The Neural Representation of Polysemy: the Case of Dot-objects

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Abstract

Abstract and concrete concepts are generally considered fundamentally distinct categories. However, many concepts have both concrete and abstract senses, for instance *book* can refer to both a physical object (as in *a torn book*) and the abstract content (as in *an interesting book*). How is the meaning of such concepts represented in the brain? In this thesis, we address this question in the light of Pustejovsky's dot-object hypothesis (Pustejovsky, 1995, 2011). According to the hypothesis, words such as *book* and *lunch* are dot-objects: a class of logically polysemous words which have multiple senses that are closely bound together. As a result of the close binding, both senses can be accessed simultaneously (as in *read the book*), however sometimes only a single aspect is emphasised by the context (e.g. *the book burned, he summarised the book*).

We argue that the complex meanings of the dot-objects are represented and manipulated in semantic hubs in the brain, where all aspects of conceptual knowledge converge and are represented in a modality-independent manner (thus accommodating diverse aspects of knowledge such as that cakes are made of pastry and are related to both birthdays and diabetes).

We present three experiments investigating the neural representation of three dot-object categories with clear concrete and abstract senses: print matter such as *book* (OBJECT • INFORMATION), meal concepts such as *lunch* (FOOD • EVENT), and institution such as *church* (BUILDING • ORGANISATION). In all the experiments, participants read the dot-objects in a minimal context which elicited either the concrete or the abstract interpretation (e.g. *open the book / consult the book, cook the lunch / organise the lunch*). We found the neural distinction between the concrete and abstract interpretations of the dot-objects differed from the concrete-abstract distinction observed for mono-sense nouns; instead the differential effect was most evident in the anterior temporal lobe (ATL), an area argue to be the semantic hub.

The result suggests that 1) the distinct senses of a dot-object are associated with a single, unspecified structure in the mental lexicon, thus aligning with the dot-object theory; 2) when in context, the semantic representation is specified by instantiation to a particular sense. In addition, we also observed variations between the *book*-like and the *lunch*-like dot-objects, suggesting a graded representation mechanism within the ATL. Finally the third experiment showed that the MEG gamma-band frequency power could distinguish the neural correlates of the concrete and abstract interpretations; notably the divergence occurred 400ms and later post-stimulus onset. Given the established role in the literature of the gamma-band in integration processes, we conclude that the meaning instantiation only occurred at the later integration stage.

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Problem description

Entities in the world generally fall into two categories: concrete and abstract. Concrete concepts (e.g. *chair*, *apple*) usually have rich sensory-motor properties and are easy to imagine, whereas abstract concepts (e.g. *justice*, *idea*) are considered to be heavily dependent on our language experience (Paivio, 1986, 1991; Schwanenflugel & Stowe, 1988; Wiemer-Hasting & Xu, 2005; Vigliocco et al., 2009). Neuroimaging studies support this intuition: the areas most activated by concrete concepts are regions related with processing multimodal information, while the neural correlates of abstract concepts largely overlap with the areas involved in general language processing (D'Esposito et al., 1997; Wise et al., 2000; Jessen et al., 2000; Grossman et al., 2002; Noppeney & Price, 2004; Binder et al., 2005; Sabsevitz et al., 2005; Wang et al., 2010, 2012).

Yet one subtlety which has been largely neglected thus far is that many so-called polysemous words have both concrete and abstract senses. A well-known example is the word *book*, which can refer to both a physical object (e.g. *burn the <u>book</u>*) and its abstract content (e.g. *believe the <u>book</u>*) (Pustejovsky, 1995; Jackendoff, 1997).

Caramazza & Grober (1976) identified twenty-six senses of another polysemous word, line, including a concrete and continuous mark sense, as in gas line, a line of trees, and many other abstract senses, as in <u>*line*</u> *of reasoning*, <u>*line*</u> *of business*.

In fact, malleable concepts such as *book* and *line* are pervasive in daily life. In particular for some of them like *book*, the multiple senses are linked by certain logical relations and exhibit ambiguity in a systematic manner, a phenomenon termed *logical polysemy* (or *regular polysemy*, *systematic polysemy*) in linguistics (e.g. Apresjan, 1973; Cruse, 1986; Copestake & Briscoe, 1995; Pustejovsky 1995; Jackendoff, 1997). For instance, the concrete and the abstract sense of *book*, along with others such as *catalogue* and *magazine*, are linked by the relation that the print matters hold information (Pustejovsky, 1997). Some other words such as *church, hospital, school*, can in turn refer to the organisation and/or the building/location the organisation is located. Other examples include words refer to food and/or the event of eating (e.g. *lunch, dinner*), to the livestock and/or the meat (e.g. *chicken, lamb*), among many others.

Interestingly for some logically polysemous words, the distinct senses are even more closely related and can be perfectly accessed in one expression, a phenomenon called ***co-predication*** in the linguistic parlance. This phenomenon is intensively studied in Pustejovsky's Generative Lexicon (GL) framework. Considering the examples (1a-1c) below taken from Asher & Pustejovsky (2006). By contrast, some words refer to utterly unrelated things, i.e. homonyms. For instance the word bank cannot refer to both the financial institution and the river bank at the same time, thus the sentence of example (1d) is not acceptable. What is more, for some other logical polysemous words like lamb and chicken, co-predication is also problematic (1e).

(1)

a. *The book was a huge pain to lug home and turned out to be very uninteresting.*

b. *Lunch was delicious but took forever.*

c. *The Sunday newspaper weighs 5 lbs and documents in depth the economic news of the week.*

d. **The bank specializes in IPO's and is being quickly eroded by the river.*

e. **The lamb is cute and delicious.*

In order to account for the co-predication phenomenon, Pustejovsky proposed that such words as in (a-c) are dot-objects: the distinct senses are coherently bound together via a "dot" operator, resulting in a complex concept that allows for co-predication (i.e. both senses can be accessed simultaneously) as well as meaning shifting (i.e. only one aspect of the meaning is emphasised) (Pustejovsky 1995, 2011; Asher & Pustejovsky, 2006). The meaning of *book*, for instance, can be seen as a dot-product of a concrete object component and an information component (OBJECT • INFORMATION). When the context selects a more specific sense (e.g. *the book burned*, or *I summarized the book for her*), a process called *coercion-by-dot-exploitation takes place.* Some other classic examples of dot-objects are listed below adapted from Pustejovsky's work.

(2)

a. PHYSICAL_OBJECT • INFORMATION: *book, catalogue*

b. FOOD • EVENT: *lunch, dinner*

the lunch was delicious but took forever.

c. LOCATION • SOCIAL _GROUP: *hospital, church*

People gathered in front of the church to protest against its decision.

d. PHYSICAL _OBJECT • LIQUID: *bottle*

John grabs the bottle and drinks it.

e. PROCESS • STATE: *examination, arrival*

The party will begin after John's flamboyant arrival.

It is not yet known whether all polysemous words are treated in the brain in the same way, but the phenomenon of co-predication strongly suggested that the different senses of a dot-object are associated with a single lexical entry in the mental lexicon. A handful of psycholinguistic studies have looked at the intricate relation between the sense components of the dot-objects. Srinivasan & Snedeker (2011) studied four-year-old children who had only limited meta-linguistic abilities (e.g. they were unable to count the number of words in a sentences; they do not realise the relation between a word form and the meanings), and found the children could understand the concrete and abstract senses of the *book*-like concepts equally well. As a result they argued that the two senses had a common mental representation. Frisson (2015) conducted a reaction-time and an eye-tracking experiment on comprehending the *book*-like words in a concrete or an abstract context. The results also suggested that the concrete and abstract senses were equivalent. For instance in the eye-tracking experiment, no facilitating effect was found when a sense was repeated as in typical ambiguity resolution, implying that the two senses of *book*-like words had an even closer relation than other typical polysemy.

What are the neural representations of the dot-objects such as *book* and *lunch*? In this thesis, we examined three dot-object categories which contain both a concrete and an abstract sense component using functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG). We positioned the dot-objects in a minimal concrete or abstract context, i.e. a verb-noun phrase (e.g. *open the book* / *consult the book*; *cook the lunch* / *organise the lunch*). The information print matter category (i.e. the *book*-like concepts) and the meal category (i.e. the *lunch*-like concepts) were examined in two fMRI experiments respectively. Specifically, we compared the neuroanatomical distinction between the dot-objects that were coerced into the concrete and the abstract interpretation to the typical, mono-sense concrete and abstract concepts. In another experiment, we investigated the oscillatory neural dynamics of reading those verb-noun phrases through MEG, with an emphasis on the timing of coercion.

The central question addressed by the fMRI experiments is whether the coerced concrete and abstract senses of dot-objects are represented in the brain differently to mono-sense concrete and abstract concepts. And if so, what are the differences? First, if the neural distinction between the coerced dot-objects is similar to the typical concrete-abstract distinction, we can speculate that the mental representation of a dot-object is a simple combination of the two sense components, and each component can be accessed independently a mental representation more close to the one of homonyms (Fig. 1.1). Conversely, if the concrete- and abstract-coerced dot-objects yield a different neural distinction from the typical one, it is more likely that the meaning of a dot-object is represented as a whole in semantic memory and a biasing context will render the on-line meaning shift into different directions (Fig. 1.1).

The single lexical entry hypothesis pertaining to polysemy indeed predicts the second scenario. Furthermore according to the Generative Lexicon theory of Pustejovsky, word meanings are encoded as an underspecified structure, i.e. the *qualia* structure, which contains the essential meaning components and enables flexible interpretations of the word in different contexts. In the case of dot-object and coercion-by-dot-exploitation, it can be seen as a more specific interpretation is unpacked by selecting a subset of the concepts qualia (Fig. 1.2). In terms of neural representation, this underspecified structure seems to mirror the general, overall semantic knowledge about entities, including not only the sensory-motor properties but also the abstract knowledge about facts, associations with other entities in the world, and so forth.

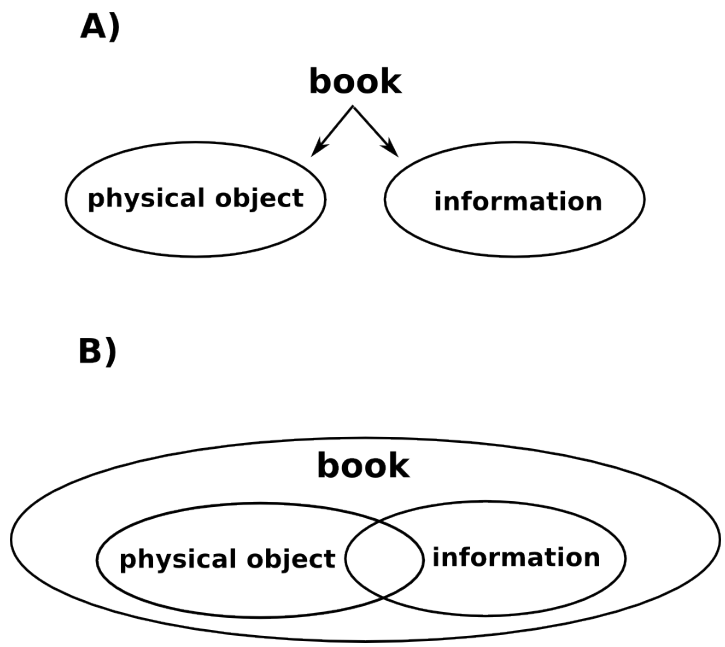

Figure 1.1: The graphical depictions of the two hypothetical models for the mental representation of the dot-objects. A. The dot-object *book* is a simple combination of the two sense components, and each component can be accessed independently (similar to the multiple-lexical-entry model pertained to homonyms). B. The dot-object is represented as a single underspecified structure, as the single-lexical-entry hypothesis predicts. Both senses can be accessed simultaneously and a biasing context will render the on-line meaning shift into different directions.

It has been recently proposed in neuroscience that there are some semantic hubs in the brain that are responsible for this high-level, modality-independent concept knowledge (Patterson et al., 2007; Binder & Desai, 2011; Lambon Ralph, 2014). The anterior temporal lobe (ATL) has been the spotlight in this line of arguments. The ATL is initially noted in studies with semantic dementia (SD) patients. Lesions in the bilateral ATL lead to loss of concept knowledge across all categories and all modalities. Interestingly one of the typical symptoms of SD is the impairment of specific conceptual knowledge, for instance the SD patients usually have more difficulty in basic-level concepts like *dog*, *chair* compared to the more general concepts like *animal*, *furniture* (e.g. Hodges et al., 1996; Rogers, et al., 2006; Patterson et al., 2007; Wright et al., 2015). The sensitivity of the ATL to specific concept knowledge has

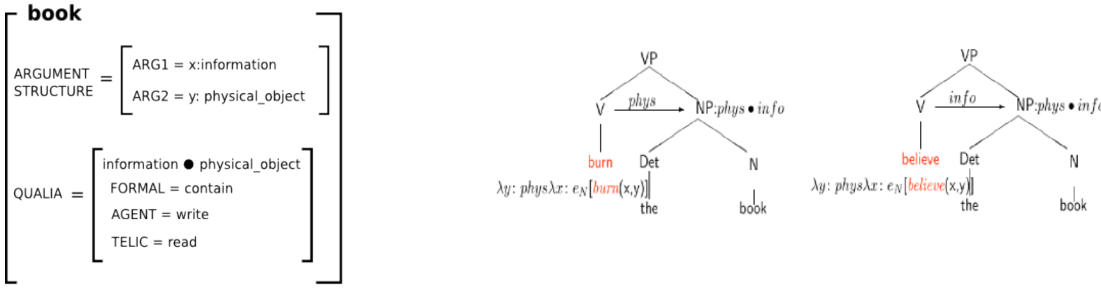

Figure 1.2: Left: The sample schema of the *book* dot-object in the Generative Lexicon Framework (adapted from Pustejovsky, 1997). Right: The depictions of the concrete and the abstract coercion (cit. Pustejovsky).

also been found with healthy subjects in neuroimaging experiments (e.g. Tyler et al., 2004; Rogers et al., 2006; Clarke & Tyler, 2014).

In this thesis, we also would like to emphasise the interaction between semantic composition and lexical semantics. The meaning representation of a word in the long-term memory and the on-line meaning retrieval are typically treated as separate components. Yet we argue that the word meaning in fact largely determines what compositional processing can happen. As to dot-objects, the semantic composition plays an even more defining role than to the unambiguous concepts. To illustrate, *book* can be an object and/or the abstract information, and the appropriate interpretation has to be determined in the context (e.g. *a torn book / a difficult book, pick up the book / explain the book*). By contrast, meanings of the simple concepts (e.g. *pick up the flower / explain the plan*) rely less on semantic composition, in other words, the meaning of flower or plan in the above examples rarely depends on the context.

1.2 Thesis outline

In this thesis we investigated the implications of the single lexical entry hypothesis in regard to the neural representations of both concrete and abstract concepts. We use functional magnetic resonance imaging (fMRI) as well as magnetoencephalography (MEG) to probe the meaning representation of dot-objects as well as the coercion mechanism in the brain. FMRI gives snapshots based on the oxygen level of the blood in the brain. The snapshot images of the brain can have millimetre spatial resolution, which allows us to paint a fine-grained picture of the neuroanatomical profiles of the meaning representation. However the hemodynamic responses fMRI measures are rather slow, therefore the time resolution of fMRI is usually about several seconds. MEG, on the other hand, measures the electro-physiological activities of the neurons. It has a temporal resolution of millisecond, which provides a different angle to answer the research question.

Given the prominent distinction between concrete and abstract concepts, we selected the dot-object categories which clearly had a concrete and an abstract sense. Firstly we studied the most representative category, information print matter (OBJECT • INFORMATION), such as *book* and *magazine*. During the fMRI experiments, participants read the polysemous words in a minimal context, i.e. a verb-noun phrase, which elicited either the concrete or the abstract interpretation (e.g. *open the book* / *consult the book*). The second fMRI experiment investigated another classic dot-object category, meal concepts (FOOD • EVENT) including *lunch* and *dinner*. We followed the same approach of the first experiment that the dot-object words were put in a concrete or an abstract verbal context (e.g. *cook the lunch* / *organise the lunch*). The results of both experiment are consistent with the linguistic hypothesis that that the meaning of a dot-object concept is stored as a single complex structure, or qualias in Pustejovsky's word; when in context, the meaning is coerced into a more specific representation. Finally we examined three dot-object categories together in the MEG experiment. Besides the two categories examined with fMRI, we chose another dot-object category, institution (BUILDING • ORGANISATION), including words such as *school* and *church*. We focused on the oscillatory neural dynamics during reading the dot-object words in context.

We probe the concrete-abstract distinction by examining where, when, and how (i.e. in which frequency band) the abstract and the concrete senses of dot-objects can be discriminated using multivariate pattern analysis (MVPA). In the two fMRI experiments, we examined where in the brain they could be distinguished. Despite some discrepancies between the two categories, both experiments pointed to the anterior temporal lobe (ATL). Given the role of ATL in modality-independent concept representation and concept specification, we argue that the results are compatible with the linguistic hypothesis that, (1) the representation of those concepts involves a single, underspecified structure; (2) in context, the representation instantiates to a more specific one.

The MEG experiment, in turn, highlighted the gamma-band frequency in differentiating the different kinds of semantic composition (i.e. concrete vs. abstract, coercion vs. non-coercion). The gamma-band has been indicated in a variety of combinatorial processes, including sentence comprehension (Weiss et al., 2003; Hald et al., 2006; Penolazzi et al., 2009), world knowledge retrieval (Hagoort et al., 2004), perceptual and conceptual feature binding (Matsumoto & Lidaka 2008; Friese et al., 2012), and so forth. Moreover the gamma-band activity patterns of the concrete- and abstract-coerced dot-objects diverged not before 400ms post-stimulus onset, suggesting that coercion took place not only after the lexical knowledge retrieval but also the initial semantic integration.

1.3 Road-map

The next chapter gives a comprehensive review on related research about 1) concept representation, focusing on the neural distinction between concrete and abstract concepts and the semantic-hub theory; and 2) the neural mechanism of comprehending polysemy and semantic composition. We also briefly introduce the background of neuroimaging and multivariate pattern analysis (MVPA). In chapter 3, we present the fMRI experiment on the dot-object category of OBJECT • INFORMATION. Chapter 4 presents the second fMRI experiment on the other dot-object category, FOOD • EVENT. In chapter 5 we present the MEG experiment in which three dot-object categories were examined. At last we conclude our investigation in chapter 6 and provide a general discussion.

Chapter 2

Related Work

How word meanings are represented in the brain is a central topic of concept representation. In this thesis we address this issue by investigating the meaning representation of logical polysemy in the brain. First, we review the research on the neural representation of concepts and the more semantic hub theory, followed by a throughout overview in section two of the neural distinction between concrete and abstract concepts in psychology, neuropsychology and cognitive neuroscience. In section three we turn to the psycholinguistic research on comprehending polysemy and coercion, then in section four we extend the review into semantic composition as it is the crucial mechanism of ambiguity resolution. In the last section we provide a brief introduction of neuroimaging methods and multivariate pattern analysis (MVPA).

2.1 The neurobiology of concept representation

How entities are organised in the mind has also been the central issue of cognitive science since its early times (e.g. Rosch 1973, 1975; Rosch et al., 1976; Rosch & Mervis, 1975, 1981; Medin & Smith, 1984; Murphy & Medin, 1985). Early psychologists have identified the basic level categories that have a superior status in human conceptual system (Brown 1958, 1965; Kay 1971, Rosch et al., 1976). Basic level entities, such as *dog, chair*, are first learned by children, most frequently used in everyday life, and possesse "an ideal balance between internal similarity and external distinctiveness" (cit. Ungerer & Schmid, 2006). Following Wittgenstein's family resemblances theory, Rosch & Mervis (1975) proposed the prototype theory that objects in the world were organised as clusters centred on prototypes, e.g. *robin* as the prototype for *bird*, *apple* as the prototype for fruit.

Patients with category-specific deficits have shed great light on the neural basis of human concept system. Warrington & Shallice (1984) documented four patients that showed a discrepancy between their ability to identify inanimate objects, living things, and food, and they reasoned that the concepts were categorised in the mind based on features. For instance living things are mostly represented by their visual features whereas inanimate objects such as *hammer* and *chair* are characterised more by their functional features. The author further argued that features of different modalities were stored in modality-specific sub-systems in the brain. By contrast, some have argued for a domain-specific account, stating that these category-specific deficits arise from the evolutionary value of the categories themselves (Caramazza & Shelton, 1998; Caramazza & Mahon 2003; Capitani et al., 2003).

This issue has also been intensively examined in neuroimaging experiments with healthy subjects. Although the underpinning mechanism remains a matter of debate, a concept knowledge map in the brain starts to emerge (Martin et al., 1995; Chao et al., 1999; Ishai et al., 1999; Martin & Chao, 2001; Haxby et al., 2001; Bookheimer, 2002; Thompson-Schill, 2003; Martin, 2007; Mahon et al., 2007; Binder et al., 2009; Fairhall & Caramazza 2013; Bruffaerts et al., 2013). Studies contrasting living and non-living things consistently showed that living things tended to activate the medial ventral temporal lobe while non-living things were more lateral (e.g. Chao et al., 1999; Perani et al., 1999). Among non-living things, the tool category reliably activated the posterior lateral temporal lobe, and it has been showed that this regions is also sensitive to knowledge of action and verb reading (Martin et al., 1995; Chao et al., 1999; Perani et al., 1999; Bedny et al., 2008; Binder et al., 2009; Peelen et al., 2012). Two highly specific areas were also identified: the fusiform face area (FFA), which is a small area in the medial fusiform gyrus that is particularly sensitive to face stimuli (Kanwisher et al., 1997), and the parahippocampal place area (PPA), an area in the posterior parahippocampus that shows high sensitivity to building as well as large objects (the parahippocampal place area, PPA) (Aguirre et al.,1996; Ishai et al., 1999; Konkle & Oliva, 2012).

Nevertheless the research above emphasises the sensorimotor aspects of concept knowledge but does not take into account the extremely rich body of high-level, modality-independent knowledge about entities as well as abstract concepts. With respect to the neural basis of such knowledge, the semantic hub theories have achieved much progress recently (Rogers et al., 2004; Patterson et al., 2007; Binder & Desai, 2011; Lambon Ralph, 2014). The core of the theories is that there is a "hub" (or hubs) in the brain in which such modality-independent knowledge is stored and manipulated.

The anterior temporal lobe (ATL) has been the centre of the semantic hub hypothesis. Lesions in the ATL lead to loss of concept knowledge across all categories and modalities, and severely impair specific concept knowledge (Hodges et al., 1996; Warrington, 1975; Breedin et al., 1994; Damasio et al., 1996; Hodges & Patterson 1996; Mummery et al., 2000; Nestor et al., 2006; Lambon Ralph et al., 2010a, 2010b; Wright et al., 2015). Similar effects have been replicated with healthy subjects using fMRI and TMS (e.g. Gorno-Tempini & Price, 2001; Tyler et al., 2004; Rogers et al., 2006; Spitsyna et al., 2006; Pobric et al., 2007; 2010a; 2010b; Binney et al., 2010; Visser et al., 2010; Peelen & Caramazza, 2012). To account for this phenomenon, some proposed the "spokes-and-hub" model (Rogers et al., 2004; 2006; Patterson et al., 2007; Lambon Ralph, et al., 2010a; Lambon Ralph, 2015). As the name suggests, the "spokes-and-hub" model consists of multiple modality-specific yet interconnected subregions distributed in the brain, i.e. the spokes, and the single "hub", i.e. the ATL, that is shared by the spokes and represents modality-independent concept knowledge. The authors argued that this model could account for the various observations of semantic deficits that a a-hub model would fail to explain. Rogers et al. (2004) constructed a computational model based on this framework and it could predict the patient data. The model learned a variety of features such as visual, functional, and encyclopedic, and the features were fused in the hub to form a modality-independent representation. Critically, cross-modality generalisation was done via the hub, for instance when given an object name, the system has to go through the hub to retrieve the other information such as the shape, colour, function, and so on. Lambon Ralph et al. (2010) also highlighted the computational nature of the ATL. The authors tested six semantic dementia patients ranging from mild to severe semantic impairment, with a new assessment which emphasising the underneath modality-independent knowledge rather than surface similarity. As the semantic hub theory predicted, they found the more severe the semantic impairment was, the more the patients relied on the surface similarity.

Another potential hub location is the angular gyrus, which rests on the junction of the parietal, temporal, and occipital lobe. Similar to the "spokes-and-hub" model, Binder & Desai (2011) proposed a multi-level representation architecture which included a high-level, modality-independent convergence hub. The authors examined a large number of neuroimaging studies; in the meta-analysis of Binder et al., 2009, the authors examined 120 neuroimaging studies of semantic processing, and revealed seven major semantic regions across the brain. For instance the left inferior frontal gyrus (IFG) was shown to play a crucial role in language production and various combinatory processing, and the posterior cingulate cortex (PCC) and the precuneus were related to the episodic memory retrieval and mental imagery during language processing. Different from the "spokes-and-hub" architecture, however, their hub in Binder & Desai (2011) stretched from the angular gyrus (AG), the posterior middle temporal lobe, to the ATL. In particular, they underlined the role of the angular gyrus in receiving and integrating information from various modality-specific cortices, and it might played a crucial part in representing complex event concepts like *birthday party*.

2.2 The distinction between abstract and concrete concepts

2.2.1 Hypotheses in psychology

The concreteness effect is a well-established phenomenon in psychology: concrete concepts are easier to remember, learned earlier by children, and processed faster with different psychological experiment paradigms. There are two major hypotheses that have been proposed to account for the concreteness effect. One is the influential Dual-Coding Theory (DCT), which was initially framed by Paivio in the 1970s based on a series behavioural experiment. DCT ascribes the concreteness effect to the fact that concrete concepts are more prone to evoke mental imagery and supported by their rich sensorimotor properties and real world experience (Paivio, 1986, 1991). Alternative to DCT, Schwanenflugel and colleagues proposed the Context Availability hypothesis, arguing that abstract concepts relied more on their contextual associations whereas the concrete concepts depended more on their intrinsic properties. Therefore when given sufficient contextual information, the concreteness effect could be eliminated (Schwanenflugel & Stowe, 1988; Schwanenflugel et al., 1992). These two hypotheses have been subjected to numerous investigations in psychology and cognitive neuroscience (e.g. Breedin et al.1994; Kounios and Holcomb, 1994; Holcomb et al., 1999;

Altarriba 1999; Jesson et al., 2000; Binder et al., 2005; Wiemer-Hastings and Xu, 2005; Crutch & Warrington 2005; Adorni & Proverbio,2012). Although they are not mutually exclusive, the majority results corroborate the claims of the Dual-Coding theory.

Opposed to the viewpoint that abstract concepts are elusive and fully dependent on language, the embodied view of concept representation argues that abstract concepts are also underpinned by concrete knowledge. The pioneering embodied theory toward abstract concept is the metaphor account described in Lakoff & Johnson (1980). They analysed the linguistic usage of abstract words, and argued that the way we comprehend abstract concepts is we projecting the abstract concepts into the concrete domain so as to draw inference from our concrete experience. According to this theory, for example, we understand time as property thus it can be lost and gain, and anger is something can be built up, explode and distinguish. This theory is also supported by some neuroimaging evidence (Borodistsky & Ramscar, 2002; Gibbs 2006; Desai et al., 2011, 2013). Another influential embodied theory, the Grounding cognition views conceptual knowledge as multimodal and dynamic (Barsalou, 2003, 2008). For instance, the meaning of *dog* consists of not only the look, the barks, the touch of the fur, but also our life experiences with them and the encyclopedic knowledge we learned about dogs. Therefore the mental representation of the concept dog is a result of all those multimodal information and involves a widespread distribution of brain regions. Taken this approach, the embodied theory extends the DCT, suggesting that abstract concepts are also represented in a multimodal fashion, albeit the internal states such as introspective properties and situational information play a more important role (Barsalou 1999, 2003, 2008; Barsalou & Wiemer-Hastings, 2005; Wiemer-Hastings & Xu, 2005). For example in the property-generation experiment reported in Wiemer-Hasting & Xu (2005), participants generated more properties about mental experience and social context for abstract concepts compared to concrete concepts. Vigliocco and colleagues focused the affective factor for abstract concepts. According to their hypothesis, experiential information, language and emotion all serve as crucial dimensions of concept knowledge. Given the fact that abstract concepts are lack of reliable sensorimotor properties, they argued that emotion played the principal role in representing abstract concepts (Vigliocco et al., 2009, 2014; Kousta et al., 2009, 2011).

