The Neuro-cognitive Bases of Idiom Processing

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Contents

This is for ‘Marlboro’ (Montreal) and ‘friendly’ (benign) tumors,

for ‘plastic pot stories’ (tupper ware parties) and ‘parmesan’ (Penaten) cremes,

and, of course, for highly qualified ‘tigers’ (doctors).

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Statement of originality

The studies presented here investigate whether individual differences in cognitive control modulate idiom processing. Study 1 investigated how the eye-movements of older adults differ from younger adults when reading idiomatic sentences. Study 2 investigated whether a virtual lesion in the prefrontal cortex impairs idiom comprehension. These studies report novel findings with respect to age-related differences in idiom processing and to the neural substrates recruited in idiom comprehension. Previous analyses of the data in study 1 had been presented in posters at the meeting of the Canadian Society for Brain, Behavior and Cognitive Science in September 2011 (Kingston, ON), at the Mental Lexicon conference in October in 2012 (Montreal, QC), and at the annual meeting of the Society for the Neurobiology of Language in 2014 (Amsterdam, The Netherlands). A previous analysis of the data in study 2 was presented in a poster at the annual meeting of the Society for the Neurobiology of Language in 2013 (San Diego, CA).

Contribution of authors

The current dissertation is manuscript-based and contains one eye-tracking experiment (study 1) and one rTMS experiment (study 2). Study 1 was conceptualized by Dr. Debra Titone, programmed by Naveed Sheikh, analyzed by Katja Häuser and Dr. Georgie Columbus, and written up by Katja Häuser, under the supervision of Drs. Titone and Baum. Study 2 was conceptualized, carried out, analyzed, and written up by Katja Häuser, under the supervision of Drs. Baum and Titone.

Abstract

Idioms (e.g. *kick the bucket*, *break the ice*) are a fascinating aspect of human communication because processing idioms (e.g. *kick the bucket*) requires both lexical-semantic skills to activate and retrieve stored representations of figurative forms and meanings (*to die*), but also executive functions of cognition that inhibit co-activated literal representations (*to strike a pail with one's foot*). The set of experiments presented in this thesis investigates whether the dual semantic nature of idioms requires greater levels of cognitive control among language users than comparable literal language does. Study 1 takes a psycholinguistic approach and investigates whether older adults process idiomatic sentences differently from younger adults – a question that is interesting given that healthy aging normally yields impairments in cognitive control but spared or even improved lexical-semantic skills. Study 2 takes a neuropsychological approach and investigates whether an rTMS-induced 'temporary lesion' of the prefrontal cortex, the region most commonly associated with cognitive control, leads to performance deficits in idiom comprehension.

The findings of Study 1 suggest that older adults preferentially activate figurative meanings when processing idioms, whereas younger adults activate both literal and figurative meanings. This age-related 'commitment' to figurative meanings was not modulated by individual differences in cognitive control, suggesting that the life-long language exposure to idiomatic forms in older adults has facilitated the mental representation of idioms to an extent that literal meanings of such fixed expressions are not accessed anymore and thus control-related demands during processing are minimal.

Study 2 was conducted on younger individuals and showed that inhibiting the ventro-lateral prefrontal cortex by means of rTMS leads to slowed comprehension of low-familiar idioms, potentially because these items involve a maximal semantic conflict between a less-known figurative and a more prominent literal meaning. However, only individuals with inherently lower levels of cognitive control showed such difficulties with low-familiar idioms, suggesting that these individuals have an inherently weaker capacity to balance competing meanings during language comprehension, which makes them more susceptible to aggravated processing circumstances, such as those introduced by rTMS.

In sum, the data presented in this thesis support the notion support the notion that cognitive control is only taxed during idiom comprehension under conditions of challenging or compromised processing circumstances (such as after rTMS).

French Abstract

Les expressions idiomatiques (passer l'arme à gauche, briser la glace) sont un aspect fascinant de la communication humaine car le traitement de ces expressions (par exemple passer l'arme à gauche) requiert à la fois des compétences lexicales et sémantiques afin d'activer et récupérer les représentations stockées des formes figuratives et de leur sens (mourir) ainsi que des fonctions exécutives pour inhiber les représentations littérales co-activées (déplacer son arme du côté gauche). L'ensemble des études présentes dans cette thèse vise à déterminer si la double nature sémantique des expressions idiomatiques requiert un plus grand niveau de contrôle cognitif de la part des locuteurs que des expressions littérales comparables. La première étude emploie une approche psycholinguistique pour tester l'hypothèse que les adultes âgés traitent les expressions idiomatiques différemment des jeunes adultes, une question intéressante sachant que le vieillissement normal est associé à des troubles du contrôle cognitif mais à une préservation voire même une amélioration des compétences lexico-sémantiques. La deuxième étude adopte une approche neuropsychologique et teste l'hypothèse qu'une lésion temporaire (induite par r-TMS) du cortex préfrontal, une région communément associée au contrôle cognitif, provoque des déficits de la compréhension des expressions idiomatiques.

Les résultats de la première étude suggèrent que les adultes âgés « activent » préférentiellement le sens figuratif quand ils traitent les expressions idiomatiques, tandis que les jeunes adultes « activent » à la fois le sens littéral et le sens figuratif. Cette activation préférentielle du sens figuratif des adultes âgés n'est pas modulée par des différences de contrôle cognitif. Cela suggère que l'exposition répétée aux expressions idiomatiques au cours de la vie des adultes âgés

a facilité leur représentation mentale au point que le sens littéral de ces expressions n'est plus activé et donc que les demandes cognitives pendant ce traitement sont minimes.

La deuxième étude a été réalisée sur de jeunes adultes et montre que l'inhibition du cortex préfrontal ventro-latéral avec la r-TMS provoque un ralentissement de la compréhension des expressions idiomatiques peu familières, car celles-ci impliqueraient un conflit sémantique maximal entre un sens figuratif moins bien connu et un sens littéral plus saillant. Cependant, seules les personnes avec un niveau de contrôle intrinsèque assez bas ont montré des difficultés. Cela suggère que, pendant la compréhension du langage, ces personnes ont une capacité intrinsèque plus faible à traiter plusieurs significations en compétition, ce qui les rend plus sensibles à des conditions d'altération du traitement cognitif, telles qu'induites par la r-TMS.

En résumé, les données présentées dans cette thèse sont en accord avec l'idée que le contrôle cognitif n'est impliqué pendant la compréhension d'expressions idiomatiques que dans des contextes difficiles ou d'altération du traitement cognitif (r-TMS).

Chapter 1: General Introduction

1.1 Idioms: Definitions and Theories

'Don't count your chickens ... – *it takes too long.*'

'I think, therefore ... *I get a headache*.'

'If you can't stand the heat ... *go swimming*.'

'When the blind leadeth the blind ... *get out of the way*.'[1]

Understanding figurative language is a fascinating aspect of human communication. Studies have shown that the ability to flexibly use and fully comprehend figurative expressions develops very late in adolescence (Ackermann, 1982; Nippold & Rudzinski, 1993). Young children often do not have the necessary language skills to understand figurative meanings and show a literal bias when interpreting idiomatic expressions – often with a humorous effect, such as in the above examples where an elementary school teacher gave her students a list of incomplete sayings and proverbs, and asked the class to provide endings for each.

The focus of the current dissertation is one instance of such figurative language, idioms. Idioms are fixed linguistic expressions whose meaning cannot be derived from a compositional analysis of their component words (Swinney & Cutler, 1979). Consider the phrase *kick the bucket*. There is no direct way that a literal analysis of this phrase (*strike a pail with one's foot*) can map onto the figurative meaning *to die suddenly*. Idioms are often considered a 'special' or 'atypical' case of language due to their inherent incompatibility between literal and figurative meanings (Langlotz, 2006), and have attracted much attention in the psycholinguistic literature.

[1] Retrieved online from *http://www.mannet.com.au/gmm/bitz/sayings.htm*.

Idioms differ from other types of figurative language, such as metaphors and proverbs. Metaphorical expressions such as *my lawyer is a shark* or *my love is a rose* use semantic properties from a 'vehicle' domain (*shark; rose*) and attribute these features to a topic domain (*lawyer; love*; Kintsch, 2000), whereas idioms do not involve such mappings. Proverbs, in turn, such as *Carry coals to Newcastle* or *Don't count your chickens before they are hatched*, allude to prototypical instances of actions that involve a clear historical motivation (Glucksberg, Brown, & McGlone, 1993). Even though some idioms may have been motivated historically, present-day language users rarely recognize these motivations anymore, so that some authors refer to idioms as 'frozen metaphors' in order to highlight their non-transparent and non-motivated nature (Glucksberg, 2001).

Idioms vary along a number of linguistic variables such as familiarity, decomposability, and literal plausibility (see Titone & Connine, 1994b; Libben & Titone, 2008; Titone & Libben, 2014). Familiarity, for example, refers to the degree to which the figurative meaning of an idiom is known among language users in a particular linguistic community. Decomposability, in turn, describes to what extent the literal meanings of an idiom's constituent words map onto the figurative meaning of the phrase. In non-decomposable idioms (e.g. *kick the bucket*), this mapping is not straightforward because there is no direct way in which the constituent words *kick* and *bucket* can map onto the idiomatic meaning *die*. In decomposable idioms, in contrast, the constituent words directly map on to the figurative meaning. In the idiom *pop the question*, for example, *question* refers to a marriage proposal and *pop* to uttering it (Gibbs, Nayak, & Cutting, 1989). Finally, literal plausibility indicates whether a literal analysis of an idiom is meaningful or not, independent of the figurative meaning of the phrase. For example, *bite the*

bullet can be analyzed in a meaningful way because it is literally possible to bite a bullet. The idiom *fall from grace,* in contrast, cannot be analyzed in such a meaningful way because one cannot literally fall from grace (Gibbs & Nayak, 1989; Gibbs, Nayak, & Cutting, 1989).

Due to the dual semantic nature of idioms, the comprehension of these expressions is often thought to be different from the comprehension of normal literal language, which does not involve such a semantic ambiguity. Thus, the psycholinguistic literature has proposed special 'idiom models' of processing to describe how idioms are comprehended and how their figurative meanings are derived. The following sections will introduce the three most influential accounts of such idiom models: non-compositional, compositional, and hybrid views (Bobrow & Bell, 1973; Swinney & Cutler, 1979; Gibbs & Nayak, 1989; Gibbs, Nayak, & Cutting, 1989; Gibbs & O'Brien, 1990; Titone & Connine, 1999; Libben & Titone, 2008; Caillies & Butcher, 2007).

1.1.1 The non-compositional view

The most traditional perspective on idioms is the non-compositional account (Bobrow & Bell, 1973; Swinney & Cutler, 1979), which argues that idioms are nothing more than long words with arbitrarily stipulated meanings, which are stored in a special section of the mental dictionary. According to this view, during idiom processing, the parser will first try to compute the literal meaning of the phrase, and access the idiomatic meaning only in a second step when this literal analysis has failed to make sense (Bobrow & Bell, 1973). Consequently, idiomatic meaning comprehension requires a particular 'idiom mode' (Bobrow & Bell, 1973) which is only instantiated when a literal analysis of linguistic input is not meaningful in a given context. According to another non-compositional approach (Swinney & Cutler, 1979), idiomatic and

literal analysis of an idiom commence at the same time once the idiomatic phrase is encountered, but the idiomatic analysis will yield faster results, because the idiom is stored as a unit in the lexicon and can be accessed directly, whereas the literal analysis requires a full compositional assembly. Thus, even though non-compositional models differ with respect to their predictions as to the time course of idiom processing (and in particular, at which time point figurative and literal meanings of an idiom become available), they share the view that there is no semantic overlap or mapping between literal and figurative meanings: idioms are non-compositional chunks of language.

1.1.2 The compositional view

In contrast to the non-compositional view, which highlights the frozen nature of idioms, some authors have argued that a compositional analysis of idioms can facilitate idiom processing to a large extent (Gibbs & Nayak, 1989; McGlone, Glucksberg, & Cacciari, 1994; Gibbs, Nayak, & Cutting, 1989; Gibbs & O'Brien, 1990). According to compositional accounts of idiom processing, one argument against the notion that idioms are just long words is that many idioms can be modified internally and still be understood. For example, an idiom such as *by and large* can be syntactically modified by negation, a form manipulation which would not be possible if idioms were just long words (cf. Langlotz, 2006; pp. 39):

> Tom: By and large, the economy seems to be doing well.
> Ned: By but not so large! Have you seen the latest unemployment figures?

In addition to this, several authors have argued that even in non-decomposable idioms, where no direct semantic mapping between component words and figurative meaning exists, there are still semantic constraints imposed by the component words, which determine how that particular idiom can be used. For the idiom *kick the bucket*, for example, even though it is acceptable to say *He lay dying all week*, it is impossible to say *He lay kicking the bucket all week*. Such a modification is not possible because *kicking* denotes a discrete and sudden act, which conflicts with the notion of a week-long duration. Similarly, the fact that *get* in *get the picture* denotes a sudden event makes it more likely for someone to interpret the idiom *get the picture* as *quickly understanding a situation* rather than *slowly understanding a situation* (Hamblin & Gibbs, 1999). Thus, compositional views of idiom processing have argued that figurative meanings of idioms are not completely arbitrarily stipulated, but may be actively built from a compositional analysis of the idiom's constituents (Gibbs, Nayak & Cutting, 1989; Hamblin & Gibbs, 1999). Under this compositional view, not even non-decomposable idioms are completely frozen because they still involve a great deal of internal flexibility, and because their component words restrict the ways in which the idiom can be used semantically.

1.1.3 Hybrid views

The third and last idiom account is the hybrid or constraint-based view. Hybrid views resolve the conflict between traditional, non-compositional accounts and compositional perspectives on idiom processing, as they incorporate aspects from both of these views (Titone & Connine, 1999; Libben & Titone, 2008; Caillies & Butcher, 2007; Titone, Columbus, Whitford, *et al.*, 2015; Titone & Libben, 2014). According to these models, idioms are both unitary word configurations *and* compositional word sequences. Idiom comprehension is described as a constraint-

satisfaction process during which both literal and figurative meanings of an idiom have to be integrated into the larger discourse context (Titone & Libben, 2014; Libben & Titone, 2008). In order for this to happen most efficiently, the parser must take into account several variables at different time windows. Idiom familiarity, for example, can speed up comprehension at the very early stages of processing and can thus facilitate a quick retrieval of the idiomatic form (Libben & Titone, 2008). Decomposability, in contrast, will affect later, post-access stages of idiom resolution, when the idiomatic meaning as a whole has to be integrated into the larger discourse context. In addition, hybrid views of idiom comprehension acknowledge the impact that context can have on the speed of idiom processing. For example, idioms can be read faster when a preceding context biases the interpretation of the phrase towards its figurative meaning, rather than when the idiom is presented in a neutral context (McGlone, Glucksberg & Cacciari, 1994; experiment 2). In sum, hybrid views acknowledge the phrase-like and word-like character of idioms, and argue that idiom-inherent characteristics (familiarity and decomposability) as well as contextual factors constrain the speed with which these expressions can be processed.

1.2 Idioms and cognitive control

In recent years, several studies have investigated whether the comprehension of idioms requires greater levels of cognitive control or executive functions than the comprehension of comparable literal expressions (Galinsky & Glucksberg, 2000; Cacciari, Reati, Colombo *et al.*, 2006; Papagno, Lucchelli, Muggia, & Rizzo, 2003; Papagno & Caporali, 2007; Rizzo, Sandrini, & Papagno, 2007). These studies often refer to the experimental finding that literal language processing is largely automatic (Stroop, 1935; Miller & Johnson-Laird, 1976), so that people cannot help but activate literal word meanings while processing an idiom. This automatic

activation of literal constituents should impose greater demands on cognitive control to keep the multiple activated meanings in a temporary loop and coordinate the selection of figurative meanings, through the active inhibition of literal meanings.

In neuropsychology, *cognitive control* has been used as an umbrella term to broadly define the executive components that are engaged to achieve a particular cognitive goal (Miller, 2000; Miller & Cohen, 2001; Baddeley & Della Salla, 1996; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver, Paxton, Locke, & Barch, 2009; Aron, 2007; Tanji & Hoshi, 2008; MacDonald, Cohen, Stenger, & Carter, 2000). Cognitive control is involved in complex acts of cognition, for example in overriding habitual or automatic responses (for example, in the Stroop task), during self-monitoring and self-feedback, and also during modifying and changing behaviour in light of new information or altered task demands. The literature frequently stresses two key aspects about cognitive control, specifically, the fact that it is *top-down* and *resource-limited* (MacDonald *et al.*, 2000; Miller, 2000). Cognitive control is *top-down* in that it describes the controlled and voluntary (but not necessarily conscious) configuration of the cognitive system in its own performance, according to external or internal demands. Cognitive control is *resource-limited* because there is only a certain amount of material which working memory can hold and which central resources can operate on before resources are depleted (Baddeley & Della Salla, 1996).

From a neuro-anatomical view, cognitive control is often associated with activity in specific areas of the left and right prefrontal cortex (PFC). The PFC is a cyto-architectonically heterogeneous area (see Sallet, Mars, Quilodran, *et al.*, 2012; Yeung, 2013, for anatomical

views) with rich functional connections to posterior and subcortical brain regions (MacDonald *et al.*, 2000; Botvinick *et al.*, 2001; Miller, 2000; Miller & Cohen, 2001; Koechlin, Ody, & Kouneiher, 2003; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; Aron, 2007; Badre, 2008). Several models of PFC function have been proposed to account for the complex set of cognitive processes associated with cognitive control (MacDonald *et al.*, 2000; Badre & Wagner, 2007; Fuster, 2000; Stuss, 2011; Duncan, 2001). One very influential theory, for example, holds that the anterior cingulate cortex (ACC), a region in the medial PFC, forms a regulatory feedback loop with more lateral regions of the PFC, specifically the dorso-lateral prefrontal cortex (DLPFC; Botvinick *et al.*, 2001). According to this hypothesis, the ACC monitors for the occurrence of conflict in cognitive actions and, in case a conflict is detected, signals to the DLPFC the need for increased top-down control. The DLPFC then biases and constrains neural activation levels so that contextually appropriate responses can be selected and executed.

Given that the prefrontal cortex is fundamentally involved in the concept of cognitive control, it is not surprising that cognitive control has also been investigated from a neuropsychological point of view. For example, several clinical populations who normally present with impairments in cognitive control, such as individuals with schizophrenia and Alzheimer's disease, often show neural lesions, degeneration or abnormal levels of activation in prefrontal cortex regions (Kaufmann, Pratt, Levine, & Black, 2010; Volk & Lewis, 2002; West, 1996). Analysis of post-mortem prefrontal cortex tissue in individuals with schizophrenia, for example, has revealed reduced levels of GABA-synthesizing enzymes and of membrane transporters, which are responsible for the re-uptake of GABA into the pre-synaptic terminal (Volk & Lewis, 2002). Since GABA is the most prevalent inhibitory transmitter in the brain, this might explain why

schizophrenia is associated with below-average performance in tasks that gauge cognitive control (Volk & Lewis, 2002).

In addition to clinical population groups, impairments in cognitive control are also associated with healthy aging older adults. For example, several neuro-imaging studies have demonstrated that the aging prefrontal cortex shows the steepest rate of gray and white matter atrophy, whereas more posterior regions, in particular the occipital cortex, appear to be more robust to age-related changes (Greenwood, 2007). Age-related impairments in cognitive control have also been associated with impairments in prefrontal-striatal dopamine networks (West, 1996) and with alterations in prefrontal metabolic activity, such as oxygen and glucose regulation (Dennis & Cabeza, 2008).

The current thesis represents an effort to apply the framework of cognitive control to the study of idiomatic language, by asking whether processing and comprehending idioms requires greater levels of cognitive control than the comprehension of comparable literal language. As the previous sections have illustrated, past research has investigated cognitive control from a neuro-anatomical and neuropsychological point of view. Thus, in order to uncover the role of cognitive control during idiom processing, both approaches are adopted here. The following sections and paragraphs will review the extant literature on idioms and cognitive control.

1.2.1 Idioms and cognitive control: The neuropsychological perspective

1.2.1.1 Idiom processing in clinical patients

As noted above, the neuropsychological approach has related idiom comprehension to cognitive control by investigating individuals with Alzheimer's Disease (AD) and schizophrenia. The rationale for most of these studies is that, if these patients, who normally present with dysfunctions in executive mechanisms of cognition, are found to be impaired at idiom comprehension, then this provides evidence for the claim that idiom processing requires cognitive control.

Despite the large number of investigations devoted to this issue (see Cacciari & Papagno, 2012; for review), the majority of such studies on clinical patient groups has obtained little convincing evidence to support the claim that idiom processing is impaired in populations with control-related deficits (Kempler, Van Lancker, & Read, 1988; Papagno, Lucchelli, Muggia, & Rizzo, 2003; Rassiga, Lucchelli, Crippa, & Papagno, 2009; Schettino, Lauro, Crippa, *et al.*, 2010; Iakimova, Passerieux, Denhiere, *et al.*, 2010, Pesciarelli, Gamberoni, Ferlazzo, *et al.*, 2014; Titone, Levy & Holzman, 2002). A straightforward interpretation of many of these studies is often difficult or even impossible due to methodological idiosyncracies. Here, we will review two examples from the literature that illustrate some of the problems associated with these studies.

In a recent study, Schettino *et al.* (2010) investigated idiom comprehension in individuals with schizophrenia, using a yes/no decision task as to whether a picture correctly represented an

idiomatic sentence. Half of the pictures corresponded to the correct idiomatic interpretation and the other half to the opposite of the idiomatic meaning (e.g., for the Italian idiom *tirare la cinghia* (to starve, to be very poor), the picture would show a rich man dining at a restaurant). According to the results, patients with schizophrenia were more likely to choose the incorrect picture than the control group, and especially so when the idiom had a plausible literal interpretation (see also Titone, Levy & Holzman, 2002). The authors explain their results by arguing that the patients' idiom comprehension difficulties were due to their deficits in inhibitory control, which render individuals with schizophrenia unable to sufficiently suppress the unwanted literal meaning of literally-plausible idioms.

However, a significant concern with this interpretation is that the schizophrenia patients in the study were also impaired on a literal control task with non-idiomatic sentences, suggesting that their task difficulties resulted from a more basic impairment in language comprehension, rather than a particular impairment in processing figurative language. Numerous other studies have similarly demonstrated comprehension difficulties with both idiomatic *and* literal language in clinical populations (Papagno *et al.*, 2003; Papagno & Caporali, 2007; for a review see Cacciari & Papagno, 2012). Thus, these studies provide only very inconclusive evidence that idiom comprehension requires greater levels of cognitive control than comparable literal language, or that idiom comprehension is impaired in patients with executive function deficits.

A second issue of potential concern has to do with the heterogeneous nature of the experimental items used in some studies. For example, Kempler, Van Lancker, & Read (1988) tested Alzheimer's patients with mild, moderate and severe degrees of cognitive impairment, using a figurative sentence-to-picture matching paradigm. Participants were presented with 'familiar

phrases' (phrases which are stereotyped and have a non-literal meaning, according to the authors), and were asked to choose the correct picture from among four items. The stimuli showed the correct figurative interpretation, a representation of a single word in the phrase, the opposite meaning of the phrase, or an unrelated distractor. In order to assess the comprehension of literal language, participants were also tested on a word-to-picture and a sentence-to-picture matching task. The results showed that, whereas the control group performed close to ceiling on all tasks, the performance of all three groups of Alzheimer's patients was significantly impaired in the test of figurative phrases but not in the two tests of literal language comprehension. In addition, an analysis of the error types in the figurative language task showed that patients had a significant bias to choose the single-word distractor (81% of all errors). The authors attribute the patients' performance to impairments in meaning access and the recognition of patterns or Gestalts (as in figurative phrases that have to be retrieved from memory in chunks), and conclude that Alzheimer's disease diminishes the ability to understand figurative language.

However, as mentioned above, a major weakness of this study is the type of stimuli used. The item pool was heterogeneous with respect to the phrasal complexity of the non-literal expressions, but also with respect to the degree of decomposability (or metaphoric transparency) among items. More specifically, Kempler *et al.* (1988) compared proverbial sayings with a high degree of decomposability (*While the cat's away, the mice will play)* to non-decomposable and literally implausible idioms (*He's living high on the hog)* and other familiar phrases such as *The truth, the whole truth and nothing but the truth*, which do not have a figurative character in the first place.

This is problematic because different types of figurative language likely involve distinct processing strategies and recruit non-overlapping brain structures. For example, a recent fMRI

study (Hillert & Buracas, 2009) has shown that literally- plausible idioms activate different brain areas (the left DLPFC and also medial frontal areas such as BA 10 and BA 32) than literally-implausible idioms (the left VLPFC and adjacent areas; but see Lauro, Tettamanti, Cappa, & Papagno (2008); Zempleni, Haverkort, Renken, & Stowe (2007) for contrasting results). Similar concerns may be raised with regard to other studies which did not control for characteristics such as syntactic complexity, degree of metaphoric motivation or literal plausibility, which are all known to affect idiom processing (Papagno & Caporali, 2007; Papagno *et al.*, 2003; Rassiga et al., 2009; Iakimova *et al.*, 2010).

