the social one, suggest that the task is more difficult task, and thus more susceptible to TMS interference.

Additional analyses for the whole subject sample

We ran additional analyses including all subjects, with the priming effect (i.e., faster reaction times in congruent compared to incongruent condition) found in the control condition used as between factor.

Table 3 reports the mean of the effects for each site (Vertex, sATL and IPS) and for each group of participants (namely showing or not showing a priming effect in the control condition).

CATEGORY – group	Vertex	sATL	IPS
QUANTITY - no priming in Vertex	85.323	34.442	-3.768
QUANTITY – priming in Vertex	-69.743	-24.574	6.963
SOCIAL - no priming in Vertex	31.015	22.547	-20.068
SOCIAL – priming in Vertex	-33.636	31.571	10.265

Table 3: mean of the effects for each site (Vertex, sATL, IPS) and for each group of participants (showing or not a priming effect in the Vertex).

A repeated measure ANOVA on the priming effect, with TMS site (Vertex, sATL, IPS) as within subject factor and the presence of priming effect in the control condition as between factor was performed separately for quantity and social categories.

For the quantity category, the main effect of the presence of priming was significant (F(1,32)= 15.805, p< .001, η=.331; error(32)= 7182.178), whereas the effect of TMS site was not significant (F(2,64)= .076, p= .927, η=.002; error(64)= 4166.366). A significant interaction between TMS site and the presence of the priming effect (F(2,64)= 13.698, p< .001, η=.300) was also present. Holm-Bonferroni corrected (Holm, 1979) pairwise comparisons (control site vs IPS and control site vs sATL) were run separately for the subjects manifesting the priming effect and for those not manifesting the priming effect in the control condition. In the first sample, IPS stimulation, but not sATL stimulation, abolished the priming effect present in Vertex. In fact, a significant difference emerged between Vertex and IPS site (t(19)= -4.080, p= .001, corrected-p= .002, corrected-α= .025, Cohen’s d= .912), but not between Vertex and sATL site (t(19)= -1.909, p= .071, corrected-p= .071, corrected-α= .05, Cohen’s d= .427). Also in the second sample, a significant difference emerged between Vertex and IPS (t(13)= 4.139, p= .001, corrected-p= .002, corrected-α= .025, Cohen’s d= 1.106), but not between Vertex and sATL sites (t(13)= 1.796, p= .096, corrected-p= .096, corrected-α= .05, Cohen’s d= .480). In this case, however, a reduction of the adaptation effect present in the Vertex was found for both the IPS and the ATL, but was significant only for the former site.

For the social category, the effect of TMS site (F(2,64)= 2.602, p= .082, η=.075; error(64)= 3658.592) and the presence of the priming effect (F(1.32)= .492, p= .488, η= .015; error(32)= 3365.162) were not significant, whereas the interaction between TMS site and the presence of the priming effect (F(2,64)= 5.272, p= .008, η=.141) was significant. Pairwise comparisons with Holm-Bonferroni correction were run separately for the subjects with and without the priming effect. In the first group, both the sATL and IPS stimulations abolished the priming effect present in Vertex, with differences emerging between Vertex and sATL (t(21)= -3.227, p= .004, corrected-p= .008, corrected-α= .025, Cohen’s d= .689) and between Vertex and IPS (t(21)= -2.806, p= .011, corrected-p= .011, corrected-α= .05, Cohen’s d= .598). In the second group, no significant differences were found between Vertex and, respectively, IPS (t(11)= 2.222, p= .048, corrected-p= .096, corrected-α= .025, Cohen’s d= .641), and sATL (t(11)= .476, p= .643, corrected-p= .643, corrected-α= .025, Cohen’s d= .138), with both the ATL and the IPS showing a non significant reduction of the adaptation effect of the Vertex.

Summarizing, the results using all the subjects and the priming effect as a further variable in the analyses are consistent with the results found only for subjects showing a priming effect in the Vertex. Considering the subjects not showing a priming effect in the control condition, both the IPS and the ATL reduced the adaptation effect found on the Vertex for both stimulus categories.