2.2.2 Evidence from cognitive neuropsychology

Evidence from lesion studies supports the intuition that concrete and abstract concepts differ qualitatively. Double-dissociation of concrete and abstract concepts has been found in patients with semantic deficit (Warrington 1975, 1981; Warrington & Shalice, 1984). A reversed concreteness effect with semantic dementia (SD) patients has been frequently reported (e.g. Breedin et al., 1994; Yi et al., 2007; Bonner et al., 2009; Macoir 2009; Pagagno et al., 2009). Many ascribed the reversed concreteness effect to the gross lost of sensorimotor concept features due to the lesions in the anterior temporal lobe. Yet Crutch & Warrington (2005) found patient evidence supporting an alternative account that the concrete-abstract distinction lied in their different organising principles. The patient of Crutch and Warrington suffered from semantic refractory access dysphasia, a neuromodulatory disorder; the typical phenomena included response inconsistency, reversed word frequency effect, and greater sensitivity to the semantic relatedness. Crutch and Warrington observed a double-dissociation: the patient seemed to lose the ability of perceiving semantic relatedness among abstract concepts (e.g. *deceit, trick, steal, cheat*) whereas this effect was preserved for concrete concepts (e.g. *goose, pigeon, crow, sparrow*), on the other hand the reversed pattern was seen with semantic associations (e.g. abstract: *exercise, healthy, fitness, jogging*; concrete: *farm, cow, tractor, barn*). This finding mirrored the results from studies with healthy subjects that concrete concepts are more self-sustained whereas abstract concepts more rely on associations (e.g. Wiemer-Hastings & Xu, 2005)

2.2.3 Evidence from cognitive neuroscience

The distinction between concrete and abstract concepts has also been found with healthy subjects in cognitive neuroscience studies. Consistent to the Dual-Coding theory, the overall result suggests that concrete concepts involve a wide distribution of multimodal brain areas while the abstract concepts largely overlap with the language areas. Nevertheless the observations seem to vary significantly across studies depending on the specific experimental design and stimulus, implying that this neural distinction is the result of the interplay of many factors.

EEG/ERP

The N400 component is the main manifestation of the concreteness effect in ERP. Compared to abstract concepts, concrete concepts typically evoke an anterior-distributed N400, sometimes accompanied by a late frontal negativity and/or N700. N400 is the most consistent ERP component associated with language process and particularly with the semantic respect. Initially it was identified with processing semantic violation (Kutas & Hillyard, 1980, 1984), but it also showed in various paradigms including referring real world knowledge (e.g. Hargoot, 2003; Kuperberg et al., 2008); animate violation (e.g. Paczynski et al., 2006). The typical N400 effect is widespread across the scalp with a central-parietal tendency; however the N400 for concreteness has a more anterior distribution (e.g. Kounios & Holcomb, 1994; Holcomb et al., 1999). West & Holcomb (2000) found that the late negativity, namely N700, was most eminent when participants were instructed to generate mental imagery, arguing that the N700 effect was associated with mental imagery. Welcome et al. (2011) and Adorni & Proverbio (2012) also demonstrated that imagery-based, multimodal knowledge had a crucial contribution to the concreteness effect (but see Barber et al. (2013) for a different argument that N400 and N700 observed for concrete concepts reflected the difference in the level of processing and meaning activation).

Neuroimaging

Neuroimaging experiments (fMRI as well as PET) demonstrated that concrete and abstract concepts are underpinned by at least partially different neural circuits. By and large abstract concepts are mainly associated with language system, including the left inferior frontal gyrus and the superior temporal lobe, whereas concrete concepts activate a distribution of bilateral multimodal brain regions that are responsible for representing object knowledge and mental imagery. For instance, DEsposito et al. (1997) found the left posterior inferior temporal gyrus (pITG) was more activated when the participants actively imagined concrete objects than when they passively listened to abstract words. Wise et al. (2000) examined with PET the neural activities associated with viewing and hearing nouns that varied in imageability, and found the activity in the left mid-fusiform gyrus increased with increasing noun imageability regardless of the presentation modality, whilst the right Superior Temporal Gyrus (STG) showed the reversed effect. Grossman et al. (2002) used abstract words as a neutral probe to investigate the animate vs. inanimate distinction, and found both words for implements and abstract concepts recruited the left posterolateral temporal cortex and the left prefrontal cortex, whereas animal words activated the ventral-media occipital area. The results imply that abstract concepts contain little sensorimotor information and rely tremendously on the verbal system. Jesson et al. (2000) used an encode-recall paradigm to examine the concreteness effect. The left inferior frontal gyrus (IFG), namely Brocas area, was shown to be activated by abstract concepts while concrete concepts recruited a broader bilateral network including the left anterior IFG (more anterior than the Brocas area identified in the same study), the lower bilateral parietal lobe, the posterior cingulated gyrus and the precuneus. Binder et al. (2005) also compared the fMRI activities of reading concrete and abstract words with a lexical decision task, and the results corroborated the Dual Coding theory: reading concrete concepts involved both hemisphere while abstract concepts was almost confined in the left hemisphere. Moreover concrete concepts recruited the bilateral posterior cingulate gyrus and the precuneus, which were associated with mental imagery. Yet the temporal lobe was surprisingly absent in that study. Sabsevitz et al. (2005) later conducted a similar experiment but in which participants judged the semantic similarity instead of judging word or non-word, and indeed the concrete concepts additionally activated the ventral temporal lobe. Therefore they argued that the lexical decision task in Binder et al. (2005) did not elicit sufficient semantic knowledge to activate the temporal lobes (see similar proposal in Kan et al. (2003) with property verification task).

Indeed different task demands and stimulus choices seem to influence the observed neural activities. For example, though there is little dispute over the role of the precuneus in mental imagery (hence for concrete concept representation), DEsposito et al. (1997) identified the precuneus was more activated by the abstract condition. The reason seems to lie in their task manipulation that actively generating mental images of objects in fact de-activated the precuneus, since the precuneus is also part of the neural default-mode network which is more active during mind-wandering. Fiebach & Friederici (2004) argued that the different strategies adopted by the participants for concrete and abstract concepts resulted in the neural distinction. Consequently they conducted a lexical-decision experiment (by which they argued the task demands were equal for both concrete and abstract conditions), and found effects in the left hemisphere only. Pexman et al. (2007) looked into the issue of ambiguity based on the hypothesis that abstract concepts are intrinsically more ambiguous. They included both ambiguous and unambiguous words. In contrast to typical findings, the abstract condition activated a more widespread activation and no regions was found for the concrete > abstract comparison.

To our knowledge, there are two meta-analyses concerning the concrete-abstract neural distinction. Binder et al. (2009) analysed 120 neuroimaging studies of semantic processing. The contrast between concrete / perceptual vs. abstract / verbal knowledge revealed a widespread distribution of perceptual foci, including the bilateral angular gyrus, the left mid-fusiform gyrus, the left dorsomedial prefrontal cortex (DMPFC), the left precuneus / posterior cingulate cortex (PCC); on the other hand the verbal foci included the left inferior frontal gyrus (IFG) and the left superior temporal sulcus (STS). Wang et al. (2010) conducted a meta-analysis with 19 neuroimaging studies on the topic of concrete-abstract neural distinction. They found the traditional language processing regions were robustly activated more by abstract concepts, including the left IFG, mid-superior temporal gyrus (M/STG). Meanwhile the left precuneus, posterior cingulated gyrus, fusiform gyrus, and the parahippocampal were identified for the concrete > abstract effect. Wang and colleagues further carried out a study with multivariate analysis (MVPA), a more sensitive analysis approach, and showed that the concrete-abstract distinction could be found across the whole brain, suggesting that the distinction was more profound than previous presumed.

2.3 Polysemy and coercion

So far we have summarised the research on neurobiology of concept representation and the neural distinction between concrete and abstract concepts. As the review shows, most experiments in this field are done with simple concepts and on the single-word level. In this thesis, we look into a more complex scenario in which concept meanings shift depending on the context. Specifically we investigate this issue by means of logical polysemy, i.e. dot-objects. In the current section, we review neurolinguistic evidence about polysemy comprehension and coercion. And in the next section, we extend the review to the neural mechanism of semantic composition in general, including not only language processing but also concept combination.

2.3.1 Polysemy and homonymy are represented differently in the brain

Most words in nature language are ambiguous but in many different ways. Linguists and lexicographers have made an important dichotomy between two types of ambiguity. Homonyms like *bat* have multiple unrelated meanings (e.g., nocturnal mouse-like mammal with forelimbs modified to form membranous wings and a club used for hitting a ball in various games). In such cases, the distinct meanings are taken to be the expression of distinct entries in the mental lexicon, i.e. different words that accidentally share the same word form. Such cases are contrasted with polysemies like mouth, that also have multiple, but related senses (e.g., the opening through which food is taken in and vocalizations emerge and an opening that resembles a mouth, e.g., of a cave). The distinction between homonymy and polysemy is not always easy to make, but linguists and lexicographers agree that at least in the clearest cases, polysemous words are associated with a single lexical entry whose conceptual meaning encodes the different senses (Lyons, 1977; Cruse, 1986; Ravin & Leacock, 2000; Taylor, 2003).

There is quite a bit of psychological evidence supporting the single lexical entry hypothesis concerning the meaning representation of polysemy; conversely the different meanings of homonyms are considered as multiple separate entries (Frazier & Rayner, 1990; Williams et al., 1992; Klepousniotou, 2002; Rodd et al., 2002; Beretta et al., 2005; Pylkkanen et al., 2006; Bedny et al., 2007; Srinivasan & Snedeker, 2011).

Note that following the convention, we say a polysemous word has multiple SENSES whereas a homonymous word has multiple MEANINGS. Frazier & Rayner (1990) showed their subjects homonyms like *bank* or polysemous words like *newspaper* followed by disambiguating context. They observed lexical garden paths (manifested by longer reading time) if the following context was not consistent with the most frequent interpretation of the homonym; however no such effect was observed for polysemous words. The result was taken as evidence that the multiple senses of a polysemous word were associated with a single lexical entry, as opposed to homonyms that consist of multiple entries and all but one of which were discarded after disambiguation (Swinney, 1979; Tanenhaus et al, 1979). Rodd et al. (2002) observed an ambiguity advantage that ambiguous words were processed faster and easier; importantly the advantage was only for polysemy and absent for homonymy. The authors reasoned that polysemy was facilitated by the rich semantic associations linked to one lexical entry, on the other hand the multiple lexical entries of homonyms generated competition. Evidence for this single lexical entry hypothesis was also obtained using magnetoencephalography (MEG) with a priming paradigm (Pylkkanen et al., 2006). One meaning/sense of the homonyms or polysemies was selected by a modifying word, and the targets were primed by the same ambiguous word but with the other meaning/sense selected (e.g. *river <u>bank</u>* - *savings <u>bank</u>*, *lined <u>paper</u>* *liberal <u>paper</u>*). The authors measured the M350 component which had been associated with lexical activation, and found that the polysemous targets elicited a left hemisphere M350 latency reduction, suggesting that the selected sense of the target polysemy (*liberal paper*) was already activated to certain degree even the prime had a different sense selected (*lined paper*). By contrast, homonyms resulted in a M350 delay, indicating higher competition between the different meanings.

2.3.2 Complement coercion

Within polysemy, coercion has been argued to be an important mechanism of resolving various kinds of ambiguity and meaning mismatch (Partee & Rooth, 1983; Moens & Steedman, Jackendoff 1997; Pustejovsky 1993, 1995, 2006, 2011). One of the most studied kinds of coercion in psycholinguistics is complement coercion, exemplified by *Mary began the book*. In the VP construction, a event-selected verb *begin* is combined with an entity noun, thus the object *book* is said to be coerced into an event such as *writing the book, reading the book.* The neural mechanism(s) of this process has been investigated in a considerable number of psycholinguistic studies. Most experiments found an additional cognitive cost. Many proposed that this cost was attributed to the noun undergoing a type-shifting process, i.e. the entity-denoting noun was coerced into an event interpretation, rather than other factors such as ambiguity and pragmatic inference (McElree et al., 2001; Traxler et al., 2002, 2005; Pickering et al., 2005; Frisson & McElree, 2008; Katsika et al., 2012). Frisson et al. (2011) also found the coercion effect when an eventive-adjective was combined with an entity-noun (e.g. *a difficult mountain*), compared with the cases in which the eventive-adjective was paired with an eventive noun (e.g. *a difficult exercise*).

On the neural level, it has been showed that complement coercion qualitatively differs with typical semantic or syntactic violation. In an MEG study, Pylkkanen & McElree (2007) contrasted complement coercion (e.g. *the author began the <u>book</u>*) with non-coercion and animacy-violation (*the author wrote the <u>book</u> / disgusted the <u>book</u>*). They found increased amplitudes in the anterior midfield (AMF) which was generated by a mid-line source in the ventromedial prefrontal cortex (vmPFC). Importantly this effect was only present in coercion and was not sensitive to the animacy-violation sentences. Following this work, Baggio et al. (2010) and Kuperberg et al. (2010) adopted similar experimental design and examined the ERP effect. Both coercion and anomaly sentences elictied the N400 component, but complement coercion displayed dissimilarities in both studies. In Baggion et al. (2010) complement coercion additionally evoked a later sustaining negativity. In Kuperberg et al. (2010) anomaly elicited a later component P600 as well while this effect was absent for complement coercion. Using fMRI, Husband et al. (2011) underlined the effect in the left IFG, the classic language locus, in comprehending complement coercion, implying a higher semantic composition demand.

2.3.3 Novel metonymy

Another similar mechanism that too involved context-induced meaning is novel metonymy. Though disputable, metonymy generally refers to expressions in which the salient aspect of an entity is used to indicate the whole or other part of the entity, e.g. *the Dickens on the bookshelf, Hollywood is making a big profit* (Nunberg, 1995, 2004; Lakoff 1987; Jackendoff 1997). As to novel metonymy, the interpretation has to be fully inferred from the context. For instance the Needham published in 1977 is on the bookshelf is a novel metonymy because Needham is a made-up name.

The comprehension mechanism(s) of several kinds of metonymy have been explored in psycholinguistic studies, showing that only novel metonymy elicits a processing cost compared to familiar metonymy. Frisson & Pickering (1999) examined two kinds of metonymic expressions PLACE-FOR-INSTITUTION and PLACE-FOR-EVENT. The eye-movement patterns suggested that in both cases, the familiar metonymy (e.g. *rejected by the college, protest against Vietnam*) did not incur a processing cost whereas constructing a novel metonymy (e.g. rejected by the pyramid, protest against Finland) did. Likewise, Frisson & Pickering (2007) found the processing cost using eye-tracking when readers needed to construct the producer-product metonymy with a pseudo-name (e.g. read Needham) compared to a well-known name (familiar metonymy, e.g. *read Dickens*). More recently, the ERP effect associated with metonymy such as *that ham sandwich in the corner wants to pay* was investigated, and a late positivity effect was identified regardless of the contextual information (Schumancher 2011, 2014).

2.3.4 Inherent polysemy and dot-objects

Inherent polysemy differs from novel metonymy in that the potential interpretation already exists in the word's semantics itself, i.e. they are inherent, rather than newly introduced by the context (Pustejovsky 2006, 2011; Pustejovsky & Jezek, 2008). The dot-objects are inherently polysemous by definition. Some aforementioned studies indeed included inherent polysemy stimuli. For instance, the stimulus words used in Frisson & Pickering (1999) such as college and convent were actually dot-objects of building/location and social group. And there was no additional processing cost associated with reading these words. Well-known writers like Dickens and Aristotle can also been seen as dot-objects of the person and their work. In McElree et al. (2006) and Frisson & Pickering (2007), the authors tested those well-known names and found that, given supporting contexts, there was no difficulty in interpreting the proper names as their writings. Thus the authors argued that for familiar metonymy the literal sense and the metonymic sense are equally accessible. In another study of Schumancher, 2013, the author found no additional effect for the content-container meaning shift (e.g. *he dropped the beer, she put the soup*). As a matter of fact according to the Generative Lexicon theory, concepts like beer is a dot-object of LIQUID and DRINK; the predicate, e.g. put, selects the physical sense, i.e. LIQUID, via *coercion-by-dot-exploitation* (Pustejovsky, 2011). In sum, the empirical evidence strongly suggested that accessing the embedded senses of inherently polysemous words does not incur a processing cost.

2.4 Semantic composition

2.4.1 Studies on conceptual combination in Psychology

Coercion is achieved by semantic composition. In psychology, how meanings are combined has also been a central issue. The strong compositional approach, which dates back to Frege and Montagues grammar based on formal logic, had inspired a number of logic-based models for combinatory concepts in the early days of cognitive science (Zade, 1982; Fodor & Pylyshyn, 1988; Smith et al., 1988). However those models failed to capture the flexibility and diversity of semantic composition. Later research on this topic turned to a weak compositional approach that allows more flexibility and resembles more how the brain works. For instance, Hampton (1991) attempted to generalise the successful prototype theory put forward in Roscha & Mervis (1975) to model combinatory concept meanings, proposing a composite prototype model which incorporated some rule-based modification mechanism to account for meaning shift and emergent properties. Conceptual combination is also an ideal testing ground for embodied theorists who often argue that simulation is the crucial mechanism for conceptual combination (Barsalou 2003, 2005; Wu & Barsalou, 2009). Wu & Barsalou (2009) conducted a series of property generation experiments, taking into account the factors of experiment instruction, familiarity of the combinations, and the modifier kinds. They showed that manipulating the visibility of the visual features (i.e. occlusion) greatly affected the generated properties. For example participants did not normally generate the root feature for *lawn*, however they did generate the *root* feature for *roll-up lawn*, of which the root was visible both in the neutral and the mental imagery instruction. Notably that this effect disappeared when the instruction explicitly required generating associated words. Therefore the authors concluded that people spontaneously use perceptual simulation to generate properties.

2.4.2 The neural basis of semantic composition

Semantic composition is usually investigated in the form of sentence processing, focusing on how a target word fits into the sentential or phrasal context. High temporal resolution methods such as EEG and MEG prove to be valuable tools to study this on-line meaning construction process (e.g. Kuperberg 2007, Pylkkanen 2008). Kuperberg (2007) gave a throughout review on ERP studies on this topic. The author claimed that the P600 ERP component denoted a prolonged analysis that went beyond a simple semantic violation. Based on this assumption and data from a large number of ERP studies, the author further proposed that the P600 effect was the neural signature of the combinatory mechanism(s). Pylkkanen (2008) reviewed psycholinguistic and neurolinguistic evidence on the topic of syntax-semantic mismatch. To illustrate, both complement coercion (e.g. *the author began the book*) and aspectual coercion (e.g. *the clown jumped for 10 minutes*) are typical examples because the mismatches occur only on the semantic level. Note that these mismatches cannot be resolved by a strong composition account but require the brain to flexibly generate coherent interpretations. The author emphasised the role of the mid-frontal lobe in resolving such mismatches. The mid-frontal lobe, nonetheless, has been shown to be closely associated with social cognition and theory of mind, indicating that semantic composition may involve more than just language but also other general cognitive mechanisms.

Some recent works directly addressed the combinatory process; the left inferior frontal gyrus (LIFG) and the left lateral temporal lobe (LATL) are the two important cerebral foci identified (e.g. Hagoort, 2005; Fiebach et al., 2007; Grave et al., 2010; Bemis & Pylkkanen, 2012, 2013; Westerlund & Pylkkanen, 2014; Zhang & Pylkkanen, 2015). In a review article, Hagoort (2005) emphasised the pivotal role of the LIFG in the unification operation of language processing based on the Memory-Unification-Control (MUC) model. With fMRI, Fiebach et al., (2007) adopted a novel conceptual combination paradigm which required participants maintaining several concepts in the working memory, and combined them in order to make a property judgment (e.g. *egg, boiled, long -> hard*). Although this study focused on the maintaining of semantic working memory, the results showed that the LIFG and the posterior temporal area played an essential role in this combinatory task. Grave et al., (2010) compared the fMRI activities when participants comprehended the typical, highly meaningful noun-noun phrases (e.g. lake house) and the non-typical ones (e.g. *house lake*). The non-typical phrases were derived from reversing the word order of the typical phrases, thus they required a more demanding combinatory process meanwhile the effect could be isolated from the lexical level-process. A left-lateralised neural network was recruited by the non-typical phrases, including the IFG, IPS, lpITG, suggesting smooth and successful combination; on the other hand the typical phrases mainly recruited the right hemisphere, indicating a different mechanism of the novel combination scenario. Bemis & Pylkkanen (2013) used MEG to examine the neural basis of basic linguistic combinatory process. They presented adjective-noun combinations that are in the canonical order (e.g. *red cup*) and the reversed order (e.g. *cup red*), assuming that the reversed order would not automatically incur the combinatory processing unless the task required. By manipulating the task demand, the authors found effects in the left anterior temporal lobe (LATL) and the ventromedial prefrontal cortex (vmPFC) for comprehending the canonical combinations regardless of whether the task required combination, meanwhile for the reversed order the the effect in the LATL and vmPFC only occurred in the combination-required task. Westerlund & Pylkkanen (2014) also focused on the LATL in semantic composition, but aiming at bridging the semantic composition hypothesis and the hypothesis that the ATL as a semantic hub. The authors compared low- or high-specificity concepts (e.g. *boat/canoe*) either in the combinatorial context (combined with adjectives, e.g. blue boat) or a non-combinatorial context (e.g. *xlqd boat*). The result showed an interaction between concept specificity and composition in the left ATL, such that the activation of the left ATL was modulated mostly by the low-specificity adjective-noun combinations. They argued that when in a combinatorial context, the low-specificity concepts required a greater degree of specification and thus it yielded the largest effect in the ATL; therefore the effect of concept specificity and the semantic composition might stem from a shared mechanism.

2.5 Neuroimaging and MVPA

2.5.1 A brief introduction of the main brain imaging techniques

Functional Magnetic Resonance Imaging (fMRI) has developed rapidly during the last decades and become the most popular functional neuroimaging technique to date. It can give snapshots based on the oxygen level of blood in the brain, precisely the Blood-Oxygenation-Level-Dependent response (BOLD), which has been showed to be correlated with neural activity (Boynton et al., 1996; Logothetis et al., 2001; Bandettini and Ungerleider, 2001). During functional scanning, the magnetic gradients posit a three-dimension grid on the brain, segmenting it into tens of thousands of cells called voxels, and the BOLD signal is measured at each voxel. Thus fMRI image can measure the whole brain with millimetre spatial resolution. However the hemodynamic responses fMRI measures are rather slow, therefore the time resolution of fMRI is usually about several seconds.

On the other hand there are techniques that directly measure the electrical signal generated from neurons. Electroencephalograpy (EEG) is among the earliest techniques to measure neural activities (Berger, 1929), and it has been widely used as a clinical tool as well as in research. EEG mainly measures the post-synaptic potentials by locate electrodes on the scalp; hence its spatial resolution is poor although it has a millisecond time resolution. Moreover it suffers the inverse problem that is theoretically impossible to reconstruct the original generators from the observed signal. More recently the magnetoencephalography (MEG) technique seems to provide a promising solution to the resolution dilemma: it has a high time resolution as EEG and a high spatial resolution as fMRI. MEG measures the magnetic field caused by the electric currents that are also generated from the post-synaptic potentials; it is much more precise and sensitive than EEG but it also endures the inverse problem. However the ample MEG data points allow mathematical models to reconstruct the source more accurately.

2.5.2 Neural decoding and Multivariate Analysis (MVPA)

The General Linear Model (GLM), which adapted from multiple regression analysis, has been the traditional analysis method for fMRI. GLM allows decomposition of the usually overlapped BOLD signal based on the per-defined experimental contrasts. Specifically, the actual signal of one voxel is treated as a linear superimposition of multiple BOLD activities with an assumed shape (Fig. X). The regression analysis then finds the voxels whose responses correlate the best to the pre-defined model. The regression is done with each voxel individually, hence the result has to be corrected for multiple comparisons, which poses an obstacle given the number of voxels is usually tens of thousands.

In contrast to the univariate-based GLM, the multivariate pattern analysis (MVPA) considered values from multiple voxels simultaneously. This more recent approach, which was adopted from the Machine Learning community, has been gaining popularity since the first explicit demonstration by Haxby et al., (2001). They recorded the fMRI data of the participants viewing eight categories of object pictures, and showed that the multi-voxel patterns can be recognised with a nearestneighbour classifier (Haxby et al., 2001). The key assumption of this method is that it is the distinct patterns that contain the crucial information.

Following the seminal study, more and more machine learning techniques have been introduced in analysing neuroimaging data. For instance more powerful classifiers such as the Support Vector Machine classifier (SVM) were explored (e.g. Cox & Savoy, 2003; Kamitani & Tong, 2005; Halchenko & Hanson, 2007, Formasino et al., 2008). Furthermore MVPA offers novel experiment designs that go beyond traditional condition-contrasting. For example Mitchell et al. (2008) developed a computational model that could use model built from large text-corpus to predict fMRI activities. Kriegeskorte and colleagues introduced into fMRI data analysis the Representational Similarity Analysis (RSA), which is a highly data-driven approach and can access the interrelationship among conditions, bridge data from diverse modalities, and flexibly incorporate various models to interpret the brain data (Kiani et al., 2007; Kriegeskorte et al., 2008a, 2008b; Peelen et al., 2010; Kriegeskorte, 2011; Carlin et al., 2011; Connolly et al., 2012; Fairhall & Caramazza, 2013).

Chapter 3

The Neural Representation of Dot-objects: The Case of *Book*

3.1 Introduction

The word *book* is probably the most cited term of dot-object. It represents the "information print matter" category of which the concepts refer to artefacts used to stored information; and they exhibit a systematic ambiguity between a concrete interpretation as the physical object and an abstract information interpretation (consider, e.g., *a wet book / an influential book*). As a result, in the General Lexicon framework, those words are considered as dot-objects of OBJECT • INFORMATION. As described in the Section 1.1, the two senses could be accessed simultaneously in a single expression, as in (3.1a). Furthermore some context would select only one aspect of the meaning, a process called *coercion-by-dot-exploitation* (Fig. 3.1), such as (3.1b) and (3.1c) (cf. Pustejovsky, 2011)

(3.1)

a. *The police burnt the controversial book.*

b. *Jess almost dropped the* <u>*book*</u>*, then hastily replaced it on the shelf.*

c. *The author will be discussing her new* <u>*book*</u>*.*

According the dot-object theory, meanings of those words should be represented by a single lexical entry, to which the multiple senses are systematically related. In this experiment we investigated the implications of the single lexical entry hypothesis with respect to theories of the neural distinction between concrete and abstract concepts. The question we address is, how is the meaning of the dot-object words such as *book* represented in the brain? Specifically we probe the issue that whether the coerced concrete and abstract senses of dot-objects are represented in the brain differently to mono-sense concrete and abstract concepts. If so what are the differences? To answer this question, we used functional magnetic resonance imaging (fMRI) to examine the neural activation patterns originated by reading the book-like dot-object words in a minimal context, i.e. a verb-noun phrase, that coerce them into either the concrete or the abstract interpretation (e.g. *open the* <u>*book*</u> / *consult the* <u>*book*</u>). As a comparison, we also examined the neural correlates of reading phrases that contained monosense, typical concrete and abstract concepts. This experiment design allows us 1) to compare the neural representations of the coerced concrete and abstract concepts to the typical concrete-abstract neural distinction, 2) to look into the neural representation of complex concepts and semantic composition (Fig. 3.2).