A third and final limitation of existing studies concerns the experimental task used in many idiom studies: sentence-to-picture matching (e.g. Kempler *et al.*, 1988; Papagno, 2001; Papagno, Tabossi, Colombo, & Zampetti, 2004; Papagno & Caporali, 2007; Papagno *et al.*, 2003). In most studies that have used this type of task, participants were presented with an idiomatic sentence and a subsequent array of two or more pictures (the literal representation and unrelated distractor items), and asked to choose which picture represents the previously seen sentence. A greater bias among clinical patient groups to choose the literal distractor item was then commonly interpreted as an executive impairment in suppressing literal meanings (Schettino *et al.*, 2010; Papagno & Caporali, 2007; Fogliata *et al.*, 2007; Rizzo *et al.*, 2007). One concern with regard to sentence-to-picture matching tasks is that figurative meanings of idioms are often highly abstract and difficult to capture in a picture, which could introduce confounds with regard to the visuo-spatial demands associated with processing figurative target and literal distractor pictures (Cacciari & Papagno, 2012). Specifically, pictures corresponding to the figurative meaning could increase processing demands in comparison to literal distractors, thus increasing the chance of reporting a

figurative language impairment when there is none (see Papagno & Caporali, 2007, and Cacciari & Papagno, 2012, for a discussion of this issue). In addition, sentence-to-picture matching tasks require maintaining a stimulus in working memory while encoding an array of other stimuli and establishing a match between them, which are all hallmarks of cognitive control, that is the construct that is under investigation. Thus, sentence-to-picture matching tasks may confound control-related demands associated with the task with control-related demands associated particularly with idiom comprehension.

In sum, there are a number of limitations constraining the interpretation of many idiom studies, particularly those focused on clinical patient groups; such limitations render equivocal the claim that idiom comprehension is associated with greater demands on cognitive control. Thus, another way to look at control-related demands during idiom comprehension is by examining performance in healthy aging adults. Older adults are interesting in the context of research of idioms, as aging is normally associated with declining cognitive control or working memory capacity, but spared or even improved lexical-semantic knowledge. Thus, older adults may be ideally suited for research on idioms, since the word- and phrase-like characteristics of idioms render idiom comprehension a cognitive process that requires both lexical-semantic knowledge of figurative meanings, but also flexible balancing of co-activated literal and figurative meanings. In addition to this, healthy aging – unlike clinical impairments such as Alzheimer's disease or schizophrenia – is normally not associated with a range of co-morbid psychological impairments (for example, memory loss, depression, anxiety or paranoia), which are a potential source of confound for any investigation on cognitive behavior. Since aging is of particular

relevance to the present thesis, the cognitive changes associated with healthy aging will be considered in greater detail below.

1.2.1.2 Idiom processing in aging

Cognitive abilities in healthy aging normally show a pattern of decline for some processes and relative stability for others (Hedden & Gabrieli, 2004; Greenwood, 2007; Dennis & Cabeza, 2008; Grady, 2012). Declining processes are 'fluid' cognitive functions, that is functions related to cognitive control, and include short-term maintenance and manipulation of information in working memory, encoding new memories of facts as well as cued and free recall (for reviews, see Braver & West, 2008; Salthouse, 2010; Hedden & Gabrieli, 2004; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Drag & Bieliauskas, 2009). Due to this loss in executive functions, older adults are at a disadvantage particularly when attention must be divided between two or more sources; a classic example of this is driving a car, where attention must be divided between driving, monitoring the environment, and sorting out relevant from irrelevant stimuli.

In order to explain these age-related impairments in 'fluid' cognitive functions, three conceptualizations have gained particular interest in the literature. The first hypothesis is that healthy aging leads to a decrease in processing speed (Salthouse, 1996), rendering cognitive operations of older adults overall slower, but otherwise not qualitatively different from those of younger adults. The second hypothesis holds that aging involves a declining capacity of working memory, so that mental storage space fills up more quickly in old age (Carpenter, Miyake, & Just, 1994). Because of this, cognitive operations may not be completed fully because partial products of these ongoing operations have already depleted storage space (MacDonald &

Christiansen, 2002). The third hypothesis holds that aging involves a decline in working memory capacity rooted in lowered efficiency of inhibitory mechanisms (Hasher & Zacks, 1988; Lustig, Hasher, & Zacks, 2007). Under this third account, older adults are unable to efficiently suppress contextually unimportant or distracting information, so that irrelevant material continuously enters cognitive operations. This sustained presence of distracting representations then interferes with the processing of cognitive targets.

In contrast to these age-related impairments in 'fluid' cognitive functions, there is relative stability in 'crystallized' abilities such as vocabulary, semantic memory (including autobiographical memory and memory of facts), procedural memory (memory for skills), and performance on theory of mind tasks (that is the attribution of mental states to other individuals). Specifically with respect to language, it is known that impairments in basic perceptual processes can negatively impact language processing in aging (for example, hearing or vision loss can lead to delays in the retrieval of phonological and orthographical characteristics of a word; Burke & Shafto, 2008), and there is often an age-related decline in processing syntactically complex sentences (which is probably related to the greater demands on working memory associated with such sentences; Glisky, 2007). However, there is considerable evidence that semantic and lexical processing at a discourse level are maintained in aging, despite the fact that these processes may be slower (Glisky, 2007; Burke & Shafto, 2008). Similarly, aging has little effect on the organization of semantic memory; in fact, older adults often have larger vocabularies than younger adults and their semantic memory appears to be richer, more elaborate and more inter-connected than that of younger adults (Glisky, 2007).

Given this contrasting pattern of decline and stability that is associated with aging, there are two possibilities regarding how aging could alter idiom processing. On the one hand, impairments in fluid cognitive functions such as cognitive control could render older adults less able to process idioms quickly, as the semantic ambiguity in these expressions requires flexible switching between co-activated meanings. However, the fact that language abilities remain largely intact (or even increase) with age, could also protect older adults from such control-related declines, for example through more semantically elaborate and interconnected idiom representation in the mental lexicon. Thus, it is not surprising that past studies which have investigated age-related changes in idiom resolution have found evidence for both of these views (Conner, Hyun, O'Connor Wells *et al.*, 2001; Qualls & Harris, 2003; Westbury & Titone, 2011; Hung & Nippold, 2014; Tompkins, Boada, & McGarry, 1992).

On the one hand, some studies have shown that older adults are less able than younger adults to resolve the conflict between literal and figurative meanings in idioms (Westbury & Titone, 2011; Conner *et al.*, 2001). For example, Westbury and Titone (2011) asked a group of younger and older adults to perform literally-true statements about idioms and matched literal phrases; that is, subjects judged whether idioms and non-idioms had a possible literal interpretation. The results showed that older (and not younger) adults had greater difficulties at judging whether idioms were literally true, which suggests that the older individuals were more susceptible to the conflict between literal and figurative meanings inherent in idioms. Thus, this finding could be interpreted to indicate that older adults are less able to use cognitive control and resolve the semantic ambiguity in idioms quickly, particularly when the task highlights this ambiguity in a special way.

On the other hand, some investigations have reported that older adults are better at idiom comprehension than younger adults (Hung & Nippold, 2014; Tompkins, Boada, & McGarry, 1992). This is especially true for studies requiring subjects to understand idioms primarily in their figurative meanings, for example, in tasks that require verbal idiom explanation or idiom definition. Hung & Nippold (2014), for example, asked groups of younger and older adults to verbally explain the figurative meanings of idioms, and to indicate in what kind of situation the idiom might be used. The results showed that older adults provided semantically richer, more elaborate and overall more fitting explanations for idioms than younger adults (Hung & Nippold, 2014). This suggests that lexical-semantic knowledge of figurative meanings, as well as contextual knowledge of idiom use, increase with age. In line with this, another study on age-related differences (Tompkins *et al.*, 1992) showed that older adults were faster than younger controls at identifying target words (e.g. *rat*) when these words occurred in an idiom rather than a literal control phrase (*smell a rat* vs. *see a rat*; Tompkins *et al.*, 1992). These findings indicate that figurative forms are overall intact in old age, and may even be more accessible for older adults, potentially because older adults have a life-long experience in encountering idioms.

However, how age-related differences map onto real-time idiom processing remains unknown, as most previous investigations of age-related changes in idiom comprehension have relied upon so-called 'offline' paradigms, that is paradigms which do not dissociate between early and late stages of language processing and thus reflect a multitude of cognitive operations. Offline paradigms are useful as a preliminary tool to explore broad age-related changes in idiom resolution, but they cannot address the nature of any age-related changes that emerge, or the time-course of idiom processing across the age groups. Thus, it remains unknown whether age-

related changes in idiom processing result from on-line processing of the expressions, or from higher level integration and interpretive processes.

1.2.2 Idioms and cognitive control: The neuro-anatomical perspective

In addition to the neuropsychological perspective reviewed in the previous sections, cognitive control in idiom processing has also been investigated from a neuro-anatomical perspective, using methods such as fMRI or rTMS in order to shed light on the neural substrates that underlie idiom processing. A special focus has been on the role of the prefrontal cortex, as it is this cortical area that is most often associated with cognitive control (Fogliata, Rizzo, Reati, Miniussi, Oliveri, & Papagno 2007; Oliveri, Romero, & Papagno, 2004; Rizzo, Sandrini, & Papagno, 2007; Zempleni, Haverkort, Renken, & Stowe, 2007; Mashal, Faust, Hendler & Jung-Beeman, 2008; Lauro, Tettamanti, Cappa & Papagno, 2007; Hillert & Buračas, 2009; for reviews, see Bohrn, Altmann, & Jacobs, 2012; Rapp, Mutschler, & Erb, 2012). Several models have been proposed to explain how the prefrontal cortex orchestrates cognitive control (Koechlin, Ody, & Kouneiher, 2003; Botvinick *et al.*, 2001). However, one limitation of these models is that they do not address language processing per se and are thus difficult to apply directly to idiom resolution.

One notable exception is the semantic control account of PFC function (Thompson-Schill *et al.*, 1997; Wagner *et al.*, 2001; Badre & Wagner, 2002; Badre & Wagner, 2007; Whitney *et al.*, 2011; Jefferies, 2013), which holds that neural substrates located in the ventro-lateral prefrontal cortex (VLPFC; Brodmann Areas 44/45/47; Badre & Wagner, 2007) are specifically relevant to the control of semantic memory (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997;

Thompson-Schill, D'Esposito, & Kan, 1999; Gabrieli, Poldrack, & Desmond, 1998; Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Wagner, Pare-Blagoev, Clark & Poldrack, 2001; Whitney, Kirk, O'Sullivan, *et al.*, 2011, 2012; for reviews see Badre & Wagner, 2002, 2007; Thompson-Schill, Bedny & Goldberg, 2005). According to this account, the ventro-lateral PFC mediates the retrieval of task-relevant or contextually appropriate meanings from the semantic store, by biasing neural activation in more posterior semantic storage areas through projections to the temporal cortex (for example, retrieving the 'financial institution meaning' of *bank* if that meaning is warranted by the context). In addition, the VLPFC is engaged during the fine-tuning of the retrieval products, for example in the case that several semantic representations have been retrieved from the semantic store and compete for activation (Gabrieli *et al.*, 1996; Thompson-Schill *et al.*, 1997; Badre & Wagner, 2007; Whitney, Kirk, O'Sullivan, *et al.*, 2011).

Given the importance of the VLPFC in tasks that require semantic control and the resolution between conflicting meanings, it can be hypothesized that the VLPFC should also be crucial for idioms comprehension. Specifically, one could assume that idiom comprehension may require language users to overcome the strong interfering activation of literal constituent words (Miller & Johnson-Laird, 1976), which recruits top-down influences (guided by the VLPFC) that bias activation in the semantic store so that only the figurative representation can be retrieved. In cases in which literal word meanings of an idiom constitute strong distractors (for example, in low-familiar idioms, where figurative meanings are less known and literal meanings more salient), it is possible that figurative *and* literal meanings are retrieved from the semantic store and compete for integration. In these cases, the VLPFC may fine-tune these retrieval products by maintaining all retrieved semantic representations and selecting one meaning over the other. On

a neuro-anatomical level, these executively-demanding operations should rely on neural substrates in the prefrontal cortex, specifically its ventro-lateral portion. In the following sections, we review the neuroimaging literature (fMRI and rTMS studies) on idiom comprehension, specifically with respect to whether idioms recruit the ventro-lateral PFC.

1.2.2.1 fMRI studies

In line with the predictions from the semantic control account, previous investigations using fMRI have implicated the ventro-lateral PFC in idiom processing (Zempleni *et al.*, 2007; Lauro *et al.*, 2008; Mashal *et al.*, 2008; Boulenger *et al.*, 2009; Hillert & Buracas, 2009). In addition to this, there is also evidence (albeit more sparse and less consistent across studies) that the dorsolateral PFC (BA 9 and 46) is involved in idiom comprehension (Hillert & Buracas, 200; Lauro *et al.*, 2008).

For example, in an fMRI study by Zempleni *et al.* (2007), participants were asked to silently read idiomatic and matched literal sentences for comprehension. The fMRI results showed that idiomatic sentences elicited stronger activity in the left (but also right) inferior frontal gyrus (that is the ventro-lateral PFC; BA 45 and BA 47) and in the left and right middle temporal gyrus (BA 21). The authors argue that idioms, due to their inherent semantic ambiguity, are more effortful to process than comparable literal language and thus activate neural regions in the PFC associated with executive control (Zempleni *et al.*, 2007). In another study, Hillert and Buracas (2009) monitored participants' brain activity while subjects performed meaningfulness judgments on auditory idiomatic and literal phrases (*He was shooting the breeze* vs *He met her in the mall*). According to the results, figurative relative to literal phrases elicited greater activity in

the left VLPFC, left DLPFC, and left superior frontal gyrus (that is BA 44, 45, BA 47, BA 8 & 9; Hillert & Buracas, 2009). Thus, these findings are consistent with the notion that the prefrontal cortex is active during idiom comprehension, perhaps because this region orchestrates the retrieval of literal and figurative meanings from the semantic store (the temporal cortex), and selects the figurative representation over the literal one.

This conclusion is also supported by two recent fMRI meta-analyses, which investigated the converging neural foci among different fMRI experiments on idioms (Rapp, Mutschler, & Erb, 2012, supplementary material; Bohrn, Altmann, & Jacobs, 2012). For example, Rapp *et al.* (2012) used activation likelihood estimates to find the common neural activation sites in five idiom studies (Zempleni *et al.* 2007, Lauro *et al.*, 2008, Mashal *et al.* 2008, Boulenger *et al.*, 2009, Hillert & Buracas, 2009). The results showed that idiomatic vs literal phrases activated a left-lateralized network, with strongest activation in the left VLPFC, left middle temporal gyrus (BA 21), and also left DLPFC (BA 9), again supporting the relevance of the prefrontal cortex for idioms. The other meta-analysis (Bohrn *et al.*, 2012), in turn, compared the same idiom studies as the Rapp *et al.* (2012) review, and used effect-size signed differential mapping, a method that takes into account the effect sizes reported for single voxels, rather than assigning equal weight to all voxels (such as in the method used by Rapp *et al.*, 2012). In line with the results from Rapp *et al.* (2012), the findings of this study also showed a predominantly left-lateralized network, with idioms eliciting greater activity in the left VLPFC and the left middle temporal gyrus. Moreover, Bohrn and colleagues' (2012) study also found considerable right-hemispheric activation in the same neural regions, a result not reported by Rapp *et al.* (2012). Thus, even though the results of these two studies are not completely in agreement with respect to the

lateralization of idiomatic language processing (which might be related to the use of different analysis methods), both meta-analyses indicate that idioms activate the prefrontal cortex, and in particular the left ventro-lateral PFC.

1.2.2.2 rTMS studies

Whereas fMRI is a useful tool to illustrate the neural regions that are associated with a cognitive function, it cannot establish whether there is a causal relationship between cognitive behavior and a particular neural region. This means that the above-cited fMRI studies cannot address whether the PFC (and particularly the VLPFC) is fundamentally necessary to process idioms. A more direct means of investigating brain-behavior relationships is through the use of transcranial magnetic stimulation (TMS; Wassermann, 1998; Pascual-Leone, 1999). TMS is a procedure that relies on the principle of induction, where brain activity in focal neural regions is influenced by a magnetic field that is generated through an electrical current passing through a figure-of-eight coil that is held close to the head. The magnetic pulses pass through the skull and can either increase or decrease neural excitability in underlying brain tissue, depending on the frequency and duration of stimulation, the neural region stimulated, and the experimental task that is being used (for an overview of TMS studies on language processing and their stimulation protocols; see Lavidor, 2012). TMS can be used both online (that is, event-related, trial-by-trial, during the experimental task), and offline (before the experimental task), and within a single pulse and repetitive pulse protocol (rTMS). With respect to the effects of stimulation, many TMS studies on language have established that a repetitive low-frequency protocol (TMS at 1-4 Hz; Lavidor, 2012) is inhibitory, that is decreases neural excitability for language processing. Evidence is

more mixed with respect to the effects of high-frequency stimulation protocols (5-10 HZ; Lavidor, 2012).

The number of TMS studies on idioms to date is rather limited (Oliveri, Romero, & Papagno, 2004; Rizzo, Sandrini, & Papagno, 2007; Fogliata, Rizzo, Reati, *et al.*, 2007; Sela, Ivry, & Lavidor, 2012). Moreover, the results obtained by these studies are only partly consistent with the fMRI findings reported above. One way in which the TMS studies are in agreement with the findings obtained from fMRI, is that idiom processing recruits the dorsolateral prefrontal cortex (DLPFC; Fogliata *et al.*, 2007; Rizzo *et al.*, 2007). Two studies found that correct idiom comprehension in a sentence-to-picture matching task decreased significantly when online high-frequency rTMS was applied to the left and right (Rizzo *et al.*, 2007), and the left DLPFC (Fogliata *et al.*, 2007). In both studies, this rTMS-related decrease in accuracy was idiom-specific, as it was not present for literal stimuli, and it was also not present when a control site was stimulated which had no function in language (vertex, in both studies). The authors suggest that rTMS stimulation to the DLPFC specifically disrupts idiom comprehension, because idioms increase the need for executive control in inhibiting unwanted literal meanings (Fogliata *et al.*, 2007; Rizzo *et al.*, 2007). However, one concern in both studies is again the use of a sentence-to-picture matching task. As argued previously, the difficulties with depicting abstract figurative meanings may render the use of such tasks somewhat problematic, specifically in research on idiomatic language (Cacciari & Papagno, 2012). Another issue of concern in these studies is the stimulation protocol. Both studies used stimulation parameters, which – in terms of their frequency, intensity and duration – have previously been reported to be *facilitatory* for language processing, rather than inhibitory (cf. Lavidor, 2012). In line with this, both of these TMS studies

also reported that, following stimulation to the DLPFC, there was a general decrease in reaction times among participants, for both idioms and literal phrases. Thus, it is somewhat difficult to clearly evaluate the findings obtained in these two idiom studies.

With respect to the ventrolateral PFC, the frontal region primarily implicated by idiom studies using fMRI, the evidence from TMS is equivocal. The sole rTMS study that focussed on this cortical area (Oliveri *et al.*, 2004; identical data are reported in Papagno, Oliveri, & Lauro, 2002) did not produce any significant effects for stimulation to the VLPFC. This investigation used a low-frequency offline (that is, generally inhibitory) stimulation protocol and again, an idiomatic sentence-to-picture matching task. Subjects' performance on idioms and matched literal sentences was compared following VLPFC stimulation and a 'baseline task without rTMS' (no further specifications are given; see Oliveri *et al.*, 2004). The results showed that VLPFC stimulation did not lead to any significant changes in the speed or accuracy with which participants responded to idiomatic stimuli. The authors concluded that rTMS stimulation to the left VLPFC does not have a disruptive effect on idiom comprehension (but see Rapp *et al.*, 2012, Bohrn *et al.*, 2012; Zempleni *et al.*, 2007; Lauro *et al.*, 2008; Mashal *et al.*, 2008; Boulenger *et al.*, 2009; Hillert & Buracas, 2009; for conflicting evidence).

The lack of an effect in this study is rather surprising, as it conflicts with the results from previous fMRI experiments and meta-analyses (Zempleni *et al.*, 2007; Lauro *et al.*, 2008; Mashal *et al.*, 2008; Boulenger *et al.*, 2009; Hillert & Buracas, 2009; Rapp *et al.*, 2012, Bohrn *et al.*, 2012). Oliveri *et al.'s* (2004) results are also not in keeping with research that has specifically associated ventral portions of the PFC with controlled semantic processing (Badre & Wagner, 2007; Badre *et al.*, 2005; Wagner *et al.*, 2001; Jefferies, 2013).

However, there are two methodological issues in the Oliveri *et al.* (2004) study that could explain why VLPFC stimulation failed to yield significant effects. First, the authors used exclusively high-familiar idioms, that is, idioms that have a strongly salient figurative meaning. Hybrid accounts of idiom processing (Titone & Connine, 1999; Libben & Titone, 2008) predict that such items, because they are highly over-learned, can be retrieved from semantic memory directly, and involve little or no competition from literal word meanings. The lack of semantic competition from literal constituents could explain why Oliveri *et al.* (2004) found no VLPFC-related effects: The stimulated area might not have been necessary for idiom comprehension in the first place, because the idiomatic items used in the study could be retrieved directly, without controlled input of the VLPFC.

The second methodological issue concerns an aspect of the rTMS protocol used in this study. The authors used an EEG cap to localize cortical stimulation sites, which is a common, albeit somewhat crude means of localizing cortical target sites. Research has shown that in about 10% of all measurements conducted in such a way, adjacent and possibly functionally distinct cortical regions are, in fact, targeted (Herwig, Satrapi, & Schoenfeldt-Lecuona, 2003). This concern is not trivial in the context of this particular study because the cortical target site is located at the side of the head, close to the temple, where the TMS coil can shift easily due to jaw twitches of the participant, and the experimenter needs to hold the coil in position throughout stimulation. In addition, research has shown that only a specific neural area within the left VLPFC is maximally sensitive to tasks that involve semantic control (Badre *et al.*, 2005; Whitney, Kirk, O'Sullivan, *et al.*, 2012). This particular region has been interpreted as a 'neural convergence zone' for

semantic control (Badre &Wagner, 2007), as it was sensitive to several semantic manipulations such as weak versus strong cue–target associations in semantic relatedness judgments. Without the help of a precise neuro-anatomical guidance system, it is nearly impossible to target such a specific site.

Thus, there are a number of methodological issues associated with the sole previous rTMS study that investigated the involvement of the VLPFC in idiom comprehension (Oliveri *et al.*, 2004), leaving the question as to its role unanswered.

1.3 The present study

The two experiments presented in this dissertation were designed to address whether idiom processing involves greater levels of cognitive control than the processing of comparable literal language. To investigate this, we used behavioural methods to examine age-related changes during idiom processing, and neuro-anatomical methods to target the neural substrates of cognitive control.

Study 1 adopts a neuropsychological perspective by investigating whether older adults, who normally present with impairments in cognitive control but stability in lexical-semantic aspects of language, differ from younger adults during the online resolution of idiomatic language. Past studies on idiom comprehension in aging had primarily used offline paradigms and yielded conflicting evidence, indicating that there is both age-related decline and stability with respect to idiom processing. Thus, Study 1 was designed to address how older adults may differ from younger adults using an online reading paradigm (via eye-tracking), to evaluate both early stages (access of the figurative form in memory) and late stages (semantic analysis and integration into a sentence context) of idiom processing.

Study 2 adopts a neuro-anatomical perspective to address whether neural substrates in the ventro-lateral PFC, a neural convergence zone for semantic control (e.g. Badre & Wagner, 2007), are fundamental to idiom comprehension. As described earlier, previous studies on this issue had obtained conflicting findings, with fMRI studies consistently showing an involvement of this cortical region in idiom comprehension (Lauro *et al.*, 2008; Zempleni *et al.*, 2007), whereas a previous rTMS study failed to corroborate these findings (Oliveri et al., 2004). Thus, Study 2 used an rTMS paradigm to more carefully address the relevance of the VLPFC for idiom comprehension.

Both studies in the current thesis used exclusively verb-determiner-noun idioms (e.g., *kick the bucket*, *break the ice*, *blew a fuse*) to ensure that the item pool was homogeneous. Both studies also tested for the effects idiom familiarity, a variable known to influence idiom processing (e.g. Libben & Titone, 2008), but which many previous studies had failed to take into account.

Chapter 2: Study 1

Idiom Processing is Enhanced in Healthy Aging:

Evidence from Eye Movement Measures

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2.1 Abstract

Idiom comprehension (e.g., *kick the bucket*) requires that people integrate intended figurative meanings (e.g., *to die*) while inhibiting literal interpretations (e.g., *to strike a pail with one's foot*). Because of the need to balance prior knowledge with meaning selection, idioms are interesting with respect to healthy aging, which normally involves a decline in computational aspects of cognition (executive control) but stability in lexical-semantic memory.

We investigated age differences in idiom processing using eye-tracking. Younger and older adults read sentences containing literal control phrases or idioms, presented in a canonical or a non-canonical form (e.g., *He kicked the bucket* vs. *He kicked the black bucket*). To assess whether people integrate figurative or literal interpretations after reading an idiom, sentences contained a disambiguating region following the idioms that was literally – or figuratively – biasing.

For measures reflecting early stages of comprehension (e.g., first pass gaze duration of the idiom), older adults showed facilitation for idioms in a canonical form (*He kicked the bucket...*), suggesting a greater sensitivity to idiomatic forms compared to younger adults. For measures reflecting late stages of comprehension (e.g., total reading time of the idiom), older adults showed slower reading times when literally-biased disambiguating regions followed idioms in their canonical form, suggesting that they were more likely to interpret such idioms figuratively. This suggests that idioms may be more strongly entrenched for older than younger adults, potentially because of greater experience encountering idioms intended figuratively.

2.2 Introduction

Healthy aging is often thought to involve gradual declines in 'fluid' aspects of cognition, but a sparing or enhancement of 'crystallized' knowledge (Hedden & Gabrieli, 2004; Stine-Morrow, Loveless, & Soederberg, 1996; Stine-Morrow *et al.*, 1996). The aspects of 'fluid' cognition usually implicated include on-demand cognitive operations such as working memory encoding and short term memory maintenance, as well as executive processes that operate on the contents of working memory (Salthouse, 1996; 2010). For example, age-related declines in executive functions are accompanied by structural or functional changes in specific neural areas (West, 1996; Koechlin, Ody, & Kounheier, 2003; Greenwood, 2007; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; Miller, 2000; Braver & West, 2008). In contrast, the aspects of crystallized cognition usually implicated include semantic memory (including autobiographical memory as well as memory of facts), which remains largely intact in aging (Ackerman & Rolfhus, 1999; Schaie, 1994; Stanovich, West, & Harrison, 1995; Stine-Morrow, Loveless, & Soederberg, 1996; Stine-Morrow, Soederberg Miller, & Hertzog, 2008).