Appendix D

same category condition			different category condition				target (ITA)	target (EN)
prime (ITA)	**prime (EN)**	**pair category**	**prime (ITA)**	**prime (EN)**	**pair category**			
delfino	dolphin	ANI-ANI	cacciavite	screwdriver	TOL-ANI	X-ANI	balena	whale
ippopotamo	hippopotamus		talento	talent	SOC-ANI		cammello	camel
libellula	dragonfly		zappa	hoe	TOL-ANI		farfalla	butterfly
colomba	dove		accetta	hatchet	TOL-ANI		gabbiano	seagull
cane	dog		tranquillità	tranquillity	EM-ANI		gatto	cat
leopardo	leopard		fama	fame	SOC-ANI		pantera	panther
cavallo	horse		penuria	shortage	QU-ANI		pecora	sheep
elefante	elephant		imbarazzo	embarrassment	SOC-ANI		rinoceronte	rhinoceros
gallina	hen		abbondanza	abundance	QUA-NI		tacchino	turkey
leone	lion		mestizia	grief	EM-ANI		tigre	tiger
agnello	lamb		fobia	phobia	EM-ANI		vitello	veal
lupo	wolf		addizione	addition	QUA-NI		volpe	fox
accetta	hatchet	TOL-TOL	orizzonte	horizon	QU-TOL	X-TOL	ascia	axe
coltello	knife		agnello	lamb	ANI-TOL		forchetta	fork
sega	saw		patto	deal	SOC-TOL		martello	hammer
temperino	sharpener		ilarità	hilarity	EM-TOL		matita	pencil
cucchiaio	spoon		tormento	torment	EM-TOL		mestolo	ladle
zappa	hoe		vastità	vastness	QU-TOL		piccone	pickaxe
fucile	rifle		seduzione	seduction	SOC-TOL		pistola	gun
mannaia	cleaver		porzione	portion	QU-TOL		scure	ax
pugnale	dagger		gallina	hen	ANI-TOL		spada	sword
pettine	comb		cordialità	cordiality	SOC-TOL		spazzola	brush
pinza	pliers		ribrezzo	disgust	EM-TOL		tenaglia	tong
cacciavite	screwdriver		delfino	dolphin	ANI-TOL		trapano	drill
ilarità	hilarity	EM-EM	mannaia	cleaver	TOL-EM	X-EM	allegria	cheerfulness
trepidazione	trepidation		calo	drop	QU-EM		fermento	turmoil
felicità	happiness		coltello	knife	TOL-EM		gioia	joy
angoscia	anguish		pettine	comb	TOL-EM		panico	panic
fobia	phobia		scarsità	scarcity	QU-EM		paura	fear

tormento	torment		gruppo	group	SOC-EM		persecuzione	persecution
rabbia	anger		cane	dog	ANI-EM		rancore	grudge
ribrezzo	disgust		libellula	dragonfly	ANI-EM		repulsione	repulsion
tranquillità	tranquillity		comitiva	crowd	SOC-EM		serenità	serenity
dolore	pain		scherno	mockery	SOC-EM		sofferenza	suffering
sorpresa	surprise		decremento	decrease	QU-EM		stupore	amazement
mestizia	grief		lupo	wolf	ANI-EM		tristezza	sadness
addizione	addition	QU-QU	sgarbo	discourtesy	SOC-QU	X-QU	aggiunta	insertion
penuria	shortage		sorpresa	surprise	EM-QU		carenza	lack
decremento	decrease		dolore	pain	EM-QU		diminuzione	reduction
vastità	vastness		rabbia	anger	EM-QU		enormità	enormity
grandezza	size		interazione	interaction	SOC-QU		grossezza	thickness
porzione	portion		elefante	elephant	ANI-QU		metà	half
abbondanza	abundance		temperino	sharpener	TOL-QU		moltitudine	multitude
ammasso	heap		sega	saw	TOL-QU		mucchio	pile
scarsità	scarcity		cucchiaio	spoon	TOL-QU		piccolezza	smallness
ascesa	ascent		ippopotamo	hippopotamus	ANI-QU		rialzo	increase
calo	drop		leopardo	leopard	ANI-QU		ribasso	decline
orizzonte	horizon		coesione	cohesion	SOC-QU		traguardo	goal
cordialità	cordiality	SOC-SOC	grandezza	size	QU-SOC	X-SOC	affabilità	friendliness
patto	deal		felicità	happiness	EM-SOC		alleanza	alliance
comitiva	crowd		leone	lion	ANI-SOC		combriccola	gang
gruppo	group		trepidazione	trepidation	EM-SOC		comunità	community
coesione	cohesion		colomba	dove	ANI-SOC		condivisione	sharing
scherno	mockery		pinza	pliers	TOL-SOC		derisione	derision
seduzione	seduction		ascesa	ascent	QU-SOC		fascino	charm
fama	fame		pugnale	dagger	TOL-SOC		gloria	glory
interazione	interaction		angoscia	anguish	EM-SOC		incontro	meeting
talento	talent		fucile	rifle	TOL-SOC		merito	merit
sgarbo	discourtesy		ammasso	heap	QU-SOC		torto	wrong
imbarazzo	embarrassment		cavallo	horse	ANI-SOC		vergogna	shame

Table 1. List of the experimental stimuli for the word-word pairs.