We adopted the multivariate pattern analysis (MVPA) approach to examine in which brain areas the neural activity patterns associated with the abstract and the concrete interpretations of dot-objects can be discriminated. One prediction is that this discrimination is carried out by the same areas found to be involved in the traditional concrete-abstract distinction, such as the angular gyrus, the precuneus (concrete > abstract) and the left inferior frontal gyrus (abstract > concrete). How-

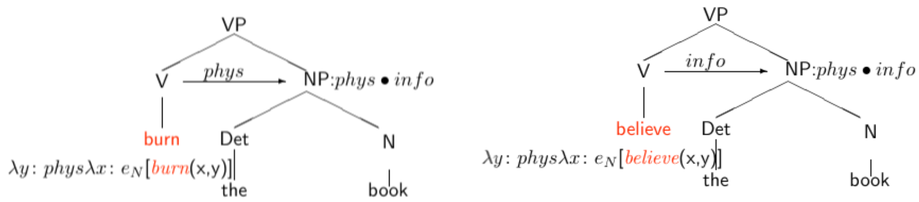

Figure 3.1: The schematic representations of *coercion by dot-exploitation* (c.f. Pustejovsky). The physical object or the information component is selected by the verbal context respectively.

ever, if the meaning of words like book really is a complex concept covering both the abstract and the concrete interpretations as Pustejovskys dot-object theory states, then we should expect to find a different discrimination effect for these further specified (i.e. coerced) interpretations. Another prediction of the dot-object theory is that we will not observe a typical semantic disambiguation effect found in homonym and polysemy comprehension, which usually involves a network of the language-related areas such as the inferior frontal gyrus (IFG), the posterior inferior temporal lobe, and the superior/middle temporal gyrus (e.g. Rodd et al, 2005; Thompson-Schill et al., 2005; Bedny et al., 2007; Gennari et al., 2007). This is again because, according to the theory, words like *book* are not ambiguous between a concrete and an abstract interpretation, so the coercion process would not involve selecting one among distinct interpretations but going from an underspecified interpretation to a more specific one. On the other end, we expect an involvement of the anterior temporal lobe (ATL) in discriminating the concrete and abstract dot-objects on two distinct grounds. On the one hand this area has been proposed to store the high-level, modality-independent knowledge of concepts (e.g. Peelen & Caramazza, 2012) and has been associated with the concept specific effect (e.g. Tyler et al., 2004; Patterson et al, 2007). Secondly the ATL also has been shown to play an essential part in semantic combination (e.g. Lambon Ralph et al., 2010; Bemis & Pylkkanen, 2012; Westerlund & Pylkkanen, 2014). Interestingly Westerlund & Pylkkanen (2014) also found an interaction between concept specificity and composition in the ATL, suggesting that the two aspects were closely related.

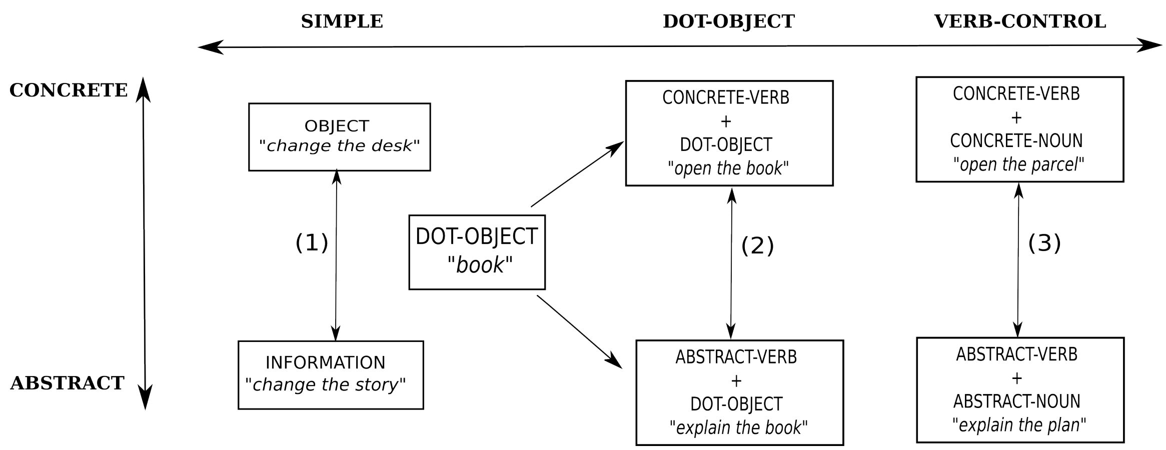

Figure 3.2: Experimental design. The three vertical lines indicate the three concrete-abstract contrasts. In the target contrast, dot-object, the dot-object words are combined with verbs that coerce the meaning into either the concrete or the abstract interpretation. The simple contrast contains typical concrete and abstract words combined with generic verbs. In the verb-control contrast, the same coercing verbs in the dot-object contrast are used but paired with unambiguous concrete and abstract nouns.

3.2 Methods and materials

3.2.1 Participants

Nineteen volunteers were recruited. Three of them were excluded from the analysis because they failed to respond or respond incorrectly in more than 10% of the trials, leaving sixteen participants for the analysis (8 female, mean age 22.5, SD: 3.42). All participants were native Italian speakers, right-handed, and had normal or corrected-to-normal vision. All procedures were approved by the ethics committee of University of Trento, and participants received a small monetary compensation.

3.2.2 Materials

All experiments were conducted in Italian. We considered 4 words from a class of dot-object concepts, informational print matter *book, magazine, catalogue, sketch*, and used verbs to coerce the meaning into either the concrete or the abstract sense. We first came up with a pool of verbs that could potentially coerce the dot-objects into either the concrete object sense or the information sense, and then we constructed all combinations of all the nouns and verbs, excluding the meaningless and ambiguous ones. Following the procedure proposed in Barca et al. (2002), thirty-eight native speakers were recruited to rate the familiarity, concreteness and imageability of each verb-noun combination. Based on the norming result, we then selected 3 concrete (*open, pick, give (as a present)*) and 3 abstract (*explain, consult, present*) verbs as the coercing verbs. We refer to this target contrast with the coercing verbs and the dot-object nouns as the dot-object contrast.

Two additional contrasts were constructed in order to 1) compare the coerced concrete and abstract dot-objects to typical unambiguous concrete and abstract concepts; 2) control for the semantic contribution from the verbs. First of all we constructed a simple concrete-abstract contrast, henceforth referred to as simple contrast that contained unambiguous nouns similar to those used in other concrete-abstract semantic knowledge studies. Specifically we chose the categories of furniture and information to approximate the partial senses of the dot-objects; we chose common household furniture such as *desk* and *sofa* because they are frequently seen with the dot-objects in real world scenarios. To keep the grammatical form the same across all the conditions, nouns of both the two categories were combined with some generic verbs (*have, give, change*) to form the verb-noun phrases. Because the verbs were constant and semantically general, the distinction of this contrast should be predominantly driven by the nouns. The second contrast, the verb-control contrast, was set up to verify that concrete and abstract discrimination in the dot-object contrast was not solely due to differences in verbs between conditions. Phrases in this contrast had the same coercing verbs as in the dot-object conditions, but the verbs were combined with their common complement words drawn from various concrete or abstract categories (e.g. *open the door, open the parcel / explain the problem, explain the plan*). Therefore this contrast should most reflect the verb semantics. Hence if the effect of the dot-object contrast were driven by the verbs only, the same effect should be picked up by this verb-control contrast too. The verb-noun combinations of these two additional contrasts were rated in the same norming experiment as described above. The experiment design and the list of stimuli can be found in Fig. 3.2 and Table 3.1.

After the norming, we selected 7 concrete and 7 abstract phrases for each contrast, resulting in 42 phrases in total (7 phrases * 2 categories * 3 contrasts). The stimuli in Italian and the English translation are listed in Table X. Phrases of each contrast were matched in length and the number of phonemes (number of letters: $t_{\text{Dot-object}}(12)=-0.46$, $p=0.65$; $t_{\text{Simple}}(12)=0.8$, $p=0.44$; $t_{\text{Verb-control}}(12)=-1.36$, $p=0.2$. number of phonemes: $t_{\text{Dot-object}}(12)=-0.27$, $p=0.79$; $t_{\text{Simple}}(12)=-1.15$, $p=0.27$; $t_{\text{Verb-control}}(12)=1.16$, $p=0.7$). All categories matched familiarity ($F(5,36)=0.27$, $p=0.93$). For each concrete-abstract contrast the concreteness and the imageability ratings differ significantly (concreteness: $t_{\text{Dot-object}}(12)=-3.82$, $p=0.0025$; $t_{\text{Simple}}(12)=-16.12$, $p=1.7e-09$; $t_{\text{Verb-control}}(12)=-7.94$, $p=4.06e-06$. Imageability: $t_{\text{Dot-object}}(12)=-2.3$, $p=0.0402$; $t_{\text{Simple}}(12)=-6.86$, $p=1.7544e-05$; $t_{\text{Verb-control}}(12)=-8.05$, $p=3.5184e-06$). The detailed results are in Table 3.2 and Fig. 3.3. None of these subjects of the norming experiment participated in the fMRI experiment.

3.2.3 Procedure

Participants were instructed to attentively read verb-noun phrases and judge whether the verb-noun combinations were meaningful. About 10% were catch trials which

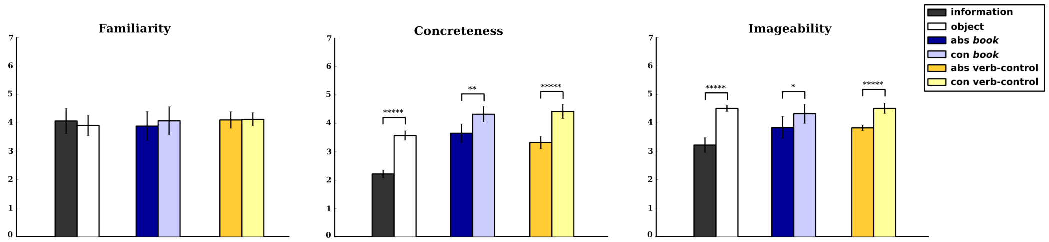

Figure 3.3: Ratings of familiarity, concreteness, and imageability of each category. Two-sample t-tests were calculated for each concrete-abstract contrast. The concreteness and imageability ratings are significantly different for all three contrasts.

contained meaningless combinations (e.g. open the sun). We adopted a slow-event design. Each trial started with a fixation cross for 500ms, followed by a verb and then an article-noun phrase, each of them was present for 450ms with a 100ms interval. A black cross then remained on the screen for 1500ms to encourage participants to form an elaborate mental representation, then a question mark was displayed for 1000ms at which point participants responded by pressing the left or right button box (counterbalanced across participants). The next trial started after 6 second fixation time (Fig. 3.4). During one scanning session, all 42 verb-noun phrases along with 5 catch trials (around 10% of all trials) appeared once in a random order. Each participant completed 6 sessions.

3.2.4 Data acquisition

All of the fMRI experiments were conducted with a 4T Bruker MedSpec MRI scanner. Structural images were acquired using a T1 weighted MPRAGE sequence with resolution 1*1*1mm. A T2*weighted EPI pulse sequence was used to acquire the functional images with parameters TR 1000ms, TE 33ms, and 26 flip angle, FoV1000*1000. Each acquisition volume contains a 64*64 matrix and 17 slices with a gap of 1mm. Voxel dimensions are 3mm*3mm*5mm.

Table 3.1: Stimulus words used in the three concrete-abstract contrasts. Each contrast contains seven concrete and seven abstract verb-noun phrases. The original Italian stimuli are showed below the English translation. The dot-objects are highlighted in bold font.

English:

	dot-objects	**simple**	**verb-control**
ABSTRACT	consult the **book**	have the idea	consult the expert
	consult the **magazine**	have the opinion	present the request
	consult the **catalogue**	change the story	present the problem
	present the **book**	change the judgement	present the plan
	present the **sketch**	change the idea	explain the motive
	explain the **book**	give the judgement	explain the expression
	explain the **sketch**	give the idea	explain the reason
CONCRETE	open the **book**	have the table	open the parcel
	open the **catalogue**	have the chair	open the envelop
	pick up the **book**	have the desk	pick up the flower
	pick up the **magazine**	change the closet	pick up the coin
	pick up the **catalogue**	change the table	pick up the ball
	give (as a present) the **book**	change the desk	give (as a present) ticket
	give (as a present) the **sketch**	give the chair	give (as a present) flower

Italian:

	dot-objects	**simple**	**verb-control**
ABSTRACT	consultare il **libro**	avere la idea	consultare l'esperto
	consultare la **rivista**	avere l'opinione	presentare la domanda
	consultare il **catalogo**	cambiare la storia	presentare il problema
	presentare il **libro**	cambiare il giudizio	presentare il programma
	presentare il **disegno**	cambiare la idea	spiegare il motivo
	spiegare il **libro**	dare il giudizio	spiegare la parola
	spiegare il **disegno**	dare la idea	spiegare la ragione
CONCRETE	aprire il **libro**	avere il tavolo	aprire il pacco
	aprire il **catalogo**	avere la sedia	aprire la busta
	raccogliere il **libro**	avere la scrivania	raccogliere il fiore
	raccogliere la **rivista**	cambiare l'armadio	raccogliere la moneta
	raccogliere il **catalogo**	cambiare il tavolo	raccogliere la palla
	regalare il **libro**	cambiare la scrivania	regalare il biglietto
	regalare il **disegno**	dare la sedia	regalare il fiore

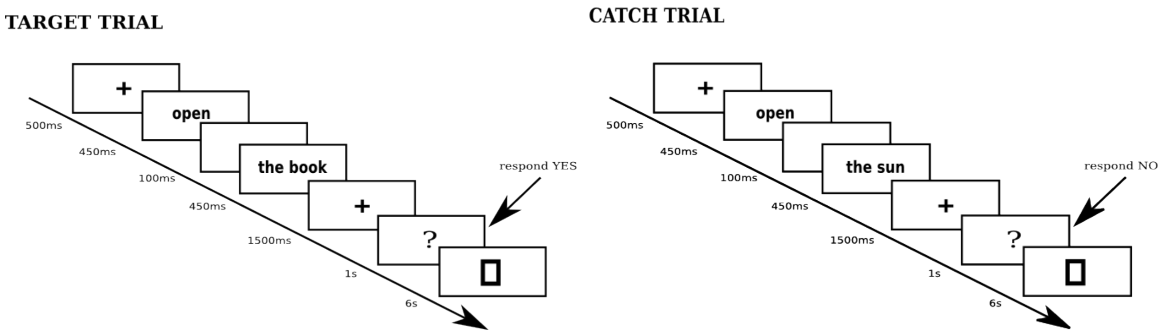

Figure 3.4: During the experiment, participants performed a semantic meaningfulness judgement task and responded by pressing the button boxes with the left or the right hand (counterbalanced across participants). In one scanning session, all the 42 verb-noun phrases along with 5 catch trials (around 10% of all trials) appeared once in a random order. Each participant completed 6 sessions.

Table 3.2: The psycholinguistic parameters of the stimulus phrases in each condition. Familiarity, concreteness, and imageability are obtained from the norming experiment with thirty-eight participants. Standard deviations are showed in parentheses.

Category	**familiarity**	**concreteness**	**imageability**	**letters**	**phonemes**
abstract Dot-object	3.9(0.51)	3.65(0.33)	3.86(0.39)	18.71(1.58)	7.57(0.90)
concrete Dot-object	4.1(0.50)	4.32(0.28)	4.34(0.34)	18.14(2.59)	7.43(0.90)
abstract Noun	4.08(0.44)	2.22(0.14)	3.24(0.26)	14.43(2.92)	6.14(0.64)
concrete Noun	4.09(0.36)	3.65(0.17)	4.04(0.11)	15.71(2.60)	6.71(1.03)
abstract Verb	4.12(0.29)	3.32(0.22)	3.85(0.10)	19.14(1.81)	7.43(0.49)
concrete Verb	4.14(0.23)	4.41(0.25)	4.53(0.18)	17.43(2.50)	7(0.76)

3.2.5 Univariate analysis

We also conducted the univariate analysis to calculate the activation maps of each of the three concrete-abstract contrasts. All the steps were carried out with FSL5.0 (http://fsl.fmrib.ox.ac.uk). Prior to the statistical analysis the functional images were corrected for motion and smoothed with a 5mm Gaussian kernel. For each scanning session of each participant, a general linear model was created to model all the six experimental conditions. The trials that the participant missed or gave a wrong response were discarded. Then the models were convolved with a double-gamma function to model the hemodynamic response. The six scanning sessions of each participant were combined with the fixed-effects single-group average method (one sample t-test). The group-level activation maps of the three contrasts were computed using a two-sample paired t-test that the concrete and the abstract conditions were modeled within-subject. The ordinary least square (OLS) mixed-effects model was applied. The z-value maps (Gaussianised T/F) were thresholded using the cluster-based method provided by the FSL software. The primary voxel-wise threshold was set to $Z>2.3$ (corresponding to $p<0.05$) and a (corrected) cluster significance threshold of $P=0.05$ was used. The activation maps of each participant were registered to the MNI-standard brain (2mm resolution) to form the final group map.

3.2.6 Regions-Of-Interest (ROIs)

We focused on seven left hemisphere Regions-Of-Interest (ROIs) which have been consistently shown to discriminate between concrete and abstract concepts, and/or to play a role in semantic interpretation processes such as disambiguation or semantic composition. The seven ROIs are 1) the anterior inferior frontal gyrus (aIFG), 2) the angular gyrus (AG), 3) the precuneus/posterior cingulate cortex, 4) the posterior ventral temporal lobe (pvTL), 5) the posterior lateral temporal cortices (PLTC), 6) the ventral anterior temporal lobe (vATL), and 7) the superior anterior temporal lobe (sATL). The ROI masks were derived from the Harvard-Oxford atlas, a probabilistic atlas that divided the whole cerebral cortex into 48 bilateral cortical subregions (Desikan, et al., 2006). We obtained each ROI mask by merging several subregions with the 25% probabilistic threshold; the MNI co-ordinates reported in other studies were also taken into account (Table 3.3, Fig. 3.5).

The functional roles of these brain regions are reviewed in detail in chapter 2, thus in this section we only recapitulate the most relevant points. The anterior inferior frontal gyrus (aIFG), the angular gyrus (AG), the precuneus/posterior cingulate gyrus

Table 3.3: Details of the seven Regions-Of-Interest (ROIs). The ROIs are derived from merging several subregions from the Harvard-Oxford probability atlas with cut-off probability threshold 25%. The extent shows the resulting number of voxels (resultion 2mm). The MNI coordinates indicate the centre of the subregion in the atlas. AG: angular gyrus, PCC: posterior cingulate cortex, pvTL: posterior ventral temporal lobe, PLTC: posterior lateral temporal cortices, vATL: ventral anterior temporal lobe, sATL: superior anterior temporal lobe

	Extent	**Merged subregions**	**MNI coord (x,y,z)**
AG			
	6148	Angular Gyrus	(-21, 37, 55)
		Lateral Occipital Cortex, superior division	(-60, 28, 57)
Precuneus/PCC			
	4199	Precuneous Cortex	(-45, 31, 55)
		Posterior Cingulate Gyrus, posterior division	(-44, 42, 54)
aIFG			
	1039	Inferior Frontal Gyrus, pars triangularis	(-20, 77, 40)
		Frontal Operculum Cortex	(-66, 74, 37)
pvTL			
	2463	Occipital Fusiform Gyrus	(-33, 23, 30)
		Temporal Occipital Fusiform Cortex	(-62, 37, 29)
		Inferior Temporal Gyrus, temporooccipital part	(-70, 35, 29)
PLTC			
	2485	Middle Temporal Gyrus, temporooccipital part	(-72, 35, 38)
		Superior Temporal Gyrus, posterior division	(-75, 52, 35)
		Planum Temporale	(-74, 53, 40)
vATL			
	958	Temporal Fusiform Cortex, anterior division	(-62, 61, 15)
		Parahippocampal Gyrus, anterior division	(-57, 62, 18)
sATL			
	1115	Superior Temporal Gyrus, anterior division	(-56, -8, -8)
		Middle Temporal Gyrus, anterior division	(-58, -8, -20)
		Planum Polare	(-50, -6, 0)

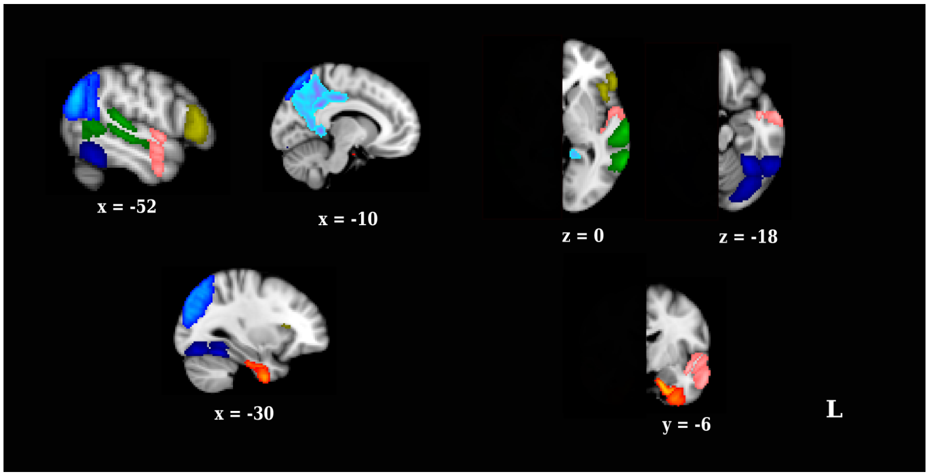

Figure 3.5: The left hemisphere region-of-interest (ROI) masks used in the ROI-based analysis. Yellow: anterior inferior frontal gyrus (aIFG); green: posterior lateral temporal cortices (PLTC); blue: angular gyrus (AG); light-blue: precuneus and the posterior cingulate gyrus; dark-blue: posterior ventral temporal lobe (pvTL); red-yellow: ventral anterior temporal lobe (vATL); pink: superior anterior temporal lobe (sATL).

and the posterior ventral temporal lobe (pvTL) are among the most typical regions found in the literature to distinguish concrete-abstract concepts (D'Esposito et al., 1997; Chao et al., 1999; Jesson et al., 2000; Wise et al., 2000; Martin & Chao, 2001; Grossman et al., 2002; Binder et al., 2005; Sabsevitz et al., 2005; Wang et al., 2012, 2014). We extend our AG ROI to the more posterior part of the parietal lobe (e.g. MNI coordinate $y < -60$) because this part is frequently indicated in neuroimaging studies contrasting concrete and abstract concepts and also usually referred as the angular gyrus (e.g. Jesson et al., 2000; Binder et al., 2005; Sabsevitz et al., 2005; Bonner et al., 2013; Seghier, 2013). The meta-analysis of Binder et al. (2009) also showed the inclusion of this area. The posterior lateral temporal cortices (PLTC) should exhibit the most prominent effect for the verb-control contrast, since this area is particularly dedicated to action and/or verb knowledge (Chao et al., 1999; Perani et al., 1999; Bedny et al., 2008; Binder et al., 2009; Peelen et al., 2012). We define the PLTC ROI based on Bedny et al. (2008) and Peelen et al. (2012) in which the

ROI was showed to be activated by all verbs and not sensitive to the verb type (e.g. verbs referred to action, motion, or event).

The functions of the anterior temporal lobe (ATL), on the other hand, seem to be more intricate. It forms part of the posited semantic hub in semantic memory that contributes to concept specification (e.g. Tyler et al., 2004; Patterson et al, 2007; Pobric et al., 2010; Peelen & Caramazza, 2012); it also plays a pivotal role in semantic composition (e.g. Mazoyer et al., 1993; Lambon Ralph et al., 2010; Bemis & Pylkkanen, 2012; Westerlund & Pylkkanen, 2014). As a result we anticipate that the left ATL is the most likely candidate to reflect the distinction between the concrete and abstract interpretations of the dot-object concepts, given their complex internal structure and the more complicated compositional processing they may incur. We further divide the ATL into the superior (sATL) and the ventral subdivision (vATL) because there is evidence showing that the two subdivisions have different functional specialisation to a certain degree [being bold for our own attention]. The sATL tends to be activated more to sentence comprehension and syntactic processing (Mazoyer et al., 1993; Hickok & Poeppel, 2004; Humphries et al., 2005). The activation of the superior temporal lobe for verbal processing, including processing abstract concepts, sometimes also extends to the sATL (e.g. Noppeney & Price, 2004; Binder et al., 2009; Ghio & Tettamanti, 2010). Conversely, the vATL has been linked to high-level processing of visual features; therefore sometimes is activated by concrete concepts (e.g. D'Esposito et al., 1997; Wise et al., 2000; Fiebach & Friederici 2004; Mestres-Misse et al., 2008; Pobric et al. 2009). Patients of semantic dementia (SD), a neurodegenerative condition that involves losses of everyday concept knowledge but episodic memory and speech ability are usually preserved, have atrophy more profound in the ventral ATL (Warrington, 1975; Breedin et al.,1994; Damasio et al., 1996; Hodges & Patterson 1996; Mummery et al., 2000; Nestor et al., 2006; Mion et al., 2010).

3.2.7 Pattern Classification

We employed multivariate pattern analysis (MVPA) to investigate the different kinds of concrete-abstract contrast in each ROI. Specifically we used a statistical classifier to distinguish between brain activity patterns associated with comprehending the concrete and abstract phrases of each contrast, i.e. the simple contrast, the dot-object contrast, and the verb-control contrast. MVPA considers the values of multiple voxels simultaneously; thus it has high sensitivity and has been successfully applied to decode a variety of neural activities (e.g. Haxby et al., 2001; Cox & Savoy, 2003; Wang et al., 2013). Within each ROI, a support vector machine (SVM) classifier was used to distinguish between concrete and abstract conditions for each of the three contrasts.

Prior to classification, each voxels time-series within each scanning session was linearly detrended to remove signal drift, then z-scored to normalize inhomogeneous neural activations. For each trial a single averaged volume was obtained by collapsing the 4 seconds of volumes that are 4 seconds after the target stimulus onset in order to account for the delay in hemodynamic response. These averaged volumes are the exemplars which were to be classified in the following classification analysis, thus for one participant one contrast contains 84 exemplars ((7 concrete + 7 abstract) * 6 sessions). The exemplars in which the participant missed or gave a wrong response were excluded in further analysis. Classification was carried out using a Support Vector Machine (SVM) classifier with a linear kernel. The within-participant classification accuracy was calculated with a Leave-One-Pair-Out cross-validation procedure: in each cross-validation iteration, one concrete exemplar and one abstract exemplar (i.e. one pair) were taken to form the test set, and the rest were used as the training set (Mitchell et al., 2004). The final accuracy was the average of all the iterations, and the chance level for classifying two categories with this cross-validation procedure is 50

P-values for the classification accuracy were calculated with a one-sample t-test against the 0.5 chance level. We calculated one-tail p-values because, if there was no difference between the two categories, the aforementioned cross-validation procedure should yield a chance level classification accuracy (a result that was considerably lower than chance level usually implied that there were pitfalls in the cross-validation procedure), and here we wanted to test whether the accuracy was better than chance. The p-value threshold was set to 0.05 and control for false discovery rate (FDR) following the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995).

3.2.8 Whole-brain parcellation analysis

To look for potential effect outside the ROIs, we ran a whole-brain parcellation analysis in addition to the ROI-based analysis. The identical classification procedure and statistics as in the ROI-based analysis were carried out in all the 96 subregions defined by the Harvard-Oxford probabilistic atlas. Following the same strategy in the ROI-based analysis, each subregion was extracted with the 25% probabilistic threshold.

3.3 Results

3.3.1 Behaviour

The mean error rate of all the sixteen participants included in the analysis was 0.05, SD=0.0204. Because we wanted participants to concentrate on forming a rich mental representation rather than responding quickly (and responses were delayed until a question mark was presented), we did not analyse reaction times. Trials without a response in 5 seconds were considered as missed trials.