Age differences in fluid versus crystallized cognition have important implications for real-time language processing, which requires a flexible balance of both knowledge and in-the-moment demands. Consistent with the general view, there is evidence that lexical and semantic representations at a word and text level (that is, crystallized linguistic knowledge) are spared in aging (despite the fact that lexical processing may be slower; Glisky, 2007; Burke & Shafto, 2008). For example, older adults often have larger vocabularies than younger adults due to their life-long language experience, and their semantic memory appears to be richer, more elaborate and more inter-connected than the semantic memory of younger adults (Glisky, 2007). Also

consistent with the general view, there is evidence that older adults experience a variety of fluid linguistic declines such as lexical retrieval difficulties (Goral, Spiro, Alberta, Obler, & Connor, 2007) and difficulty processing syntactically complex sentences (Burke & Shafto, 2008).

In this paper, we extend this line of work to investigate whether and how fluid and crystallized aspects of cognition in healthy aging are manifest for a particular aspect of language that crucially draws on such processes: the comprehension of idiomatic expressions. Idioms are commonly encountered multiword sequences that are traditionally defined as 'long words', which are semantically unanalyzable and syntactically frozen (e.g., *kick the bucket*; Swinney & Cutler, 1979; Bobrow & Bell, 1973). However, we now know that this simple definition is insufficient for characterizing the full range and variety of linguistic forms that may be classed as idioms (reviewed in Titone & Connine, 1999; Libben & Titone, 2008; Titone *et al.*, 2015). For example, there is evidence that idioms can be syntactically and semantically modified (e.g., *by and not so large*; *He didn't spill a single bean*), and that the component words of some idioms map onto the figurative meaning in a semantically transparent way (e.g., *break the ice*, *steal the show*; Gibbs & Nayak, 1989; Gibbs, Nayak & Cutting, 1989; Glucksberg, 2001). Thus, many researchers now embrace the "multidetermined" nature of idioms, which characterizes such expressions as multiword sequences that undergo some degree of semantic and syntactic decomposition during comprehension depending on the many ways particular sequences vary linguistically (Titone & Libben, 2014; Caillies & Butcher, 2007; Libben & Titone, 2008; Sprenger, Levelt & Kempen, 2006; Titone *et al.*, 2015). The implication of this view is that idioms simultaneously have both word- and phrase-like properties that can variably dominate during on-line comprehension.

Given that idioms have both word- and phrase-like aspects, there are at least two possible ways that healthy aging could impact idiom comprehension. Consistent with the idea of intact crystallized cognition in aging, older adults' life-long language experience, in combination with age-related enrichment in semantic connections (Glisky, 2007), could facilitate both the initial access of idiomatic forms and their subsequent retrieval (Hyun, Conner, & Obler, 2014). In contrast, consistent with the idea of declining fluid cognition in healthy aging, idiom processing could be more difficult, especially for later stages of comprehension, when literal and figurative representations of idioms must be maintained in working memory and integrated into an unfolding context that may be biased either figuratively or literally.

Interestingly, previous studies of idiom processing in healthy older adults have obtained evidence for age-related decline (Conner, Hyun, O'Connor Wells, Anema, Goral, Monereau-Merry, Rubino, Kuckuk, & Obler, 2011; Qualls & Harris, 2003) and age-related stability in idiom processing (Westbury & Titone, 2011; Hung & Nippold, 2014; Hyun, Conner, & Obler, 2014). For example, older adults had difficulty deciding whether an idiom was literally true (Westbury & Titone, 2011), which suggests that older adults' crystallized knowledge of figurative expressions is intact, but that they have trouble quickly deciding between dually activated literal and figurative meanings (i.e. an impairment in a fluid aspect of cognition such as executive control). Another study found that older adults outperformed younger adults in idiom production as long as the idiom was syntactically frozen (Hyun, Conner, & Obler, 2014), which also suggests that older adults rely on their greater crystallized knowledge of language, particularly when the task requires production of fixed or invariant expressions of language. Consistent with this idea, older adults have shown evidence of greater idiomatic sensitivity than

younger adults in some studies (Hung & Nippold, 2014; Westbury & Titone, 2011). For example, older adults provided more elaborate and semantically richer explanations of idioms, and performed at ceiling in a phrase-to-idiom matching task (Hung & Nippold, 2014), which both suggest that knowledge of idiomatic forms and meanings is largely preserved in aging.

Thus, given evidence for both increased and decreased sensitivity to idioms in healthy older adults, it is difficult to draw straightforward conclusions from past studies. Adding to the complexity is that in many cases, the idioms used as experimental stimuli were neither sufficiently distinguished from other types of figurative language, such as metaphors (Qualls & Harris, 2003), nor well characterized with respect to the many ways idioms differ that may impact comprehension (Hung & Nippold, 2014). As well, most previous studies have used offline tasks to investigate age-related effects on idiom comprehension – that is, tasks that reveal little about natural idiom comprehension and how the activation of idiomatic and literal representations unfolds over time as the idiomatic phrase is progressively decoded.

In the present study, we addressed these limitations by investigating whether age-related differences in idiom comprehension arise when healthy older adults (and matched younger adult controls) engage in a task where the only demand is to read (for comprehension) sentences containing idioms (or literal control phrases) while their eye movements were monitored. Eye movement studies of reading have important advantages for probing the representation of linguistic knowledge compared to other kinds of experimental tasks precisely because they afford such a natural comprehension situation, and also because they have great temporal and spatial precision about how long the eyes fixate crucial target regions of a sentence as

comprehension naturally unfolds (Rayner, 1998; Frazier & Rayner, 1982). Because of this temporal and spatial precision, it is possible to construct a comprehension time course ranging from the earliest stages of processing (i.e., when idiomatic forms are first encountered and retrieved from memory) to latest stages of processing (i.e., when idiomatic meanings are subsequently activated and integrated into a particular sentence context).

Consequently, we recorded eye movements as younger and older adults read idiomatic and literal control sentences, which allowed us to investigate age-related changes during both early and late stages of idiom processing. Further, to better understand the conditions under which idiom comprehension would be enhanced or impeded in healthy aging, we experimentally manipulated the demands of the idiom comprehension task in several ways. First, we presented idioms that varied with respect to prior ratings of their subjective familiarity (taken from Libben & Titone, 2008). Presumably, idiom processing should be easier for idioms rated as high vs. low familiar, though the effects of familiarity might be reduced for older vs. younger adults because of their greater life-long exposure to idiomatic forms (i.e., possibly rendering idioms rated as low familiar by young adults subjectively more familiar; see Whitford & Titone, submitted, for a similar preservation of linguistic knowledge in older adult bilingual readers).

Second, participants read idioms in either their canonical or non-canonical form, a manipulation that was implemented by presenting unmodified idioms (*broke the ice*) or the same idioms with an adjective inserted before the phrase-final noun (*broke the cold ice*). Here, the goal was to select adjectives that would be compatible semantically with either the figurative or literal meaning so as not to rule out either interpretation semantically. Idioms presented in their

canonical forms, particularly those that were high familiar, should be relatively easier to comprehend given that participants could rapidly retrieve knowledge about idiomatic forms and meanings from memory and easily inhibit or block activation of an idiom's literal interpretation. In contrast, idioms presented in their non-canonical forms should generate greater semantic conflict between literal and figurative meanings of the phrase by breaking up the idiomatic word configuration at the form-level, and thus potentially biasing the compositional, literal interpretation of the phrase.

Third, and as previously mentioned, we presented idioms in sentences that had a subsequent disambiguating region that was biased towards either an idiom's literal interpretation (*Bruce broke the ice by driving his snowmobile onto the thawing lake*) or its figurative interpretation (*Bruce broke the ice by quickly introducing himself to everyone at the wedding*). The rationale of placing the semantically biased context after the idiomatic phrase was that it allowed us to indirectly assess which meaning had been accessed when the idiom was encountered with no prior contextual bias. Accordingly, if a literally biased disambiguating region was read after a canonical-form idiom (*Bruce broke the ice by driving his snowmobile onto the thawing lake*), reading might be disrupted because the subsequent bias of the sentence conflicted with a likely figurative interpretation of the idiom. A similar conflict could also be induced when a non-canonical idiom precedes a figuratively-biasing disambiguating region (*Bruce broke the cold ice by quickly introducing himself to everyone at the wedding*). Thus, reading behaviour on the subsequently encountered disambiguating region could allow us to infer the degree to which older adult readers preferred one semantic interpretation of an idiom over another.

Our general predictions regarding older adults were as follows. To the extent that age-related declines in fluid cognition (i.e., selective attention or executive control) predominate during idiom processing, we might expect older adults would have difficulty reading idiomatic word sequences and subsequent figuratively biased disambiguating regions, particularly when idioms are low familiar and presented in a non-canonical form, as it would be more difficult for them to suppress the ongoing literal or compositional analysis of the sentence in favour of an idiomatic meaning. In contrast, to the extent that greater (i.e., more crystallized) life-long language knowledge predominates during idiom processing, we would expect older adults to have little difficulty reading idiomatic sequences and subsequent figuratively biased disambiguating regions, even when idioms are low familiar or are presented in a non-canonical form. Finally, to the extent that both play a role to some degree, we might find a more complex pattern of data where, for example, idioms are advantaged irrespective of familiarity, but that conditions that promote a literal interpretation of the idiom in the moment (i.e., non-canonical presentation) might lead to disruptions in comprehension for older adults.

2.3 Method

2.3.1 Participants

Twenty-one older adults from the Montreal community (seven female) participated for compensation at a rate of CAD$10 per hour. The control group consisted of 37 younger adults (27 female) that had been included in a prior study of metaphor and idiom processing, which included the same materials (Columbus *et al.*, 2015; of note, that study only focused on intact or canonical idiom presentation, thus the data reported here for the adjective-inserted idioms are

novel for the younger adults). All participants were self-reported native speakers of English, which was confirmed by a language history questionnaire modelled after the *Language Experience and Proficiency Questionnaire* (LEAP-Q) (Marian, Blumenfeld, & Kaushanskaya, 2007). The younger and older participants were matched on the following dimensions: All participants reported learning English as the first language from birth (or, in the case of bilingual speakers, English was one of the first languages learned from birth). All participants reported exclusively or predominantly English as their main language of instruction during early formal schooling (elementary and high school). In addition, all participants rated English as their dominant language at the time of testing; they also rated their current language exposure at the time of testing as highest for English in comparison to French or other languages. Demographic information and language background for the two age groups is presented in Table 1.

[Insert Table 1 here]

In addition to the language history variables, all participants also had normal or corrected-to-normal vision and no self-reported history of speech, hearing, language and/or neurological/psychiatric disorders. The two age groups were matched on number of years of formal education (see Table 1).

2.3.2 Procedure

Participants came to the lab for one session that lasted approximately two hours. Upon signing the consent form, participants completed the modified LEAP-Q questionnaire. They were then led to a quiet room where the sentence reading task was administered. Participants were

informed that they would read sentences on a screen, one at a time, while their eye movements were recorded. Each trial began with a fixation cross, presented in the middle of the screen, followed by a sentence, presented on the left side of the screen. The task was to read each sentence silently for comprehension and to press a button on a control pad to indicate when they finished reading the sentence. Yes-No comprehension questions were included on 25% of trials to ensure participants were reading for content.

2.3.3 Materials

The experimental materials consisted of 54 English idioms that had a verb-determiner-noun structure (taken from the idiom corpus in Libben & Titone, 2008) and 54 matched literal control phrases. Control phrases were created for each idiom individually by replacing an idiom's verb with another verb of approximately the same length (for example, *kick the bucket* was changed to *tip the bucket*). All idioms and literal control phrases were embedded in two-clause sentences, matched in length as closely as possible. The first clause of the sentence contained an agent (always a name), followed by the idiom (or matched literal control phrase) in the past tense (for example, *Mary kicked/tipped the bucket*). The second clause of the sentence contained a disambiguating context that supported either a figurative (Id-Id condition) or literal (Id-Lit condition) interpretation of the idiomatic phrase (e.g., Id-Id sentence: *Mary kicked the bucket after suddenly becoming seriously ill on the weekend*; Id-Lit sentence: *Mary kicked the bucket when it was blocked from her view by the chair*). In literal control phrases (*tip the bucket*), the second clause continued the first clause in a meaningful (literal) way (e.g., Lit-Lit condition: *Mary tipped the bucket to sprinkle fertilizer into her new flower garden*).

To manipulate the canonical form of the idiom, each idiom or matched control phrase was presented either with or without an adjective before the phrase-final noun (*kicked the bucket* – *kicked the black bucket*). This design resulted in a total of 6 experimental conditions (three levels for sentence type, two levels for canonical form). All stimuli were counterbalanced across six experimental lists, and lists were counterbalanced across subjects, so that every participant would see an item in only one of its six experimental conditions. Table 2 shows an example of the six experimental conditions for the idiomatic phrase *kicked the bucket*.

[Insert Table 2 here]

2.3.4 Apparatus

Participants were tested in a quiet room on an Eye-link 1000 tower-mounted eye-tracking system (SR-Research, Ontario, Canada) using a 21 inch View Sonic CRT monitor with a screen resolution of 1024 x 768 pixels. Viewing was binocular, but eye-tracking data were collected for the right eye only. Idiomatic and literal sentences were presented aligned to the left side of the screen on a single line, in yellow 10-point Monaco font on a black background. Eye movements were calibrated using a nine-point grid. Subject's heads were firmly held in place by the eye-tracker headrest throughout the experiment. Three characters subtended approximately 1° of visual angle. To determine whether the two age groups differed with respect to executive functions, participants were also tested on the AXCPT executive function task (Braver *et al.*, 2001). Background information and results of this task are presented in Appendix 1.

2.4 Results

Accuracy on the comprehension questions was high in both younger (m = 95.43%, SD = 5.82) and in older adults (m = 94.81%, SD = 6.00), with no significant differences between the two age groups ($t(55) = -1.07$, $p > .05$). This indicates that both groups were attentive during the experiment and understood the idiomatic sentences they were reading.

Our analyses of the reading measures included both early and late measures of reading (Radach & Kennedy, 2004, 2013; Rayner, 1998, 2009). Early measures included first pass gaze duration of idiomatic phrase-final nouns (GD; sum of all fixation on the noun during the first pass) and go-past time of phrase-final nouns (the sum of all fixations prior to the eyes moving to the right of the noun on the first pass). Late measures included idiom total reading time (TRT; sum of all fixation and refixation durations on the idiom), and the proportion of regressions from the disambiguating region (a binomial measure).

To analyze the data statistically, we constructed separate linear mixed-effects models for each eye-tracking measure, as implemented in the lme4 library (Bates & Sarkar, 2007) in R (R Development Core Team, 2009). Fixed effects were canonicity (a categorical variable with two levels: canonical/without adjective vs. non-canonical/with adjective), age group (a categorical variable with two levels, younger and older), idiom familiarity (a scaled continuous variable), and sentence type. Sentence type was a categorical factor consisting of two levels (literal and idiomatic) for early reading measures (GD noun and go past noun), given that readers encountered idioms or control phrases *prior* to accessing the disambiguating region. In contrast, sentence type was a categorical factor consisting of three levels (Id-Id, Id-Lit, and Lit-Lit) for

late reading measures (idiom TRT and regressions out of the disambiguating region). We used deviation coding for all omnibus models. Given that the interpretation of significance is similar to that of ANOVA when using deviation coding, to identify the source of any effect involving sentence type, we relied upon follow-up treatment coded models, which are akin to simple effects analyses to interpret significant interactions involving sentence type. Further, because of our prior work suggesting that familiarity is correlated with another dimension of idioms, decomposability (Titone & Connine, 1999; Libben & Titone, 2008), we included decomposability ratings as a control variable in all analyses. We also controlled for the length (in number of characters) of the respective region in each model (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Kliegl, Grabner, Rolfs, & Engbert, 2004). All models contained participants and items as crossed random effects, and random slope adjustments for subjects and items for all categorical variables, where appropriate. In the event that a model failed to converge, we simplified the random slope structure progressively until convergence was achieved (see Barr, Levy, Scheepers, & Tily 2013, for guidelines). To facilitate interpretation of the data reported below, means and standard deviations for all eye movement measures are presented in Table 3. Tables 4 and 5 summarize the model results for the early and late reading measures, respectively.

[insert Table 3 here]

[insert Table 4 + 5 here]

2.4.1 Early reading measures

2.4.1.1 Gaze duration for phrase-final nouns

Extreme outliers were removed from the dataset (noun GD < 80 ms or > 1000 ms), retaining 98.73% of all observations (99.21 % of all observations from the younger adults, and 99.15 % of

all observations from the older adults). Stepwise log likelihood model comparisons showed that by-subject and by-item random slopes were not warranted for this model.

We found a main effect of age group (b = 19.91, SE = 6.76, t = 2.95; see Figure 1), indicating that older adults had longer fixation times overall, regardless of whether sentences were idiomatic or literal. There was also a main effect of canonical form (b = 9.99, SE = 2.31, t = 4.32), suggesting that fixation times on nouns in non-canonical phrases (i.e. in phrases with an adjective; *kick the black bucket*) were consistently longer, regardless of age group or sentence type. The main effect of sentence type and any higher order interactions between sentence type, age group, or canonical form were not significant.

[insert Figure 1 here]

2.4.1.2 Go past times for phrase-final nouns

Extreme outliers were again removed from the dataset (go past times < 80 ms or > 2000 ms), retaining 99.05 % of observations (99.34 % of all observations from the younger adults, and 90.57 % of all observations from the older adults). Stepwise log likelihood ratio tests showed that by-item random slopes for age group were warranted in this model.

As seen in Figure 2, there was a significant three-way interaction between sentence type, age group and canonical form (b = 12.41, SE = 4.73, t = 2.62). To locate the source of the complex three-way interaction, we computed treatment-coded follow-up models with literal sentences as the baseline, in which items were split by canonical form. The results of these models showed a significant interaction between sentence type and age group only for canonical items (b = -80.20, SE = 24.64, t = -3.25), but not non-canonical items (b = 26.81, SE = 28.54, t = 0.94). An inspection of the plot for this interaction (see Figure 2) suggests that older adults were relatively

faster for nouns in canonical idioms vs. literal sentences (*kicked the bucket* vs. *tipped the bucket*), whereas the younger adults' reading times showed no difference between canonical and non-canonical idioms relative to the literal condition (i.e., there was neither facilitation nor interference compared to the literal sentences). These observations were confirmed by an additional follow-up on the model for canonical items, in which items were split by age group. The results showed a significant main effect of sentence type only in the model for the older adults (b = -67.15, SE = 24.56, t = -2.73), and not in the model for the younger adults (b = 14.30, SE = 12.43, t = 1.2)

Thus, the first pass reading data suggest that older adults showed greater idiom facilitation for idioms presented in their canonical form (*kick the bucket*), which indicates that older adults are more sensitive to idiomatic forms during natural reading than younger adults. To provide additional support for this conclusion, we now turn to later reading measures, which provide an indication of what meaning older and younger adults integrated into the unfolding sentence context after initially encountering the idioms earlier in the sentence.

[insert Figure 2 here]

2.4.2 Later reading measures

2.4.2.1 Total reading time of the idiom

We removed extreme outliers (idiom TRT < 80 ms or > 5000 ms), retaining 99.39 % of all values (99.73 % of all observations from the younger adults, and 99.30 % of all observations from the older adults). Stepwise log-likelihood ratio tests showed that by-subject random slopes

were warranted for canonical form, and that and by-item random slopes were warranted for sentence type and canonical form, respectively.

The omnibus model showed interactions between sentence type (Id-Id) and canonical form (b = 70.08, SE = 31.56, t = 2.22), and sentence type (Id-Lit) and canonical form (b = -50.39, SE = 25.82, t = -1.95). There was also a significant interaction between age group and canonical form (b = 28.91, SE = 12.93, t = 2.24), but the three-way interaction between sentence type, canonical form and age group was not significant for either Id-Id (b = -11.55, SE = 24.62, t = -0.47) or Id-Lit (b = -1.97, SE = 24.55, t = -0.08). There was also a trending towards significant interaction between sentence type (Id-Id) and idiom familiarity (b = -67.47, SE = 39.80, t = -1.70). To investigate this complex pattern of data, we computed treatment-coded follow-up models with Lit-Lit as the baseline, in which items were split by canonical form.

The model for canonical items showed a trending towards significant interaction between sentence type Id-Id and familiarity (b = -78.99, SE = 41.29, t = -1.91). Figure 3 suggests that this interaction was driven by both high- and low-familiar idioms: Whereas high-familiar idioms with a figuratively biasing context region showed visible facilitation in both age group (in comparison to the literal control Lit-Lit), low-familiar idioms were read more slowly by both age groups. This was confirmed in additional follow-up models in which we median-split items by familiarity: the results showed that there was facilitation for high-familiar idioms (b = -97.66, SE = 48.18, t = -1.70), but disruption for low-familiar idioms (b = 89.78, SE = 44.95, t = 2.0). Thus, both younger and older adults read high-familiar idioms in a canonical form more quickly, whereas they read low-familiar idioms in a canonical form more slowly.

The model for non-canonical items (*kick the black bucket*) showed a barely significant main effect of sentence type Id-Id (b = 114.32, SE = 60.70, t = 1.88), thus suggesting that reading times for idioms increased in both age groups (versus the literal control condition) when non-canonical idioms were presented with a figuratively-biasing disambiguating region (e.g. *Mary kicked the black bucket after becoming seriously ill on the weekend*). Figure 4 displays this effect by showing that both younger and older adults read non-canonical Id-Id sentences more slowly than the literal reference condition (Lit-Lit).

Thus, two key findings emerged for the TRT idiom model. First, regardless of age group, there was facilitation for high-familiar canonical idioms and slowing for low-familiar canonical idioms. Second, both younger and older showed disruptions for idioms presented in a non-canonical form, suggesting that both age groups were sensitive to the inherent semantic conflict in these items.

[insert Figure 3 + 4 here]

2.4.2.2 Regressions from the disambiguating region to earlier sentence regions

The model showed significant interactions between sentence type (Id-Id) and familiarity (b = -0.40, SE = 0.16, z = -2.56), and between age group and familiarity (b = -0.08, SE = 0.04, z = 1.95). There was also a significant interaction between sentence type (Id-Lit) and age group (b = 0.25, SE = 0.12, z = 2.02), which was superceded by a barely significant interaction between sentence type (Id-Lit), age group, and canonical form (b = -0.22, SE = 0.12, z = -1.78). To

determine the source of these complex interactions, we computed treatment-coded model follow-up models with Lit-Lit as baseline, in which items were split by age group.

Turning first to the model for the younger adults, there was a significant interaction between sentence type Id-Id and idiom familiarity (b = -0.56, SE = 0.19, z = -3.0). In order to determine whether high- or low-familiar idioms were driving this interaction, we computed follow-up models in which items were median-split by familiarity. The model for high-familiar idioms showed a significant main effect of sentence type Id-Id (b = -0.59, SE = 0.28, z = -2.12), thus suggesting that younger adults had fewer regressive eye-movements out of figuratively biasing context regions when the preceding idiom was high-familiar. Vice versa, the model for low-familiar idioms showed a significant main effect of sentence type Id-Id in the opposite direction (b = 0.63, SE = 0.26, z = 2.46), thus indicating that younger adults were more likely to regress out of disambiguating regions following low-familiar idioms. Figure 5 picks up these effects and shows that younger adults had a greater proportion of regressions for low-familiar Id-Id items (in comparison to the control condition Lit-Lit), whereas there were fewer regressions for high-familiar Id-id items (in comparison to the baseline Lit-Lit).

Turning to the model for the older adults, there was a barely significant interaction between sentence type Id-Lit and canonical form (b = -0.55, SE = 0.32, z = -1.70). To investigate the source of this interaction, we computed follow-ups models, which split items by canonical form. There were no significant effects in the model for non-canonical items, but the model for canonical items showed a trending significant main effect of sentence type Id-Lit (b = 0.39, SE = 0.22, z = 1.73). This suggests that older adults were more likely to regress out of literally biasing context regions after reading idioms presented in their canonical form (e.g. *Mary kicked the*

bucket when it was blocked from her view by the chair). This effect is picked up in Figure 6, in which older adults (and not younger adults) show a much higher proportion of regressions for canonical Id-Lit sentences (versus the control condition Lit-Lit), which suggests that the semantic conflict between a canonical idioms and the literal bias of the context region was particularly problematic for the older adults.

In sum, there were two patterns of interest here. First, younger adults (and not older adults) showed facilitation for high-familiar idioms and slowing for low-familiar idioms, suggesting that particularly younger adults were sensitive to modulations in idiom familiarity. Second, older adults were more likely to regress back to earlier portions of the sentence when reading disambiguating regions which biased a canonical idioms towards its literal meaning (e.g. *Mary kicked the bucket when it was blocked from her view by the chair*). This suggests that the older adults had particular difficulties interpreting the semantic conflict in these items.