3.3.2 Univariate analysis

Four clusters were identified for the OBJECT > INFORMATION comparison in the simple contrast. The clusters were located in the 1) left posterior fusiform gyrus and the precuneus lateralised to the left, 2) the left superior parietal lobe, 3) the left inferior parietal lobe that extends to the posterior middle temporal gyrus, and 4) the bilateral anterior cingulate gyrus and the right frontal orbital cortex. For the dot-object contrast one cluster encompassing the anterior cingulate cortex and the mid-to-right frontal lobe was found for the CONCRETE > ABSTRACT comparison. No significant effect was found for the verb-control contrast (Fig. 3.6. Table 3.4).

3.3.3 ROI-based Multivariate Pattern Analysis (MVPA)

The simple contrast could be discriminated in five out of all the seven ROIs except the superior and the ventral ATL. The verb-control contrast could be discriminated in three of the ROIs and the highest accuracy was found in the PLTC (mean accuracy=0.5604, t(15)=4.47, FDR-corrected p=0.0021). By contrast, the dot-object contrast could be most reliably distinguished in the ventral anterior temporal lobe (vATL) (mean accuracy=0.5609, t(15)=3.05, FDR-corrected p=0.0122), in which the other two contrasts were distinguishable. The dot-object contrast also yield a smaller effect in the AG (mean accuracy=0.5404, t(15)=2.46, FDR-corrected p=0.0349) and the sATL (mean accuracy=0.5402, t(15)=1.7778, FDR-corrected p<0.1). The detailed result is showed in Fig. 3.7 and Table 3.5.

Table 3.4: Univariate analysis result. The significant clusters were calculated by the cluster-based inference using the Gaussian random field (GRF) method, using the cluster-level threshold $p<0.05$ (FWER corrected). The MNI coordinates show the voxels with the local maxima z-values (Gaussianised T/F) within the cluster.

Region	**Extent**	**Cluster p**	**MNI coord**	**Z**
(1) Simple contrast				
concrete>abstract				
Left inferior-posterior fusiform gyrus & bilateral PCC/precuneus	1517	1.67e-06		
temporal fusiform cortex, posterior division			(-32,-40,-16)	4.64
cingulate Gyrus, posterior division			(-8,-38,14)	4.19
parahippocampal gyrus, posterior division			(-22,-34,-20)	3.78
Right frontal obital cortex & bilateral ACC	1515	1.67e-06		
frontal orbital cortex			(16,22,-16)	3.97
cingulate gyrus, anterior division			(0,40,12)	3.74
subcallosal Cortex			(2,10,0)	3.53
Left inferior parietal lobe & pMTG	879	0.000343		
supramarginal gyrus, posterior division			(-54,-50,14)	4.47
middle temporal gyrus, temporooccipital part			(-50,-52,12)	4.38
lateral occipital cortex, inferior division			(-48,-68,4)	3.75
Left superior parietal lobe	819	0.0006		
lateral occipital cortex, superior division			(-34,-70,40)	3.87
supramarginal gyrus, posterior division			(-38,-72,28)	3.37
abstract>concrete				
– –				
(2) Dot-object contrast				
concrete>abstract				
Mid-right prefrontal cortex	542	0.0141		
cingulate gyrus, anterior division			(4,26,12)	3.68
middle frontal gyrus			(26,30,24)	3.56
frontal pole			(20,62,22)	3.32
paracingulate gyrus			(6,40,22)	3.23
abstract>concrete				
– –				
(3) Verb-control contrast				
– –				

Table 3.5: Classification accuracy for the three concrete-abstract contrasts in each ROI. P-values were calculated with one-sample t-test (dof=15) against the 0.5 chance level, FDR corrected.

ROI	Accuracy(SEM)	P-value
Angular gyrus		
Simple	0.6095 (0.0287)	0.0038
Verb-control	0.5584 (0.0150)	0.0038
Dot-object	0.5404 (0.0164)	0.0299
Precuneus		
Simple	0.5749 (0.0224)	0.0068
Verb-control	0.5377 (0.0211)	ns
Dot-object	0.5112 (0.0183)	ns
anterior Inferior Frontal Gyrus		
Simple	0.5993 (0.0123)	7.25e-06
Verb-control	0.5559 (0.0234)	0.0308
Dot-object	0.5189 (0.0151)	ns
Posterior ventral Temporal Lobe		
Simple	0.5495 (0.0219)	0.0352
Verb-control	0.5349 (0.0224)	ns
Dot-object	0.5304 (0.0226)	ns
Posterior Lateral Temporal Cortices		
Simple	0.5562 (0.0168)	0.0068
Verb-control	0.5604 (0.0135)	0.0018
Dot-object	0.5163 (0.0135	ns
ventral Anterior Temporal Lobe		
Simple	0.5249 (0.0183)	ns
Verb-control	0.5166(0.0138)	ns
Dot-object	0.5609 (0.0200)	0.0104
superior Anterior Temporal Lobe		
Simple	0.5092 (0.0218)	ns
Verb-control	0.5184 (0.0152)	ns
Dot-object	0.5402 (0.0226)	ns

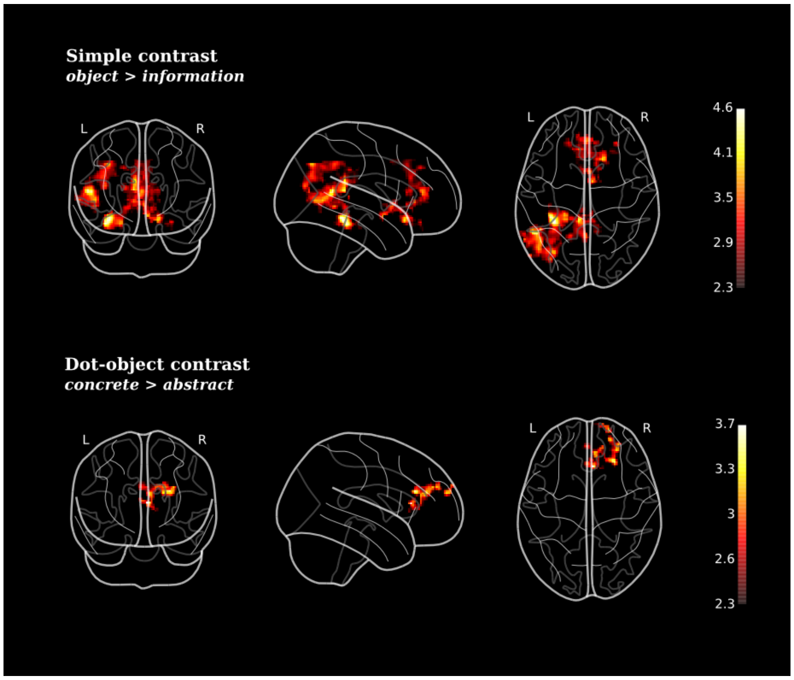

Figure 3.6: Univariate analysis result. The concrete and the abstract conditions of each contrast were compared with a two-sample paired-test. The colour bars indicate the voxel-wise Z (Gaussianised T/F) statistics thresholded by Z>2.3 ($p<0.05$). The significant clusters were calculated with the cluster-based method provided by the FSL software (cluster $p<0.05$, FDR-corrected). The individual maps were registered to the MNI-standard brain (2mm resolution) to form the final group map. Significant effects were found for the *object* > *information* comparison in the simple contrast, and the *concrete* > *abstract* in the verb-control contrast. No other significant effect was found for other comparisons.

3.3.4 Effects in the right hemisphere

We further explored the effect in the right hemisphere (RH) given that, first, the univariate analysis showed some RH effect for the dot-object contrast; moreover there is also evidence suggesting that the RH plays some parts in processing ambiguous words, although its exact role is still unclear (Chairello, 1988; Kircher et al., 2001; Chan et al., 2004; Zempleni et al., 2007; Pobric et al., 2010).

We carried out the same classification analysis in the RH counterparts of the seven ROIs, and indeed the result showed a trend that the RH was better in distinguishing the concrete and abstract dot-objects (Fig. 3.8). For the five ROIs outside the ATL,

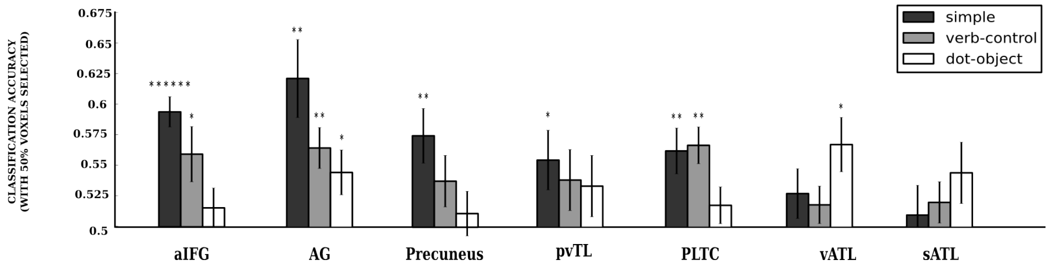

Figure 3.7: Classification accuracy for the three types of contrast in each ROI. Error bars indicate SEMS. P-values of the classification accuracy were calculated with one-sample t-test (dof=15) against the 0.5 chance level (one-tailed p-value, FDR corrected, *****$p<0.00001$, ****$p<0.0001$, ***$p<0.001$, **$p<0.01$, *$p<0.05$).

the RH ROIs achieved higher classification accuracy than their LH counterparts; one-sample t-test on the group-level accuracy showed that the right aIFG, AG, and the pvTL had $p < 0.05$ (uncorrected). To the contrary, the opposite pattern was found for the two ROIs in the ATL that the left ROIs outperformed the right ones. However the right vATL also showed a significant effect $p < 0.05$ (uncorrected).

3.3.5 Whole-brain parcellation MVPA

The dot-object contrast yielded four subregions with $p<0.05$ after correcting for multiple comparison (Table 3.6). One of them, the left anterior temporal fusiform cortex, was also within the vATL ROI. The other three subregions were in the right hemisphere, including regions in the frontal and the occipital/posterior temporal cortex. For the simple contrast, one subregion in the left anterior frontal gyrus was found. No region was found significant for the verb-control contrast after correcting for multiple comparison. This may be due to the possibility that the relevant neural activity patterns straddle across the boundaries of the atlas's subdivisions and a larger individual difference among participants. In fact three subregions showed a marginal effect ($p<0.1$, FDR-corrected) to the verb-control contrast, including two subregions locate in the PLTC ROI. The three marginal-effect subregions are the left middle temporal gyrus (mean accuracy=0.5476, $t(15)=2.79$), the left superior temporal gyrus (mean accuracy=0.5577, t(15)=3.39), and the right superior parietal lobe (mean accuracy=0.5293, t(15)=2.74).

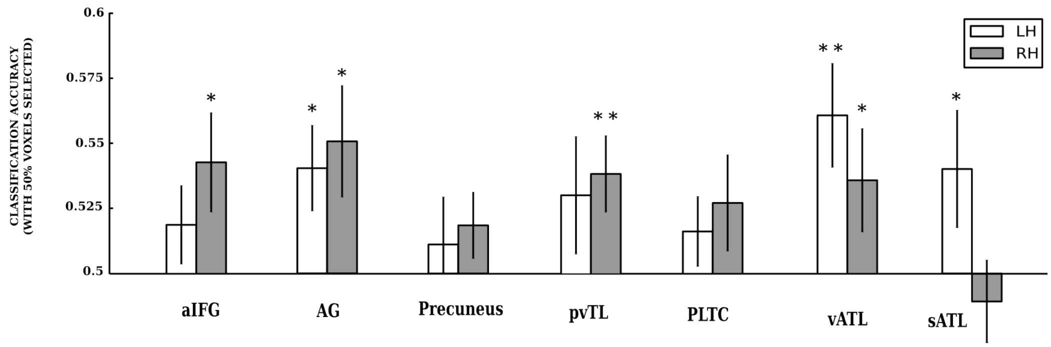

Figure 3.8: Comparing the classification accuracy for the dot-object contrast of each ROI in the left and the right hemisphere. Error bars indicate SEMS. P-values of the classification accuracy were calculated with one-sample t-test (dof=15) against the 0.5 chance level (one-tailed p-value, uncorrected, *****p<0.00001, ****p<0.0001, ***p<0.001, **p<0.01, *p<0.05).

Table 3.6: Significant subregions (corrected p<0.05) identified in the whole-brain parcellation MVPA. The identical classification procedure and statistics as in the ROI-based analysis were carried out in all the 96 subregions defined by the Harvard-Oxford probabilistic atlas. The MNI coordinates show the center of the subregion. P-values were calculated with one-sample t-test (dof=15) against the 0.5 chance level, FDR corrected.

Subregion	**Accuracy(SEM)**	**p**	**MNI coord**
(1) Simple contrast			
Left inferior frontal gyrus, pars triangularis	0.5734 (0.0174)	0.0354	(-50, 28, 8)
(2) Dot-object contrast			
Left temporal fusiform cortex, anterior division	0.5679 (0.0188)	0.0306	(-34, -4, -42)
Right intracalcarine cortex	0.5672 (0.0157)	0.0311	(4, 80, 8)
Right frontal operculum cortex	0.5620 (0.0164))	0.0261	(42, 22, 2)
Right temporal fusiform cortex, posterior division	0.5610 (0.0151)	0.0295	(38, -32, -24)
(3) Verb-control contrast			
– –			

3.4 Discussion

In this experiment, we investigated the neural representation of the archetypal class of dot-objects: artefacts that are used to stored information, such as *book* and *magazine*. Those words fall under the definition of logical polysemy that they have multiple but systematically related senses; they can refer to the concrete object (e.g. *a heavy book*) or the abstract information they carry (e.g. *an influential book*). It is generally assumed that logical polysemy words have a single entry in the mental lexicon; on the other hand, it has been showed that concrete and abstract concept knowledge is represented in different ways in the brain.

So how are these dot-object concepts represented in the brain? To probe this question, we have healthy participants scanned with fMRI while reading the dot-object nouns in combination with verbs which coerced the meaning into either the concrete or the abstract interpretation (e.g. *open the book* vs. *consult the book*). Multivariate pattern analysis (MVPA) was used to compare the neural correlates of the coerced concrete and abstract dot-objects to those elicited by typical concrete and abstract concepts (e.g. *desk* vs. *idea*). Our results revealed that the coerced concrete-coerced abstract distinction particularly engaged the ventral anterior temporal lobe (vATL), in which the typical concrete-abstract distinction was not distinguishable. Given the role the vATL plays in high-level concept representation as well as semantic composition, we argue that this effect reflects accessing the specific conceptual knowledge of the dot-objects. Accordant with the dot-object theory proposed in the Generative Lexicon of Pustejovsky, we hypothesise that the knowledge representations of the dot-objects involve an underspecified complex structure, i.e. the *qualia*; moreover when put in context, the representation instantiates to a more specific one.

The simple contrast, which consisted of simple concrete object and information concepts, replicated the typical effect found in studies on the concrete-abstract neural distinction. The object category (specifically the furniture category) could be differentiated from the information concepts such as idea and opinion in the ROIs that were often found in the literature: the angular gyrus (AG), the precuneus, the anterior inferior frontal gyrus (aIFG), the posterior ventral temporal lobe (pvTL) and the posterior lateral temporal cortices (PLTC). The univariate analysis also identified the left AG and the precuneus/posterior cingulate cortex (PCC) for the OBJECT > INFORMATION comparison, regions that have been closed related to concrete objects and mental imagery (e.g. Jessen et al., 2000; Binder et al., 2005; Sabsevitz et al., 2005). Moreover the OBJECT > INFORMATION comparison revealed the posterior parahippocampus, an area known as the parahippocampal place area (PPA) because it was shown to be specifically activated by seeing building pictures (Aguirre et al., 1998; Ishai et al., 1999) as well as large unmanipulable objects (Konkle & Oliva, 2012; He et al., 2013). Thus it is unsurprising that we found the PPA given the furniture category we used here. This comparison also identified the anterior cingulate cortex (ACC), which we attribute to a joint effect of concreteness and composition. We will discuss it in more detail in the later section.

We further demonstrated that it was the dot-object words per se, rather than the coercing verbs alone, that drove the discriminating effects found in the vATL. This is established by the observed dissociation in activation patterns between the dot-object contrast and the verb-control contrast, which consists of phrases with the same verbs but simple nouns. First the verb-control contrast was not distinguishable in the vATL. On the other hand, the verb-control contrast had the most reliably effect in the posterior sup/middle temporal lobe, an area that has been consistently found sensitive to action knowledge and verb reading (e.g. Martin et al., 1996; Chao et al., 1999; Perani et al., 1999; Grossman et al., 2002; Noppeney et al., 2005; Bedny et al., 2008; Binder et al., 2009; Peelen et al., 2012), while the dot-object contrast did not show such effect. Therefore we argue that it is the semantics of the dot-objects themselves and their interaction with the context that give rise to the neural distinction between the concrete and the abstract interpretation, rather than the verbs per se.

3.4.1 Polysemy, underspecification, and the mental representation of dot-objects

Why do the dot-object contrast and the typical concrete-abstract contrasts yield dissociated effects and why does this representation of dot-objects crucially involve the ventral anterior temporal lobe (vATL)? Our answer is that this dissociation is what we will predict on the basis of Pustejovskys refinement of the single lexical entry hypothesis which we call here the dot-object hypothesis (Pustejovsky 1995, 2011; Asher and Pustejovsky, 2006). We argue that this special nature of the dot-objects makes the underpinning neural mechanism(s) different from the one for the simple concrete and abstract concepts. And the reason that the dot-object contrast particularly engaged the vATL (which includes the anterior parahippocampus and the anterior fusiform gyrus, see Fig. 3.5), we argue, can be traced to the two roles the vATL plays which until recently have been considered distinct: as a "semantic hub" and as the centre of semantic composition.

The "semantic hub" account is initially proposed based on studies of semantic dementia (SD), arguing that the ATL is where conceptual knowledge converges (Damasio et al., 1996; Patterson, 2007). SD is a neurodegenerative condition that usually involves losses of everyday conceptual knowledge irrespective of modality; and its neuroanatomy signature is the focal damage in the anterior and ventral divisions of the temporal lobe (Warrington, 1975; Breedin et al.,1994; Damasio et al., 1996; Hodges & Patterson 1996; Mummery et al., 2000; Nestor et al., 2006). Neuroimaging studies on healthy subjects also identified the ATL as a key region for modality-independent semantic representation (e.g. Spitsyna et al., 2006; Pobric et al., 2009; Visser et al., 2010; Peelen & Caramazza, 2012). Therefore semantic hub theorists argue that although conceptual knowledge is represented in several distinct modality-specific systems across the brain (e.g. action, colour, etc.), the brains conceptual system also includes a component in which high-level, modality-independent conceptual knowledge is stored, i.e. the hub. The aforementioned evidence from both SD patients and healthy subjects led some to argue that the vATL contributes this storage. Importantly, activation in the vATL appears to be sensitive to the degree of specificity of a concept. One of the most robust findings about SD is the specificity effect: SD patients typically have more difficulty in tasks that require accessing more specific conceptual knowledge. For instance, SD patients usually show a reversed basic level effect: in contrast to normal subjects, SD patients perform better with tasks involving concepts at the superordinate level (e.g. *animal*) than with concepts at the basic level (e.g. *dog*) (Hodges & Patterson 1996; Rogers, et al., 2006; Wright et al., 2015). Moreover, SD patients' ability to recognise famous people and buildings is usually impaired (Damasio et al., 1996; Snowden et al., 2004). This sensitivity of the vATL to specificity has also been found in healthy subjects in neuroimaging experiments (Gorno-Tempini & Price, 2001; Tyler et al., 2004; Rogers et al., 2006). For instance, Tyler et al. (2004) examined the fMRI activation patterns of healthy subjects naming common object pictures, and found that the vATL was more activated in the basic-level naming compared to the superordinate-level; conversely the effect of the superordinate-level was restricted to the posterior temporal lobe. The authors reasoned that the vATL was activated when there was a need to access more specific properties and integrate information in order to make a detailed discrimination.

Echoing this conclusion, we argue that this sensitivity to specificity of the vATL also provides an explanation for our results. According to the dot-object theory, the coercion process involves coercing the concept going from a more general, underspecified representation to a more specific one. Thus, interpreting the dot-object stimuli in a specific context requires accessing conceptual knowledge at a more specific level.

In contrast, interpreting simple concepts does not usually involve such a specification process; their interpretations in a simple situation are at the basic level to begin with and remain at that level. As a consequence the simple contrast did not yield a discriminatory effect in the vATL.

The role of the ATL in semantic composition has been indicated in studies of sentence comprehension and speech processing (e.g. Mazoyer et al., 1993; Hickok & Poeppel, 2004). More recently a series of MEG studies also highlighted the role of the left ATL in a minimal semantic composition scenario, i.e. two-word combination (Bemis & Pylkkanen, 2012; Westerlund & Pylkkanen, 2014; Pylkkanen et al., 2014, Zhang & Pylkkanen, 2015). Importantly those studies demonstrated that the sensitivity of the left ATL to specificity and its role in semantic composition are not independent. In Westerlund & Pylkkanen (2014), the authors compared low- or high-specificity concepts (e.g. *fish/trout*) when the words were put in a combinatorial (i.e. combined with adjectives) or a non-combinatorial context. The result showed an interaction between concept specificity and composition in the left ATL, in that the activation of the left ATL was modulated mostly by the low-specificity adjective-noun combinations. They argued that when in a combinatorial context, the low-specificity concepts required a greater degree of specification and thus it yielded the largest effect in the ATL; therefore the effect of concept specificity and the semantic composition might stem from a shared mechanism. Although this MEG study identified a more broadly defined ATL and they could not pinpoint the effect in the subdivisions due to the limitation of MEG spatial localisation, their result is consistent with a ventral effect (personal communication). In another study, Zhang & Pylkkanen (2015) attempted to further disentangle the contribution from concept specificity and semantic composition to the effect found in the ATL. Using a similar setting that single-word specificity was manipulated in a two-word combinatorial phrase (e.g. *tomato/vegetable soup/dish*), they found the largest left ATL effect when a specific modifier was combined with a general head noun (e.g. *tomato dish*) whereas specificity only had a marginal effect in the non-combinatorial condition. This study further supports the conclusion that concept specificity and semantic composition are closely related, and the ATL plays a critical role in this mechanism. Our findings parallel these results. In our study, discrimination was observed in the left vATL for the dot-object contrast only, by which we speculate that the dot-objects require further specification when put in context. And if Pustejovsky is correct, semantic composition with dot-objects involves accessing the dot-object attributes the *qualia* in a specific way, which is not required for the "simple" concepts.

Taken together, the observations that 1) there is dissociation between regions discriminating concrete and abstract dot-objects and the typical concrete-abstract distinction, 2) the vATL selectively discriminates coerced concrete and abstract dot-objects, provide support to Pustejovskys dot-object theory: The lexical semantics of dot-object concepts involves a single underspecified concept, which can be coerced into more specific interpretations. The more specific representations elicit different activation patterns in the vATL.

3.4.2 The general effect in the angular gyrus

The other left-hemisphere ROI in which the dot-object contrast also showed a smaller but significant effect ($p<0.05$, FDR-corrected) is the left angular gyrus (AG); yet the simple-contrast and the verb-control contrast were also distinguishable in this ROI ($p<0.01$, FDR-corrected), indicating that the AG may serve a general function here. Indeed the AG has been hypothesised to be another "convergence zone" where multimodal information converges to form supramodal representations (Damasio, 1989; Binder et al., 2009; Binder & Desai, 2011; Seghier, 2013; Bonner et al., 2013). In particular Binder & Desai (2011) proposed that the AG might has a crucial role in event concept representation, given the AG's connections to other functional networks including the ones of spatial and action cognition. This proposal is consistent with our result in the AG: most of our stimuli (i.e. verb-noun phrases) depicted some sort of event, such as *present the book, explain the reason, open the parcel*. Therefore the successful classification of all the three types of contrast suggests that the AG may encode the event knowledge; and the difference between the concrete and abstract events was picked out by the multivariate analysis.

Some recent studies tried to address the question that how the two "semantic hubs", the ATL and the AG, were functionally different (Kalenine et al., 2009; Schwartz et al., 2011; Lewis et al., 2015). The overall picture suggests that the AG plays a special role in thematic relation, which is also in line with its hypothesised role in representing event knowledge (for instance, cake, candle, and balloon are thematically related in a "birthday party" event). On the other hand, it has been suggested that the ATL is specific to taxonomic relation, by which some argued that the concept representation in the ATL was in fact feature-based. Therefore we postulate that although they all evoked event knowledge, only the dot-object concepts in the coercing context required accessing the specific features and consequently recruited the ATL.

3.4.3 The implications to the neural representations of concepts

In the current study we examined the neural basis of comprehending words that are considered as associated with a single lexical entry in the mental lexicon. Taking a step further, it is interesting to consider the deeper question that why some words have multiple senses that share a single lexical entry in the mental lexicon. One intuition is that those senses are so closely related that the alternative sense(s) may be also important during comprehension. This is evidenced by the behaviour of the dot-object words that both senses can be accessed subsequently in a single sentence, as in (3.2a), thus a single-entry representation is clearly an advantage. This is not possible with homonyms, which are considered to have multiple entries, as in (3.2b), and even for some polysemous words whose different senses are more distant, as in (3.2c).

(3.2)

a. *Mary found that <u>book</u> very boring so she put it back to the shelf.*

b. **The <u>bat</u> hit the ball and flew away.*

c. **The <u>lamb</u> is cute and delicious.*

The single-entry phenomenon in (psycho)linguistics reflects the complexity of the conceptual system. However, the empirical evidence in the field of concept representation so far is largely from picture-viewing and single-word experiments; hence the complexity is usually overlooked. Thanks to the recent advance in neuroimaging technique and computational method, more researchers start to explore the complexity and the convergent evidence points to the anterior temporal lobes (ATLs). As discussed in the introduction section, these studies found the ATLs to be a semantic hub where the multimodal information converges and where a coherent concept is formed (Patterson 2007; Clarke & Tyler, 2014; Lambon Ralph, 2014); furthermore this account can explain the effect seen in concept specificity and semantic composition. Our result is in agreement to this trend of new findings that complex concept representations involve a different neural mechanism and go beyond the modality-specific brain regions. The specific category we look into in this study presents an interesting case in which the concrete and the abstract senses are closely tied together in a single word. It would be interesting to see that whether the observed effect can be generalised to other such complex concepts, such as *church* (refer to the building and/or the institution) and *lunch* (refer to the food and/or the event).

3.4.4 The effect in the right hemisphere

The dot-object contrast appeared to also engage the right hemisphere (RH). Several ROIs had higher classification accuracy in their RH part than the LH counterparts. The whole-brain parcellation MVPA and the univariate analysis also identified the right frontal and temporal regions. There are two competing accounts about the role of the RH in language comprehension. First, some have argued that regions in the RH has a similar role to their left side counterparts and may be sensitive to increased processing demands (e.g. Thompson-Schill et al., 1997; Kircher et al., 2001; Stowe et al., 2005; Zempleni et al., 2007; Pobric et al., 2010). According to this account, the effects found here could reflect the greater attentional and processing demands of the dot-object contrast. On the other hand, some have argued that in ambiguity resolution, the RH's role is to maintain multiple meanings, whereas the left hemisphere selects the appropriate one (Burgess & Simpson, 1988; Chiarello et al., 1998; Stowe et al., 2005). As we speculated in the above section, even in the coercing context, the sense of the other aspect of the dot-object may still somehow present and be easily accessible. Hence the RH may hold a more holistic representation of the dot-object concepts, i.e. the underspecified concepts spanning multiple senses of meaning; and the coercing context imposes some subtle difference and the different neural activity patterns can be discerned by MVPA.

The mid-to-right prefrontal cortex was more activated by the concrete interpretation of the dot-objects than the abstract interpretation, demonstrated by the univariate analysis (Fig. 3.6). This prefrontal effect may be parallel to the anterior midline field effect (AMF) found in MEG experiments with other kinds of coercion (Pylkkanen & McElree, 2007; Brennan & Pylkkanen, 2008; Pylkkanen, 2008). The authors proposed that the AMF effect reflect the effort of resolving meaning shifts. For instance Pylkkanen & McElree (2007) examined the neural correlates of complement coercion, exemplified by *Mary began the book* in which the verb *begin* expects an event such as writing and reading, but instead is combined with an entity noun, thus the object is coerced into an event such as *writing the book, reading the book*. They contrasted the coercion cases with non-coercion and animacy-violation sentences, and found the AMF effect only with the coercion condition. According to this account, our result may reflect the fact that the concrete-coercion (e.g. *pick up the book, open the catalogue*) has a greater degree of meaning-shift and it requires more comprehension effort than the abstract-coercion (e.g. *consult the book, explain the book*). However it could also be the consequence of the verb contexts we chose here. The abstract-coercing verbs (i.e. *consult, present, explain*) in fact expect some complement nouns with informational content, whereas the concrete-coercing verbs (i.e. *open, pick up, give (as a present)*) do not introduce such information therefore there may be more information to fill in in the concrete-coercion condition. Note that this midline effect should not be attributed simply to semantic expectancy because 1) in Pylkkanen & McElree (2007), the effect was not sensitive to anomalous sentences which had the lowest expectancy; 2) the expectancy effect typically occurs in the left hemisphere, especially the left IFG, which lacked in our result.

3.4.5 The effect of phrase comprehension

Our stand is looking at concepts in context is essential to understand the nature of concept representation. That being said, using phrases sets this study apart from the more standard ones that used single words as stimuli. A likely byproduct of this is that the neural activities associated with comprehending the phrase stimuli are nosier than single words because the neural processing becomes more complicated, and the effect becomes less salient. For instance, although our simple contrast (furniture vs.

information) is the most distinguishable one, the classification accuracy we obtain is lower than concrete-abstract decoding accuracies achieved in other single word MVPA studies (e.g. Wang et al. (2013), albeit a possible caveat is that their stimuli included many emotion words which could yield a stronger effect).

The phrase stimuli is also likely to be the reason that we found an unexpected region, the anterior cingulate cortex (ACC), for the object > information comparison in the simple contrast. The ACC, which is within the frontal attention network, has been shown to play a central role in a number of cognitive functions including error detection, conflict monitoring, decision-making, and emotion cognition (e.g. Carter et al., 1998; Bush et al., 2000; Botvinick et al., 2004). We speculate that the presence of the ACC may reflect the richer semantic information in the object category than the information category given the generic verbs (*have, give, change*) we used in both two categories. For instance in change the *sofa / idea*, the verb change carries more sensorimotor information in the concrete condition, thus it may be more cognitively engaging and/or incur a greater processing load. By contrast, the generic verbs in the abstract condition are also more "abstract" that they only convey a general sense of possessing or transfer.

3.4.6 Final remarks

We examined the mental representation of a class of logically polysemous words, "dot-objects", which are considered to have a single lexical entry but incorporate both a concrete and ab abstract sense, exemplified by the word *book*. Our results showed that the concrete and abstract interpretations of these words did not exhibit a "typical" concrete-abstract distinction found in the brain; but the ventral anterior temporal lobe (vATL) played a pivotal role of in representing the different interpretations. We argue that the vATL is responsible for the mechanism that those words, when in context, undergoing additional compositional processing to form a more specific interpretation, which supports the hypothesis that the meanings of such words are represented as a complex structure in which properties are categorised into certain fundamental types, i.e. the *qualias* (Pustejovsky 1995, 2011). Importantly, this is in accordance with other hierarchical semantic memory theories that view conceptual representation as a complex system within which the ATL serves as an integrating hub (e.g. Damasio et al., 1989; Tyler et al., 2004; Patterson 2007; Lambon Ralph et al., 2010; Lambon Ralph, 2014).

Chapter 4

The Neural Representation of Dot-objects: The Case of *Lunch*

4.1 Introduction

In the first fMRI experiment, we examined the neural representation of the classic example of logical polysemy, *book*. Concepts of this category, information print matter, are considered dot-objects consisting of a physical object and an information component (OBJECT • INFORMATION) in the Generative Lexicon framework of Pustejovsky. Our result highlighted the left ventral anterior temporal lobe (vATL) in differentiating the two interpretations; we interpreted the result as that the meaning representation of dot-objects, when in context, instantiates to a more specific representation, and the vATL plays a critical role in representing this complex conceptual knowledge.

In the second fMRI experiment reported in this chapter, we tested whether the effects observed with *book*-like dot-objects can be generalised to other dot-objects. We looked at another dot-object category, meal concepts like *lunch* and *dinner* that can refer to not only the aliment but also the event (and therefore are referred to as

FOOD • EVENT) (Fig. 4.1). As in the case of the print matter category, the meal concepts have a concrete and an abstract sense; the key characteristic is that both senses are closely tied together and can be accessed in a single expression (4a), and sometimes one aspect is more emphasised than the other depending on the context, such as in 4b and 4c.

(4)

a. *Lunch was delicious but took forever.*

b. *Don't let your dinner get cold.*

c. *Mary will not be pleased to see a total stranger at her dinner.*

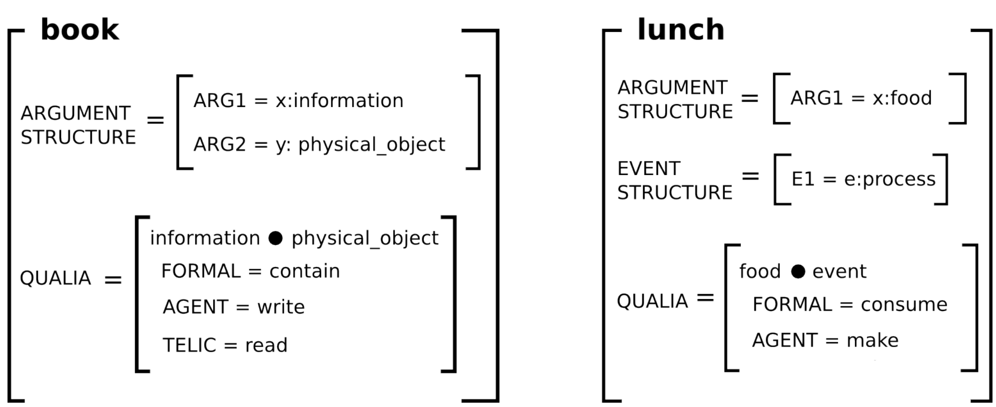

Figure 4.1: The sample schemata of the two dot-object categories examined thus far, *print matter* and *meal*, adapted from Pustejovsky, 1997. The *lunch* schema is an adaptation of the dot-object *exam*, which also refers to both the objects and the event.

We followed the same design as in Experiment 1. We set up three contrasts to 1) compare the coerced concrete and abstract interpretations, i.e. the food sense and the event sense, to typical unambiguous concrete and abstract concepts, and 2) to verify that the discriminating effect in the dot-object contrast is not solely driven by the verbs (Fig. 4.2). We applied the same ROI-based multivariate pattern analysis as in Experiment 1, focusing on the ROIs that showed discriminating effect to concrete vs. abstract concepts and/or semantic composition.

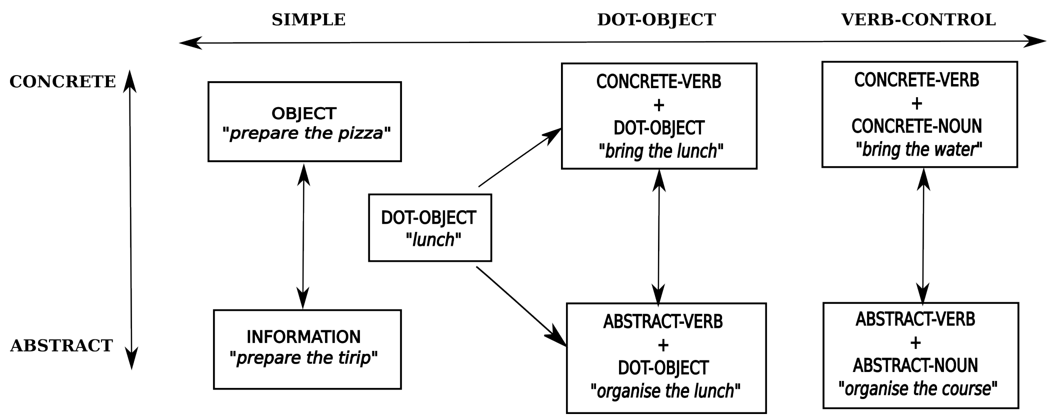

Figure 4.2: Experimental design. The three vertical lines indicate the three concrete-abstract contrasts. In the target contrast, dot-object, the dot-object words are combined with verbs that coerce the meaning into either the concrete or the abstract interpretation. The simple contrast contains typical concrete and abstract words combined with generic verbs. In the verb-control contrast, the same coercing verbs in the dot-object contrast are used but paired with unambiguous concrete and abstract nouns.

We expect that telling apart the concrete and abstract interpretations of dot-objects like *lunch* should engage the ATL as well because it also involves accessing the specific concept knowledge. Despite the commonality, we expect to observe some differences from the first experiment, as the meal category is different from the print matter category semantically. First, the abstract component here, i.e. event, is a distinctive notion viewed from both linguistic and psychological respects. And while the print matter concepts (e.g. *book, magazine*) are usually seen as concrete objects in isolation, the meal concepts like *lunch* and *dinner* are more likely to be considered as events in the first place. Second, even the concrete sense of the meal concepts appears to be more general and usually refers to a collection of food and drinks. Third, the meal concepts may involve neural representations that are specific to their semantics per se, for instance knowledge about food and social concepts (e.g. Simmons et al., 2005, 2013; Zahn et al., 2007; Ross & Olson, 2010).

With regard to those differences, we anticipate some variations of the ATL effect. First of all, the superior ATL (sATL) may play a more important part in this experiment given the event sense of the meal concepts. Both the vATL and the sATL have been identified for high-level concept representation. Yet the sATL appears to be more sensitive to speech processing and sentence comprehension (Mazoyer et al., 1993; Hickok & Poeppel, 2004; Humphries et al., 2005; Visser and Lambon Ralph, 2011). The sATL has also been occasionally identified for abstract > concrete comparison (e.g. Noppeney & Price, 2004; Binder et al., 2009; Tettamanti et al., 2008; Ghio & Tettamanti, 2010; Hoffman et al., 2015), which is usually ascribed to the extension of effect in the superior temporal lobe. Interestingly many of those studies which identified the sATL involved sentence stimuli that bear abstract event knowledge. For instance in Ghio & Tettamanti (2010), participants passively listened to short sentences describing action events such as *I push the bottom* or abstract events such as *I appreciate the loyalty.* In a recent study, Hoffman and colleagues used distortion-corrected fMRI to examine the concreteness effect with manipulating the context (Hoffman et al., 2015). Participants made a synonymy judgement on a target word against three options preceded by a sentence context (for instance the participant read *The road is closed. We must look for an alternative*, then they selected the synonymy of the target word alternative among three choices, *substitute, ambition, discretion*). The target word could be either concrete or abstract, and the sentence context could be either relevant or irrelevant. Firstly they found, after correction for fMRI signal loss, all the subdivisions of the ATL were activated by both concrete and the abstract concepts. Secondly, there was a graded concreteness effect along the vertical axis of the ATL: the superior division was more activated by abstract words, whilst the ventral ATL was more activated by concrete words. Interestingly the authors further found that, although both showed an abstract > concrete effect, the sATL and the IFG reacted differently to the context manipulation: while the IFG had the greatest activation in the irrelevant context condition, the sATL gave the greatest response when the context was coherent. This differentiation suggests that the function of the sATL is enriching semantic representation rather than exercising semantic control. In all, we expect that the greater information and integration demand that the event sense brings about will have an influence on the ATL effect, especially it may give rise to a larger effect in the sATL.

4.2 Methods and Materials

4.2.1 Participants

Fifteen volunteers were recruited (8 female, mean age 23, SD: 2.9). All participants were native Italian speakers, right-handed, and had normal or corrected-to-normal vision. All procedures were approved by the ethics committee of University of Trento, and participants received a small monetary compensation.

4.2.2 Materials

The experiment was conducted in Italian. We selected three words from the FOOD • EVENT dot-object category: *lunch, dinner*, and *aperitif*, which is a very common concept in Italy (*aperitivo*) that refers to a before-meal event with light alcoholic drinks and snacks to open the appetite. It can be a formal reception as well as a get-together among friends, in the meantime it also refers to the food and drinks, especially the alcoholic beverage usually served.

Again we used verbs to coerce the meaning into either the concrete or the abstract sense, following the same selection and norming procedure as Experiment 1. First we came up with a pool of verbs that could potentially be the coercing verbs, then we constructed the combinations that were to be rated familiarity, concreteness and imageability. Thirty-three native speakers were recruited in the norming study and none of them participated in the fMRI experiment. Based on the norming result, we selected 3 concrete (*cook, bring, pack*) and 3 abstract (*cancel, reserve, organise*) verbs to form the phrases in the dot-object contrast. As Experiment 1, we constructed two additional contrast, i.e. the simple and the verb-control contrast. The simple contrast consisted of categories that approximated the partial senses of the dot-objects, i.e. man-made food (e.g. *pasta, pizza*) vs. event concepts (e.g. *trip, party*). To keep the grammatical form the same across all the conditions, nouns of both the two categories were combined with some generic verbs (pay, prepare) to form the verb-noun phrases. The verb-control contrast contained phrases with the same verbs as in the dot-object conditions, but the verbs were combined with their common complement words drawn from various concrete and abstract categories (e.g. *pack the gift, bring the water / organise the course, reserve the place*). Each contrast had 6 concrete and 6 abstract phrases, resulting in 36 phrases in total (6 phrases * 2 categories * 3 contrasts), the full stimulus set is showed in Table 4.1.

Phrases of each contrast were matched in length and the number of phonemes (number of letters: $t_{\text{Dot-object}}(10)=-1.50$, $p=0.16$; $t_{\text{Simple}}(10)=-0.26$, $p=0.80$; $t_{\text{Verb-control}}(10)=1.31$, $p=0.22$. number of phonemes: $t_{\text{Dot-object}}(10)=1.58$,, $p=0.14$; $t_{\text{Simple}}(10)=0.0$, $p=1.0$; $t_{\text{Verb-control}}(10)=1.31$, $p=0.22$). All categories matched familiarity ($F(5,30)=0.85$, $p=0.51$). The concreteness and imageability ratings are significantly different for all the three concrete-abstract contrasts except the imageability the dot-object contrast ($t(10)=-1.22$, $p=0.25$). The detailed results are in Table 4.2 and depicted in Fig. 4.3.

4.2.3 Procedure

The procedure is identical to Experiment 1; we repeat the description here. Participants were instructed to attentively read verb-noun phrases and judge whether

Table 4.1: Stimulus words used in the three concrete-abstract contrasts. Each contrast contains seven concrete and seven abstract verb-noun phrases. The original Italian stimuli are showed below the English translation. The dot-objects are highlighted with bold font.The simple contrast contains the simple, mono-sense concrete and abstract concepts paired with the same generic verbs. The verb-contrast consists of the same coercing verbs but paired with their common complement nouns.

	dot-objects	**simple**	**verb-control**
ABSTRACT	cancel the **dinner**	pay the travel	cancel the decision
	cancel the **aperitif**	pay the trip	cancel the enrollment
	reserve the **lunch**	pay the party	reserve the concert
	reserve the **dinner**	prepare the travel	reserve the place
	organise the **dinner**	prepare the party	organise the course
	organise the **aperitif**	prepare the meeting	organise the day
CONCRETE	pack the **dinner**	pay the pasta	pack the package
	cook the **lunch**	pay the pizza	pack/wrap the present
	cook the **dinner**	pay the risotto	cook the dish
	bring the **dinner**	prepare the bread	cook the recipe
	bring the **lunch**	prepare the risotto	bring the water
	bring the **aperitif**	prepare the pasta	bring/fold the shirt

Original stimuli in Italian

	dot-objects	**simple**	**verb-control**
ABSTRACT	annullare la **cena**	pagare il viaggio	annullare la decisione
	annullare l'**aperitivo**	pagare la gita	annullare l'iscrizione
	prenotare il **pranzo**	pagare la festa	prenotare il concerto
	prenotare la **cena**	preparare il viaggio	prenotare il posto
	organizzare la **cena**	preparare la festa	organizzare il corso
	organizzare l'**aperitivo**	preparare l'incontro	organizzare la giornata
CONCRETE	confezionare la **cena**	pagare la pasta	confezionare il pacco
	cucinare il **pranzo**	pagare la pizza	confezionare il regalo
	cucinare la **cena**	pagare il risotto	cucinare il piatto
	portare la **cena**	preparare il pane	cucinare la ricetta
	portare il **pranzo**	preparare il risotto	portare l'acqua
	portare l'**aperitivo**	preparare la pasta	portare la camicia

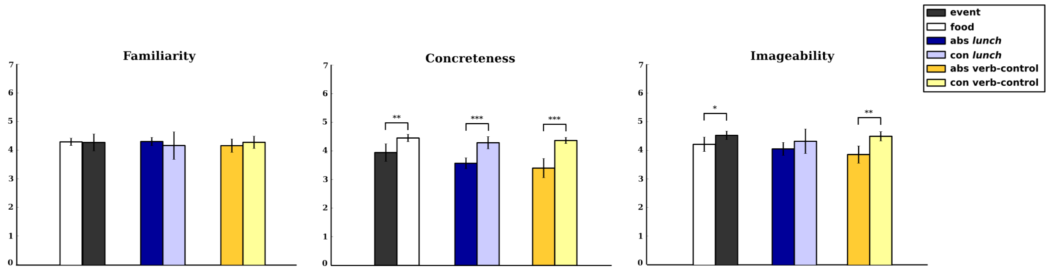

Figure 4.3: Ratings of familiarity, concreteness, and imageability of each category. Two-sample t-tests were calculated for each concrete-abstract contrast. The concreteness and imageability ratings are significantly different for all three contrasts.

Table 4.2: The psycholinguistic parameters of the stimulus phrases in each condition. Familiarity, concreteness, and imageability are obtained from the norming experiment with thirty-eight participants. Standard deviations are showed in parentheses.

Category	**familiarity**	**concreteness**	**imageability**	**letters**	**phonemes**
dot-object abstract	4.20(0.49)	3.58(0.19)	4.06(0.23)	18.33(2.13)	8.0(1.15)
dot-object concrete	4.34(0.14)	4.29(0.22)	4.33(0.43)	16.50(1.71)	7.0(0.82)
simple abstract	4.33(0.13)	3.95(0.31)	4.22(0.25)	16.33(2.29)	6.83(0.69)
simple concrete	4.31(0.30)	4.46(0.13)	4.53(0.15)	16.00(1.73)	6.83(0.69)
Verb-control abstract	4.20(0.24)	3,41(0.34)	3.86(0.30)	20.00(1.63)	8.17(0.69)
Verb-control concrete	4.31(0.22)	4.37(0.11)	4.50(0.16)	17.83(2.27)	7.33(1.25)

the verb-noun combinations were meaningful. About 10% were catch trials which contained meaningless combinations. We adopted a slow-event design. Each trial started with a fixation cross for 500ms, followed by a verb and then an article-noun phrase, each of them was present for 450ms with a 100ms interval. A black cross then remained on the screen for 1500ms to encourage participants to form an elaborate mental representation, then a question mark was displayed for 1000ms at which point participants responded by pressing the left or right button box (counterbalanced across participants). The next trial started after 6 second fixation time (Fig. 4.4). During one scanning session, all 36 verb-noun phrases along with 4 catch trials (10% of all trials) appeared once in a random order. Each participant completed 6 sessions.

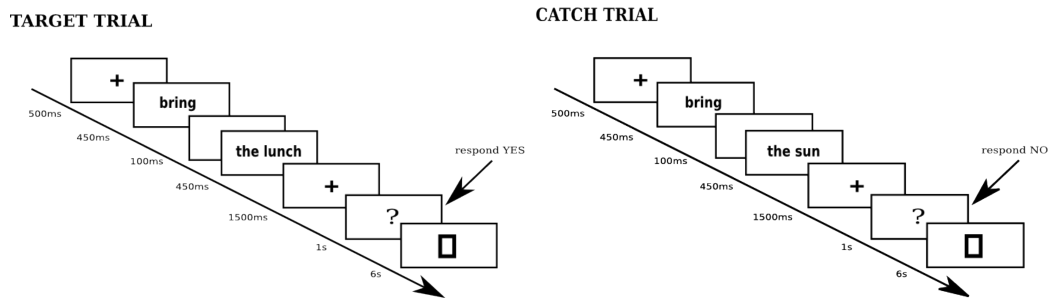

Figure 4.4: Experimental paradigm. Participants performed a semantic meaningfulness judgement task and responded by pressing the button boxes with the left or the right hand (counterbalanced across participants).

4.2.4 Data acquisition

All of the fMRI experiments were conducted with a 4T Bruker MedSpec MRI scanner. Structural images were acquired using a T1 weighted MPRAGE sequence with resolution 1*1*1mm in the beginning of the experiment. A T2*weighted EPI pulse sequence was used to acquire the functional images with parameters TR 1000ms, TE 33ms, and 26 flip angle, FoV1000*1000. Each acquisition volume contains a 64*64 matrix and 17 slices with a gap of 1mm. Voxel dimensions are 3mm*3mm*5mm.

4.2.5 Analysis

The same analyses as in Experiment 1 were applied. First we conducted the univariate analysis to calculate the activation maps of all the three concrete-abstract contrasts. Then we performed the multivariate pattern analysis (MVPA) in the seven ROIs as in Experiment 1, and we also compared the effect in the left and right ROI. At last we examined all subregions across the whole brain with MVPA. The seven ROIs are: 1) the anterior inferior frontal gyrus (aIFG), 2) the angular gyrus (AG), 3) the precuneus/posterior cingulate gyrus (PCC), 4) the posterior ventral temporal lobe (pvTL), 5) the posterior lateral temporal cortices (PLTC), and 6) the superior anterior temporal lobe (sATL) and 7) the superior anterior temporal lobe (vATL).

The ROI details are in Table 3.3 and Fig. 3.5. All the technical details are the same as Experiment 1 and can be found in chapter 3.

4.3 Results

4.3.1 Behaviour

The error rates of the fifteen participants range from 2.5% to 16% (mean error rate 0.07, SD 0.05). Because we wanted participants to concentrate on forming a rich mental representation rather than responding quickly (and responses were delayed until a question mark was presented), we did not analyse reaction times. Trials without a response in 5 seconds were considered as missed trials.

4.3.2 Univariate analysis

Four clusters were identified for the food > event comparison in the simple contrast. Three clusters were located in the bilateral frontal cortex, including both the dorsolateral part and the medial frontal cortex. The bilateral thalamus and insula were also activated. Another cluster was found in the right angular gyrus. The abstract > concrete comparison of the verb-control contrast identified two clusters in the mid-precuneus /posterior cingulate cortex and the medial prefrontal cortex. No significant effect was found for the dot-object contrast (Fig. 4.5, Table 4.3).

4.3.3 ROI-based Multivariate Pattern Analysis (MVPA)

We examined the same seven left-hemisphere (LH) ROIs as in Experiment 1. Again, the simple contrast was the most distinguishable contrast; the classification accuracy was significant in four ROIs: the aIFG, the AG, the PLTC, and the sATL. For the dot-object contrast, in contrast to Experiment 1, we did not observe a significant effect in the left-hemisphere ATL, neither ventral nor superior. However, this contrast could be distinguished in the AG, the precuneus/PCC, and the pvTL. Finally, the verb-control contrast could be distinguished in the AG, the precuneus/PCC as well, along with the PLTC (Fig. 4.6, Table 4.4).

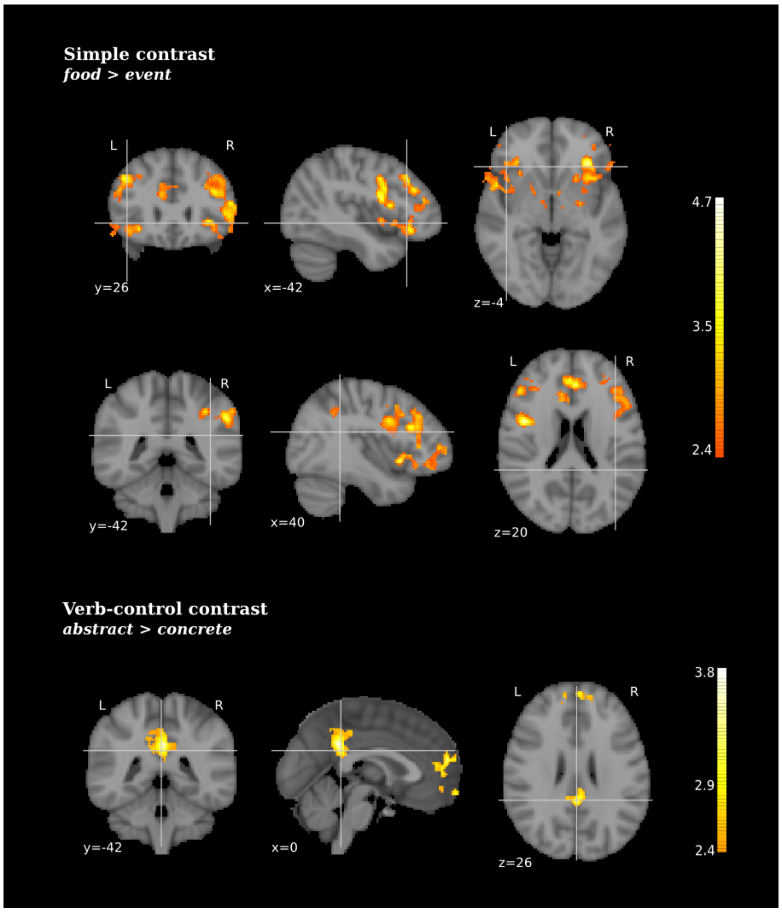

Figure 4.5: Univariate analysis result. The concrete and the abstract conditions of each contrast were compared with a two-sample paired-test. The colour bars indicate the voxel-wise Z (Gaussianised T/F) statistics thresholded by Z>2.3 (p<0.05). The significant clusters were calculated with the cluster-based method provided by the FSL software (cluster p<0.05, FDR-corrected). The individual maps were registered to the MNI-standard brain (2mm resolution) to form the final group map. Significant effects were found for the *food* > *event* comparison in the simple contrast, and the *abstract* > *concrete* in the verb-control contrast. No other significant effect was found for other comparisons.

Table 4.3: Univariate analysis result. The significant clusters were calculated by the cluster-based inference using the Gaussian random field (GRF) method, with the cluster-level threshold p<0.05 was used (FWER corrected). The MNI coordinates show the voxels with the local maxima z-values (Gaussianised T/F)within the cluster.

Region	**Extent**	**Cluster p**	**MNI coord**	**Z**
(1) Simple contrast				
concrete>abstract				
Left frontal cortex	4090	1.07e-14		
frontal pole			(-22,42,32)	4.73
precentral gyrus			(-44,2,20)	4.39
cingulate gyrus, anterior division			(2,36,22)	4.21
thalamus			(-10,-8,2)	4.16
middle frontal gyrus			(-48,30,26)	4.11
inferior frontal gyrus, pars opercularis			(-46,6,26)	3.95
Right dorsolateral frontal cortex	1691	1.19e-07		
middle frontal gyrus			(40,24,24)	3.85
precentral gyrus			(36,6,30)	3.62
inferior frontal gyrus, pars triangularis			(52,26,14)	3.58
Right medial frontal cortex & basal ganglia	939	9.36e-05		
frontal orbital cortex			(34,30,-4)	4.3
insular cortex			(40,14,-6)	4.07
frontal pole			(54,42,-8)	3.92
thalamus			(6,-2,6)	3.26
Right posterior parietal lobe	382	0.0448		
supramarginal gyrus, posterior division			(54,-42,36)	4.09
superior parietal lobule			(32,-46,42)	3.88
angular gyrus			(44,-46,36)	2.79
abstract>concrete				
– –				
(2) Dot-object contrast				
– –				
(3) Verb-control contrast				
abstract>concrete				
Bilateral PCC/precuneus	637	0.0066		
cingulate gyrus, posterior division			(2,-44,32)	3.84
precuneous cortex			(4,-48,42)	2.94
Medial prefrontal cortex	439	0.0495		
frontal pole			(0,56,18)	3.29
paracingulate gyrus			(-2,56,14)	3.24
– –				

Table 4.4: Classification accuracy of the ROI-based multivariate pattern analysis. Results are compared for the three types of concrete-abstract contrasts. P-values were calculated with one-sample t-test (dof=14) against the 0.5 chance level of the classification accuracy. Significant values are highlighted (FDR corrected). The target dot-object contrast could be significantly distinguished in three left hemisphere ROIs in the posterior parietal and temporal lobe, and in the two right hemisphere ATL ROIs.