[insert Figure 5 + 6 here]

2.5 Discussion

The principal question that motivated this study was whether young and older adults exhibit different patterns of performance during the online resolution of idiomatic expressions. Older adults are interesting within the context of idiomatic language since they normally present with spared or even improved lexical-semantic knowledge about language and figurative forms ('crystallized' functions), but with impairments in 'fluid' aspects of cognition and in simultaneously activating multiple meanings in working memory (Stine-Morrow *et al.*, 1996; Hedden & Gabrieli, 2004). In line with this, previous studies on idiom resolution had indicated

that, even though knowledge about idiomatic forms is preserved or even increases in aging (Hung & Nippold, 2014; Hyun, Conner & Obler, 2014), the dual semantic nature of idioms may sometimes pose difficulties for older adults (Westbury & Titone, 2011). However, these past studies had primarily focussed on off-line measures of idiom processing. In this study, we used an online paradigm to address the processing level at which age-related differences in idiom comprehension arise – during early stages, when the idiomatic form is accessed and retrieved from memory, or during later semantic stages when figurative and literal meanings are integrated into the sentence context. We conducted an eye-tracking study with three experimental manipulations. First, we presented idioms in a canonical and non-canonical form (i.e. with an adjective, *kicked the black bucket*). Second, we presented idioms with a disambiguating region that biased the interpretation of the idiom either towards its figurative (*Mary kicked the (black) bucket after becoming seriously ill on the weekend*) or literal interpretation (*Mary kicked the (black) bucket when it was blocked from her view by the chair*). Third, we varied idiom familiarity, which reflects how frequently an idiom is encountered in a linguistic community.

The results indicate that older and younger adults exhibit both common and dissociating patterns of performance in idiom reading, at both early and late stages of reading. With respect to common patterns, both younger and older adults had comprehension difficulties when reading idiomatic sentences which contained an idiom in its non-canonical form (e.g. *Mary kicked the black bucket after becoming seriously ill on the weekend*; TRT idiom). Thus, in both age groups, the modifier (e.g. kicked the *black* bucket) had a strong disruptive effect by breaking up the canonical configuration of the idiom, potentially because it induced a semantic conflict between

the literal nature of the idiom and its known figurative meaning. Both age groups seemed to be sensitive to this conflict and experienced comprehension difficulties when reading these items.

In contrast to this, dissociating patterns between the age groups emerged both at the form access level, and at the level of semantic integration. At the form level, older adults read idioms presented in their canonical form (*kicked the bucket*) more quickly than their literal control expressions (*tipped the bucket*), whereas younger adults read both items equally fast. This suggests that older adults can access stored configurations of idioms more quickly in memory, presumably because these items are better represented in the minds of older versus younger people. Thus, this aspect of our data supports the notion of spared 'crystallized' language abilities in aging, and a preserved or even improved knowledge about idiomatic forms in older individuals (Hung & Nippold, 2014; Westbury & Titone, 2011).

At the level of semantic integration, younger adults could understand and integrate a figuratively disambiguating region more quickly when the preceding idiom was high-familiar (e.g., *Bailey* spread the word *about the party to all her friends by sending an email*; proportion of regressions). In contrast, comprehension of disambiguating regions was more difficult for younger adults when the preceding idiom was low-familiar (e.g., *Rosemary* took the veil *because she had always wanted to devote her life to God*). The fact that older adults did not show the same pattern could indicate an age-related insensitivity to the familiarity of idiomatic meanings, an aspect which we will revisit in a later part of this discussion.

Also at the meaning integration level, older adults were more likely to experience comprehension difficulties when reading canonical idioms biased towards their literal interpretations (e.g. *Mary kicked the bucket when it was blocked from her view by the chair*). For these items, older adults showed a greater proportion of regressive eye movements out of the literally-biasing disambiguating region, which indicates that older adults processed the sentence exclusively figuratively until they began reading the disambiguating region. When this disambiguating region did not match with the assumed figurative interpretation of the idiom, they were forced to regress back to other parts of the sentence, presumably to facilitate re-interpretation. Such reading difficulties did not emerge for the younger adults, who regressed equally often out of literally-biasing disambiguating regions (e.g. *Mary kicked the bucket* when it was blocked from her view by the chair) and the equivalent region in literal control sentences (e.g. *Mary tipped the bucket* to sprinkle fertilizer into her new flower garden). Thus, whereas younger adults seemed to access and maintain both literal and figurative meanings of idioms, older adults seemed to have difficulties activating multiple semantic representations, and instead accessed only the figurative meanings of idioms. This aspect of our data is in line with the notion that impairments in 'fluid' aspects of cognition put older adults at a disadvantage when understanding language, especially so when the experimental task highlights the dual semantic nature or conflict inherent in an expression in a certain way (such as in non-canonical form presentation of an idiom, or when the tasks requires switching between literal and figurative meanings of an idiom; Westbury & Titone, 2011).

In sum, the data of the present investigation corroborate previous studies and show that representations of figurative meanings are intact in aging, but that older adults have difficulty at

simultaneously activating literal and figurative meanings of idioms. In the following lines, we will discuss two potential reasons which may account for these age-related difficulties in activating multiple meanings.

2.5.1 Age-related impairments in executive functions

One potential reason why older adults activate only figurative meanings during idiom processing is age-related deficits in the ability to maintain semantically-conflicting representations in working memory. A potential benefit of activating only figurative meanings, rather than entertaining figurative *and* literal meanings, is that the amount of activated information in working memory is reduced and interference from semantically conflicting representations is minimized. This reduces workload during language processing, which could benefit elderly people in particular because healthy aging normally leads to a decline in executive mechanisms of cognition. The older adults' performance on the AXCPT executive control task (see Appendix 1) indeed showed that they had detriments in executive functions when compared to the younger adults, so it would seem likely for them to employ such strategies during language processing. In addition, such an interpretation of our data would be line with models that describe cognitive aging as a reduction in resources available for cognitive operations (see Burke & Shafto, 2008), and more particularly, as an impairment in working memory capacity that reduces the efficiency of language processing (Carpenter, Miyake, & Just, 1994). Thus, under this view, older adults may activate only figurative meanings of idioms as part of a (possibly general) strategy which reduces workload during language processing (see Miyake, Just & Carpenter, 1994, or Miyake, Carpenter, & Just, 1994; for such a thesis in lexical ambiguity and syntactic ambiguity resolution).

Even though this interpretation may seem feasible, age-related impairments in executive functions are unlikely to account for our findings for two reasons. First, another recent investigation in our lab showed that, in younger adults (i.e., the same as those reported here for the canonical condition only), individual differences in executive functions do not modulate idiom processing (Columbus *et al.*, 2015). In that study, we compared the reading times of younger adults for idiomatic sentences to their reading times for metaphoric sentences, while also taking into account individual differences in executive control. The results showed that metaphors were read more quickly by high-executive control individuals and more slowly by individuals with low levels of executive control. In contrast, idioms were read equally quickly by both groups, regardless of individual levels of executive control. This pattern of data suggests that metaphor (and not idiom) processing is modulated by executive functions, presumably because metaphors involve a more transparent mapping between literal and figurative meanings, so they are more likely to be compositionally assembled during comprehension. In contrast, idioms (for which a transparent mapping is normally absent), need to be retrieved from memory directly and are thus not normally influenced by executive control. Thus, this previous study suggests that, at least in younger adults, idiom processing is not substantially modulated by executive control. Second, in the present study, we explicitly tested whether executive control impairments in the older adults could account for the differences in idiom reading, by running additional models on the group of older adults that included individual cost scores in executive control as a fixed effect (the BX-BY comparison from the AXCPT task, which reflects the processing cost between a condition high in cognitive load and a condition low in cognitive load;

see Appendix 1). Mirroring the results for the younger adults (Columbus *et al.*, 2015), we found no relation between executive functions and idiom reading times in the older adults.

Overall then, it is unlikely that impairments in executive functions of cognition can account for the age-related difficulties at activating multiple semantic representations. This, however, does not indicate that age differences in idiom processing are completely unrelated to executive control. The sample of older participants in our study likely over-represented the most high-performing and mobile older adults (Grady, 2012; Hedden & Gabrieli, 2004), since all of the older participants were able to come to our lab and undergo two hours of experimental testing. Similarly, we know from the language background questionnaires we administered, that all of the older adults had some command of French as a second language. An active lifestyle has been shown to improve cognitive functioning in old age (Colcombe & Kramer, 2003), and cognitive advantages associated with speaking a second language have also been proposed (e.g. Bialystok, Craik, Klein & Viswanathan, 2004). Thus, it is possible that older adults from a less high-functioning background (monolingual adults, or individuals recruited and tested at senior centres or care-giver facilities) would have yielded different results with respect to the role of executive functions.

2.5.2 Age-related entrenchment of figurative meanings

An alternative explanation as to why older adults activate only figurative meanings during idiom comprehension arises when one considers that figurative meanings are more entrenched in this group of participants. Under this view, older adults did not activate literal meanings of idioms, because their life-long exposure to idiomatic forms could have changed the manner in which

they process figurative language in discourse. For example, it is known that vocabulary continues to grow in old age and that this can also augment language processing (Schaie, 1994; Stanovich, West, & Harrison, 1995; Stine-Morrow, Loveless, & Soederberg, 1996; Ackerman & Rolfhus, 1999; Stine-Morrow *et al.*, 2006).

Thus, the fact that older adults have lived longer and have had greater exposure to idiomatic forms, could have rendered figurative meanings more accessible for this population, for example, through lowered activation thresholds for figurative forms (see Simpson, 1984; Balota, 1983; and Neill, 1989; for such an account in lexical ambiguity) or through distinct and contextually elaborate mental representation which provides a bolster against interfering literal constituents (Perfetti & Hart, 2002). This representational change could result in the observed 'figurative-only' mode with which older adults seem to process idioms in the current study (i.e. literal meanings are not accessed by these participants unless required by context). A similar conclusion was drawn in another study (Hyun, Conner, & Obler, 2014), which showed that idiom production accuracy in older adults (but not younger adults) was correlated with the degree of syntactic frozenness of the idiom. Thus, the more syntactically invariant an idiom was, the more likely older adults were to correctly produce it. According to the authors, this pattern may have resulted from the greater experience in producing fixed expressions that older adults have had – an advantage that younger adults do not have because they have fewer years of language experience. This interpretation also matches with a recent investigation in our lab (Häuser, Baum, & Titone, 2015), in which we found that younger individuals who had less experience with a second language (L2 acquisition late in life) processed idioms in their L1 more quickly than individuals who had learnt a second language early in life. The sum of these findings

suggests that a greater entrenchment or a more exclusive lifetime expertise with a language can facilitate the comprehension of figurative meanings in that language.

Importantly, this view also provides an explanation as to why the reading times of older adults were not influenced by idiom familiarity, whereas in the younger adults, idiom familiarity did clearly have an impact. At first sight, one might wish to attribute this finding to a potentially age-related insensitivity to frequency distributions of language. For example, in line with our findings, as aforementioned, a recent study showed that idiom familiarity was a significant predictor of correct idiom production in younger adults, but not older adults (Hyun, Conner, & Obler, 2014). In addition, past research has shown (albeit inconsistently) that word frequency differently impacts younger and older adults, with younger adults being more likely to benefit from word frequency during reading and during text recall (Stine-Morrow, Loveless, & Soederberg, 1996; but see Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006, for contrasting findings). Applied to the present investigation, such an account would suggest that the younger adults were able to use increased idiom familiarity to more quickly understand the idiomatic meaning, whereas the older adults were unable to do so (although the reasons for this would remain somewhat obscure). Even though we cannot fully exclude such an interpretation for our data, a far more likely explanation emerges when one considers that the idiom familiarity ratings for this study were obtained from the norms of a prior investigation on undergraduate students (Titone & Connine, 1994b). Thus, these ratings might not map well onto our group of older adults. In fact, for the older adults in this study, it is possible that *all* idiomatic stimuli in the task (high and low familiar) were processed uniformly as 'high-familiar', given the greater knowledge of idiomatic forms in this population overall. This would explain why older adults

did not require specifically a high-familiar idiom in a non-canonical form or in a literally biasing sentence context, in order to experience a maximal semantic conflict between literal and figurative meanings. Any (low- or high-familiar) idiom sufficed for this, due to the repeated activation of idiomatic forms that older adults have encountered over their lifespan.

In this context, it is relevant to address one potentially problematic aspect of our study, namely the high amount of figurative language in our reading task. Past research has shown that older and younger adults process language differently with respect to how much discourse or task context these two groups use to establish 'mental structures' or 'situational models' during text processing (Van Dijk & Kintsch, 1983; Madden 1988; Wingfield, Aberdeen, & Stine, 1991; Stine & Wingfield, 1994; Stine-Morrow, Loveless, & Soederberg, 1996). For example, older adults benefit more from semantically constraining context than younger adults when processing degraded auditory or visual targets (Madden, 1988; Stine & Wingfield, 1994), suggesting that older adults rely more heavily on contextual information during reading to compensate for an otherwise impoverished signal. In addition, older people have been shown to read early sections of text passages much more slowly than later sections of the same passages (Stine-Morrow, Loveless & Soederberg, 1996), potentially because they allocate more time early on to establish a situational context or mental structure for the text, which then facilitates their reading during later text sections. Presumably for the same reason, older adults also benefit more from text headers than younger adults (for example, '*Driving A Car'*, or '*The First Space Voyage'*), because they can more effectively use such information to establish a discourse model against which subsequent text passages are evaluated and interpreted (Miller & Stine-Morrow, 1998). With respect to the present investigation, such findings could indicate that the older adults used

their awareness of the high amount of figurative language in the task to establish a 'figurative' situational model. The presence of this figurative mental model could have made the older adults commit entirely to figurative meanings, i.e. to put them into some kind of figurative processing 'mode' (Bobrow & Bell, 1973) in which literal meanings were not accessed unless required.

We noted some general awareness among our participants as to the nature of the investigation; for example, upon finishing the eye tracking task, many participants (both younger and older adults) asked whether the study was about figurative language. That this awareness also had an impact on sentence reading can be seen in Figure 4, for example, where both participant groups showed reading difficulties for (canonical) Lit-Lit phrases obtained from high-familiar idioms. It is possible that participants recognized the idioms after which these literal phrases were modelled, and this awareness led to slowed reading. Due to the established age-differences in context use, the older adults could have made use of this figurative awareness to a greater extent than the younger adults, by activating only figurative meanings of idioms. However, if this were true, one should have expected effects of familiarization in the course of the experiment for the older adults, indicated by fewer and shorter fixations on idioms during later parts of the experiment. We tested for such a possibility in our models, by including trial number as a fixed effect. This changed neither the size nor the direction of any of the results reported above. Overall then, despite participants' general awareness as to the nature of the experiment, it is unlikely that the older adults used this knowledge to their own advantage by establishing a figurative situational model which facilitated idiom reading.

2.5.3 Summary and conclusion

The present study investigated age-related changes in the online processing of idiomatic sentences by employing an eye tracking paradigm with younger and older adults. Three key findings emerged. First, older adults showed greater facilitation than younger adults when idioms were presented in their canonical forms (*kicked the bucket* vs *kicked the black bucket*), suggesting that older adults can access figurative configurations in memory more quickly. Second, older adults showed disruptions when reading canonical-form idioms biased towards their literal interpretations (*Mary kicked the bucket when it was blocked from her view by the chair*), thus indicating that older adults activate primarily figurative (and not literal) meanings during idiom processing. Both effects are most likely caused by the life-long exposure to idiomatic forms in older adults, which has probably furnished mental representations of idioms with a semantically more elaborate structure and contextual richness than is the case in younger adults. Third, individual differences in executive functions did not predict idiom reading in older adults, which corroborates similar results obtained for idiom processing in younger adults (Columbus *et al.*, 2015). Further studies are required to investigate to what extent other individual differences among older language users (e.g. knowledge of a second language) may modulate figurative and literal meaning activation in idiom processing.

Table 1

Demographic information and language background for younger and older adults. Standard deviations in parentheses.

	Younger Adults	Older Adults
N	37	21
Age	22.46 (2.64)	65.65 (7.86)
Formal education (yrs)	15.98 (2.49)	15.50 (3.10)
L2 Age of Acquisition	9.26 (6.65)	> 18
L2 formal instruction (yrs)	> 8	< 4

Table 2

Experimental items for the idiom *kick the bucket* in the six experimental conditions: Canonical Id-Id, Id-Lit, Lit-Lit, and non-canonical Id-Id, Id-Lit, Lit-Lit.

Id-Id	Mary kicked the (black) bucket after becoming seriously ill on the weekend.
Id-Lit	Mary kicked the (black) bucket when it was blocked from her view by the chair.
Lit-Lit	Mary tipped the (black) bucket to sprinkle fertilizer into her new flower garden.

Table 3

Means (and standard deviations) for all dependent variables in literal and idiomatic sentences, over canonical form and age group.

		Canonical Items		**Non-Canonical Items**	
Dependent Variable		Younger	Older	Younger	Older
Gaze Duration Noun	Idiom	248 (40)	281 (62)	277 (51)	310 (88)
	Literal	264 (61)	297 (95)	266 (53)	325 (77)
Go Past Time Noun	Idiom	301 (77)	378 (80)	329 (81)	461 (139)
	Literal	304 (99)	459 (156)	332 (125)	421 (110)
Total Reading Time Idiom	Id-Id	833 (305)	990 (460)	1304 (505)	1574 (694)
	Id-Lit	842 (343)	1058 (471)	1178 (408)	1500 (625)
	Lit-Lit	843 (323)	973 (393)	1218 (517)	1496 (654)
Proportion of Regressions (Disambiguating Region)	Id-Id	.36 (.22)	.42 (.24)	.45 (.27)	.53 (.25)
	Id-Lit	.31 (.24)	.49 (.21)	.40 (.27)	.52 (.26)
	Lit-Lit	.35 (.23)	.40 (.24)	.39 (.28)	.54 (.26)

Table 4

Effect sizes (b), standard errors (SE), and *t*-values for the GD noun and go-past noun logistic LMER models.

	GD Noun			**Go Past Noun**		
Fixed Effects	*b*	*SE*	*t*	*b*	*SE*	*z*
Sentence Type	-3.60	2.31	-1.56	-1.93	4.73	-0.41
Canonical Form	9.99	2.31	4.32	14.69	4.72	3.11
Age Group	19.91	6.76	2.95	59.64	10.07	5.92
Idiom Familiarity (scaled)	-5.17	3.88	-1.33	-4.84	8.40	-0.58
Sentence Type * Canonical Form	2.42	2.32	1.04	9.34	4.73	1.97
Sentence Type * Age Group	-2.59	2.31	-1.12	-5.50	4.73	-1.16
Canonical Form * Age Group	2.36	2.31	1.02	0.51	4.73	0.11
Sentence Type * Familiarity	3.09	2.31	1.34	-2.77	4.72	-0.59
Canonical Form * Familiarity	3.23	2.30	1.40	7.35	4.70	1.56
Age Group * Familiarity	-2.57	2.30	-1.12	-4.47	6.10	-0.73
Sentence Type * Canonical Form * Age Group	-1.70	2.31	-0.74	12.41	4.73	2.62
Sentence Type * Canonical Form * Familiarity	2.40	2.30	1.04	-5.49	4.71	-1.17
Sentence Type * Age Group * Familiarity	4.25	2.31	1.84	2.44	4.72	0.52
Canonical Form * Age Group * Familiarity	-1.08	2.30	-0.47	5.58	4.70	1.19
Sentence Type * Canonical Form * Age Group * Familiarity	3.76	2.30	1.63	0.58	4.71	0.12
Control Predictors	*b*	*SE*	*t*	*b*	*SE*	*t*
(Intercept)	278.89	7.26	38.40	363.99	11.20	32.50
Decomposability (scaled)	-1.10	3.69	-0.30	-1.70	6.82	-0.25
Region length (scaled)	5.38	3.42	1.57	7.99	6.33	1.26

Random Effects	Variance	Variance
Subject	2154.42	3409.38
Item	378.87	2089.86
Item | Age Group	*n/a*	800.78
Residual	9590.07	40051.44

Table 5

Effect sizes (b), standard errors (SE), and *t*/*z*-values for the TRT idiom and proportion of regressions logistic LMER models.

	TRT Idiom			**Proportion of Regressions**		
Fixed Effects	*b*	*SE*	*t*	*b*	*SE*	*z*
Sentence Type Id-Lit	11.06	40.78	0.27	-0.02	0.16	-0.11
Sentence Type Id-Id	39.81	39.53	1.01	0.05	0.16	0.31
Canonical Form	126.57	27.44	4.61	0.21	0.04	4.88
Age Group	125.88	52.64	2.39	0.35	0.15	2.41
Idiom Familiarity	-4.01	21.81	-0.18	-0.06	0.09	-0.72
Sentence Type Id-Lit * Canonical Form	-50.39	25.82	-1.95	-0.13	0.12	-1.04
Sentence Type Id-Id * Canonical Form	70.08	31.56	2.22	0.11	0.12	0.88
Sentence Type Id-Lit * Age Group	43.04	24.55	1.75	0.25	0.12	2.02
Sentence Type Id-Id * Age Group	-29.60	24.62	-1.20	-0.20	0.12	-1.62
Canonical Form * Age Group	28.91	12.93	2.24	0.02	0.04	0.47
Sentence Type Id-Lit * Familiarity	33.84	41.00	0.83	0.20	0.16	1.29
Sentence Type Id-Id * Familiarity	-67.47	39.80	-1.70	-0.40	0.16	-2.56
Canonical Form * Familiarity	8.56	13.16	0.65	0.04	0.04	1.03
Age Group * Familiarity	2.88	8.70	0.33	0.08	0.04	1.95
Sentence Type Id-Lit * Canonical Form * Age Group	-1.97	24.55	-0.08	-0.22	0.12	-1.78
Sentence Type Id-Id * Canonical Form * Age Group	-11.55	24.62	-0.47	0.01	0.12	0.11
Sentence Type Id-Lit * Canonical Form * Familiarity	25.05	25.94	0.97	-0.02	0.12	-0.17
Sentence Type Id-Id * Canonical Form * Familiarity	10.59	31.78	0.33	0.15	0.12	1.22
Sentence Type Id-Lit * Age Group * Familiarity	1.69	24.62	0.07	0.02	0.12	0.19
Sentence Type Id-Id * Age Group * Familiarity	21.31	24.80	0.86	0.15	0.12	1.24
Canonical Form * Age Group * Familiarity	-2.76	8.72	-0.32	0.00	0.04	-0.10
Sentence Type Id-Lit * Canonical Form * Age Group * Familiarity	10.71	24.62	0.44	-0.14	0.12	-1.16

	TRT Idiom			Proportion of Regressions		
Sentence Type Id-Lit * Canonical Form * Age Group * Familiarity	7.44	24.80	0.30	0.09	0.12	0.75
Control Predictors	*b*	*SE*	*t*	*b*	*SE*	*t*
(Intercept)	1125.23	55.64	20.22	-0.36	0.16	-2.24
Decomposability (scaled)	-6.30	18.72	-0.34	0.05	0.09	0.58
Region length (scaled)	114.23	27.96	4.09	0.01	0.08	0.14
Random Effects		Variance			Variance	
Subject		144448.2			1.03	
Subject | Canonical Form		4913.7			*n/a*	
Item		17499.8			0.50	
Item | Sentence Type Id-Lit		57031.2			0.52	
Item | Sentence Type Id-Id		51425.4			0.50	
Item | Canonical Form		5158.0			*n/a*	
Item | Sentence Type Id-Lit| Canonical Form		3221.5			*n/a*	
Item | Sentence Type Id-Id| Canonical Form		20817.4			*n/a*	
Residual		206623.0			*n/a*	

Figure 1

Gaze durations on phrase-final nouns, depending on age group and canonical form. Error bars indicate standard errors of the mean (subject-weighted).

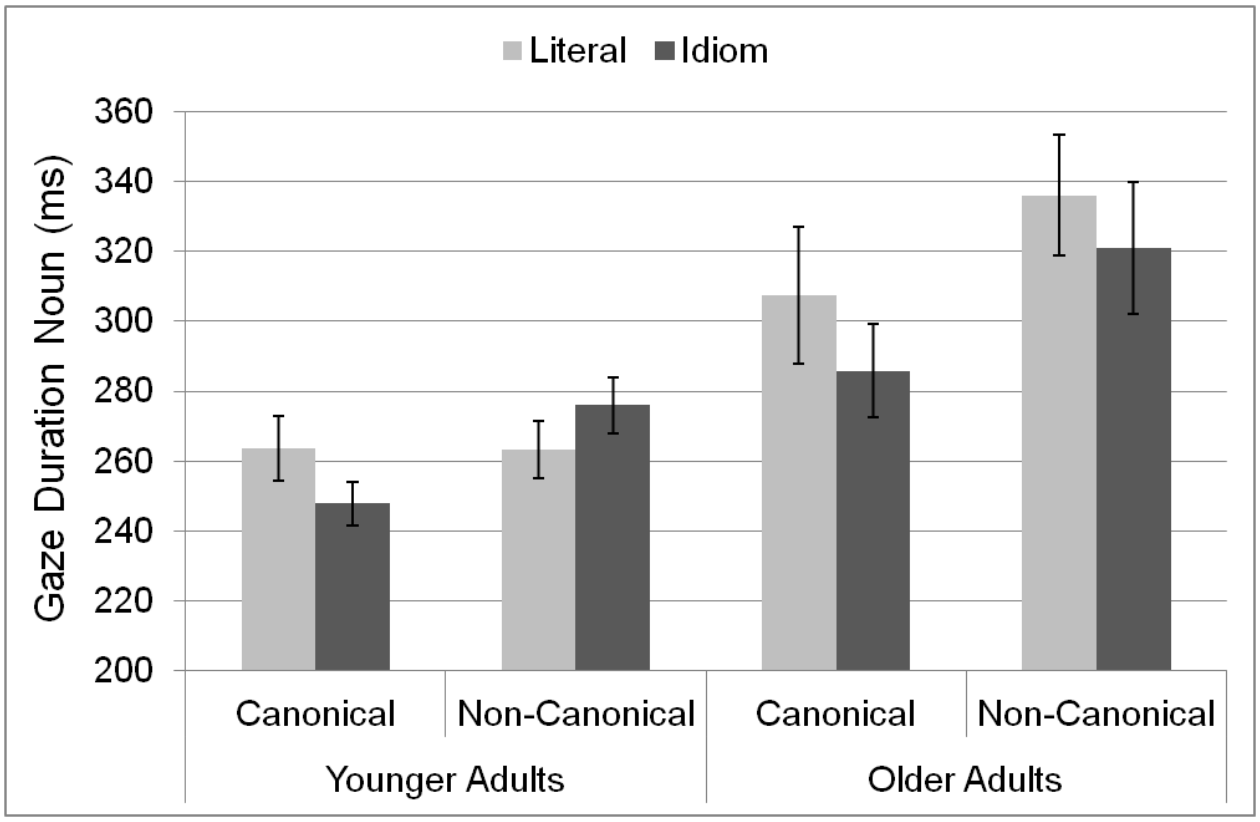


Figure 2

Go Past Times (± SEM, subject-weighted) for phrase-final nouns in idioms and matched literal phrases, depending on age group and canonical form.