ROI	**Classification accuracy (SEM)**	
	LH	RH
Angular gyrus		
Simple	**0.5686 (0.0250)**	0.5342 (0.0207)
Verb-control	**0.5572 (0.0230)**	0.5456(0.0176)
Dot-object	**0.5466 (0.0183)**	0.5290 (0.0224)
Precuneus/posterior cingulate cortex		
Simple	0.5469 (0.0252)	0.5288 (0.0232)
Verb-control	**0.5583 (0.0154)**	0.5533(0.0250)
Dot-object	**0.5583 (0.0190)**	**0.5500 (0.0200)**
anterior inferior frontal gyrus (aIFG)		
Simple	**0.5630 (0.0221)**	0.4995 (0.0239)
Verb-control	0.5155 (0.0247)	0.5604 (0.0271)
Dot-object	0.4945 (0.0187)	0.5380 (0.0208)
posterior ventral temporal lobe (pvTL)		
Simple	0.5586 (0.0314)	0.5564 (0.0264)
Verb-control	0.5045 (0.0151)	0.5248 (0.0213)
Dot-object	**0.5530 (0.0209)**	0.5352 (0.0229)
posterior lateral temporal cortices (PLTC)		
Simple	**0.5828 (0.0268)**	0.5157 (0.0256)
Verb-control	**0.5458 (0.0206)**	0.5401 (0.0230)
Dot-object	0.5393 (0.0234)	0.5363 (0.0207)
ventral ATL		
Simple	0.5285 (0.0235)	0.5282 (0.0227)
Verb-control	0.4948 (0.0242)	0.5226 (0.0188)
Dot-object	0.4988 (0.0177)	**0.5637 (0.0157)**
superior ATL		
Simple	**0.5677 (0.0177)**	0.5375 (0.0251)
Verb-control	0.4928 (0.0198)	0.5233 (0.0194)
Dot-object	0.5309 (0.0198)	**0.5584 (0.0160)**

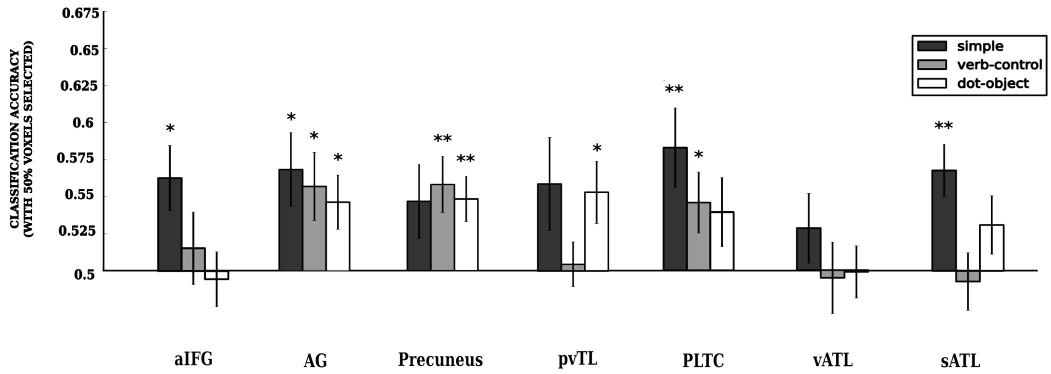

Figure 4.6: Classification accuracy for the three types of contrast in each ROI. Error bars indicate SEMS. P-values of the classification accuracy were calculated with one-sample t-test (dof=14) against the 0.5 chance level (one-tailed p-value, FDR corrected, *****p<0.00001, ****p<0.0001, ***p<0.001, **p<0.01, *p<0.05).

The right-hemisphere (RH) ATL ROIs, on the other hand, clearly outperformed their LH counterparts (Fig. 4.7). Specifically the classification accuracies of the right vATL and the sATL, and the precuneus/PCC were significant ($p<0.05$, FDR-corrected); we also observed a marginal effect between the left and right vATL ($F(1,28)=-2.98$, $p<0.1$).

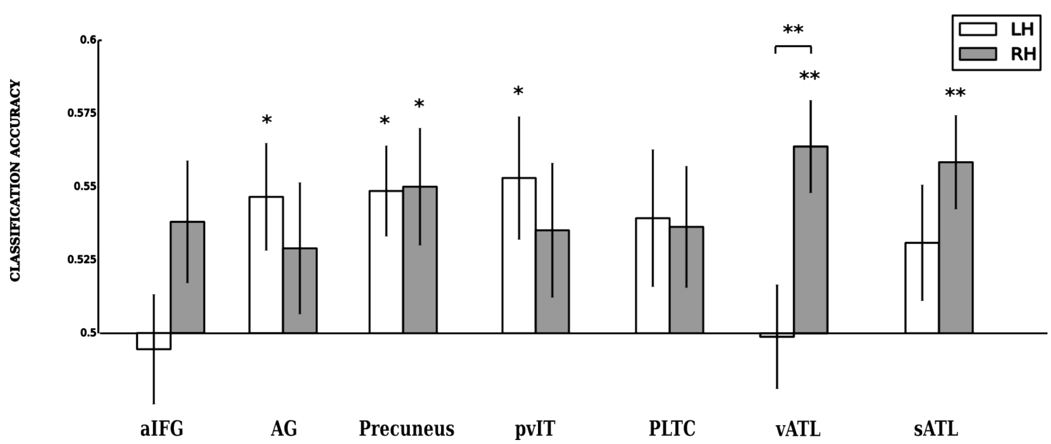

Figure 4.7: Comparing the classification accuracy for the dot-object contrast of each ROI in the left and the right hemisphere. Error bars indicate SEMS. P-values of the classification accuracy were calculated with one-sample t-test (dof=14) against the 0.5 chance level (one-tailed p-value, uncorrected, *****p<0.00001, ****p<0.0001, ***p<0.001, **p<0.01, *p<0.05)

4.3.4 Whole-brain parcellation MVPA

The simple contrast yielded thirty-seven subregions across the whole brain with p¡0.05 after correcting for multiple comparison. Three of them had $p<0.001$ (FDR-corrected), which are the left IFG, pars opercularis division, the left frontal medial cortex, and the left posterior parahippocampal gyrus. For the dot-object contrast only two subregions, the left juxtapositional lobule cortex and the left cuneal cortex were significant after multiple comparison correction. No region was found to be significant for the verb-control contrast.

4.4 Discussion

In Experiment 2, we investigated a second category of dot-objects: meal concepts such as *lunch* and *dinner*. These words, as well, have been claimed to have a single entry in the mental lexicon, just as the information print matter concepts, such as *book* and *magazine*, discussed in the last chapter. And just as in the case of the information print matter category, the meal category is considered as consisting of a concrete and an abstract sense component: i.e. a food sense and an event sense. As with other dot-objects, one aspect is more focused than the other sometimes, depending on the context (e.g. *a delicious lunch* vs. *a long lunch*). Like what we argued with the print matter category in the last chapter, we hypothesise that those words have a single entry in the mental lexicon. When put in a coercing context, the word's meaning instantiates from an underspecified representation to a more specific one; and the anterior temporal lobe (ATL) plays a key role in representing this complex meaning representation.

As in Experiment 1, we used verbs to coerce the dot-objects into either the concrete or the abstract interpretation (e.g. *cook the dinner* vs. *cancel the dinner*), and applied classification analysis to distinguish between their neural representations. Consistent to our prediction, the dot-object contrast engaged the ATL. Nevertheless the meal category here displayed three disparities from the print matter category. First, the ATL effect was found in the right ATL instead of the left. Second, the effect also extended to the sATL. Third, the dot-object contrast could be distinguished in the other ROIs that have been associated with concrete object representation whereas this effect was absent in the Experiment 1.

4.4.1 A shift of focus within the ATL

Given the fact that our materials are linguistic, one would expect the more reliable effect to be in the left hemisphere. Yet we already observed minor right hemisphere (RH) effects in the previous experiment; and in the current experiment, one of the main findings is that the dot-object contrast engages the right ATL instead of its left counterpart. Moreover, whereas the ventral division of the ATL was emphasized in Experiment 1, both the superior and ventral divisions exhibited the discriminating effect for the current dot-object category.

The relationship between the left and right ATLs has been a matter of debate. Some argue that the LH and RH ATLs work in a similar way. Semantic dementia (SD) patients normally suffer from bilateral ATLs damage. A more recent study with twenty patients with unilateral ATL damage (Lambon Ralph et al., 2010) demonstrated that although the left-unilateral cases were doing relatively worse in language fluency, unilateral damage did not result in the profound disruption of semantic memory. The authors argued that the two ATLs functionally complement each other to make a more robust system. Repetitive TMS studies with healthy subjects also lent support to this account, showing that the temporal lesion produced by TMS in both the left and right ATL had a similar effect to semantic processing (Pobric et al., 2009, 2010). On the other hand, divergence between the left and right ATL has been observed, especially in social cognition. Overall evidence suggests that the left ATL is biased toward verbal stimuli while the right ATL favours pictorial stimuli, in particular famous faces (e.g. Snowden et al., 2004; Mion et al., 2010). Patients with right ATL lesion may experience more difficulty with their social ability (e.g. Liu et al., 2004; Irish et al., 2014). Moreover the right superior ATL has been associated with reading words regarding social knowledge (Zahn et al., 2007, 2009; Ross & Olson, 2010).

In the brain as a whole, the LH and the RH show divergent functionality. Although it is not uncommon to observe a bilateral network in language experiments, the RH has been found to be more active with high comprehension demand (Mazoyer et al., 1993; Humphries et al., 2001; Humphries et al., 2001; 2005; Bookheimer, 2002; Menenti et al., 2008) and figurative language processing (e.g. Bottini et al., 1994; Coulson & Wu, 2005; Mashal et al., 2007; Diaz & Hogstrom, 2011). In lexical ambiguity resolution, it has been claimed that the LH's role is said to be to select the appropriate interpretation, whereas the RH maintains a representation of all alternative interpretations (Burgess & Simpson 1988; Chiarello, 1988; Jung-beeman 2005; Pylkkanen et al., 2006). In a MEG study on polysemy, Pylkkanen and colleagues measured the M350 component (equivalent of the EEG N400 component) with a priming paradigm. As predicted from the single-lexical-entry hypothesis, they found a facilitatory effect (decreased M350) in the LH for the related senses of a polysemous word (e.g. *lined paper liberal paper*); by contrast, the M350 in the RH had a longer latency, suggesting that the two senses might shadow each other in the RH. Admitting that further evidence was needed, the authors speculated that the LH and the RH work in a qualitatively different manner in polysemy comprehension (Pylkkanen et al., 2006).

In the light of these findings summarised above, we interpret our findings as follows. We argue that 1) our finding about the *lunch*-like dot-objects being discriminated in the right ATL indicates that the interpretation of this type of dot-objects, as well, does not involve disambiguation, but reaching a more specific meaning representation when in context; however, 2) the dissociation we observed between the left and right ATLs supports the claims that the there is a division of labor between the ATLs in the two hemispheres. One possible reason why further specification of *lunch*-like dot-objects involves the right rather than the left ATL is that an event such as *lunch* and *aperitif* usually is a social occasion; hence it has a right ATL bias as the right ATL is shown to play a more important role in social knowledge.

With respect to the additional recruitment of the sATL, the answer might lie in two threads of evidence. First, as described in the introduction, the sATL is sometimes found to be more activated by abstract than concrete concepts (Noppeney & Price, 2004; Tettamanti et al., 2008; Binder et al., 2009; Ghio & Tettamanti, 2010; Wang et al., 2010; Hoffman et al., 2015). The second thread of evidence is that the right sATL is shown to be sensitive to reading words concerning social knowledge (Zahn et al., 2007, 2009; Ross & Olson, 2010; Olson et al., 2013). In an fMRI study described in Zahn et al. (2007), healthy subjects read pairs of words containing abstract social knowledge (e.g. *brave-honor*). The authors found the right superior ATL (sATL) activation among a number of social cogniton areas. Moreover they correlated the brain activation to the descriptiveness (an index equivalent to specificity) of the social behaviour, and found that the right sATL was the only region that showed a significant correlation. A further study with frontotemporal dementia patients confirmed the right sATL effect (Zahn et al., 2009).

To summarise, the ATL also plays a pivotal role in representing the meaning of the meal category of dot-objects, corroborating the hypothesis that the related senses of a dot-object are stored as an underspecified structure, and when in context, it instantiates into a more full-fledged representation. Nonetheless the focus shifted from the left ventral ATL to the right ATL, and additionally recruited the superior division. We attribute this shift to the semantics of the meal category examined in the current experiment: concepts such as *dinner* and *lunch* contain a social component; in addition, such concepts are more abstract than the *book*-like dot-objects; both of these aspects would explain the involvement of the sATL.

4.4.2 The dot-objects are also distinguishable in ROIs outside the ATL

Outside the bilateral ATLs, the dot-object contrast could be distinguished in the left angular gyrus (AG), the bilateral precuneus/posterior cingulate cortex (PCC), and the left posterior ventral temporal lobe (pvTL). First, note that the left AG showed the same result pattern in both fMRI experiments that it could discriminate all the three contrasts. Thus it further strengthens our argument that the AG has a general role in representing event knowledge.

The left precuneus/PCC, besides the dot-object contrast, also showed discriminating effect for the verb-control contrast; and this region was activated by the abstract > concrete comparison of the verb-control contrast. Therefore we speculate that the precuneus/PCC may be evoked by the specific verbs chosen here. Previous research has linked this region to episodic memory and mental imagery, consequently it should be more activated by concrete concepts (Jessen et al., 2000; Binder et al., 2005; Sabsevitz et al., 2005). We reproduced this effect with the simple object > information comparison in Experiment 1; however, the abstract > concrete comparison of the verb-control contrast in the current experiment recruited this region, along with a cluster in the medial prefrontal cortex. We relate this observation to the other studies that also reported this effect (D'Esposito et al., 1997; Tyler et al., 2001; Tettamanti et al., 2008; Ghio & Tettamanti, 2010). D'Esposito et al. (1997) explicitly compared imagining objects and passively listening to abstract words. Compared to generating object images, the abstract condition elicited the bilateral precuneus and the right superior frontal gyrus. In a PET study, Tyler et al (2001) included both concrete and abstract verbs and nouns. The abstract > concrete comparison regardless the word class identified the PCC. In Tettamanti et al. (2008), participants listened to sentences referring to action or abstract events (e.g. *I push the bottom, I appreciate the loyalty*), and the sentences were either affirmative or negative (e.g. *I do not push the bottom*). Again the abstract condition activated the PCC more than the concrete condition, or in their words, the concrete condition was more de-activated than the abstract condition. Ghio & Tettamanti (2010) replicated this finding with a similar design. Furthermore the dynamic causal modelling (DSM) analysis showed that the left superior temporal gyrus (LSTG) propagated to the PCC in the abstract-sentence reading condition. The authors reasoned that the abstract > concrete effect was in fact the de-activation of the action-related sentence condition, owing to the fact that the PCC is in the default mode network. Our observation is in agreement with this explanation. Note that the abstract > concrete comparison of the verb-control contrast identified the PCC as well as the other main site of the default network, the media prefrontal cortex. Moreover all the aforementioned studies (except D'Esposito et al. (1997), however their concrete condition involved actively generating mental images) used verb stimuli as our experiment. Hence verbs and/or event knowledge might have a greater contribution to the de-activation of the PCC.

The other ROI that showed a distinguishing effect for the dot-object contrast is the left pvTL, which contains the posterior part of the inferior temporal lobe and the fusiform gyrus. We predicted that the pvTL should be sensitive to the concrete conditions given this region's central role in object knowledge (e.g. Thompson-Schill et al., 1999; Chao et al., 1999; Martin & Chao, 2001; Haxby et al., 2001; Bookheimer 2002; Thompson-Schill, 2003; Martin, 2007); and indeed the effect was found with the simple-contrast in Experiment 1 but absent in the target dot-object contrast. We interpret the significant distinguishing effect here as the concrete-coerced dot-objects, i.e. the food sense, resemble normal concrete concepts to a certain degree. There was a marginal effect for the simple-contrast but it fell short of reaching significance ($p<0.1$ after FDR-corrected). Yet it raises the question that why the concrete-coerced dot-object in the first experiment (i.e. the object sense of, for instance, *book*) did not show any such concreteness effect. One potential explanation is that the concrete and the abstract interpretations of the *book*-like concepts are more close to each other, and the notion of, say, "consult the book", is more concrete than the notion of organise the lunch. The norming results seemed to confirm this intuition: The concreteness ratings for the concrete and the abstract phrases of the *book*-like dot-objects had a difference with $p<0.001$ (independent two-sample t-test), while this value of the *lunch*-like dot-objects was $p<0.0001$. Though not significant, the "abstract *books*" were perceived slightly more concrete than the "abstract *lunch*" (mean concreteness ratings 3.65+/-0.33 vs. 3.58+/-0.19).

Another possible explanation to the recruitment of the pvTL by the dot-object contrast is that food concepts are remarkably salient in the brain. There are several studies in concept representation that are specifically dedicated to the food category (e.g. Ross & Murphy, 1999; Simmons et al., 2005, 2013; Martin, 2007). In an fMRI study by Simmons et al. (2005), participants viewed pictures of high-caloric food such as cheeseburgers and cookies. And they found that the food pictures reliably activated not only the bilateral insula, which is within the primary gustatory cortex and is responsive to taste, but also the pvTL compared to building pictures. Interestingly we also found similar and even stronger effect here that the food concepts in the simple-contrast (e.g. *pizza, pasta, bread*) activated large bilateral networks, in particular the bilateral insular cortices; and the simple-contrast could be distinguished in thirty-seven subregions in the whole brain classification analysis. It is in fact unsurprising given the special role of food plays in life. Hence the food sense that was coerced from the meal concepts (e.g. *bring the lunch, cook the dinner*) evoked sufficient activities in the pvTL, a multimodal brain region that is crucial to object knowledge representation. Yet the effect was not strong or consistent enough across individuals to be captured by the univariate analysis.

4.4.3 Final remarks

In this experiment, we investigated the other category of dot-objects: meal concepts such as *lunch* and *dinner*. Likewise, we argue the meaning representation of these dot-objects is associated with a single, unspecified meaning structure in the mental lexicon, as the information print matter concepts in Experiment 1. This conclusion is drawn on the distinguishing effect in the ATL for the concrete- and the abstract-coerced interpretations, i.e. *lunch* as the food or as the event. However, the current experiment highlights the right ATL, and additionally recruite the superior division of the ATL (sATL). We attribute the variations to the more abstract and sociality-related nature of the meal category.

Chapter 5

Oscillatory MEG Gamma-band Activity Dissociates Concrete and Abstract Coercion: A Decoding Study

5.1 Introduction

In the first two experiments we looked separately with fMRI at two categories of dot-objects: print matter (OBJECT • INFORMATION) such as *book* and *magazine*, and meal (FOOD • EVENT) such as *lunch* and *dinner*. The motivation for looking at one category a time is that we expected distinct fMRI activation patterns for each semantic category: clearly the concept *book* is quite different from the concept *lunch*. Moreover, we were also interested in the question of whether the neural representation of a dot-object could be seen as a simple combination of the neural representation of its partial sense for example, whether the neural representation of abstract-coerced *book* resembled that of information concepts like *story* or *opinion*, or whether concrete-coerced *lunch* is represented similarly to simple food concepts such as *pizza* or *steak*.

Although some variations were observed between the two categories, both experiments highlighted the anterior temporal lobe (ATL), the key brain region in representing high-level concept knowledge. We argued that the result supported the hypothesis that the multiple senses of dot-objects were stored as a single unspecified structure in the mind; and the coercion process (e.g. *open the* <u>*book*</u>*, consult the* <u>*catalogue*</u>*, organise the* <u>*dinner*</u>*, bring the* <u>*lunch*</u>) elicited a more specific meaning representation.

One question left unanswered is the temporal dynamics of accessing the specific knowledge, i.e. coercion. In this Chapter, we discuss a third experiment in which we used Magneto-Encephalo-Graphy (MEG) to examine address two limitations of the previous two studies. fMRI has two major limitations due to the delay response of the BOLD signal. First, we do not have a high enough temporal resolution to study the temporal dynamics of coercion. Second, we do not have enough experiment time to examine a wider range of concepts. MEG allows us to overcome these shortcomings. Like EEG, MEG measures the electrophysiological signals generated by the neurons with a high temporal resolution. Unlike EEG, however, MEG also enjoys a high spatial resolution of several millimeters. In addition, using MEG, stimulus presentation time is much shorter than with fMRI, which allowed us to study, in addition to the two categories in the previous fMRI experiments, a third dot-object category, institution (BUILDING • ORGANISATION) covering concepts like *school, church, hospital, government*, and *company*, which also have one concrete and one abstract sense component. The word church can refer in same cases to the building/location, as in (5.1.a); in other cases, like (5.1.b), it can refer to the organisation. Moreover, as with the other dot-objects, both senses can be accessed simultaneously in a single expression as in (5.1c) and (5.1d).

(5.1)

a. *The church was burned down in the great fire of London.*

b. *The church owned and managed the majority of the schools in this area.*

c. *People gathered in front of the church to protest against its decision.*

d. *The school is located in a fancy neighbourhood and charges very expensive tuition fee.*

As in the previous experiments, we used verbs to coerce the dot-objects into the concrete or the abstract interpretation. Given that our focus here is the coercion effect that is in common to all the semantic categories, we examined only two concrete-abstract contrasts: the target dot-object contrast and the verb-control contrast. The three dot-object categories have an equal number of target concepts in each condition (Table 5.1).

The high temporal resolution of EEG/MEG has provided unique insight to the neural dynamics during language comprehension; particularly the oscillatory neural dynamics, the ever-going rhythmic activities observed in EEG and MEG data, is argued to be the key to understanding how the vast numbers of neurons work together. The theta (4-7Hz) and gamma (>40Hz) bands are the two main frequency bands that have been identified to play crucial but disparate roles during language comprehension: The slow theta rhythm has been linked to lexical memory retrieval (Bastiaansen et al., 2005, 2008), whereas the rapid gamma rhythm is responsible for variant combinatorial processes in language processing (Weiss et al., 2003; Hagoort et al., 2004; Matsumoto & Lidaka 2008; Friese et al., 2012). Another frequency band of interest for language comprehension is the lower-beta band (17-20Hz) because it has been recently showed to be linearly related to the N400 ERP component (Wang et al., 2012).

What is the crucial rhythm for coercion? To address this issue, we adopted the single-trial classification approach to examine in which frequency band the neural activities of the concrete- and the abstract-coerced dot-objects can be distinguished. Decoding MEG data has been gaining momentum recently (e.g. Guimaraes et al., 2007; Fuentemilla et al., 2010; Carlson et al., 2011) and a variety of machine learning techniques have been successfully applied in decoding semantic representations (e.g. Murphy & Poesio, 2010; Chan et al., 2011; Sudre et al., 2012; van de Nieuwenhuijzen et al., 2013; Clarke et al., 2012, 2014; Simanova et al., 2014). In this experiment, we calculated the time-frequency representation (TFR) of every single-trial. Instead of collapsing all the trials of one condition, we use a Support-Vector-Machine (SVM) classifier to distinguish the single-trial TFRs of the concrete and the abstract condition. We performed the classification with each frequency band separately to investigate which one encoded the concrete-abstract distinction.

The gamma-band has been indicated in a variety of combinatorial processes, including sentence comprehension (e.g. Hald et al., 2006; Penolazzi et al., 2009), world knowledge retrieval (Hagoort et al., 2004), feature binding (e.g. Tallon-Baudry & Bertrand, 1999; Friese et al., 2012). Hence we expect that the neural distinction between the concrete- and the abstract-coerced dot-objects should lie in the gamma-band activities. The effects in the other two frequency bands are less certain given our current model. The theta-band seems to be involved in lexical retrieval at a rather general level. For example theta-band was identified in experiments comparing real words vs. pseudowords, open-class vs. closed-class words (Bastiaansen et al., 2005). Therefore since our target words are equal at the lexical level, we expect to see no theta-band difference. The lower beta-band has been associated with syntactic processing: the power increases as the sentences are more syntactically complicated, and the synchronisation breaks down when there is a syntactic violation (Haarmann 2002;

Table 5.1: Sample stimulus words used in the two concrete-abstract contrasts, *dot-object* and *verb-control*. Each contrast contains three semantic categories. The experiment is conducted in Italian. The original Italian stimuli are showed below the English translation. Dot-objects are highlighted in bold font.

		dot-objects	**verb-control**
abstract			
	PRINT MATTER	consult the **book**	consult the expert
		*consultare il **libro***	*consultare l'esperto*
	MEAL	organise the **lunch**	organise the course
		*organizzare il **pranzo***	*organizzare il corso*
	INSTITUTION	evaluate the **hospital**	evaluate the condition
		*valutare **l'ospedale***	*valutare la condizione*
concrete			
	PRINT MATTER	pick up the **book**	pick up the coin
		*raccogliere il **libro***	*raccogliere la moneta*
	MEAL	bring the **lunch**	bring the water
		*portare il **pranzo***	*portare l'acqua*
	INSTITUTION	build the **hospital**	build the apartment
		*edificare **l'ospedale***	*edificare l'appartamento*

Weiss 2005; Bastiaansen & Hagoort, 2015). As the syntactic structure did not differ in the current experiment and coercion is usually considered as purely semantic, we also predict that the lower beta-band will not differ among the experiment conditions.

Based on our conclusion drawn from the previous fMRI experiments about the ATL in coercion, we further inspect the gamma-band activities in the bilateral ATLs. Recently a series of MEG experiments have highlighted the left ATL in semantic composition (Bemis & Pylkkanen, 2012, 2013; Westerlund & Pylkkanen, 2014; Pylkkanen et al., 2014, Zhang & Pylkkanen, 2015). These studies observed a general activity increase in the left ATL in the combinatorial conditions (the combinations were two-word phrases such as *blue boat, red cup, tomato soup*). More interestingly, the activity increase was proportional to the amount of semantic information required in the combinatorial condition. For instance in Westerlund & Pylkkanen (2014), the authors found the combination-related signal increase in the left ATL only when the concepts were at the general level, e.g. *red boat*, and the effect disappeared when the concepts were specific, e.g. *red canoe*. They argued that the general concepts like boat incurred greater demand of meaning specification in a combinatorial setting, whereas such demand was not required for concepts that were already specific, e.g. *canoe*.

The current dot-objects conditions seem to be analogue to the low-specificity combinatorial cases in the studies of Pylkkanen and colleagues, that the dot-objects are coerced into more specific representations. However it is unclear that whether the specificity effect will be affected by concreteness in terms of gamma-band frequency. Thus far, studies on feature binding have only focused on sensorimotor features (e.g. Tallon-Baudry & Bertrand, 1999; Friese et al., 2012; Schneider 2008; Matsumoto & Lidaka 2008; van Ackeren et al., 2014). Yet studies about the unification operations in language suggested that the effect of the gamma-band frequency should be high-level and supramodal (e.g. Weiss et al., 2003; Hagoort et al., 2004; Penolazzi et al., 2009). Therefore we predict that 1) if the gamma-band frequency in the ATL is manipulated by the type of the features (i.e. concrete vs. abstract), we would observe the concrete-abstract distinction with both dot-object and verb control contrasts; 2) by contrast, if it is related to semantic composition and the amount of semantic information, we should see no effect for the verb-control contrast. Nevertheless the two aspects could interact with a complicated mechanism beyond the scope of the current experiment design.