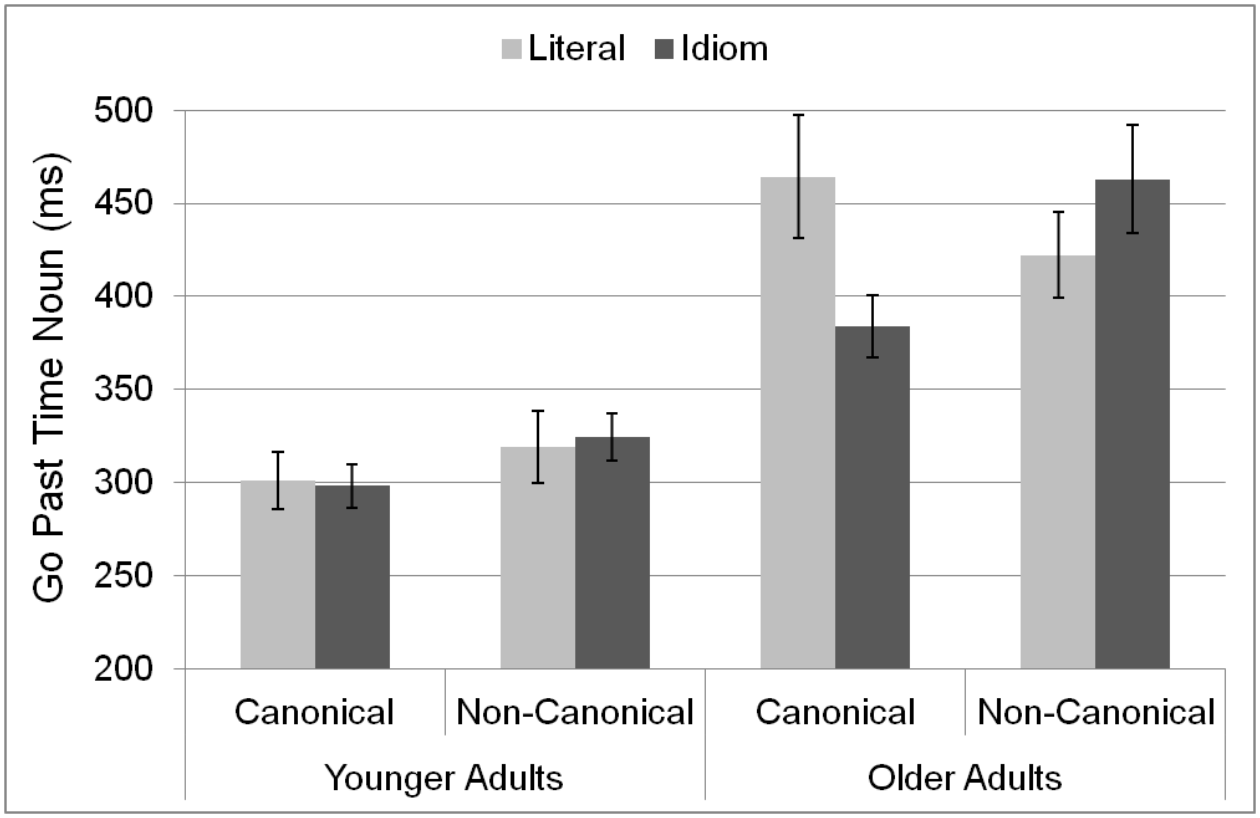
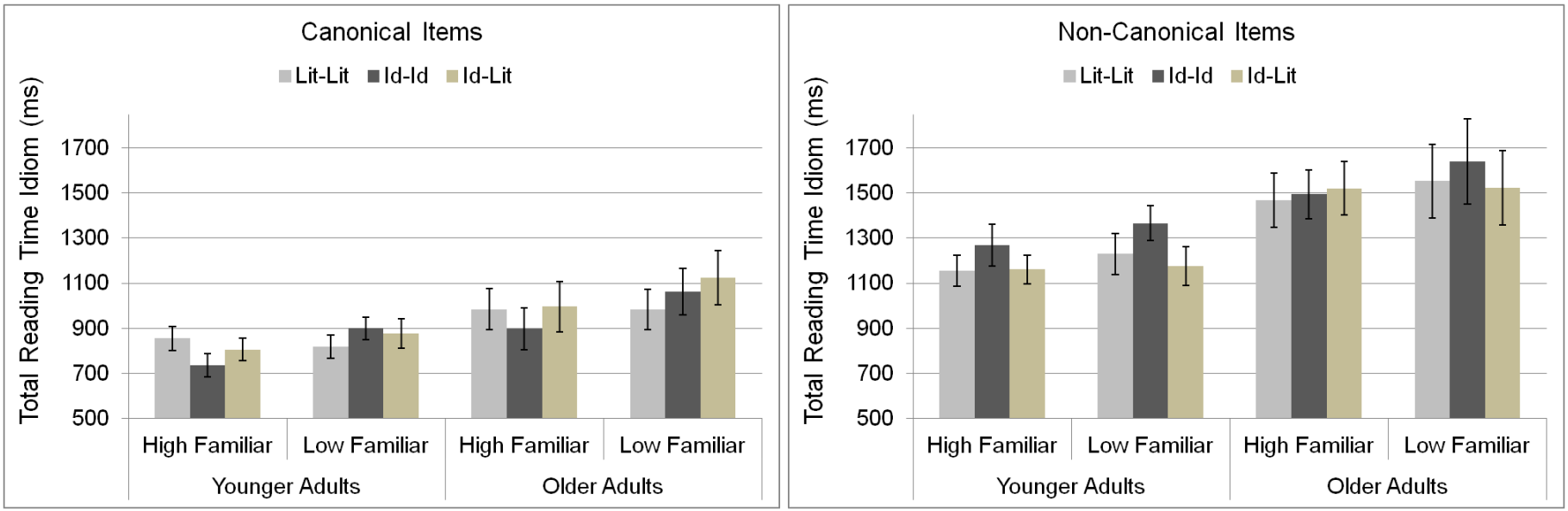


Figure 3

Total reading times (± SEM, subject-weighted) on canonical items (left panel) and non-canonical items (right panel) in younger and older adults, depending on sentence type and idiom familiarity.



Lit-Lit: Mary tipped the bucket to sprinkle fertilizer into her new flower garden.

Id-Id: Mary kicked the bucket after becoming seriously ill on the weekend.

Id-Lit: Mary kicked the bucket when it was blocked from her view by the chair.

Figure 4

Total reading times (±SEM, subject-weighted) on the idiom in younger and older adults, depending on sentence type and canonical form.

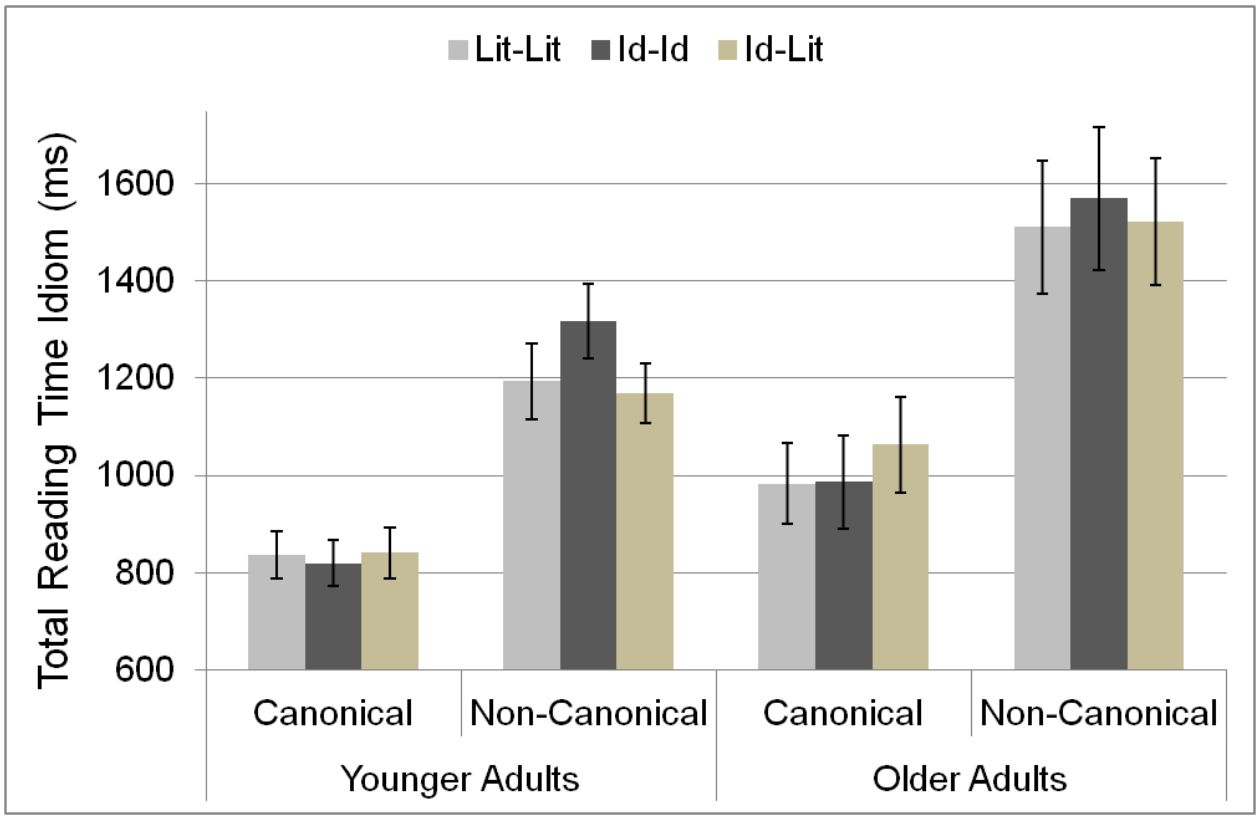


Figure 5

Proportion of regressions (±SEM, subject-weighted) out of the disambiguating region in younger and older adults, depending on sentence type and idiom familiarity.

Lit-Lit: Mary tipped the bucket to sprinkle fertilizer into her new flower garden.

Id-Id: Mary kicked the bucket after becoming seriously ill on the weekend.

Id-Lit: Mary kicked the bucket when it was blocked from her view by the chair.

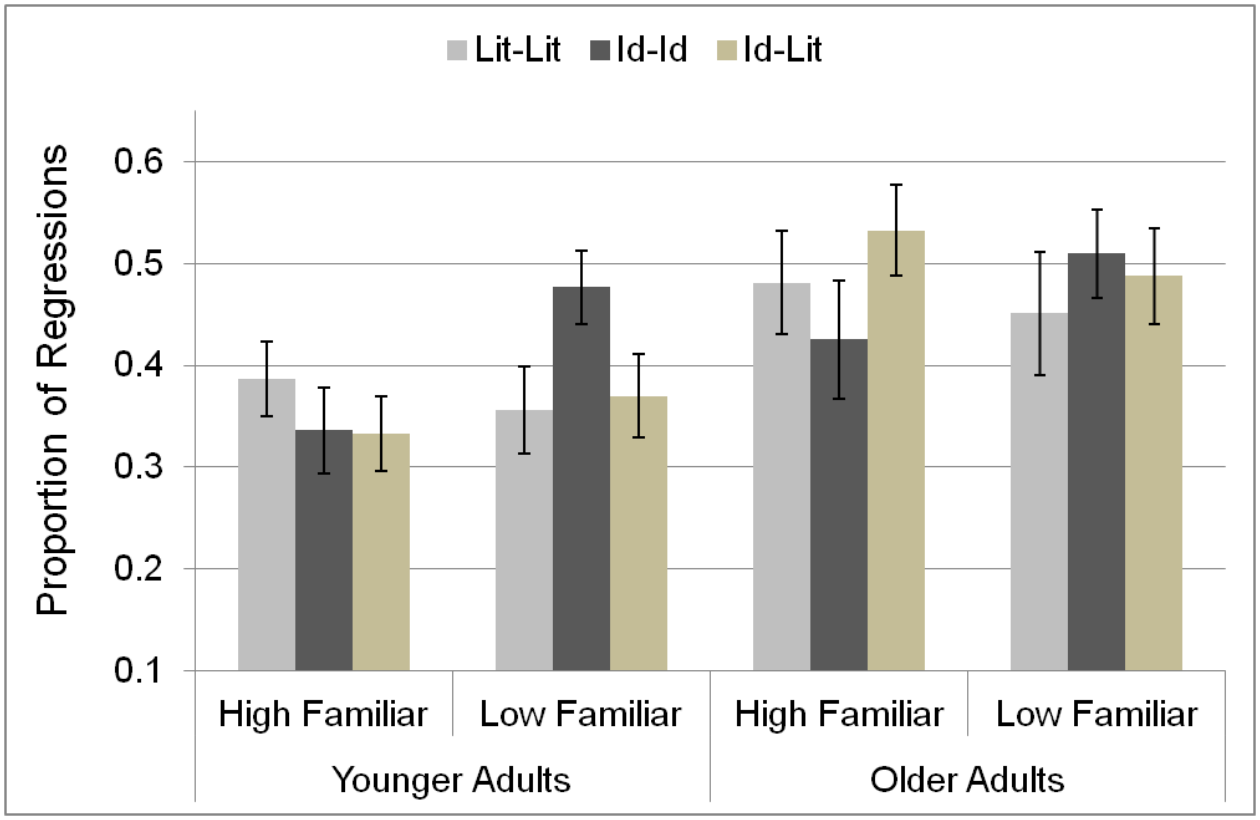
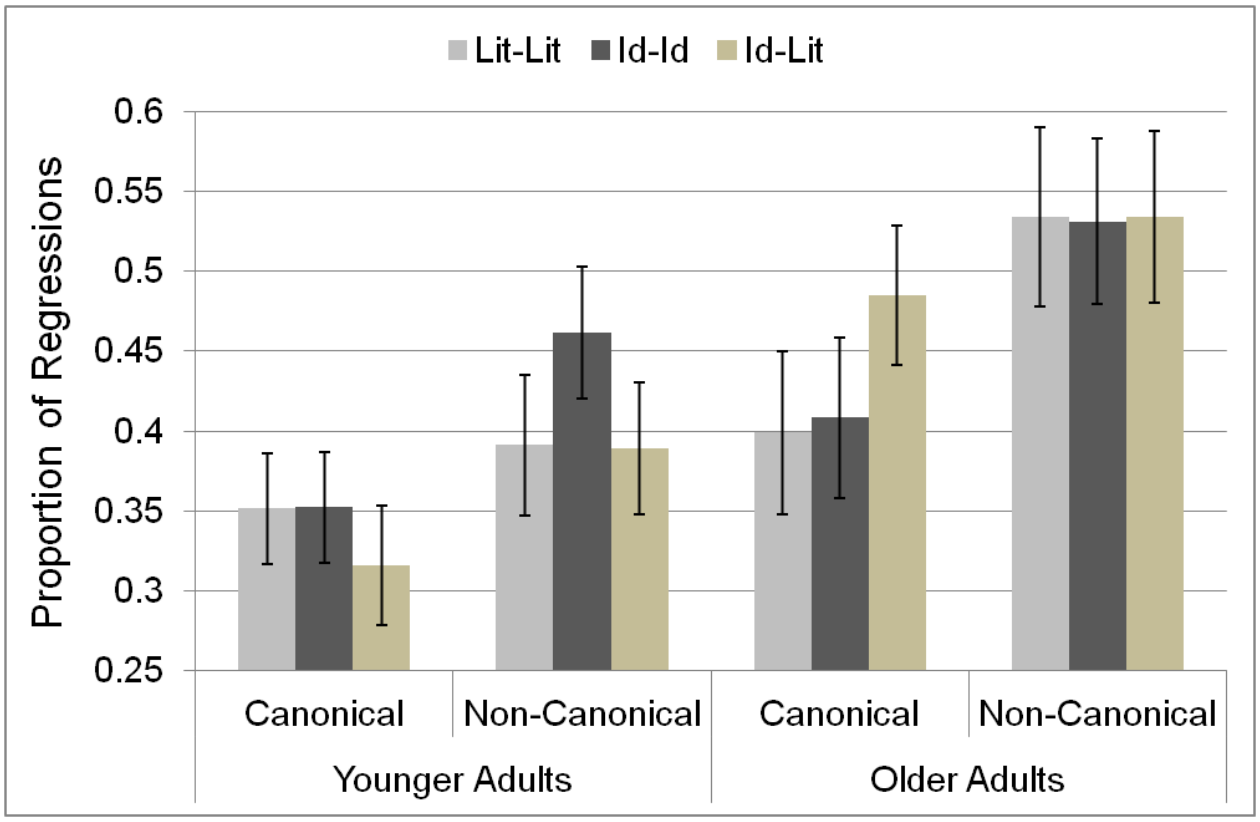


Figure 6

Proportion of regressions (± SEM, subject-weighted) out of the disambiguating region in younger and older adults, depending on sentence type and canonical form.



2.6 Appendix: AXCPT task

To assess group differences in executive control, we administered the AXCPT executive function task; a version of the continuous performance task (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956). Participants were seated in front of a screen and saw a continuous stream of letters, presented in cue-probe pairs, one letter at a time. They were instructed to press a target button when the letter *X* was preceded by an *A*, and another non-target button for all other stimuli (including *A*, as well as any *X* that is not preceded by an *A*). *AX* trials accounted for 75% of all trials, so that the appearance of an *X* cued a strong automatized response to press the target button because it is the correct response in the majority of trials. In trials where *X* was *not* preceded by an *A (BX* trials, with *B* indicating any letter that is not *A*), participants need to inhibit a strong pre-potent response in order not to press the target button. For each subject, we computed an average BX-BY cost score for reaction times on correct trials, by subtracting the average reaction time on *BY* trials (trials without *A* or *X*: executive control load minimal) from the average reaction time on *BX* trials (trials in which *X* is not preceded by *A*: executive control load maximal). The results (see Table 6) show a higher cost score for the older than for the younger adults, indicating lower levels of executive control for this participant group.

Table 6

Mean RTs (in ms) and cost score for the incongruent (high load in executive functions) and congruent condition (low executive function load) in the AXCPT task. Standard deviations in parentheses.

	Younger Adults	Older Adults
Incongruent	400 (127)	580 (136)
Congruent	355 (89)	484 (118)
Cost	**45 (39)**	**96 (17)**

Preface to Study 2

Study 1 investigated the relationship between idiom processing and cognitive control from a neuropsychological perspective, by investigating whether age-related impairments in cognitive control would disadvantage older adults (relative to younger adults) during idiom processing or whether an increased life-long experience using idioms would provide older adults with a more enriched and potentially more accessible memory for idiomatic forms.

The results of Study 1 showed no evidence that aging negatively impacts idiom processing, at least for idioms read in their canonical form. Specifically, older adults showed a different pattern of meaning activation relative to the younger adults, which indicated that they committed preferentially to figurative meanings of idioms. The older adults also had measurable impairments in cognitive control (as indicated by the AXCPT, a common executive function task), however, these control-related deficits did not predict their idiom performance. Thus, the 'figurative commitment' in older adults does not appear to be a consequence of age-related impairments in simultaneously activating or selecting among multiple meanings during language processing. Rather, it seems that the greater lifetime experience with figurative forms which older adults have had, has entrenched figurative meanings to an extent that older adults do not typically access literal meanings during idiom processing anymore.

Nonetheless, as noted earlier, the participants in the study may represent a limited sample of older individuals without significant cognitive control impairments. Moreover, as reviewed in the introduction, previous investigations have pointed to a role of prefrontal cortical regions, known to support cognitive control, in idiom processing (Rapp *et al.*, 2012; Bohrn *et al.*, 2012;

Zempleni *et al.*, 2007; Lauro *et al.*, 2008). Thus, another way of examining the relationship between cognitive control and idiom processing is from a neuro-anatomical perspective, by specifically investigating the role of the prefrontal cortex (PFC) during idiom comprehension. As described earlier, the PFC has been described as a neural convergence zone that mediates increased control-related demands, by solving cognitive conflicts that occur during a task (Bottvinick *et al.*, 2001). The ventral part of the PFC appears to be crucial to mediate semantic conflicts (Thompson-Schill *et al.*, 1997; Wagner *et al.*, 2001; Badre & Wagner, 2002; Badre & Wagner, 2007; Whitney *et al.*, 2011; Jefferies, 2013), so this neural area should play a highly prominent role for idioms. Therefore, before dismissing the influence of cognitive control in idiom comprehension, we undertook a second study to further explore the relationship between cognitive control and idiom processing. Specifically, investigating how the ventral part of the PFC relates to idiom comprehension was the goal of Study 2.

Chapter 3: Study 2

The Role of the Ventrolateral Prefrontal Cortex in Idiom Comprehension: An rTMS Study

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3.1 Abstract

Previous research is equivocal with respect to the neural substrates of idiom processing. Particularly elusive is the role of the ventro-lateral prefrontal cortex (VLPFC), a region implicated in semantic control generally. Although fMRI studies have shown that the VLPFC is active during idiom processing, rTMS studies have failed to corroborate a clear role of this prefrontal region.

We investigated this issue using a semantic meaningfulness judgment task that compared idiom comprehension following rTMS stimulation to the VLPFC relative to a control site (vertex). We also investigated whether differences among comprehenders in general cognitive capacity modulated the role of the VLPFC.

The results suggest that the processing of low-familiar idioms is particularly disrupted by rTMS to the VLPFC, potentially because these items involve a maximal semantic conflict between a salient literal and less-known figurative meaning. Of note, this pattern only emerged in individuals with lower cognitive control capacity, indicating that inherently weaker processing circumstances are especially compromised through rTMS. Taken together, the results corroborate prior fMRI studies and illustrate potential boundary conditions linking the VLPFC to idiom processing.

3.2 Introduction

One aspect of language processing that is particularly challenging is the resolution of semantically ambiguous information across many linguistic levels, for example, words, phrases and sentences. In this paper, we are particularly interested in how this challenge plays out during the comprehension of idiomatic phrases, such as *kick the bucket*. According to classic definitions, idioms are relatively more complex than "normal" literal language because their figurative meanings (*to die*) are often distinct from the compositional meaning created by the combination of their constituents (*to strike a pail with one's foot*; Nunberg, Sag, & Wasow, 1994). Indeed, according to the traditional view, idioms are nothing more than long words that have arbitrarily stipulated meanings (Bobrow & Bell, 1973; Swinney & Cutler, 1979; reviewed in Libben & Titone, 2008; Titone *et al.*, 2015).

However, the traditional view of idioms is likely an oversimplification (Gibbs & Nayak, 1989; Gibbs, Nayak, & Cutting, 198; Gibbs & O'Brien, 1990), given that many idioms have internal semantic structure, and can be modified both semantically and syntactically (e.g. *convicted minimalist spills bean*, or *by and not so large*; Gibbs & Nayak, 1989; MacGlone, Glucksberg, & Cacciari, 1994). For example, in idioms such as *pop the question*, the individual component words can be semantically analyzed to contribute in a metaphorical way towards the figurative meaning (e.g. *pop* refers to a sudden act and *the question* refers to a marriage proposal; Gibbs, Nayak, & Cutting, 1989). Thus, to accommodate both the dual holistic and compositional nature of idioms, hybrid or constraint-based views have attributed both word-like and phrase-like qualities to idioms (Titone & Connine, 1999; Libben & Titone, 2008).

According to such models, idiom processing involves the simultaneous co-activation of figurative and literal meanings, and the speed with which these representations become available is determined by several constraints (Titone & Libben, 2014; Titone & Connine, 1999). One such constraint of great relevance to this study is idiom familiarity. Idiom familiarity is typically defined as the degree to which an idiomatic sequence is known in a linguistic community irrespective of its meaning, though, measures of familiarity are likely to be related to its figurative usage. Accordingly, high-familiar idioms are over-learned and deeply entrenched within a given linguistic community, and can be recognized as holistic units very quickly, in a way that might potentially trump activation of literal word meanings (e.g. Cronk, Lima, & Schweigert, 1993; Cacciari & Tabossi, 1988). In contrast, low-familiar idioms are less known within a language community, thus, the literal meanings of the constituent words are more likely to remain active in memory during comprehension.

3.2.1 Cognitive control and idiom processing

A hybrid or constraint-based characterization of idiom processing implies that people frequently activate potentially conflicting semantic representations when they encounter idioms. Consequently, under these circumstances, idiom processing could be computationally more demanding compared to other non-idiomatic aspects of language, and may require the additional recruitment of general cognitive control capacity to resolve any semantic ambiguity that arises (Galinsky & Glucksberg, 2000; Glucksberg, Newsome, & Goldvarg, 2001; Papagno & Vallar, 2001; Titone, Holzmann, & Levy, 2002; Papagno & Caporali, 2007).