5.2 Methods and Materials

5.2.1 Participants

Twelve volunteers were recruited for the MEG experiment (7 female, mean age 24.58, SD: 3.476). All participants were native Italian speakers, right-handed, and had normal or corrected-to-normal vision. All procedures were approved by the ethics committee of University of Trento, and participants received a small monetary compensation.

5.2.2 Materials

This experiment was also conducted in Italian. The stimulus phrases were selected by the same procedure as the fMRI experiments: firstly we came up with a pool of verbs that could potentially be the coercing verbs, and then we constructed the combinations that were to be rated familiarity, concreteness and imageability. The ratings were from the same norming studies as describe in chapter 3 and chapter 4. Stimuli of the institution category were rated by thirty-three native speakers and none of them participated in the MEG experiment.

After norming, ten concrete and ten abstract verb-noun phrases were selected from each dot-object category, resulting in sixty phrases (30 concrete & 30 abstract) in the dot-object contrast. The phrases contained fifteen dot-object nouns, five for each category (PRINT MATTER: *book, magazine, catalogue, sketch, diary*; MEAL: *lunch, dinner, aperitif, banquet, feast*; INSTITUTION: *hospital, office, school, church, hotel*). Sixty phrases were also selected to form the verb-control contrast in which the coercing verbs were combined with their common complement. Sample stimuli are shown in Table X. The full list in Italian and the English translations can be found in the appendix. Phrases of each contrast were matched in length and the number of phonemes (number of letters: $t_{\text{Dot-object}}(58)=0.81$ $p=0.42$; $t_{\text{Verb-control}}(58)=-1.36$, $p=0.2$. number of phonemes: $t_{\text{Dot-object}}(58)$=-0.45, p=0.65; $t_{\text{Verb-control}}(58)$=-1.68, p=0.10). All the 4 categories matched familiarity (F(3,116)=1.23, p=0.3). For each concrete-abstract contrast the concreteness and the imageability ratings differ significantly (concreteness: $t_{\text{Dot-object}}(58)$=9.03, p=1.2e-12; $t_{\text{Verb-control}}(58)$=12.61, p=2.93e-18, Imageability: $t_{\text{Dot-object}}(58)$=4.06, p=0.00015; ttextsubscriptVerb-control(58)=8.51,

5.2.3 Procedure

Participants were sitting comfortably in front of the screen and instructed to read the verb-noun phrases. The task is to detect the anomal combinations (e.g. open the sun) by pressing a button box with the left or the right hand (counterbalanced across participants). One third was catch trials which contained the anomal phrases.

During one trial in the experiment, the verb and the article-noun were presented in sequence for 500ms respectively, with a variable inter-stimulus interval (IST) from 550ms to 700ms. A question mark then appeared for 1000ms at which point participants pressed the button box if they saw an anomal phrase. No response was required for target trials in order to reduce movement artefact. The next trial started after 1500ms (plus a time jittering from 250 to 500ms) fixation time (Fig. 5.1).

All the 120 target phrases (4 category * 30 phrases) were present at least once. Three-fourths of them (i.e. 88) were present twice and half of them (i.e. 60) were present three times, resulting 268 (120+88+60) times of showing target phrases. In addition 134 catch trials were constructed, thus the participants read 402 phrases in total during the experiment (1/3 catch trial). The 402 phrases were randomised and split to six sessions, each session had 67 phrases and lasted 5 to 6 minutes.

Table 5.2: The psycholinguistic parameters of the stimulus phrases in each condition. Familiarity, concreteness, and imageability are obtained from the norming experiment with thirty-eight participants. Standard deviations are showed in parentheses.

Category	familiarity	concreteness	imageability	n_letters	n_phonemes
abstract-DotObject	3.69(0.52)	3.25(0.48)	3.59(0.47)	18.07(1.69)	7.67(0.79)
concrete-DotObject	3.73(0.49)	4.16(0.26)	4.07(0.43)	18.57(2.20)	7.77(0.88)
abstract-Verb	3.87(0.36)	3.12(0.48)	3.58(0.41)	19.33(1.76)	8.13(0.81)
concrete-Verb	3.87(0.47)	4.36(0.23)	4.38(0.29)	18.27(2.93)	7.63(1.17)

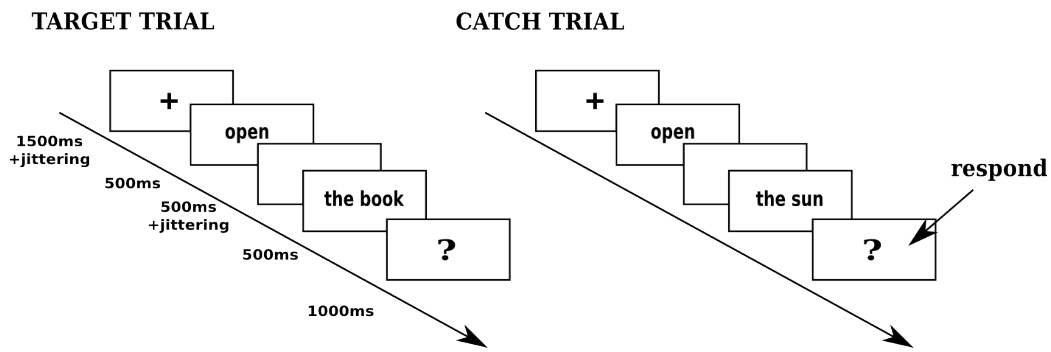

Figure 5.1: Experimental paradigm. Participants performed a semantic meaningfulness judgement task and responded by pressing the button boxes with the left or the right hand (counterbalanced across participants) when they saw a meaningless combination. No response was required for the target trials in order to reduce movement artefact.

5.2.4 Data acquisition and preprocessing

MEG data was recorded with a 306-channel (204 first order planar gradiometers, 102 magnetometers) MEG system (Elekta-Neuromag Ltd., Helsinki, Finland), sampling rate at 1KHz. Recoding was conducted in a magnetically shielded room (AK3B, Vakuum Schmelze, Hanau, Germany). Prior to recording, three fiducials (nasion, left and right preauricular) and five head position indicators (HPIs), and around 300 headshape points were recorded.

Preprocessing was carried out with the Matlab fieldtrip toolbox (Oostenveld et al., 2011). The 204 gradiometers were analysed. Noisy sensors were visually inspected and excluded from further analysis. One session continuous data were firstly removed linear trend, and filtered by a Butterworth IIR filter with bandpass frequency

[1,150]Hz. A notch filter was also applied to remove the 50Hz line noise. Secondly we performed the Independent component analysis (ICA) to remove EOG, ECG, and high frequency artefacts. After ICA, the continuous data were initially segmented into 1200ms epochs, 200ms before the noun presentation onset and 1000ms after. Epochs underwent visual inspection, the ones contaminated by artefacts as well as the ones with wrong behaviour responses were discarded.

5.2.5 Wavelet decomposition and decoding analysis

Prior to wavelet decomposition, data of each sensor were centered to the mean and scaled to unit variance. Wavelet decomposition was computed with MNE-python's build in function single_trial_power (Gramfort et al., 2013). For each epoch, the morlet wavelet was calculated for 41 frequencies range from 2 to 112Hz, with a step of 3Hz. The numbers of cycles were set as half for each frequency. Baseline correction was applied with the 100ms pre-onset interval. The results were a time-frequency representation for all 204 sensors of every epoch.

We constructed the single-trial decoding datasets with 0-800ms post-stimulus onset of every epoch (i.e. one experiment trial of reading a verb-noun phrase) as one exemplar (Fig. 5.2). The features were made of the power at the 800 time points and averaged into three frequency bands of interest: theta (5-8Hz), lower-beta (14-20Hz), and gamma (59-89Hz). One exemplar has 163,200 features (204 channels by 800 time-points). We further excluded the bad sensors of each participant, resulting in around 150,000 features for each participant. The decoding analysis was carried out with the three frequency band feature sets separately.

Firstly we conducted two two-way classifications to discriminate the concrete and the abstract conditions of the two contrasts. A linear support vector machine (SVM) classifier with C=-1 (i.e. soft margin) was used to distinguish the four categories. Before classification, each feature was z-scored within one experiment session. Classification was carried out for each participant with a Leave-One-Session-Out cross-validation procedure: during one cross-validation iteration, the classifier was trained with five sessions of data and tested on the left-out session; the final accuracy was the average of the six iterations. One thousand features were selected in each iteration using a one-way-ANOVA. Note that the feature selector was trained with the training data only thus there was no double-dipping. One-tail p-values for the classification accuracy were calculated with a one-sample t-test against the 0.5 chance level, bonferroni corrected. In order to track the temporal dynamics, we performed the same classification analysis but with data of every 100ms time window.

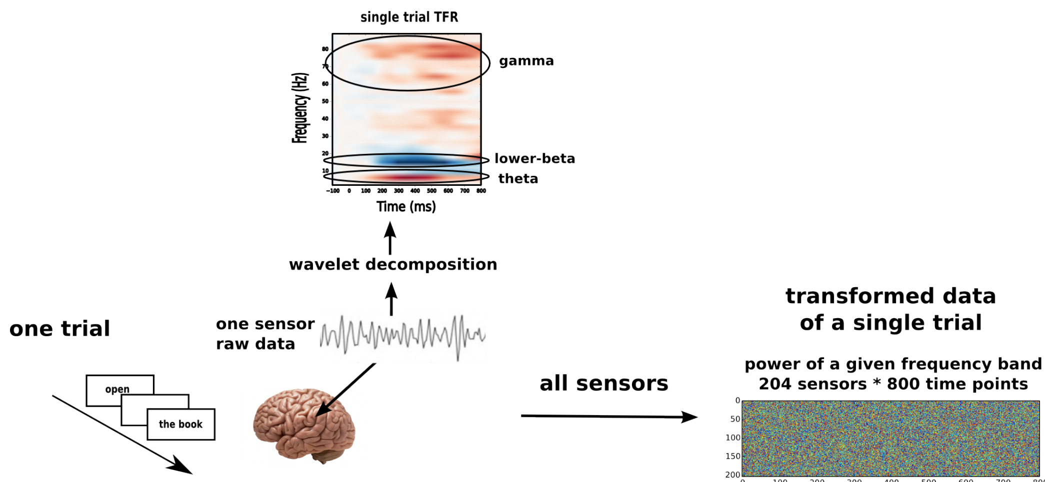

Figure 5.2: Process of constructing a single trial of the decoding datasets. Raw data are segmented into 1200ms epochs for every trial (200ms before and 1000ms after the noun presentation onset). Epoched data of each sensor are transformed to the time-frequency representation (TFR) with the morlet wavelet decomposition. And then the resulting power values are averaged for each pre-defined frequency band. The final transformed data of one trial are represented as a sensor-by-time matrix. We analyse 204 gradiometer sensors and 800ms time points.

We also tracked the weights that the SVM classifier assigned to every feature. The mechanism of a SVM classifier is to find a hyperplane that can best separate the two classes, and the separating hyperplane is actually a function. Thus the weights can be interpreted as how important the feature is in differentiating the two classes. Or say if a feature has a great weight, the feature exhibits clearly different values in the two classes. For each participant, we summed up the weights of the six cross-validation iterations and selected the features with weight > 0.01; and then the individual weight maps were added up to form the group weight map.

We further performed the four-way classification to ensure that all the four conditions were distinguishable. If so, the difference between the concrete and abstract dot-object conditions cannot be solely due to the verbs. For instance if the neural responses of *open the book* and *open the parcel* (and likewise *consult the book* and *consult the expert*) are distinctive from each other as well, we would be able to claim that the difference between *open the book* and *consult the book* is not simply driven by the different verbs.

5.2.6 Time-frequency analysis

At last we compared the mean temporal frequency representations (TFRs) of power of the bilateral ATLs of each condition Specifically, the same wavelet decomposition as in the decoding analysis was computed for each 100ms-preoneset to 800ms-poststimulus single-trial epoch: the morlet wavelet was calculated for 41 frequencies range from 2 to 112Hz, with a step of 3Hz. Baseline correction was applied using the averaged power of the 100ms preonset interval. And then the resulting single-trial TFRs of each condition were averaged to produce a mean TFR.

The two ATL sensor clusters were shown in Fig. 5.3. Each cluster contained six pairs of the gradiometer sensors irrespectively. We focused on two time windows: 100-400ms and 400-700ms after the critical word, i.e. the noun presentation onset. For every participant, we calculated the averaged power of each cluster (the bad sensors were excluded) and each frequency band (the same as defined in the decoding analysis above), then the averaged powers were z-scored using the baseline value of the 100ms pre-onset window. The mean powers of all participants were compared with the random-effect ANOVA.

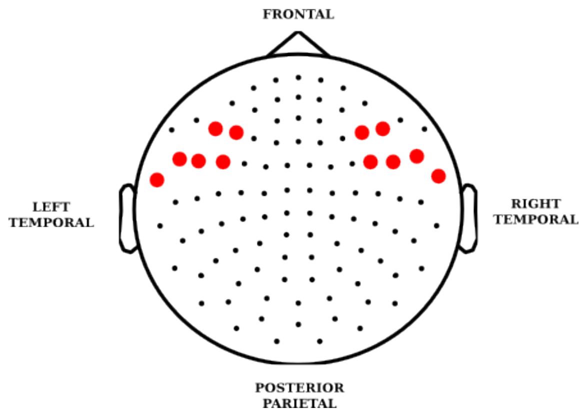

Figure 5.3: The bilateral ATL sensors used in the time-frequency analysis.

5.3 Results

5.3.1 Behaviour

The overall error rates of all the twelve participants are no greater than 10% (mean 0.065, SD=0.024). The false negative, i.e. the participant detected the target concept as a catch trial, is very low for all participants, ranging from 0 to 5%.

5.3.2 Two-way classification and sensitivity analysis

Both of the two concrete vs. abstract contrasts could be distinguished well above chance with the gamma feature set ($\text{accuracy}_{\text{Dot-object}} = 0.6327$, $t(11) = 3.47$; $\text{accuracy}_{\text{Verb-control}} = 0.6413$, $t(11)=8.53$. Fig. 5.4A). The theta and the lower-beta band did not show any effect.

The SVM weight maps from the gamma band feature sets demonstrated different temporal-topographical profiles between the two contrasts (Fig. 5.4B). Visual inspection revealed that during the first 400ms, the left posterior temporal sensors were important for both contrasts. However there are two major differences between the

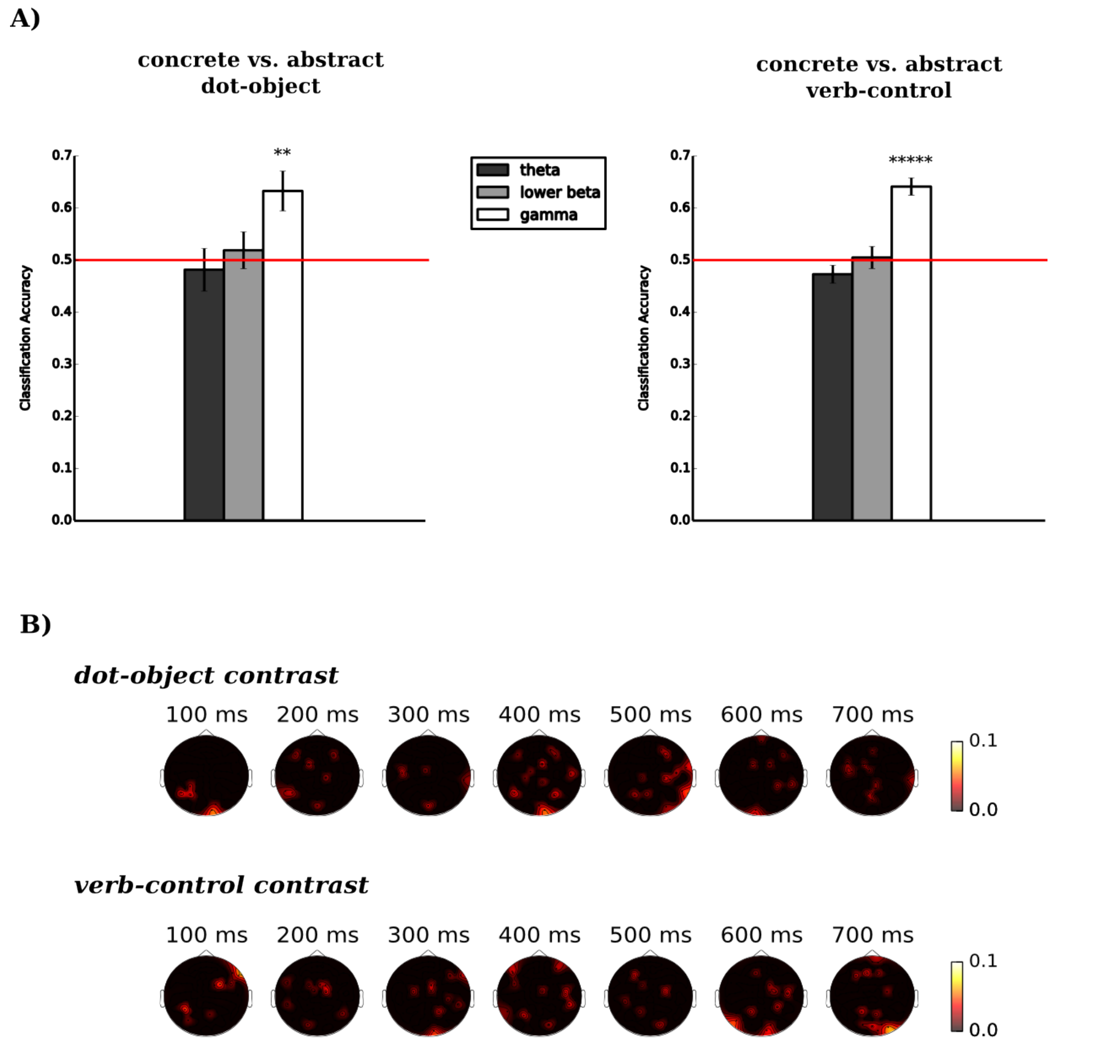

Figure 5.4: Two-way classification of the dot-object and the verb-control contrast. Both contrasts can be distinguished significantly above the 0.5 chance level marked by the red line (one-sample t-test against the chance level, corrected). Error bars indicate SEM. The effect is only present in the gamma band among the three frequency bands of interest. The one-way ANOVA shows the gamma band accuracy is significantly higher (p<1e-05) for both contrasts. The topographical graphs at the bottom show the group-level SVM weight maps trained with the gamma band datasets. Plotted weights are the sum of the individual participants. Visual inspection suggests that the two contrasts rely on different temporal and topographical features. Particularly the dot-object map shows that the most informative time period appears to be the 400-500ms, and notably during the 500ms the important features concentrate in the right hemisphered.

two contrasts. First for the dot-object contrast, the most informative time window appeared to be the 400-500ms, and notably during the 500ms the important sensors concentrated in the right hemisphere. To the contrary, for the verb-control contrast, the later time periods, i.e. 600-700ms seemed to be more crucial, especially the posterior sensors.

The result of the time-window analysis is showed in Fig. 5.5. The later time-window (after 400ms) is critical to the dot-object contrast, suggesting that there was an integration or specification process that occurred later. The verb-control contrast, by contrast, did not show such a timing effect. Significant but minor effects were in the 200-300ms and the 700-800ms time windows.

5.3.3 Four-way classification

The four conditions could also be distinguished with the gamma feature set (mean accuracy 0.3523 (chance level 0.25), p=0.0212, bonferroni corrected). A repeated measure ANOVA showed that the accuracy of the three frequency bands were significantly different ($p<10e\text{-}06$). The result and the confusion matrix are depicted in Fig 5.6.

5.3.4 Time frequency analysis

Finally we also examined the grand energy of the gamma-band frequency that averaged across all the trials in the bilateral ATLs. We looked one early (100-400ms) and one later time window (400-700ms) respectively. The only significant difference was the abstract dot-object vs. concrete dot-object in the later time window (Fig. 5.7), with the abstract condition elicited greater power ($F(1,22) = 2.43$, p=0.0335, uncorrected). The repeated measures ANOVA gave a marginal effect among the four conditions ($F(3,33) = 2.42$, p=0.08).

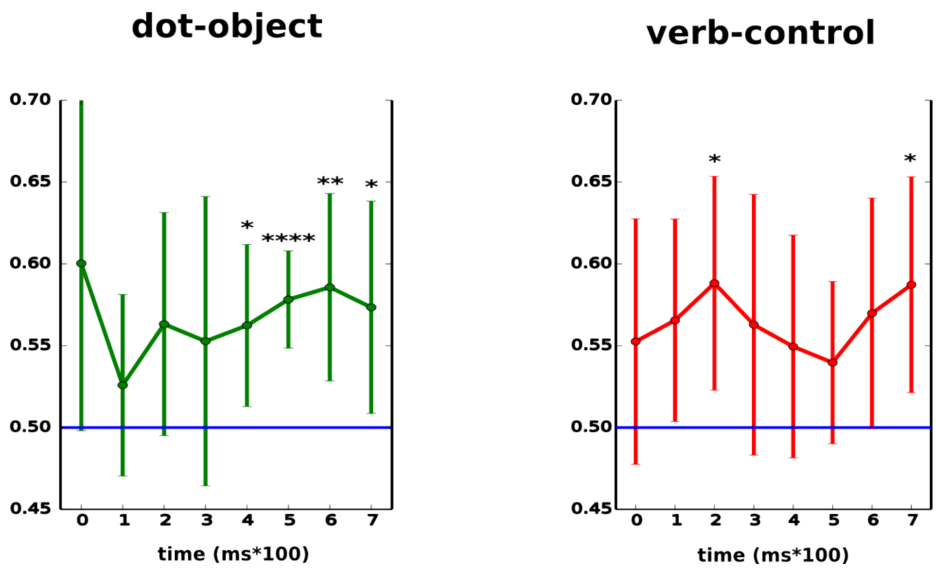

Figure 5.5: Classification accuracy by every 100ms time window. P-values were calculated by one-sample t-tests (dof=11), bonferroni corrected (****p<0.0001, ***p<0.001, **p<0.01, *p<0.05) The concrete and abstract dot-objects (left, in green) could be most reliably distinguished after 400ms. The verb-control contrast (right, in red), on the other hand, did not showed a clear time-window advantage. Significant but minor effects were in the 200-300ms and the 700-800ms time windows.

5.4 Discussion

In the MEG experiment we investigated the meaning representation of dot-objects through the oscillatory neural dynamics. Three kinds of dot-objects from different semantic categories are included in this experiment: print matter (OBJECT • INFORMATION), meal (FOOD • EVENT), and institution (BUILDING • ORGANISATION). We adopted the single-trial decoding approach to probe the time frequency profiles of the coercion-by-dot-exploitation process across the three semantic categories. Support-Vector-Machine (SVM) classifier was used to classify the neural correlates of the concrete- and abstract- coerced dot-objects (e.g. *pick up the book,*

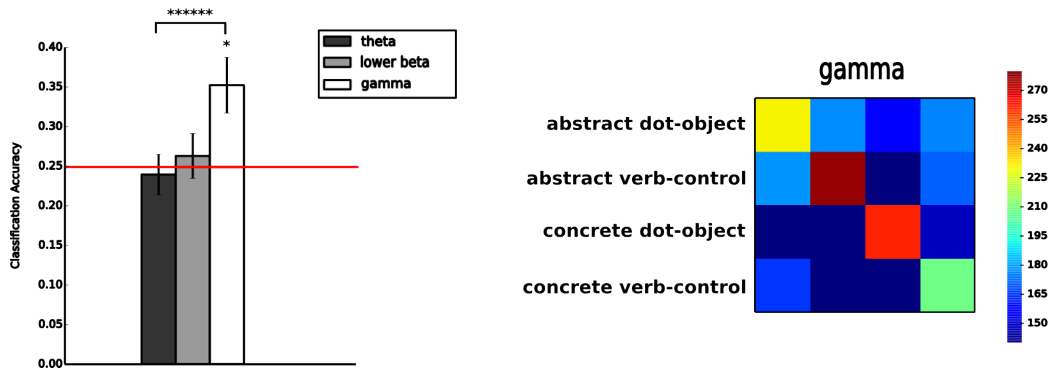

Figure 5.6: The result of classifying all the four experiment conditions. As in the two-way classification, only the gamma band dataset achieves significant accuracy among the three frequency bands of interest ($p<0.05$, corrected). A repeated measure ANOVA shows that the three accuracy values are significantly different ($p<10e\text{-}06$). The right column depicts the 4-way confusion matrix of the gamma band dataset.

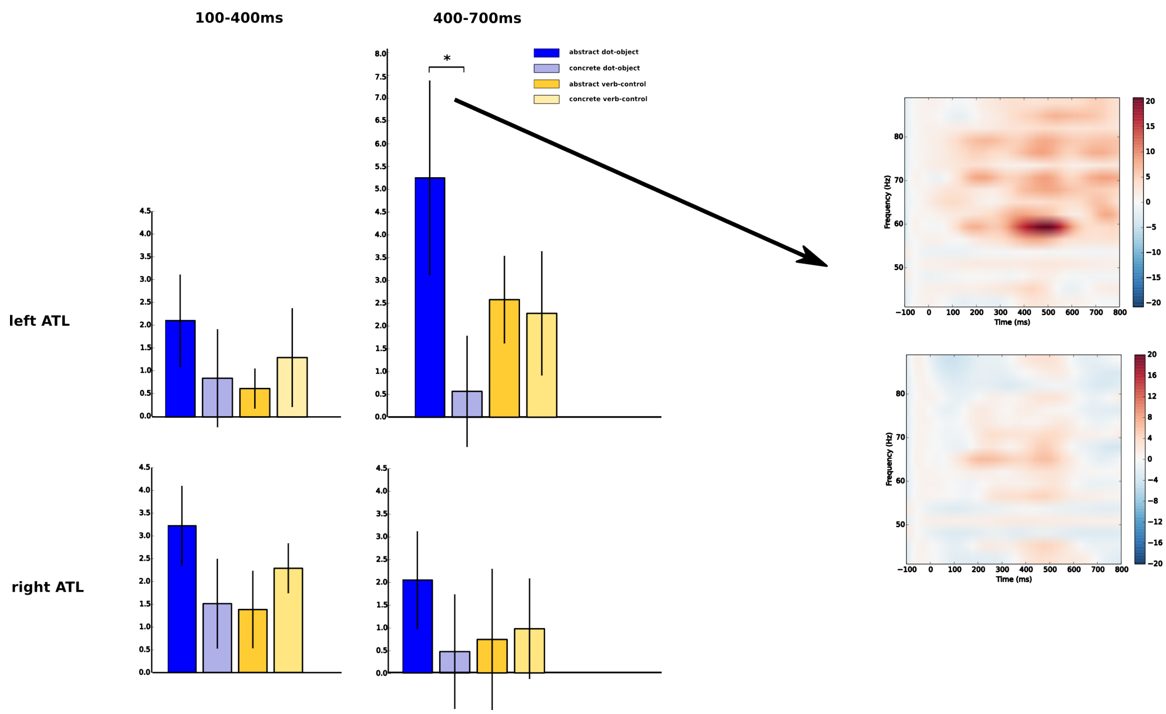

Figure 5.7: Result of the time-frequency analysis. The averaged gamma-band power of the four conditions are compared at bilateral ATLs in two time windows. The random effect ANOVA shows that the only difference is in the left ATL between the abstract dot-object (dark blue) and concrete dot-object (light blue) in the later time window ($p<0.05$, uncorrected). The effect can be seen in the time-frequency representation plots on the right.

consult the *book*) as well as the non-coercion concrete and abstract phrases as a comparison (e.g. *pick up the coin, consult the expert*). The result demonstrated that only the gamma-band frequency (60-90Hz) showed a distinguishing effect to the different types of verb-noun combinations. This finding aligns with the large body of evidence that the gamma-band rhythm plays a pivotal role in various combinatorial processing (Tallon-Baudry & Bertrand, 1999; Bertrand & Tallon-Baudry. 2000; Weiss et al., 2005; Hagoort et al., 2004; Matsumoto & Lidaka 2008; Penolazzi et al., 2009; Friese et al., 2012; van Ackeren et al., 2014; Bastiaansen & Hagoort, 2015).

Further time-window analysis showed that the gamma-band activity patterns of the concrete- and abstract-coerced dot-objects diverged after 400ms poststimulus. Comparatively the verb-control contrast did not have a clear timing bias; it displayed a minor distinguishing effect as early as 200ms, which agrees with the observation that the early stage of lexical retrieval can be seen in MEG as early as 170-250ms (Pylkkanen & Marantz, 2003). Therefore the results support the hypotheses that there is an extra operation, namely the coercion process, happening in the later period.

Finally the left ATL exhibited a gamma-band power increase to the abstract-coerced dot-object condition compared to the concrete-coerced condition after 400ms. This effect was not present for the non-coercion conditions. We attribute the left ATL effect to the greater amount of semantic composition and/or activated semantic knowledge in the abstract-coercion condition.

5.4.1 The role of gamma frequency in combinatorial processing

The hypothesis that the gamma band frequency is responsible for various linguistic combinatorial processing has been tested comprehensively in a large body of experiments (e.g. Hagoort et al., 2004; van Berkum et al., 2004; Hagoort, 2005; Hald et al., 2006; Penolazzi et al., 2009. And a recent review by Bastiaansen & Hagoort, 2015). Hagoort and colleagues have been exploring the stages of language processing, arguing that there are three main components: retrieval, unification, and control; and the gamma-band has been emphasised in the unification processing (e.g. Hagoort et al., 2004; Hagoort, 2005; Hald et al., 2006; Bastiaansen & Hagoort, 2015). In a seminal study of Hagoort et al., (2004), they compared the EEG activities of reading two types of violation sentences: violating the semantics and violating the world knowledge. For instance the sentence the dutch trains are sour is clearly wrong in terms of the semantics, whereas the dutch trains are white is a correct sentence but it clashes with the common knowledge that the dutch trains are yellow. Interestingly the gamma-band had the greatest power increase in the world knowledge violation condition and a minor increase in the correct sentence condition, while the effect was missing in the semantic violation condition. The authors interpreted the result as considering the gamma frequencies an index of successful integration, and the real world knowledge violation imposed the greatest integration demand.

The gamma band has also been highlighted in perceptual and conceptual feature binding (Tallon-Baudry & Bertrand, 1999; Schacter 2007; Schneider et al., 2008; Friese et al., 2012; van Ackeren et al., 2014). Tallon-Baudry & Bertrand (1999) proposed an influential framework in which the induced gamma band activity (iGBA) served as the pivotal mechanism in binding various aspects of information to form a coherent object representation. In a recent study, Friese et al., (2012) examined the MEG iGBA attenuations when participants viewed pictures or words of concrete objects. Using a priming paradigm, the authors isolated two iGBA effects: one in the posterior cortex that is sensitive to the presentation modality (picture vs. words), and the other one in the anterior cortex that is sensitive to the concept semantics regardless of the presentation modality.

In summary, the convergent evidence demonstrates that the gamma-band have a general integration role that operates in different domains and at different levels. Those findings are compatible with our result that the different verb-noun combinations yielded distinct gamma-band spatial-temporal activity patterns. In the following analysis, we explored the crucial time period for coercion and the effect in the anterior temporal lobe (ATL).

5.4.2 Coercion occurs in later in time

The time-window analysis showed that the gamma-band activity patterns of the concrete- and abstract-coerced dot-objects diverged after 400ms poststimulus, whereas the verb-control contrast did not have a clear timing preference (the classification accuracy was modestly above chance ($p<0.05$) at the 200ms and 700ms time windows). The result is best accommodated by the hypothesis that coercion occurs after the dot-object meaning is initially retrieved from the memory and meets the verb context, which is also in agreement with our argument that the coercion process involves accessing the specific concept knowledge to form a context-relevant representation.

The later discriminating effect strongly suggests that the divergence is driven by post-lexical processing. It is well-established that the 400ms time window is critical for semantic processing. The ERP N400 component is most prominently seen in semantic violation (e.g. Kutas & Hillyard, 1980, 1984; Kutas & Federmeier, 2000; Kuperberg et al., 2003; among the others), and it can be consistently found in various paradigms including referring real world knowledge (e.g. Hagoort, 2004), animate violation (e.g. Paczynski et al., 2006), and concreteness effect (Kounios & Holcomb, 1994; Holcomb et al., 1999; Barber et al., 2013). Its MEG equivalent M350 has been identified as well (Embick et al., 2001; Halgren et al., 2002; Pylkkanen & Marantz, 2003; Pylkkanen et al., 2004; Simon et al., 2012). For instance, Halgren et al. (2002)

replicated the N400 effect with MEG, showing a negative-going waveform in reading incongruous sentences. Simon et al. (2012) compared the early response (¡ 200ms) and M350 in reading ambiguous single words, and found the early response was most sensitive to word length while deep semantic processing (e.g. meaning entropy) only affected the later response. Hence the divergence between the concrete and abstract the dot-objects, we argue, most likely took place after the initial meaning integrated with the context in the brain, and the distinction was capture by the classifier in the later time windows.

5.4.3 The ATL effect

Our previous fMRI experiments highlighted the bilateral anterior temporal lobes (ATLs). In the light of the role of ATL as a semantic hub, we argued that coercion involved accessing the specific concept knowledge of the dot-objects in semantic memory. Interestingly a series of MEG experiments have underlined the left ATL in semantic composition as well as in meaning specification. As already summarised in the introduction section and discussed in chapter 2, those studies provided consistent evidence that there was an interaction between semantic composition and concept specificity. The result pattern is best explained by the possibility that semantic composition evoked ample information and specific concept knowledge. Friese et al., (2012) also found a dissociation between the posterior and anterior gamma-band effect: the posterior effect was sensitive to low-level perceptual features whereas the anterior effect reflected the conceptual features.

In this experiment we also examined the averaged gamma-band power in the bilateral ATLs. The left ATL showed a power increase in the abstract-coerced dot-object condition in the 400-700ms time window. This enhanced gamma-band activity suggests there might be more composition demand and/or richer semantic knowledge in the abstract-coercion cases, which contained verbs that elicited the abstract aspect of the dot-objects (e.g. *consult the book, organise the dinner, evaluate the hospital*). It is typically argued that abstract concepts have a relatively impoverished semantic representation. However we speculate that is not the case for the abstract-coercion condition, as the brain has to decide the appropriate in-context interpretation. Indeed there was no gamma-band effect for the non-coercion cases. Regarding the question we posed in introduction that whether the concreteness would make a difference, our result are more in line with the account that the gamma-band in the left ATL is not sensitive to the feature type (i.e. concrete or abstract); this observation also aligned with the hypothesis that the ATL represents high-level, modality-independent semantic knowledge.

5.4.4 Final remarks

In this MEG experiment we investigated the meaning representation of dot-objects through the oscillatory neural dynamics. Three kinds of dot-objects from different semantic categories are examined together. The single-trial decoding approach showed that the gamma-band neural activities play a central role in verb-noun combination in general.Importantly, the gamma-band activities associated with the concrete- and abstract-coercion diverged in the later time-window (after 400ms), suggesting coercion may happen after the initial lexical retrieval as well as the early stage of semantic integration.

Chapter 6

Discussion

6.1 Discussion

The present thesis examined the neural representation of dot-objects: a class of logical polysemy of which the meaning consists of distinct sense components, exemplified by the word *book* (i.e. a dot-object of OBJECT • INFORMATION). Particularly, we focused on categories of dot-objects that clearly have a concrete and an abstract component, such as *book*, *lunch* (FOOD • EVENT), *church* (BUILDING • ORGANISATION). The overarching research question of this thesis is: How are the dot-objects that have distinct sense components represented in the brain? To answer this question, we conducted three experiments. In all the experiments, healthy participants read the dot-object words in a concrete or an abstract context, i.e. the meaning of the dot-object was *coerced* into either the concrete or the abstract interpretation (e.g. *open the* <u>*book*</u> / *explain the* <u>*book*</u>, *pack the* <u>*lunch*</u> / *organise the* <u>*lunch*</u>). Concrete and abstract concepts usually activate different neural circuits in the brain. However, we found the neural distinction between the concrete and abstract interpretations of the dot-objects differed from the typical concrete-abstract distinction; instead the differential effect was most evidenced in the anterior temporal lobe (ATL). Given the role of the ATL in high-level, modality-independent knowledge representation, the result suggests that the distinct senses of a dot-object are associated with a single, unspecified structure, in line with the dot-object theory in the Generative Lexicon framework.

The first (*book*) and the second fMRI experiment (*lunch*), however, displayed some discrepant effects within the ATL. The *book*-like dot-objects underlined the ventral division in the left hemisphere (LH), the epicentre of the semantic hub. On the other hand, the *lunch*-like dot-objects yielded the right hemisphere (RH) ATL, both the ventral and the superior divisions. As discussed in more detail below, we attribute this shift to the meaning differences between the two categories and the grade representation mechanism within the ATL.

In the third experiment, we investigated the transient neural oscillatory activities using MEG. The neural distinction between the concrete and abstract interpretations of the dot-objects was found only in the gamma-band frequency power. Moreover the divergence took place after 400ms post-stimulus onset. The gamma-band plays a crucial role in integrating process in general, including sentence comprehension, world knowledge integration, and feature binding. Therefore we conclude that the neural correlates of the concrete- and abstract-coercion diverge at the later integration stage. This observation further supports our argument that the meanings of dot-objects are represented as a single unspecified structure. Specifically, the neural mechanism of reading the dot-objects in context may involve retrieving this unspecified representation, which subsequently integrates with the context and instantiates to a more specific representation.

The key conclusion of this thesis is the distinct senses of a dot-object are represented as a single, underspecified meaning structure in the brain. How did we come to the conclusion exactly? Two threads of research provided important insights. First, as neurolinguistic studies of polysemy suggest, the distinct senses of a dot-object should be linked to a single lexical entry. Ample empirical evidence demonstrates that homonymy and polysemy are represented in different ways in the brain. Homonyms are words that have distinct meanings; those meanings are not related but only accidentally share the same word form. For instance the English word *bank* has two distinct meanings: the edge of lake and river or the financial institution. In fact the financial *bank* is believed to derive from the medieval Italian word *banca* which literally means "table, counter". By contrast, polysemous words are words that have multiple but related senses. For instance the financial *bank* is also a polysemy as it can refer to the organisation (e.g. *bank is evil*) or the actual location (e.g. *the bank is after the next traffic light*), moreover it can be used as a verb referring to banking activities. Consistent to the intuition, convergent neurolinguistic evidence suggests that the related senses of a polysemous word are associated with a single lexical entry, conversely the meanings of a homonym are stored in multiple lexical entries (Frazier & Rayner, 1990; Williams et al., 1992; Klepousniotou, 2002, 2012; Rodd et al., 2002; Beretta et al., 2005; Pylkkanen et al., 2006; Bedny et al., 2007).

The second line of insight comes from the research of semantic memory. It is widely accepted that different concept categories are associated with at least partially distinct neural circuits. For instance, although the underlying mechanisms remain controversial, contemporary neuroimaging experiments have consistently found animal concepts activate the ventral and medial temporal lobe, whereas tools and action concepts tend to recruit the more lateral and posterior temporal lobe (Chao et al., 1999; Ishai et al., 1999; Martin & Chao, 2001; Haxby et al., 2001; Bookheimer 2002; Thompson-Schill, 2003; Martin, 2007; Mahon et al., 2007; Binder et al., 2009). Also, the divide between concrete and abstract concepts has been manifested by neuroimaging experiments with healthy subjects as well as lesion studies, which generally show that concrete concepts are associated with sensorimotor knowledge and mental imagery; whilst abstract concepts mostly overlap with language comprehension

(Warrington 1975, 1981; Warrington & Shallice, 1984; Kounios & Holcomb, 1994; D'Esposito et al., 1997; Holcomb et al., 1999; West & Holcomb, 2000; Wise et al., 2000; Jessen et al., 2000; Grossman et al., 2002; Noppeney & Price, 2004; Binder et al., 2005; 2009; Sabsevitz et al., 2005; Wang et al., 2010, 2012; Welcome et al., 2011; Adorni & Proverbio, 2012; Barber et al., 2013).

Nevertheless the case of dot-objects poses questions on this probably simplified view. How does the brain represent concepts like the dot-objects, of which the meanings encompass diverse concept categories? We argue that the answer lies in the semantic hub theories, which claim that there is a hub (or hubs) in the brain that represents the comprehensive knowledge about all the concepts (Rogers et al., 2004; Patterson et al., 2007; Binder & Desai, 2011; Lambon Ralph, 2014). Concisely, we argue that the single-entry to which the senses of a dot-object associate is most likely represented by such semantic hub, and our experiment results also attest this hypothesis.

6.1.1 The semantic hub theory and how it relates to the meaning representation of dot-objects

The critical role that ATL plays in semantic memory was firstly brought to light by studies of semantic dementia (SD). SD patients progressively lose concept knowledge across all categories and modalities, and they have particular difficulty in specific concepts (e.g. *bird* opposed to *animal*, *robin* opposed to *bird*) (Hodges et al., 1996; Wright et al., 2015). Such effects were replicated with healthy subjects using fMRI (e.g. Gorno-Tempini & Price, 2001; Tyler et al., 2004; Rogers et al., 2006; Spitsyna et al., 2006; Visser et al., 2010; Peelen & Caramazza, 2012) as well as TMS (Pobric et al., 2007; 2010a; 2010b), showing the ATL was sensitive to high-level concept knowledge and concept specificity.

Semantic hub theorists argue that the hub is an indispensable component to the semantic system. First of all, humans have a rich collection of declarative knowledge about entities in the world that is far beyond the sensorimotor attributes of objects. A simple concept like *apple*, for example, contains an assortment of knowledge such as it is used to produce cider, Melinda and Granny Smith are different types of apple, and it is said to have played an important role in the discovery of gravity. Admittedly not all of them is relevant depending on the context, however the brain must have certain mechanisms to store and manipulate the various knowledge that is not associated with a particular modality.

Strong embodiment and connectivity theorists argued that concept representation could arise from the distributed nodes and the complex interplay among them (e.g. Elman, 2004, 2009; Pulvermuller, 2012). The hub theorists argued against this view backed by evidence from both patients and healthy population. Patterson et al. (2007) proposed a "spokes-and-hub" view based on a extensive review on both studies of semantic dementia as well as related studies with healthy subjects. As suggested by the name, the "spokes-and-hub" model consists of multiple modality-specific yet interconnected regions and a shared, amodal hub. In particular, the authors argued that only this convergence hub could account for the semantic impairment data, such that the loss of all general concept knowledge and the concept specificity effect. Crucially, the hub encodes the deep structure of concept knowledge, which allows us to make generalisation about concepts across all modalities, such that *pear* is similar to *light bulb* but also similar to *banana*. The "spokes-and-hub" view also obtained support from computational modelling. Rogers et al. (2004) built a theoretical model to predict the neuropsychological data. The model learned features from different modalities (e.g. visual, functional, and encyclopedic) and formed a modality-independent representation in the hub. A key feature of this model is that the hub is essential for cross-modality generalisation, for instance when given an object name, the system had to go through the hub to retrieve the other information such as the shape, colour, function, and so on. In Lambon Ralph (2014), the author compared the hub, which included the bilateral ATLs, to the "recipe" of baking a coherent concept; thus the absence or distortion of the hub could lead to the break-down of the conceptual system, like the same ingredients could result in a tasty pizza or a piece of hard bread. Likewise, Binder & Desai (2011) proposed a multi-level representation architecture which included a high-level, modality-independent convergence hub, supported by a large body of evidence from neuroimaging studies. Different from the spokes-and-hub architecture, however, their hub stretched from the angular gyrus, the posterior middle temporal lobe, to the ATL.

In summary, we argue that our findings about the ATL in representing the dot-objects are in line with the semantic hub theory. The complex meaning structures and the consequent context-dependent meaning shifting resulted in the differentiating effect in the ATL. Nonetheless we also observed variations within the ATL: the print matter category underlined the left ventral ATL, whereas the meal category emphasised the right ATL. Theses variations and potential functional specialisations within the subdivisions of the bilateral ATLs have also puzzled the semantic-hub theorists. In this thesis, we try to provide some explanations regarding those variations based upon our particular stimuli.

6.1.2 The differential functional specialisation within the semantic hub

More and more neuroscientists start to see the brain as a graded system; this notion has been repeatedly stated or implied in the semantic hub literature as well. The convergence zone proposed in Binder & Desai (2011) consisted of a ribbon of brain regions from the inferior parietal lobe to the ATL. However they also suggested the inferior parietal lobe, mainly the angular gyrus (AG), might specialise in event knowledge while the temporal lobe might mainly store entity concepts. Lesion and healthy subject studies showed that the ATL appeared to be primarily related to taxonomic relation, implying that the guiding representation principle of the ATL might be feature-based; meanwhile the inferior parietal lobe seemed to play a more general role (Schwartz et al., 2011; Lewis et al., 2015). In fact in the current study, the AG could distinguish all the concrete-abstract contrasts in both *book* and *lunch* fMRI experiments and all the three contrasts (coercion or non-coercion), irrespective of the type of the verb-noun combination. Thus we postulate that the AG is sensitive to event knowledge and/or composition in general.

For the semantic hub theorists who consider the ATL as the only hub, the graded effect within and between the bilateral ATLs is also in evidence. Although lesion data strongly favour the view that the bilateral ATLs have similar functions and serve as a redundant system (e.g. Hodges et al., 1996; Rogers et al., 2006; Lambon Ralph et al., 2010), there is evidence even from studies from the same research group suggesting a graded effect between the bilateral ATLs. For instance, Hoffman et al., (2015) found that all the subdivisions of the ATL were activated by both concrete and the abstract concepts. Interestingly they also identified a graded concreteness effect along the vertical axis of the ATL: the superior division was more activated by abstract words, whilst the ventral ATL (vATL) was more activated by concrete words. Visser & Lambon Ralph (2011) examined the bilateral ATL effect in processing both pictures and auditory words. Though both the left and right ATL were activated by both modalities, supporting the hypothesis that the bilateral vATLs function similarly, the authors found the auditory words had a left ATL bias. In particular the left superior ATL (sATL) responded not only to the auditory words but also the environmental sounds. The authors concluded that their findings clearly showed that the representation mechanism within the ATL was graded owing to the differences in the brain connectivity.

Another body of research emphasises the role of the right ATL in social cognition, including viewing famous faces and reading social words (Liu et al., 2004; Snowden et al., 2004; Zahn et al., 2007, 2009; Chan et al., 2009; Mion et al., 2010; Ross & Olson, 2010; Olson et al., 2013; Irish et al., 2014;). In an fMRI study described in Zahn et al. (2007), healthy subjects read pairs of words containing abstract social knowledge (e.g. *brave-honor*). The authors found the right superior ATL (sATL) was activated along with a number of social cognition areas. Moreover they correlated the brain activation to the descriptiveness (an index equivalent to specificity) of the social behaviour, and found that only the right sATL showed a significant correlation. The finding strongly suggests that the right sATL is sensitive to semantic specificity, as the other subdivisions of the ATL, but is also biased by other aspects.

To sum up, we argue that the meaning representations of both categories of dot-objects are stored as a single and to-be-specified structure underpinned by the ATL. However the effect variations reflect the differential functional specialisation within the ATLs. Specifically, concepts like *book* might be primarily seen as objects and the different sense components could be considered as the different intrinsic features of *book* (e.g. physical or functional). On the contrary, concepts like *lunch* seem to be more abstract in the concrete-abstract spectrum. For instance, even the concrete sense of *lunch* as food is more general than concepts such as *bread* or *apple*. Moreover the event sense component may trigger a more complicated mechanism, especially with their social elements.

6.1.3 Interaction between the lexical semantics and semantic composition

The final point we would like to stress in this thesis is the interaction between lexical semantics and semantic composition. Meaning representation in the long-term memory and the meaning retrieval / semantic control are normally treated as separate components in semantic memory literature (e.g. Hagoort, 2005; Lambon Ralph, 2014). While we do agree with this distinction, we argue that the word meaning plays a pivotal role in determining the retrieval mechanism. For dot-objects, the exact on-line interpretations rely on semantic composition to a greater degree than the unambiguous concepts. For instance, the appropriate interpretation of *book* is often determined in the context (e.g. *a torn book / a difficult book, pick up the book / explain the book*); by contrast, meanings of the simple concepts are usually less altered by the context (e.g. *flower* and *plan* in *pick up the flower / explain the plan*).

This issue seems to be neglected in psycholinguistics. To our knowledge, only a couple of MEG studies recently have systematically examined this interaction. Westerlund & Pylkkanen (2014) tried to bridge the semantic composition hypothesis and the concept specificity effect regarding the role of the ATL as the semantic hub. The authors compared low- or high-specificity concepts (e.g. *boat/canoe*) either in the combinatorial context (combined with adjectives, e.g. *blue boat*) or a non-combinatorial context (e.g. *xlqd boat*). The result showed an interaction between concept specificity and composition in the left ATL, such that the activation of the left ATL was modulated mostly by the low-specificity adjective-noun combinations (e.g. *bolu boat* rather than *blu canoe.* They argued that when in a combinatorial context, the low-specificity concepts required a greater degree of specification and thus it yielded the largest effect in the ATL; therefore the effect of concept specificity and the semantic composition might stem from a shared mechanism. In another study, Zhang & Pylkkanen (2015) attempted to further disentangle the contributions from concept specificity and semantic composition. Using a similar setting that single-word specificity was manipulated in a two-word combinatorial phrase (e.g. *tomato/vegetable soup/dish*), they found the largest left ATL effect when a specific modifier was combined with a general head noun (e.g. *tomato dish*) whereas specificity of the head noun itself (e.g. *soup/dish*) only had a marginal effect in the non-combinatorial condition. This study further supports the conclusion that concept specificity and semantic composition are closely related, and the ATL plays a critical role in this mechanism. In conclusion, the current findings in the thesis mirror their results that we observed the discriminating effects in the ATL: the dot-objects can be seen as some initially general, unspecified concept, and they require greater specification via semantic composition which is not required for the simple concepts.

Chapter 7

Appendix

The full stimulus list of Experiment 3 (English and the orginal Italian)

		dot-objects	**verb-control**
ABSTRACT	PRINT MATTER	consult the catalogue	consult the expert
		consult the book	consult the list
		consult the magazine	consult the section
		present the catalogue	present the problem
		present the diary	present the plan
		present the sketch/design	present the programme
		present the book	present the question
		present the magazine	explain the situation
		explain the design	explain the reason
		explain the book	explain the word
	MEAL	cancel the banquet	cancel the meeting
		cancel the lunch	cancel the concert
		cancel the dinner	cancel the decision
		organise the lunch	organise the corse
		organise the dinner	organise the day
		organise the aperitif	organise the service
		reserve the feast	reserve the place
		reserve the lunch	reserve the intervention

		reserve the dinner	reserve the shipping
		reserve the aperitif	reserve the exhibition
	INSTITUTION	help the hospital	help the people
		help the office	help the process
		help the church	help the growth
		help the school	help the development
		support/sustain the hospital	support/sustain the effort
		support/sustain the church	support the proposal
		support/sustain the school	support the economy
		evaluate the hospital	evaluate the effectiveness
		evaluate the office	evaluate the condition
		evaluate the hotel	evaluate the situation
CONCRETE	PRINT MATTER	buy the catalogue	buy the chair
		buy the diary	buy the sofa
		buy the magazine	buy the table
		pick up the catalogue	pick up the wood
		pick up the diary	pick up the flower
		pick up the sketch	pick up the fruit
		pick up the book	pick up the coin
		pick up the magazine	pick up the ball
		give the catalogue (as a present)	give the ticket (as a present)
		give the book (as a present)	give the ring (as a present)
	MEAL	pack the lunch	pack/fold the shirt
		pack the dinner	pack the vegetable
		pack the aperitif	pack the package
		cook the lunch	cook the meat
		cook the dinner	cook the dish
		cook the banquet	cook the food
		cook the feast	cook the recipe
		bring the lunch	bring the dress
		bring the dinner	bring the shirt
		bring the aperitif	bring the water

	INSTITUTION	demolish the hospital	demolish the wall
		demolish the office	demolish the house
		demolish the school	demolish the foundation
		demolish the hotel	demolish the tower
		build the hospital	build the villa
		build the church	build the flat
		build the school	build the fortress
		renovate the hospital	renovate the flat
		renovate the office	renovate the museum
		renovate the church	renovate the house

Original Italian stimulus set

		dot-objects	**verb-control**
ABSTRACT	PRINT MATTER	consultare il catalogo	consultare l'esperto
		consultare il libro	consultare l'elenco
		consultare la rivista	consultare la sezione
		presentare il catalogo	presentare il problema
		presentare il diario	presentare il progetto
		presentare il disegno	presentare il programma
		presentare il libro	presentare la domanda
		presentare la rivista	spiegare la situazione
		spiegare il disegno	spiegare la ragione
		spiegare il libro	spiegare la parola
	MEAL	annullare il banchetto	annullare l'incontro
		annullare il pranzo	annullare il concerto
		annullare la cena	annullare la decisione
		organizzare il pranzo	organizzare il corso
		organizzare la cena	organizzare la giornata
		organizzare l'aperitivo	organizzare il servizio
		prenotare il cenone	prenotare il posto
		prenotare il pranzo	prenotare l'intervento
		prenotare la cena	prenotare la spedizione
		prenotare l'aperitivo	prenotare la mostra

	INSTITUTION	aiutare l'ospedale	aiutare il popolo
		aiutare l'ufficio	aiutare il processo
		aiutare la chiesa	aiutare la crescita
		aiutare la scuola	aiutare lo sviluppo
		sostenere l'ospedale	sostenere lo sforzo
		sostenere la chiesa	sostenere la proposta
		sostenere la scuola	sostenere l'economia
		valutare l'ospedale	valutare l'efficacia
		valutare l'ufficio	valutare la condizione
		valutare l'albergo	valutare la situazione
CONCRETE	PRINT MATTER	comprare il catalogo	comprare la sedia
		comprare il diario	comprare il divano
		comprare la rivista	comprare il tavolo
		raccogliere il catalogo	raccogliere la legna
		raccogliere il diario	raccogliere il fiore
		raccogliere il disegno	raccogliere la frutta
		raccogliere il libro	raccogliere la moneta
		raccogliere la rivista	raccogliere la palla
		regalare il catalogo	regalare il biglietto
		regalare il libro	regalare l'anello
	MEAL	confezionare il pranzo	confezionare la camicia
		confezionare la cena	confezionare la verdura
		confezionare l'aperitivo	confezionare il pacco
		cucinare il pranzo	cucinare la carne
		cucinare la cena	cucinare il piatto
		cucinare il banchetto	cucinare il cibo
		cucinare il cenone	cucinare la ricetta
		portare il pranzo	portare l'abito
		portare la cena	portare la camicia
		portare l'aperitivo	portare l'acqua
	INSTITUTION	demolire l'ospedale	demolire il muro
		demolire l'ufficio	demolire la casa

demolire la scuola	demolire le fondamenta
demolire l'albergo	demolire la torre
edificare l'ospedale	edificare la villa
edificare la chiesa	edificare l'appartamento
edificare la scuola	edificare la fortezza
ristrutturare l'ospedale	ristrutturare l'appartamento
ristrutturare l'ufficio	ristrutturare il museo
ristrutturare la chiesa	ristrutturare la casa

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