In neuropsychology, cognitive control has been defined as the top-down regulated and resource-limited capacity of the cognitive system to configure its own performance through appropriate adjustments in behavior (Wood & Grafman, 2003; Bottvinick, Braver, Barch, Carter, & Cohen, 2001). For example, increased demands on cognitive control are associated with detecting cognitive conflicts (Bottvinick *et al.*, 2001), inhibiting irrelevant information (Ridderinkhof, Ullsperger, Crone, & Nieuwenhhuis, 2004), enhancing activation of relevant information (Aron, Robbins, & Poldrack, 2004), as well as monitoring and sending feedback about performed actions and behavior (Wood & Grafman, 2008). Thus, applied to idiom processing, cognitive control can be used to describe the effortful actions of the cognitive system when faced with evaluating literal and figurative meanings of an idiom against the discourse or sentence context, enhancing activation for figurative meanings, and suppressing activation for literal meanings.

One way to investigate the relationship between idiom processing and cognitive control is by use of clinical patient groups who normally present with impairments in cognitive control. For example, such control-related deficits have been described as a hallmark of Alzheimer's disease or schizophrenia, so it stands to reason that individuals with these disorders would also show idiom-related deficits. Indeed, several studies have shown that this may be the case. For example, Alzheimer's and schizophrenia patients were found to be more likely to associate an idiom with its literal than with its figurative meaning in a sentence-to-picture or sentence-to-word matching task (see Papagno *et al.*, 2003; Rassiga *et al.*, 2009; Schettino *et al.*, 2010). This could suggest that clinical deficits in cognitive control render such individuals unable to sufficiently inhibit the activation of literal phrase meanings when processing an idiom. However, these studies are somewhat diminished by the fact that they did not consistently include a literal control condition,

which makes it difficult to assess if the reported effects were truly idiom-specific (Rassiga *et al.*, 2009). In other studies where a literal control condition was actually included, the performance of the clinical patient groups was also impaired in this control task (Schettino *et al.*, 2010). Thus, investigations on clinical patients groups have obtained only preliminary evidence for the hypothesis that idiom comprehension requires greater levels of cognitive control than the comprehension of literal language.

Importantly, the findings from studies that have addressed neurotypical individuals without clinical impairments do not support a relationship between idiom processing and cognitive control. For example, a recent study from our group showed that healthy older adults (individuals often reported to experience control-related deficits) are not impaired in understanding the figurative meanings of idioms (Häuser, Sheikh, Columbus *et al.*, submitted), and indeed, may benefit from longer life-long exposure to language in preferentially processing idioms' figurative meanings. Similarly, another study from our group showed that individual differences in cognitive control do not modulate idiom processing in healthy younger adults (Columbus *et al.*, 2015). These findings indicate that any relationship between cognitive control and idiom processing may be specific to clinically-compromised populations, or may only appear under particularly demanding comprehension circumstances. In sum, the neuropsychological evidence for a role of executive functions in idiom processing is rather mixed.

Another way to study the relationship between idiom processing and cognitive control is by using neuroimaging to investigate activation of the prefrontal cortex (PFC), the neural region generally associated with cognitive control (Norman & Shallice, 1986; Miller & Cohen, 2001;

Duncan, 2001; Goldman-Rakic, 1995; Baddeley & Della Sala, 1996; for reviews, see Wood & Grafman, 2008; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Miller, 2000; Braver, Paxton, Locke *et al.*, 2009; Miller, 2000; MacDonald *et al.*, 2000). Many studies describe the PFC as a neural convergence zone for cognitive control, as it upholds, directs and manipulates representations in working memory to bias willful cognitive actions in a context-relevant way (Thompson-Schill, Bedny, & Goldberg, 2005; see Miller, 2000; Duncan, 2001). As such, the PFC is active during response conflicts, selective attention, or context updating (for reviews see Tanji & Hoshi, 2008; Koechlin, Ody, & Kouneiher, 2003; West, 2003; Braver, 2012). This is consistent with a common metaphor that describes the function of this cortical area as a switch operator, which determines which railway track a train will use at any given point in time (Miller, 2000; Wood & Grafman, 2003). Given that idiom processing involves the sustained co-activation of conflicting semantic representations in working memory (Titone *et al.*, 2015), it stands to reason that this cortical region may be involved in the processing of idioms as well, a topic to which we now turn in detail.

3.2.2 Idiom processing and the prefrontal cortex

Several neuroimaging studies have implicated the prefrontal cortex during idiom processing. For example, in a recent fMRI study (Hillert & Buracas, 2009), participants were asked to silently read for comprehension idioms (e.g. *She held the torch*) and non-idiomatic literal control phrases (e.g. *He met her in the mall*). According to the results, the contrast idiomatic vs literal phrases activated cortical areas in the dorsolateral prefrontal cortex (DLPFC, BA 9 and 46, see Petrides & Pandya, 1999; Yeung, 2013; Tanji & Hoshi, 2008) and also in the ventro-lateral prefrontal cortex (VLPFC; BA 44 and 45 in that study), a prefrontal site slightly inferior to the DLPFC.

Thus, this suggests that the semantic conflict between literal and figurative meanings inherent in idioms requires controlled processing that is mediated by the PFC.

Indeed, and of relevance to the present study, several fMRI studies have shown that the ventro-lateral PFC region may be crucial during idiom processing (see Zempleni, Haverkort, Renken, & Stowe, 2007; Mashal, Faust, Hendler & Jung-Beeman, 2008; Lauro, Tettamanti, Cappa & Papagno, 2008). For example, Lauro and colleagues (2008) used a sentence-to-picture matching task and asked participants to identify the picture that correctly depicted a previously seen idiomatic (e.g. *He has a green thumb*) or literal control phrase (e.g. *The boy is eating an apple*). The distractor showed the opposite meaning of the idiomatic or literal phrase (e.g. for the idiom *tirare la cinghia*, to be very poor, the distractor showed a rich man dining at a restaurant). According to the results, correct performance on idiom trials activated bilaterally the VLPFC (BA 44 and 45), whereas literal trials activated bilateral parietal areas (BA 40). Thus, this study not only suggests that idioms and literal phrases may be processed in non-overlapping cortical areas, but also that idioms primarily activate the VLPFC, potentially because of the semantic conflict inherent in these expressions. This view is also supported by two recent review papers that investigated the common neural activation sites in several idiom studies (Bohrn, Altmann, & Jacobs, 2012; Rapp, Mutschler, & Erb, 2012). Both meta-analyses found that idiomatic vs literal phrases activate a left-lateralized network, with strongest activation in the left middle temporal gyrus (BA 21) and the left VLPFC (Bohrn, Altmann, & Jacobs, 2012; Rapp, Mutschler, & Erb, 2012). Thus, even though the meta-analyses and the Lauro *et al.* (2008) study are not in complete agreement as to the hemispheric lateralization of idiomatic language, they both converge on the view that idioms activate the ventro-lateral PFC.

Such work linking the VLPFC to idiom processing is interesting, in light of other studies that link the VLPFC to the cognitive control of semantic memory generally (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999; Gabrieli, Poldrack, & Desmond, 1998; Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Wagner, Pare-Blagoev, Clark & Poldrack, 2001; Whitney, Kirk, O'Sullivan, *et al.*, 2011; Whitney *et al.*, 2012; for reviews see Badre & Wagner, 2002, 2007; Thompson-Schill, Bedny & Goldberg, 2005). For example, the VLPFC has been associated with tasks that require the controlled retrieval of semantic representations that are not activated automatically through strong cue-target associations. Such situations include when a target word needs to be retrieved that is only weakly semantically related to a cue word (Badre & Wagner, 2007; Thompson-Schill *et al.*, 1997). Similarly, the VLPFC is also active in tasks that require post-retrieval selection, for example, when the subordinate meaning of a lexically ambiguous word competes for activation with automatic activation of its dominant meaning (Whitney, Jefferies, & Kircher, 2011). In both cases, the VLPFC is thought to guide the retrieval of task-relevant semantic information from storage sites in the temporal cortex, either by enhancing activation of task-relevant knowledge or inhibiting task-irrelevant representations (Thompson-Schill *et al.*, 1997; Badre *et al.*, 2005). In light of these observations, the VLPFC may also support the mechanisms that guide the retrieval of figurative and literal meanings of idioms from temporal storage sites, maintain such representations in working memory, and engage in meaning selection by up-regulating activation of figurative meanings while simultaneously down-regulating activation of literal meanings.

However, one potential concern with past studies linking the VLPFC to idiom processing is that they are inherently correlational insofar as they exclusively rely upon the pattern of brain

activation measurable when people encounter idioms. Of note, such patterns of activation may be a cause or consequence of comprehension, thus limiting the ability to develop a decisive mechanistic account. A more direct means of experimentally testing the role of the VLPFC in idiom processing is through the use of stimulation paradigms, such as repetitive transcranial magnetic stimulation or rTMS (Pascual-Leone, 1991; Wassermann, 1998). In rTMS, a coil with a rapidly changing current is held above the skull and produces a strong, focal magnetic field, thus creating an 'artificial lesion' in underlying brain tissue (Wassermann, 1998). The magnetic field passes painlessly through the skull and transiently introduces noise into neural performance, which in turn can be measured in behavioral tasks. In contrast to research with fMRI, rTMS leads to changes in cognitive performance which can be causally related to a dysfunction of the stimulated neural region (Devlin & Watkins, 2007).

Of relevance here, several rTMS studies have shown that stimulation to the prefrontal cortex impairs idiom comprehension. However, whereas past fMRI studies implicated both the dorso- and the ventro-lateral PFC, rTMS evidence to date has only supported a role for the dorso-lateral PFC (Fogliata, Rizzo, Reati, Miniussi, Oliveri, & Papagno, 2007; Rizzo, Sandrini & Papagno, 2007; Sela, Ivry, & Lavidor, 2012). For example, two studies found that idiom comprehension was impaired when rTMS was applied to the left (Fogliata *et al.*, 2007) and right DLPFC (Rizzo *et al.*, 2007). In both studies, participants showed a greater bias to choose the literal distractor of an idiom in a sentence-to-picture matching paradigm, suggesting a dysfunctional inhibitory mechanism (guided by the DLPFC) which normally suppresses literal word meanings during idiom comprehension. A similar conclusion was drawn from another idiom study that used transcranial direct current stimulation (tDCS) to simultaneously increase and decrease neural

excitability. Sela, Ivry, and Lavidor (2012) showed that when facilitating the left DLPFC and inhibiting the right DLPFC, participants were more accurate relating idioms (*bite the bullet*) with figurative target words (*accept*) than with literal target words (*flavor*). This pattern did not emerge when tDCS stimulation was reversed (i.e. facilitation of the right and inhibition of the left DLPFC), which suggests that particularly the left DLPFC may be crucial to process figurative meanings of idioms. Thus, previous rTMS and tDCS studies are consistent in demonstrating that a stimulation-induced enhancement of prefrontal control mechanisms leads to more successful inhibition of the literal meaning of the idiom.

However, in contrast with prior work on the dorso-lateral PFC, the only rTMS study examining the VLPFC failed to find any idiom-specific effects (Oliveri *et al.*, 2004). In that investigation, a sentence-to-picture matching task was used to compare the comprehension of idiomatic and matched literal phrases following stimulation to the VLPFC and a baseline without rTMS. Stimulation to the VLPFC led to a general decrease in accuracy for both idiomatic and literal sentences. Thus, it is difficult to interpret these findings specifically with respect to the role of the VLPFC in idiom processing as opposed to in processing more generally. For example, cortical stimulation to the VLPFC could have caused global performance deficits in a multiple-choice task with several response options. As well, differences among idioms could have led to differential patterns of VLPFC recruitment, however, this was not investigated.

In sum, existing research on the role of the VLPFC in idiom comprehension is divided: fMRI studies support the view that this cortical area is associated with idiom processing, whereas rTMS studies do not clearly support its involvement.

3.2.3 The present study

The goal of the present study was to investigate whether idiom processing relies on neural substrates in the VLPFC through the use of an rTMS paradigm. The experiment addressed three primary questions.

First, we examined whether the VLPFC is specifically implicated in idiom comprehension. Several previous rTMS and fMRI studies (Fogliata *et al.*, 2007; Rizzo *et al.*, 2007; Oliveri *et al.*, 2004; Lauro *et al.*, 2008) used sentence-to-picture matching tasks to assess idiom comprehension. Such tasks may be problematic due to the overt presence of the literal response option and the visuo-spatial difficulties associated with depicting abstract figurative meanings (Papagno & Caporali, 2007; Cacciari & Papagno, 2012). The present study used a semantic meaningfulness judgment task in an effort to avoid these concerns.

Second, we investigated whether VLPFC demands are modulated by idiom familiarity, which is known to influence idiom processing (Schweigert, 1986; Titone & Libben, 2014; Titone & Connine, 1999). We expected that low-familiar idioms, in particular, would be prone to rTMS-induced disruptions, because these phrases involve a maximal semantic conflict between a less-known figurative meaning and a more salient literal meaning. In contrast, rTMS should only minimally disrupt high-familiar idioms, because they have a highly salient figurative meaning that likely represents a dominant interpretation.

Third, we investigated whether inherent differences among participants in cognitive control capacity (as reflected by the Simon task; Simon & Berbaum, 1990; Zorzi & Umiltá, 1995) influence idiom processing. Previous studies supporting the role of executive functions in idiom

processing had primarily addressed clinical patient groups, such as individuals with Alzheimer's disease or schizophrenia (Papagno *et al.*, 2003; Schettino *et al.*, 2010; Rassiga *et al.*, 2009; Titone, Levy & Holzman, 2002). These individuals usually exhibit a range of co-morbid cognitive impairments (for example, memory loss, depression, anxiety or paranoia), making it difficult to attribute any deficits that emerge to reductions in cognitive control.

3.3 Method

3.3.1 Participants

Sixteen native English speakers from the Montreal community between the ages of 18 and 28 years participated in the experiment (9 female; mean age = 22.63 years). They were screened for any relative or absolute contraindications for rTMS (Wassermann, 1998) upon their arrival at the laboratory. Informed written consent was obtained from all participants. Participants had no history of speech/language or hearing impairments, as well as no personal or family history of seizures, epilepsy, and psychiatric or neurological disorders. All participants were strongly right-handed, with a mean right-handedness score of 86 (range: 67 – 100) on the Edinburgh Handedness Inventory (EHI; Oldfield, 1971).[2] The study was approved by the local research ethics committee. A recent brain scan (T1-weighted, structural scans) and participants' consent to its release were mandatory in order to take part in the study.

[2] On the EHI a person is right-handed if they have a right-handedness score of more than 40.

3.3.2 Design and Procedure

The design of the study consisted of four predictors, *stimulation site* (VLPFC vs. vertex, a control site which has no function in language), *sentence type* (idiomatic vs. literal), *idiom familiarity* (a scaled variable; obtained from Libben & Titone, 2008), and *cognitive control* (another scaled variable; assessed through the Simon task; Blumenfeld & Marian, 2011, see below). Our dependent variables were the speed and accuracy that participants completed the experimental task (meaningfulness judgments on idiomatic and matched literal sentences). Participants came to our lab twice, corresponding to two sessions of rTMS stimulation (to be detailed below), and performed the experimental task immediately after rTMS stimulation had ceased. The testing sessions were separated by at least one week. The Simon task was only administered once to each subject, during the first testing session prior to the rTMS-paradigm.

3.3.3 Experimental Task

We employed a meaningfulness judgment task for auditorily presented sentences that contained idioms or matched literal phrases. Participants heard idiomatic and literal stimuli over closed earphones (type Sennheiser HD 280 pro) and indicated, by pressing one of two buttons on a response pad, whether the item they heard was meaningful or not. Task instructions (presented on a screen) read: "In this experiment you will listen to spoken English sentences. Your task is to indicate, by pressing a button, if each sentence is meaningful or not. Before the presentation of a sentence, a fixation cross will appear on the screen in front of you. Once the sentence has ended, the question < Meaningful – NO / YES ? > will appear. Make your judgment by pressing the RIGHT ARROW button for YES (MEANINGFUL), and the LEFT ARROW button for NO

(NOT MEANINGFUL). Try to respond as quickly and accurately as possible. Please press Enter to indicate that you are ready to begin the experiment."

All trials began with a fixation cross, displayed in the middle of the screen for 1000 ms, followed by the auditory presentation of the stimulus sentence in front of a white screen. Time-locked to the offset of the auditory item, the response prompt "Meaningful - NO / YES ?" was displayed on the screen (the order of NO / YES corresponded to the fact that the left arrow button indicated *no, non-meaningful* and the right arrow button indicated *yes, meaningful*). The response prompt stayed on the screen until the participant made a response, with the maximal response time set to 4000 ms. If a participant failed to make a response during this time, the computer automatically initiated the next trial.

Task instructions and response prompts appeared on a 17" (43 cm) by 24" (61 cm) Dell 32 bit computer monitor with a 60 Hz refresh rate and a screen resolution of 1680 x 1050 pixels; participants were seated at a distance of about 60 cm between their eyes and the screen.

3.3.4 Stimuli

To create the experimental stimuli, we selected 54 verb-determiner-noun idioms (*kick the bucket*, *break the ice*) from the Libben and Titone (2008) idiom corpus. The idioms ranged between high and low-familiar on a scale from 1-7 (1 meaning that the idiom is never encountered, and 7 meaning that the idiom is frequently encountered; mean familiarity = 3.37; SD = 0.82). Literal control phrases were created for each idiom by replacing the main verb of the idiom with a verb of approximately the same length that fit the noun semantically; for example, *spill the beans* (idiomatic) was matched with *cook the beans* (literal control).

Subsequently, each idiomatic and literal phrase was embedded in a sentence. Each sentence consisted of two clauses: the first clause always started with an agent (a name; e.g. *Dolan* ...), followed by the idiom / matched literal phrase in the past tense (e.g. ... *spilled / cooked the beans* ...), followed by a supporting context (e.g. ... *when he mentioned the surprise party to his friend / before he started adding vegetables to the soup pot*). Non-meaningful versions of each sentence were created by replacing one word in the sentence context with a semantically anomalous word of the same grammatical class, which made a meaningful interpretation of the sentence impossible (e.g. *Dolan spilled the beans when he returned the surprise party to his friend / Dolan cooked the beans before he started adding duration to the soup pot*).

Overall, there were a total of 216 experimental items counterbalanced over four experimental conditions: idiomatic meaningful, idiomatic non-meaningful, literal meaningful, literal non-meaningful. For an example of the experimental items for the idiom *bear one's* cross, see Table 1.

[Insert Table 1 here]

To create auditory versions of each experimental sentence, we recorded the 216 items in a sound-attenuated booth using an AKG C 420 III PP condenser microphone and a Marantz professional digital recorder. A native female speaker of North American English was asked to read out every sentence with a natural-sounding intonation, with the microphone positioned about 5 cm from her mouth To keep prosodic differences between the recordings minimal, the speaker was instructed to use the same prosodic pattern for each sentence. Upon recording, the 216 auditory items were transferred to a computer and edited using Praat (version 5.3.44; Boersma & Weenink, 2013) to ensure that sentence onset and offset were standardized. In order to make sure

there were no significant differences in the average length of the experimental items, we compared the average sentence length of all auditory stimuli across the four conditions. A one-way ANOVA revealed no significant differences [$F(3, 212) = 0.39$, $p = 0.76$].

To determine the order in which the 216 auditory items were presented during the task, all items were randomized using a Latin square randomization (Edwards, 1951) with *sentence type* and *meaningfulness* as blocking factors, and were distributed evenly across two experimental lists (corresponding to VLPFC and vertex stimulation sites). Each list contained two items of any given idiom quadruplet. The same number of idiomatic and literal, as well as meaningful and non-meaningful, sentences occurred on each list. Finally, as a precautionary measure, we re-created both experimental lists with reversed item order, resulting in a total of four experimental lists. The order of stimulation site (VLPFC or vertex first) and list administration was counterbalanced across participants.

3.3.5 TMS Protocol

We used a standard virtual lesion rTMS protocol, compatible with established TMS safety guidelines (Wassermann, 1998). Repetitive trains of TMS at 1 Hz (600 in total) were delivered to the neural target area for about 10 minutes, which was expected to induce a transient decrease in corticospinal excitability and concurrent disruption of cognitive tasks associated with the stimulated brain region, lasting for about 10-15 minutes (Pascual-Leone, 1999; Rossi, Hallet, Rossini & Pascual-Leone, 2009). In preparation for each testing session, before participants came to the lab, their brain scans were imported into Brain Sight 2 software (Rogue Research, Montreal, Canada) to determine the two sites of cortical stimulation (VLPFC/experimental, and

vertex/ control), as well as the left hand motor area. Upon a participant's arrival at the laboratory, we performed MRI-to-head co-registration, using three anatomical landmarks on the head (tip of the nose, bridge of the nose, as well as superior lateral edge of the tragus of the left and right ear) whose position was assessed using an infrared tracking system (Polaris, Northern Digital, Waterloo, Canada). Upon successful co-registration, infrared tracking was used to monitor the position of the coil with respect to the participant's brain. For all stimulations, we used a 70mm figure-of-eight coil, driven by a high-speed magnetic stimulator that produced short duration biphasic pulses (Magstim Rapid 1400, Wales, U.K). The stimulator was controlled through Presentation software (Neurobehavioral Research), installed on a Dell Precision M 60 laptop, driven by an Intel® Core ™ 2 CPU T 7600 processor.

To ascertain the maximal strength that could be used for the experimental stimulation, we determined the resting motor threshold (RMT) for each participant. Two EMG surface electrodes were placed over the first dorsal interosseus muscle of a participant's right hand. Single TMS pulses were then delivered to their left motor cortex hand area, with the TMS coil aligned tangentially to the skull and the coil's handle pointing posteriorly. Stimulation intensity and coil position were adjusted until the EMG electrodes recorded a signal greater than 50μV for a minimum of five trials out of ten.

After RMT was determined, the experimental stimulation began. The intensity level was set to 110% of the RMT value. As noted, rTMS stimulation was applied to the target site (VLPFC or vertex) in trains of 600 pulses at 1 Hz. Five participants reported discomfort during rTMS

stimulation to the VLPFC, caused by strong muscle twitches in the jaw. For these subjects, the intensity level was reduced accordingly.

Based on past work from our group, we estimated that rTMS stimulation at the frequency level we used should yield a 10 – 15 min inhibitory effect (see Boroojerdi, Prager, Muellbacher & Cohen, 2000; Gerschlager, Siebner & Rothwell, 2001; Shum, Shiller, Baum & Gracco, 2011), which we determined to be sufficient to complete the idiom task. To confirm that participants indeed had enough time to finish the idiom task before any rTMS effects trailed off, we conducted a post-hoc analysis of the logfiles created for each experimental run. The mean completion time of the experimental task was 10.25 minutes across subjects and sessions (maximum = 11.25 min.; minimum = 9.32 min.; *SD* = 0.44 min).

Based on prior work (Pascual-Leone, 1999; Walsh & Cowey, 2000), we expected that TMS should primarily slow a participant's reaction times, rather than lead to a decline in accuracy. However, past rTMS and tDCS studies on idiom comprehension consistently reported effects on accuracy (Rizzo *et al.*, 2007; Fogliata *et al.*, 2007; Sela *et al.*, 2012), suggesting that rTMS not only slows cognitive performance, but also makes it more prone to errors. Thus, our expectation was somewhat open as to whether rTMS effects should arise for both reaction times and accuracy.

3.3.6 Localization of Stimulation Sites

For stimulation to the left VLPFC, we used the Montreal Neurological Institute (MNI) coordinates (x = -54, y = 21, z = 12), corresponding to the left mid ventral prefrontal cortex or pars triangularis, BA 45. We chose this site specifically because it has been reported to be maximally sensitive to distant semantic relationships in studies on semantic retrieval in the

context of competing alternatives (Badre & Wagner, 2007; Whitney, Kirk, O'Sullivan *et al.*, 2011; Whitney *et al.*, 2012).

For vertex–rTMS we used the MNI coordinates $x = 0$, $y = -30$, $z = 80$ (Ko *et al.*, 2008) to guide rough coil placement, and then adjusted the stimulation sites individually for each participant, determining vertex as the highest point of the skull located medially between both hemispheres (Leitão, Thielscher, Werner, *et al.*, 2012). The mean MNI coordinates for Vertex-rTMS across subjects were [$x = 0.16$, $y = -23.37$, $z = 80.19$].

The cortical site for the left hand motor area was also determined individually for each participant, as the knob-like structure in the pre-central gyrus of the left hemisphere that is shaped like an omega in the axial plane and looks like a hook in the sagittal plane (see Yousry, Schmid, Alkadhi, *et al.*, 1997). The mean MNI coordinates across subjects for the hand motor area were [$x = -35.08$, $y = -17.94$, $z = 51.23$].

3.3.7 Simon Cognitive Control Task

The Simon task is a computer-based interference task (for a review, see Lu & Proctor, 1995), and is based on the observation that participants execute a motor response more quickly and more accurately if the response is spatially congruent to the stimulus location, even when stimulus location is not relevant to the task. The original Simon effect was obtained with auditory stimuli (Simon & Small, 1969), but it has also been replicated with color as the relevant dimension (see Simon & Berbaum, 1990; Zorzi & Umiltá, 1995), as in the current adaptation.

Participants saw red and blue squares appear on the left or right side of a screen. Each trial started with a fixation cross, displayed for 500 ms at the centre of the computer monitor, followed by the appearance of the color square. When the square was blue, subjects were instructed to press a button on the left side of the keypad with their left hand. When the square was red, they were instructed to press a button on the right side with their right hand. The maximal response time was set to 1700ms. In congruent trials, the screen location of the square and the response side determined by the square color were identical, whereas in incongruent trials, they were not. Cognitive control load is proportionally greater in incongruent trials, since participants need to overcome the prepotent response to press the button on whichever side they saw the stimulus appear (Hommel, 1993).

We computed the mean correct response time for each participant in congruent and incongruent trials, excluding outliers that were more than 2.5 standard deviations from the mean (92 out of 3841 cells in total; 2.4 % of all data points). Based on these values, we computed a cognitive control cost score for each participant, by subtracting the average reaction time on congruent trials (easy trials, i.e. low demand on cognitive control) from the average reaction time on incongruent trials (hard trials, i.e. high demand on cognitive control). Thus, a higher Simon cost score reflects a greater difference between hard and easy trials, and thus lower levels of cognitive control.

3.4 Results

We constructed linear mixed-effects (LME) models with random slopes where appropriate, as implemented in the lme4 library (Bates, 2005; Bates & Sarkar, 2005) within R (R Development Core Team, 2009). The dependent variables were accuracy (a binomial factor), and correct

reaction times (RT; in milliseconds), time-locked to the offset of the auditory sentence. The independent variables were *sentence type* (a categorical variable with two levels: Idiomatic versus Literal), *site of stimulation* (a categorical variable with two levels: stimulation to VLPFC and vertex), *idiom familiarity* (a scaled continuous variable based on prior ratings from Libben & Titone, 2008), and the *Simon cost score* (a scaled continuous variable; see above). All models also included meaningfulness as a control factor. Because idiom familiarity and decomposability are correlated (Libben & Titone, 2008; Titone & Connine, 1994b), all models included idiom decomposability as a control factor. We used deviation coding for all omnibus models and model splits. Table 2 displays the average RT and accuracy rates, as well as the standard errors for these measures, by sentence type and site of stimulation.

[insert Table 2 here]

3.4.1 Accuracy

Stepwise log-likelihood model comparisons (Baayen, Davidson, & Bates, 2008; Barr *et al.*, 2013) showed that by-subject and by-item random slopes were warranted for idiom familiarity and sentence type, respectively.

We found a significant interaction between sentence type and idiom familiarity (b = -0.36, SE = 0.17, t = 2.12). To investigate what was driving this interaction, we performed a model split in which we split items by sentence type. Thus, we computed two models, one for literal sentences, and another one for idiomatic sentences. The results showed a main effect of familiarity only in the model for idiomatic items (b = 0.40, SE = 0.14, t = 2.95) and not in the model for literal items (b = 0.03, SE = 0.16, t = 0.18). Thus, this suggests that response accuracy decreased for low-familiar idioms, but increased for high-familiar idioms.

However, only the accuracy decrease for low-familiar idioms was statistically significant, as a second model split of the omnibus model showed, where we median-split items by familiarity. There was a significant main effect of sentence type only for low-familiar items (b = -0.98, SE = 0.21, t = -4.63), but not high-familiar items (b = -0.4, SE = 0.28, t = -1.5; see Figure 1).

Overall, this indicates that responses to low-familiar idioms were less accurate than responses to literal phrases, regardless of stimulation site or individual differences in cognitive control. No other main effects or interactions reached significance in the omnibus accuracy model (main effect of site of stimulation: b = -0.18, SE = 0.12, t = -1.46; main effect of cognitive control: b = -0.06, SE = 0.14, t = 0.43; main effect of the control variable meaningfulness: b = 0.01, SE = 0.12, t = 0.09). Table 3 shows the statistical results for all model comparisons in the accuracy and reaction time LMER models.

[Insert Figure 1 here]

[Insert Table 3 here]

3.4.2 Reaction Times

Prior to analysis, the correct reaction time data were trimmed minimally (Baayen & Milin, 2010), through exclusion of extreme outliers (60ms < RT > 3000 ms). All values were then square-root-transformed to achieve approximate homoscedasticity of residuals. Log-likelihood model comparisons indicated that by-subject random slopes were warranted for sentence type and site of stimulation. By-item random slopes were warranted for sentence type.

The main effect of the control variable 'meaningfulness' was not significant (b = -0.18, SE = 0.26, t = -0.71) and was not considered further. Analyses revealed a significant four-way interaction among sentence type, site of stimulation, idiom familiarity and cognitive control (b =

-1.12, *SE* = 0.52, *t* = -2.18). To investigate what was driving this complex four-way interaction, we broke down the interaction using three different model splits.

In the first model split, we computed a median-split by familiarity, and then conducted two analyses, one for high-familiar items and one for low-familiar items. In the second model split, we split the omnibus model by stimulation site, separately analyzing vertex stimulation and VLPFC stimulation. In the third model split, we computed a median-split by individual levels of cognitive control, conducting separate analyses for individuals with high levels of cognitive control and those with low levels of cognitive control. The following sections report these three different model splits.

3.4.2.1 Model split by familiarity

Within high-familiar items (see Figue 2, right panel), there was a significant three-way interaction among sentence type, site of stimulation and cognitive control (*b* = -2.02, *SE* = 0.75, *t* = -2.71). To further investigate what was driving this interaction, we examined RT data for each site of stimulation (vertex, VLPFC). The results yielded a trend towards a significant interaction between sentence type and cognitive control only for stimulation to the VLPFC (b = -1.59, SE = 0.83, t = -1.90); no such interaction emerged for stimulation to the vertex site (b = 0.35, SE = 0.60, t = 0.58). A further split by sentence type within the VLPFC stimulation condition showed a trend toward an effect of cognitive control for literal (b = 1.76, SE = 1.01, t = 1.75) but not idiomatic items (b = 0.19, SE = 1.18, t = 0.16), suggesting that, as cognitive control cost scores increase (indexing lower levels of cognitive control), response times to literal items increase for these literal control sentences modelled after high-familiar idioms. This trend is barely visible in Figure 2 (right panel), where high-familiar literal sentences show longer reaction times than

high-familiar idiomatic sentences under VLPFC stimulation (for individuals with low cognitive control). No further effects emerged in the model for high-familiar idioms.

Turning to the model for low-familiar items, there was also a significant three-way interaction among sentence type, site of stimulation and cognitive control (b = 1.49, SE = 0.72, t = 2.08; Figure 2, left panel). To examine this interaction, we split this model by site of stimulation, as was done for the high-familiar items. The model for stimulation to vertex showed no significant main effects or interactions (main effect of sentence type: b = 1.17, SE = 0.74, t = 1.59; main effect of cognitive control: b = -1.27, SE = 0.84, t = 1.52; interaction between sentence type and cognitive control: b = -0.70, SE = 0.60, t = -1.16; note that Figure 2 (left panel) suggests a slowing for low-familiar idioms in the vertex condition in high-control individuals, but this effect did not reach statistical significance).

In the model for stimulation to VLPFC, the interaction between sentence type and cognitive control was not significant either (b = 0.76, SE = 0.53, t = 1.44), but there was a significant main effect of sentence type in this model (b = 1.37, SE = 0.69, t = 1.99), suggesting that response times for low-familiar idiomatic sentences under VLPFC stimulation were slower than response times to matched literal sentences. Even though the interaction with cognitive control did not reach significance, it is apparent in Figure 2 (left panel) that the effect is only visible for individuals with low-cognitive control (and see subsequent sections, where the effect indeed emerges only for individuals with low cognitive control). No further effects emerged in the model for low-familiar idioms.

3.4.2.2 Model split by site of stimulation

The model for stimulation to vertex (see Figure 3, left panel) showed no significant main effects or interactions (main effect of sentence type: b = -0.89, SE = 0.53, t = 1.66; main effect of familiarity: b = -0.17, SE = 0.29, t = -0.59; main effect of cognitive control: b = -1.20, SE = 0.89, t = -1.34; three-way interaction between sentence type, idiom familiarity and cognitive control: b = 0.21, SE = 0.35, t = 0.60). However, the model for stimulation to VLPFC (Figure 3, right panel) showed a significant three-way interaction among sentence type, idiom familiarity and cognitive control (b = -0.86, SE = 0.38, t = -2.27). To further investigate the source of this interaction, we split the model further by cognitive control. There were no main effects or interactions in the model for individuals with high levels of cognitive control (main effect of sentence type: b =0.72, SE = 0.84, t = -0.86; main effect of familiarity: b = -0.20, SE = 0.32, t = -0.61; interaction between sentence type and familiarity: b = 0.40, SE = 0.63, t = 0.64). However, the model for low-control individuals yielded a significant interaction between sentence type and idiom familiarity (b = -1.13, SE = 0.53, t = -2.15), supporting the pattern shown in the graph (Figure 3, right panel), which illustrates that individuals with low levels of cognitive control were slower for low-familiar idioms under VLPFC stimulation, but faster for high-familiar idioms relative to literal control sentences. However, only the slowing for low-familiar idioms was statistically significant, as another model split indicated: there was a main effect of sentence type only in low-familiar idioms (b = 2.00, SE = 0.78, t = 2.57) and not in high-familiar idioms (b = -0.52, SE = 1.17, t = -0.45).

Thus, the second model-split of the omnibus model (in which we split by stimulation site) showed that stimulation to the VLPFC resulted in prolonged response times to low-familiar

idioms relative to literal control sentences only in individuals with low levels of cognitive control.

3.4.2.3 Model split by cognitive control

In examining the data for participants with high levels of cognitive control, analyses showed no significant main effects or interactions, despite patterns that may be gleaned from the left panel of Figure 4 (main effect of sentence type: b = 1.02, SE = 0.67, t = 1.50; main effect of site of stimulation: b = -0.30, SE = 1.04, t = -0.28; main effect of familiarity: b = -0.28, SE = 0.29, t = -0.99; three-way interaction between sentence type, site of stimulation and familiarity: b = 0.97, SE = 0.77, t = 1.27).

In contrast, the model for individuals with low levels of cognitive control (Figure 4, right panel) showed a significant three-way interaction among sentence type, site of stimulation and idiom familiarity (b = -1.38, SE = 0.70, t = -1.98). To investigate the source of this interaction, we performed another model split, in which we split items by site of stimulation. The results showed a significant interaction between sentence type and idiom familiarity only in the model for stimulation to VLPFC (b = -1.13, SE = 0.53, t = -2.15), and not in the model for stimulation to vertex (b = 0.19, SE = 0.55, t = 0.34). Not surprisingly, further analysis revealed a significant main effect of sentence type only for low-familiar idioms (b = 2.01, SE = 0.76, t = 2.64) and not for high-familiar idioms (b = -0.52, SE = 1.17, t = -0.45; see Figure 4 right panel).

3.4.2.4 Summary

Overall, the reaction time analyses showed two things of interest: First, rTMS stimulation to the VLPFC slowed response times to low-familiar idioms primarily for individuals with lower levels of cognitive control. Second, there was a trend under VLPFC stimulation for individuals with low cognitive control to respond more slowly to literal sentences modelled after high-familiar idioms.

[Insert Figure 2 here]

3.5 Discussion

Our main question of interest was whether an rTMS-induced 'artificial lesion' to the left VLPFC (specifically, BA 45) would lead to a comprehension disadvantage for idiomatic but not literal sentences. We hypothesized this neural region would be active during idiom comprehension because of its involvement in tasks that require the controlled selection among competing representations (Badre & Wagner, 2002, 2007; Badre *et al.*, 2005; Whitney, Kirk, O'Sullivan *et al.*, 2011; Whitney *et al.*, 2012). According to our hypothesis, such circumstances should apply to idioms because they have semantically conflicting literal and figurative meanings. Our expectation was that low-familiar idioms, in particular, should be prone to rTMS-induced disruptions, because these items involve a maximal semantic conflict between a less familiar figurative meaning and a proportionally more salient literal meaning.

Indeed, our findings suggest that the VLPFC is crucial to the understanding of low-familiar idioms in particular: Following stimulation to this neural target site, meaningfulness judgments

to low-familiar idioms were significantly slower than responses to matched literal control phrases, particularly for individuals with low levels of cognitive control. One possible explanation for this finding is that low-control individuals have an inherently weaker ability to use controlled processing and suppress conflicting semantic representations during language comprehension. Thus, low-familiar idiomatic phrases put these individuals at a disadvantage due to the maximal semantic conflict these expressions involve. Even though our data indicate that under normal circumstances (vertex stimulation), this disadvantage for low-control individuals does not surface behaviorally, we expect it to still be present, presumably making neural computations inherently noisier. Aggravated processing circumstances (stimulation to the VLPFC) then add even more noise to cognitive computations and delay the contextual integration of semantic concepts with highly competing meanings (low-familiar idioms).

According to our data, low-control individuals also had difficulties when understanding literal sentences if these were derived from high-familiar idioms (e.g. *Hannah* tilted the bucket *to drink the last drop of rain water in it*; derived from the high-familiar idiom 'kicked the bucket'). Such sentences likely induced a similarly strong semantic conflict as did low-familiar idioms, given that a well-known figurative form competes maximally with an otherwise literal sentence. Especially within the design of the present study, the figurative form in these sentences may have been dominant, because of the large amount of figurative language overall. Low-control individuals were more susceptible to the semantic conflict in these items and showed slowing when rTMS was applied to the VLPFC, potentially because they could not sufficiently inhibit activation of the well-known figurative meaning.

Thus, both of these findings corroborate studies that associate the VLPFC with increased selection demands due to the presence of multiple competing semantic representations (Thompson-Schill et al., 1997; Badre & Wagner, 2007). In addition, the present data findings help to resolve the conflicting findings from previous fMRI studies – which had shown VLPFC activation in idiom tasks (Zempleni *et al.*, 2007; Lauro *et al.*, 2008) – and prior rTMS studies, which had failed to corroborate a role for the VLPFC in idiom comprehension (Oliveri *et al.*, 2004). The present findings extend previous studies using fMRI insofar as they show that VLPFC-recruitment during idiom comprehension is modulated by individual differences in cognitive control.

Precisely how such individual differences in cognitive control are manifested in concrete neuro-anatomical substrates of the brain remains unknown. However, several studies have linked individual differences in executive functions to white and gray matter variations in the frontal cortex (Fornito, Yücel, Wood, *et al.*, 2004; Forstmann, Jahfari, Scholte *et al.*, 2008). For example, Forstmann *et al. (*2008) investigated axonal diameter, fiber density and coherence of white matter tracts in the frontal lobes of high- and low-control individuals. The results showed that high-control individuals (as measured by the Simon task) have a stronger coherence in white matter tracts of the fronto-occipital fasciculus, a fiber tract that connects the lateral frontal cortex with more posterior brain regions, among them the temporal lobe. Importantly, this fiber tract has been implicated by several studies as the main sub-cortical pathway mediating semantic processing (the *ventral stream;* Duffau, Gatignol, Mandonnet *et al.*, 2005; Saur, Kreher, Schnell, *et al.*, 2008). The results of the present investigation are compatible with such findings; one could assume, for example, that idiom comprehension (and presumably the comprehension of

semantic ambiguities in general; Boulenger, Hauk & Pulvermüller, 2009) crucially relies on the VLPFC to balance and evaluate the conflicting meanings, and this process is additionally modulated through the integrity of white matter tracts that ensure the quick and efficient information transfer from semantic storage sites in the temporal lobe and the frontal cortex.

Unfortunately, the present data are unable to discern whether the VLPFC is specifically implicated in idiom comprehension or whether its role is a more general one, indexing increased workload or effortful processing for any instance of selection demands (Boulenger, Hauk & Pulvermüller, 2009). On the one hand, one could argue from the present data that the VLPFC has a more general role, given that rTMS stimulation to the VLPFC also slowed the comprehension of *literal* phrases when these were modelled after high-familiar idioms. One could argue, as suggested above, that such stimuli likely induced a strong semantic conflict and that the slowing that was associated with processing these literal phrases likely indexed just another instance of the resolution of strong semantic conflict (Jefferies, 2013; Badre *et al.*, 2005; Badre & Wagner, 2007). On the other hand, it is also possible to argue from these data that the VLPFC was implicated in the current study specifically due to the presence of idiomatic phrases, on the assumption that participants recognized the highly-familiar idioms, triggering activation of the VLPFC (Lauro *et al.*, 2008; Zempleni *et al.*, 2007).

However, to date there is more evidence in the extant literature to suggest that the role of the VLPFC in idiom comprehension is related to more general effortful processing circumstances, rather than to a specific brain response to figurative language. For example, VLPFC-activation has also been observed in lexical ambiguity resolution (Rodd, Davis & Johnsrude, 2005) and the comprehension of semantically unexpected constituent words (Van Petten & Luka, 2006). Thus,

it seems that the activation or input of the VLPFC in the present study and in previous investigations may be best explained as a brain response to general instances of cognitive conflict or heavy burden on the language processing system (Boulenger, Hauk, & Pulvermüller, 2009).

Specifically with respect to idioms, why would the VLPFC be primarily implicated in resolving semantic conflicts of low-familiar idioms? According to hybrid views of idiom comprehension, idioms are accessed through a network of interconnected nodes whose activation spreads sequentially within and between the component words (Titone & Connine, 1999; Titone & Libben, 2014). Thus, the connection strength among individual constituents depends on the frequency with which the unit is activated (Jescheniak & Levelt, 1994; Levelt, Roelofs, & Meyer, 1999). For low-familiar idioms, this connection is most likely weaker than in high-familiar idioms, due to the lack of repeated activation for these less-frequently encountered items. Thus, because low-familiar idioms are less tightly bound as a unit, their literal constituent words should lead to greater interference during processing (Kan & Thompson-Schill, 2004). The co-activation of multiple meanings then calls on VLPFC-guided control mechanisms that maintain these meanings in a temporary loop, evaluate them against the sentence context, and finally select the figurative meaning by suppressing all unwanted literal representations.

This interpretation could also explain the absence of an idiom-specific effect in the one previous rTMS study that investigated the VLPFC (Oliveri *et al.*, 2004). In that study, only high-familiar idioms were used, i.e. items that likely involve very little interference from literal constituents, because their configurations are highly over-learned. Such circumstances should minimize

controlled processing demands and, consequently, decrease VLPFC-input. A previous EEG study supports this view (Rommers, Dijkstra, &Bastiaansen, 2013), as it demonstrates that high-familiar idioms involve only minimal activation of literal constituent words. Rommers *et al.* (2013) analyzed the N400 EEG component (see Kutas & Federmeier, 2009; for review) to index semantic integration difficulties that participants experienced when they were reading idiomatic and matched literal sentences for comprehension. The experimental sentences were modified in that idioms and matched literal phrases were preceded by a strong biasing context and key constituent words of the idiomatic or literal phrases were replaced with either semantically related or unrelated words (e.g. in the Dutch idiom *tegen de lamp lopen*, lit. *to walk against the lamp*, fig. *to get caught*; 'lamp' was replaced with 'candle' [related] or 'fish' [unrelated]). The results revealed that word substitutions in literal control sentences elicited a graded pattern of N400s, with related words eliciting a significantly smaller N400 than unrelated words, thus suggesting fewer integration difficulties when participants were reading contextually related rather than unrelated words. In high-familiar idioms, in contrast, there was no graded N400; that is, the brain response was the same to related and unrelated words. The authors argue that familiar idioms do not require compositional word-by-word processing in the way that literal language does, so that unrelated word substitutions in these expressions do not increase control-related processing demands.

In sum, previously obtained evidence (Oliveri *et al.*, 2004; Rommers *et al.*, 2013) and the data from present investigation indicate that control-related processing demands increase (and involve VLPFC-input to a greater extent) when several semantic representations are maximally conflicting (such as in low-familiar idioms), whereas control-related demands are minimal when

one representation is highly salient compared to the others (Oliveri *et al.*, 2004; Rommers *et al.*, 2013).

Finally, one limitation of the present may lie in the nature of the semantic meaningfulness judgment task. For example, one problem with such a kind of task is that the distinction between 'meaningful' and 'not meaningful' may not be dichotomous but variable, for example some people may have difficulties assigning meaning to a sentence such as *Sarah blew a fuse when the beverages she had studied most weren't on the test* (intended to be non-meaningful), whereas other people may find such a sentence actually analyzable (for example, Sarah may be training to become a bar keeper). Second, meaningfulness judgment tasks may be problematic to use especially for addressing the question whether idiomatic language induces a semantic conflict. Non-meaningful sentences arguably elicit a semantic conflict just based on the fact that they are not analyzable, which in turn clouds any interpretation about semantic conflicts related specifically to idioms. Thus, one issue for future research is to investigate the role of the VLPFC in idiom comprehension by means of an experimental task which keeps such confounding factors minimal, for example during online reading.

3.6 Conclusion

To date, investigations of the role of the ventro-lateral prefrontal cortex (VLPFC) in idiom processing have been equivocal, with fMRI studies consistently demonstrating its involvement (Zempleni *et al.*, 2007; Lauro *et al.*, 2008; for reviews see Rapp *et al.*, 2012; Bohrn *et al.*, 2012), and rTMS studies failing to corroborate this result (Oliveri *et al.*, 2004).

The present investigation used a meaningfulness judgment task to test whether rTMS stimulation to the VLPFC and a control site (vertex) differentially affects the comprehension of idiomatic and matched literal sentences. Our prediction was that rTMS should disrupt the comprehension of low-familiar idioms, in particular, as these items involve a maximal semantic conflict between a less known figurative and a more salient literal interpretation.

The results corroborated this hypothesis, but individual levels of cognitive control modulated the effect: Only low-control individuals were susceptible to rTMS-induced disruptions during the processing of low-familiar idioms. In addition, VLPFC stimulation in these individuals also led to a slowing for literal sentences that had been modelled after high-familiar idioms. Thus, the role of the VLPFC in idiom comprehension may be best explained as indexing semantic conflicts in language, rather than being specific to idiom or figurative language processing. The reason why only individuals with low levels of cognitive control were susceptible to such cases of semantic conflicts may be that these individuals have an inherently lower capacity to resolve the semantic conflict in idioms, so that aggravated processing circumstances (e.g., under rTMS) add too much noise to neural computations to quickly understand semantically conflicting information.

In sum, the present data show that idiom resolution is predicted by both idiom-inherent and listener- or speaker-related characteristics, which supports hybrid or constraint-based views of idiom processing (Titone & Libben, 2014). In addition, the findings presented in this study support the notion that cognitive control modulates idiom performance primarily under compromised processing circumstances (Papagno *et al.*, 2003; Rassiga *et al.*, 2009), but not when processing is unimpaired (Columbus *et al.*, 2015; Häuser *et al.*, submitted).

Future studies need to disentangle the potentially diverging roles of the dorso-lateral (DLPFC) and ventro-lateral PFC (VLPFC) during idiom processing, and illustrate how general cognitive functions (such as cognitive control) interact with idiom-specific factors other than familiarity (for example, decomposability or literal plausibility) in constraining idiom resolution.

Table 1

Experimental items for the four sentence conditions: idiomatic/literal meaningful, idiomatic/literal non-meaningful.

Idiomatic – Meaningful	Josh bore his cross the entire flight and didn't complain about the snoring man.
Literal – Meaningful	Josh lost his cross when he dropped it in the grass on the way home from church.
Idiomatic – Not Meaningful	Josh bore his cross the entire flight and didn't stockpile about the snoring man.
Literal – Not Meaningful	Josh lost his cross when he dropped it in the stork on the way home from church.

Table 2

Means and standard errors (subject-weighted) in idiomatic and literal sentences for correct reaction times (in ms) and percentage of accuracy, depending on site of stimulation.

	Correct Reaction Times		**Accuracy**	
	M	*SE*	*M*	*SE*
Baseline/Vertex				
Idiomatic	544	54	0.88	0.02
Literal	499	41	0.93	0.01
Ventro-Lateral PFC				
Idiomatic	588	55	0.86	0.02
Literal	553	46	0.92	0.01

Table 3

Effect sizes (b), standard errors (SE), and *t-(z)* values for the correct RT and accuracy logistic LMER models.

	Correct Reaction Times			**Accuracy**		
Fixed Effects	*b*	*SE*	*t*	*b*	*SE*	*z*
Sentence Type	0.77	0.46	1.67	-0.74	0.17	-4.39
Site of Stimulation	0.90	0.76	1.19	-0.18	0.12	-1.46
Idiom Familiarity (scaled)	-0.12	0.24	-0.49	0.20	0.11	1.85
Simon Cost Score (scaled)	-0.23	0.88	-0.26	0.06	0.14	0.43
Sentence Type * Site of Stimulation	-0.22	0.52	-0.42	-0.03	0.25	-0.14
Sentence Type * Idiom Familiarity	-0.33	0.39	-0.85	0.36	0.17	2.12
Site of Stimulation * Idiom Familiarity	-0.03	0.26	-0.12	0.05	0.12	0.43
Sentence Type * Simon Cost Score	-0.29	0.36	-0.81	0.05	0.14	0.33
Site of Stimulation * Simon Cost Score	1.91	0.77	2.49	0.02	0.14	0.15
Idiom Familiarity * Simon Cost Score	0.09	0.13	0.66	-0.08	0.08	-0.98
Sentence Type * Site of Stimulation * Idiom Familiarity	-0.31	0.52	-0.61	-0.04	0.25	-0.16
Sentence Type * Site of Stimulation * Simon Cost Score	-0.19	0.52	-0.38	0.09	0.28	0.33
Sentence Type * Idiom Familiarity * Simon Cost Score	-0.30	0.26	-1.16	0.06	0.14	0.43
Site of Stimulation * Idiom Familiarity * Simon Cost Score	0.11	0.26	0.43	-0.14	0.14	-1.01
Sentence Type * Site of stimulation * Idiom Familiarity * Simon Cost Score	-1.12	0.52	-2.18	-0.02	0.28	-0.07

Control Predictors	*b*	*SE*	*t*	*b*	*SE*	*z*
Meaningfulness	-0.18	0.26	-0.71	0.01	0.12	0.09
Idiom decomposability (scaled)	0.21	0.24	0.87	0.09	0.10	0.89
Random Effects		Variance			Variance	
Subject		11.76			0.22	
Subject | Sentence Type		0.98			*n/a*	
Subject | Site of Stimulation		8.19			*n/a*	
Subject | Idiom Familiarity		*n/a*			0.03	
Item		1.67			0.52	
Item | Sentence Type		4.73			0.65	

Figure 1

Mean accuracy for idiomatic and literal sentences for individuals with low cognitive control (left panel) and individuals with high cognitive control (right panel), depending on sentence type, site of stimulation and idiom familiarity. Error bars indicate standard errors of the mean (subject-weighted).

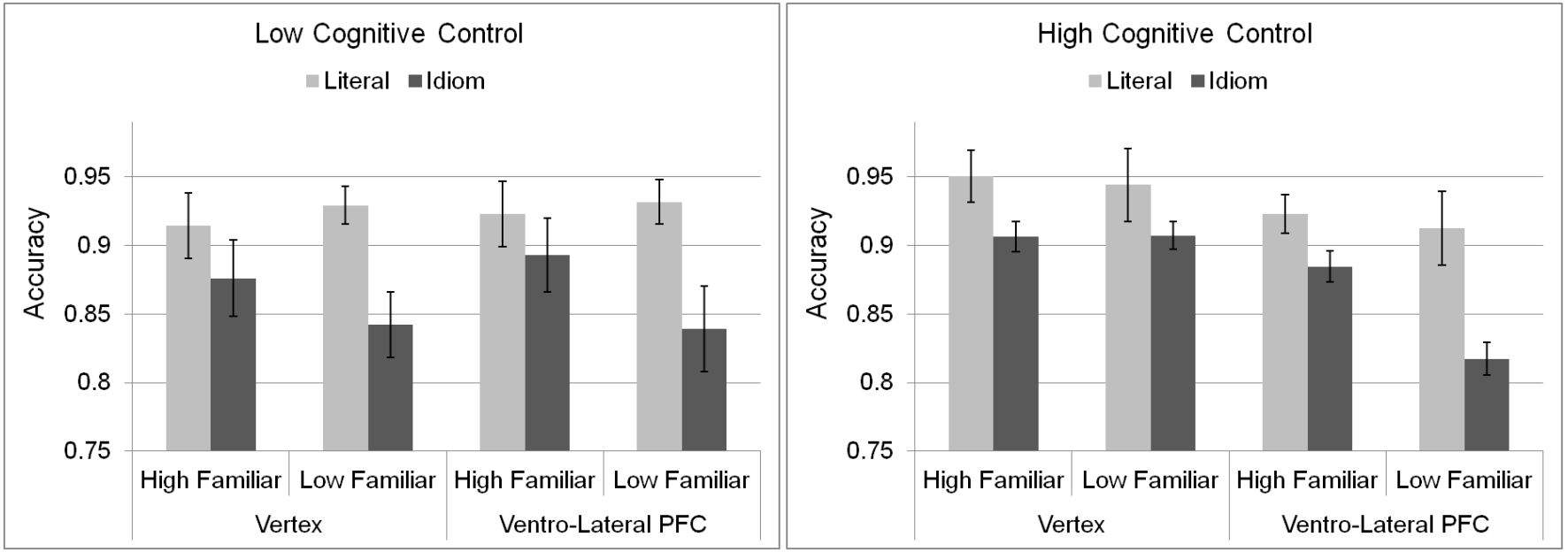


Figure 2

Mean correct reaction times (± standard errors of the mean, subject-weighted) for low- (left panel) and high-familiar (right panel) idiomatic and literal sentences, depending site of stimulation and individual levels of cognitive control.

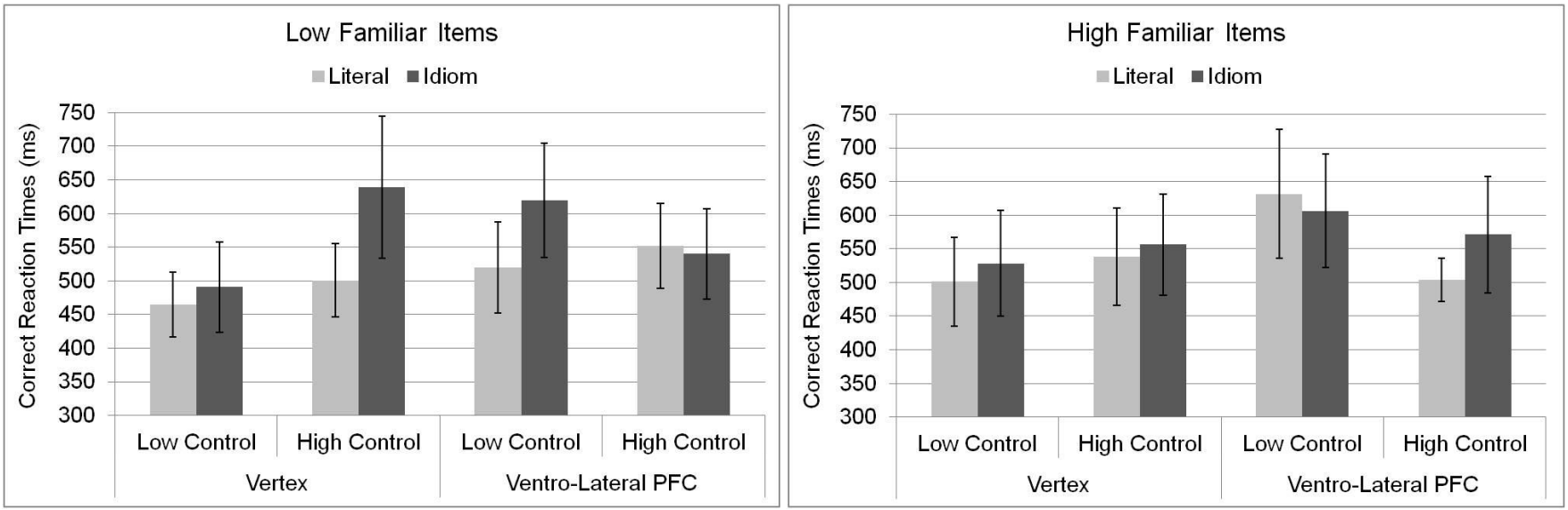


Figure 3

Mean correct reaction times (± standard errors of the mean, subject-weighted) stimulation of vertex (left panel) and VLPFC (right panel), depending sentence type, cognitive control and idiom familiarity.

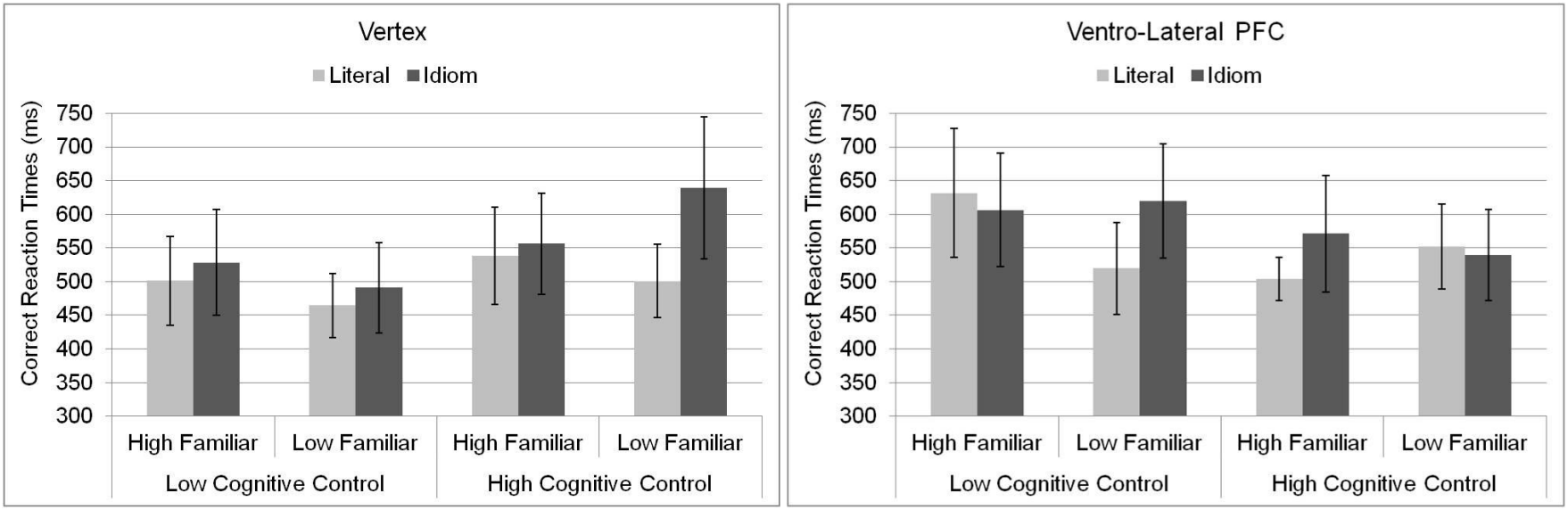
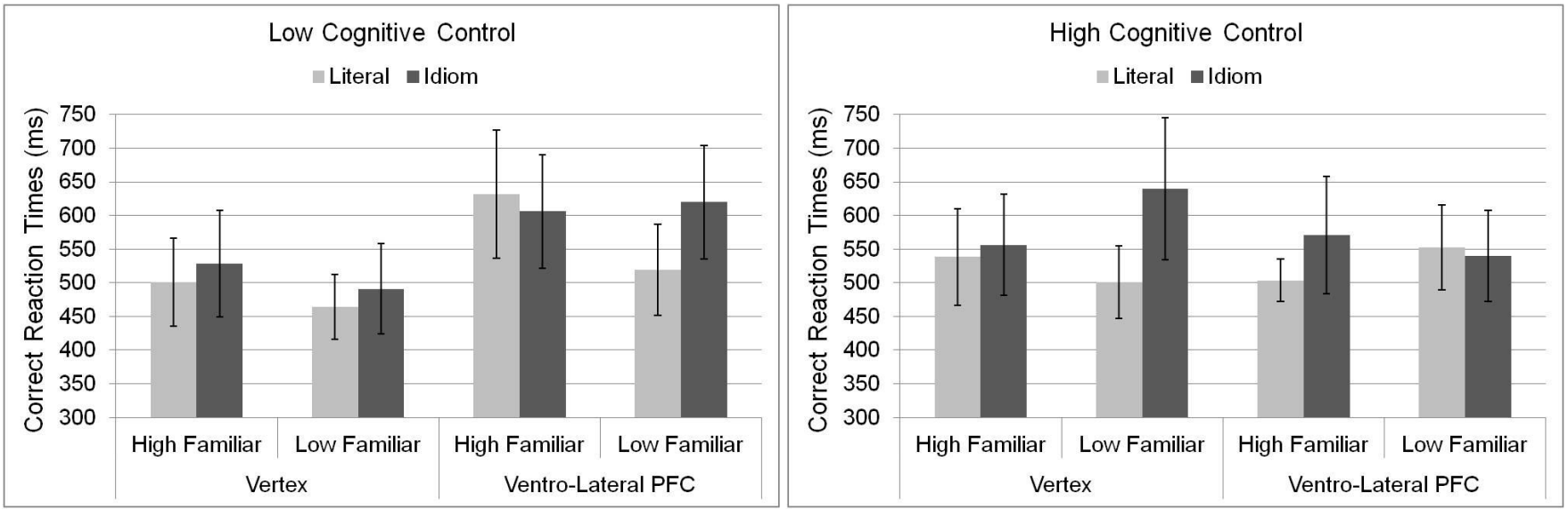


Figure 4

Mean correct reaction times (± standard errors of the mean, subject-weighted) for individuals with low cognitive control (left panel) and high cognitive control (right panel), depending on site of stimulation and idiom familiarity.



Chapter 4: General Discussion

4.1 Summary of findings

The primary question that motivated this thesis was whether the comprehension of idioms (e.g. *spill the beans, blow a fuse*), a prominent type of figurative language, requires greater levels of cognitive control than the comprehension of comparable literal language. We hypothesized that cognitive control should be crucial to process and understand idioms because these expressions, unlike literal language, have a figurative and a literal interpretation. This dual nature of idioms should call on executive functions of cognition to maintain the two meanings in working memory, evaluate them against a discourse context and enhance or inhibit activation levels for appropriate or inappropriate meanings.

In order to answer this question, two experiments were conducted. Study 1 tested whether older adults show different activation patterns for figurative and literal meanings than younger adults while reading idiomatic sentences in an eye-tracking paradigm. Older adults were selected for investigation because they normally show declines in executive functions of cognition, but relative stability or even improvement in lexical-semantic aspects of language. Thus, on the one hand, age-related impairments in cognitive control could render older adults less capable of processing the conflicting literal and figurative representations of an idiom. On the other hand, their life-long language experience with idiomatic forms could also provide older adults with a semantically more enriched, detailed and interconnected figurative form representation in memory.

Study 2 tested whether the ventro-lateral prefrontal cortex (VLPFC), a cortical region associated with increased top-down control in semantic tasks (Thompson-Schill *et al.*, 1997; Badre &

Wagner, 2007; Whitney, Kirk, O'Sullivan, *et al.*, 2011; Whitney *et al.*, 2012; Jefferies, 2013), is crucial to understand idioms. We used rTMS to test if an 'artificial lesion' (Pascual-Leone, Walsh, & Rothwell, 2000) in the VLPFC would disrupt or slow the comprehension of idiomatic sentences in a meaningfulness judgment task. The expectation was that sentences containing low-familiar idioms should be especially prone to rTMS-induced disruptions, since these items involve a maximal semantic conflict between a less known figurative and more salient literal meaning, which should maximize control-related demands in the VLPFC. An additional question of interest was to what extent baseline levels of cognitive control among participants would modulate rTMS-altered demands on idioms.

The results of Study 1 showed a complex pattern of age-related improvements and deficits in processing idiomatic sentences. Aspects of age-related improvements showed that older adults (and not younger adults) had shorter first-pass reading times for idiomatic vs literal control sentences, which suggests that lexical-semantic representations of idioms are indeed more intact and more quickly accessible for older people. Older adults were also less susceptible than younger adults to increased or reduced idiom familiarity, a finding that could also suggest that a lifetime of experience in encountering idiomatic forms has rendered older adults with a more entrenched and more accessible representation of idiomatic configurations in memory.

In contrast to this, however, older adults were disadvantaged in comparison to younger adults when a sentence context required understanding an idiom specifically in its less entrenched, literal interpretation. For this type of sentence, older adults were more likely to (over-)commit to figurative meanings than younger adults, and not access literal meanings of idioms. Thus, these findings suggest that older adults have overall spared or even more elaborate semantic

representations of idiomatic forms, but that they may have difficulty dividing attention between literal and figurative representations. Of note, individual differences in cognitive control were not predictive of idiom reading in either the group of younger or older adult participants in Study 1. Thus, the overall pattern that emerges is that, even though age-related processing differences for idiomatic sentences do occur, these group differences are more attributable to aspects of language entrenchment and experience, rather than to age-related impairments in cognitive control.

In contrast to this, the results of Study 2 showed more direct evidence to corroborate the hypothesis that idiom processing depends on intact levels of cognitive control. Specifically, Study 2 showed that idiom comprehension requires the functional integrity of neural substrates in the left ventro-lateral prefrontal cortex, and is impaired when rTMS induces an artificial lesion in this cortical area. Following stimulation to the VLPFC, participants were slower at judging whether sentences containing low-familiar idioms were meaningful or not. Thus, this finding supports the hypothesis that low-familiar idioms, in particular, recruit brain areas dedicated to top-down semantic control due to the presence of a maximal semantic conflict. Of note, only participants with low levels of cognitive control experienced rTMS-induced disruptions with low-familiar idioms, possibly because these individuals have an inherently weaker capacity to flexibly balance competing semantic representations. Supporting this interpretation, low-control individuals also experienced rTMS-induced disruptions when presented with literal sentences modelled after high-familiar idioms (e.g. *Hannah tilted the bucket to drink the last drop of rain water in it*); which suggests that these participants could not sufficiently inhibit activation of the contextually unwanted, but highly salient figurative form in these items.

In sum, whereas Study 1 indicated that control-related impairments in older adults do not modulate their abilities in idiom processing, Study 2 indicated a direct relationship between cognitive control and idiom comprehension. One way to reconcile the seemingly conflicting findings from the two studies is to suggest that cognitive control is predictive of idiom processing only under compromised or severely aggravated circumstances. In the present thesis, such compromised circumstances were created through rTMS stimulation – that is through direct inhibition of prefrontal cortex areas. Under these circumstances, idiom comprehension varied as a function of individual differences in cognitive control. Even though the older adults in Study 1 did have impairments in cognitive control overall, the deficits in these individuals may not have been severe enough to have a measurable impact on idiom processing, especially because the older adults (according to our results) could leverage their greater entrenchment of figurative meanings to more quickly access idiomatic configurations in memory. This interpretation of the present data is also in line with previous studies that addressed the relationship between idiom processing and cognitive control (for review, see Cacciari & Papagno, 2012). Studies with clinical patient groups had often reported that executive deficits in Alzheimer's disease or schizophrenia are associated with comprehension difficulties for idioms (Papagno *et al.*, 2003; Rassiga *et al.*, 2009; Iakimova *et al.*, 2010), whereas work on clinically-unimpaired or neuro-typical individuals (Columbus *et al.*, 2015) had found no such relationship between executive functions and idiom processing. Thus, the overall picture that emerges is that an impact of individual differences in cognitive control on idiom processing may be specific to significantly compromised processing circumstances.

4.2 Evaluation of results against models of idiom processing

How can these data be accounted for based on psycholinguistic research on idiom comprehension, specifically in regards to the three types of models that have been proposed (compositional, non-compositional and hybrid)? Upon initial reflection, it may be difficult to directly interpret the current data in the context of existing models of idiom processing, given that most models do not focus primarily on idiom familiarity, which was an important variable in the current experiments, but rather on decomposability. However, if we focus more on the general notion that idiom processing involves a semantic conflict and thus cognitive effort, it is possible to compare our results to existing models of idiom comprehension.

With respect to compositional models of idiom comprehension (Gibbs & Nayak, 1989; Gibbs, Nayak, & Cutting, 198; Gibbs & O'Brien, 1990), these accounts predict that idioms are semantically motivated by (and can be directly accessed through) their literal constituent words. This means that (at least under strong versions of such compositional accounts) literal word meanings are fully analyzed and contribute productively to the figurative meaning (Gibbs, Nayak, & Cutting, 1989). Consequently, compositional models do not allow for the notion of a semantic conflict during idiom processing as expressed in this thesis, because under these accounts, literal word meanings are not competing with the figurative meaning for activation; instead, they are crucial to construct the figurative meaning (Gibbs & Nayak, 1989; Gibbs, Nayak, & Cutting, 1986; Gibbs & O'Brien; also see Langlotz, 2006). In addition, compositional models are also incompatible with the idea that idiom comprehension requires cognitive effort and is slower compared to the comprehension of literal language, given that, according to these models, idioms can be compositionally assembled from their literal component words (Gibbs,

Nayak, & Cutting, 1986). Thus, the findings from Study 2 in this thesis may be interpreted as being in direct conflict with compositional models of idiom processing. Specifically, Study 2 showed that the VLPFC is recruited during idiom comprehension, a finding which is best explained by the notion that there *is* a cognitive conflict in idiom comprehension (Badre & Wagner, 2002, 2007), in contrast to what compositional models predict.

Non-compositional models of idiom processing (Bobrow & Bell, 1973; Swinney & Cutler, 1979), in contrast, seem to match with the present data at first sight, since these models hold that literal and figurative meanings of an idiom have no semantic relationship or overlap. This fits more readily with the view that there is semantic conflict in idiom processing. However, the data in the present thesis are not compatible with non-compositional models either, at least for strong versions of such non-compositional views (Bobrow & Bell, 1973). According to these accounts, idiom comprehension requires a special processing mode for figurative language, which is cognitively distinct from the processing mode for literal language. These processing modes never run simultaneously, because a figurative processing strategy is only activated after a literal computation has yielded no meaningful result (Bobrow & Bell, 1973). However, the notion that these processing modes are distinct mental operations is again not compatible with the view that they can induce a cognitive conflict, which is what Study 2 showed. Moreover, the notion that literal and figurative meanings of an idiom are computed at non-overlapping time points conflicts with the results from Study 1, which showed that idiom processing in younger adults involves the simultaneous activation of figurative and literal meanings. Thus, idiom processing involves the computation of multiple semantic representations, rather than the computation of single meanings at non-overlapping time points.

The data of the present thesis can be best accounted for by hybrid models of idiom comprehension (Cacciari & Tabossi, 1988; Titone & Connine, 1999; Libben & Titone, 2008), which attribute both phrase-like and word-like characteristics to idioms, and argue that idiom processing involves both the simultaneous activation of multiple meanings *and* direct retrieval from memory. The notion of simultaneous meaning activation is compatible with Study 1, which showed that younger adults activate literal and figurative meanings when processing idioms. It is also in line with Study 2, and with the notion that there is a cognitive conflict during idiom processing which calls on executive areas in the brain. In addition, the possibility for direct retrieval of figurative meanings that is expressed in hybrid models of idioms (Titone & Connine, 1999; Libben & Titone, 2008) is compatible with the results from Study 1, where older adults (presumably due to their life-long experience in encountering idiomatic forms) retrieved figurative meanings of idioms directly, bypassing literal meaning activation altogether. Finally, since hybrid models make graded predictions about the influence of idiom characteristics such as familiarity and decomposability, they best account for the results in Study 1, which indicated that younger and older adults were differentially sensitive to idiom familiarity (with older adults showing a reduced influence of familiarity). Thus, both studies in the present investigation are best accommodated by hybrid models of idiom comprehension and support the notion that idiom processing is mediated by a complex interplay among idiom-inherent and contextual characteristics. The present findings add to these hybrid models that individual differences in cognitive control and age-related differences between younger and older adults also pose important constraint on idiom comprehension.

4.3 Open questions and directions for future research

The current thesis reveals that there are processing differences between younger and older adults during the online resolution of idiomatic language. In addition, the findings demonstrate that the ventral part of the prefrontal cortex, as well as individual difference in cognitive control, play a role in idiom comprehension. Despite the novelty of these findings, there are several remaining questions that warrant future investigation.

First, Study 1 did not find support for the notion that there is a relationship between control-related deficits in older adults and the way these individuals process idioms. Thus, an issue for future investigation is whether such a relationship would be found for types of figurative language other than idioms, for example metaphors (i.e. *his lawyer is a shark*, *their love is like a rose*). Unlike idioms, in which literal and figurative meanings often bear no semantic relationship (Swinney & Cutler, 1979), metaphors have a high degree of semantic transparency, so they are more likely compositionally built during comprehension, rather than holistically retrieved (as might be the case for idioms; Columbus *et al.*, 2015). Thus, it is possible that metaphor processing, given the high degree of semantic motivation of these expressions, would be affected by age-related differences in cognitive control. There is only a small number of studies which has investigated age-related changes in metaphor comprehension (Monetta, Ouellet-Plamondon, & Joanette, 2007; Glucksberg & Newsome, 2002; Morrone, Declercq, Novella, & Besche, 2010), and none has investigated how specifically age-related differences in cognitive control modulate online metaphor processing. Based on a previous study of younger adults (Columbus *et al.*, 2015), where individual differences in cognitive control were found to influence metaphorical sentence reading, our expectation would be that older adults with reduced

cognitive control should be slower at metaphor processing when compared to a control group of younger adults.

A second open question pertains to the findings of Study 2. There is now evidence from both fMRI and rTMS studies that both the dorso-lateral PFC (Rizzo *et al.*, 2007; Fogliata *et al.*, 2007; Hillert & Buracas, 2009) and the ventro-lateral PFC (the present study; Zempleni *et al.*, 2007; Lauro *et al.*, 2008) are recruited during idiom processing. However, it remains unclear whether these two neural regions are both fundamentally crucial to idiom processing, and if so, whether they have similar or potentially diverging functions during idiom processing. One lingering issue is whether the DLPFC is really relevant to idiom comprehension, since it has been implicated primarily in studies which used sentence-to-matching tasks (Rizzo *et al.*, 2007; Fogliata *et al.*, 2007; Lauro *et al.*, 2008), which might increase PFC-related demands simply based on the complex set of requirements they involve (maintaining a stimulus in working memory, matching it to an array of other stimuli). Thus, one aspect that warrants further research is to compare dorso-lateral PFC input during idiom processing in a sentence-to-picture matching task and in a task that poses only minimal demands on cognitive control within a single study. The results of such a study could clarify whether DLPFC-recruitment in idiom tasks is specific to multiple-choice tasks (as been suggested previously; Papagno & Caporali, 2007) or whether it is actually related to the presence of idiomatic language.

If the results were to demonstrate that the DLPFC is actually crucial for idiom processing, the next step would be to investigate whether VLPFC and DLPFC fulfill different cognitive functions during idiom processing. For example, the DLPFC has previously been implicated in the processing of primarily high-familiar idioms (though several studies have confounded this

with additional high literal implausibility of the experimental stimuli; see Rizzo *et al.*, 2007; Fogliata *et al.*, 2007; Sela *et al.*, 2012; Lauro *et al.*, 2008), whereas the present study showed that the ventro-lateral PFC is more crucial for low-familiar idioms. Thus, an interesting direction for future research is to investigate both neural regions in one study, compare whether they are differentially sensitive to increased or reduced idiom familiarity, and also look at the impact of other idiom variables such as literal plausibility and decomposability, which are known to affect idiom processing (Titone & Connine, 1999; Libben & Titone, 2008).

A third and final issue for further research is to investigate control-related demands during idiom processing in a *production* paradigm. The experimental tasks presented in this thesis were all perceptual in nature (idiom reading in Study 1, and idiom comprehension in Study 2), even though it is very likely that control-related demands also modulate idiom production. Production tasks are fundamental to complement the findings obtained for language perception and comprehension in order to provide a more complete picture of the relationship between cognitive control and idiom processing.

4.4 Conclusion

The current dissertation investigated whether processing idioms, a prominent type of figurative language, is modulated by individual differences in cognitive control. A role for executive functions in idiom processing had indirectly been suggested by hybrid models of idioms, because these argued that processing idioms involves the simultaneous activation of competing semantic representations in working memory.

Study 1 showed that older adults access and maintain only figurative meanings of idioms, whereas younger adults access and maintain both literal and figurative meanings. This figurative 'commitment' in the older adults was not due to executive impairments in this group of subjects; rather, it is more likely that a lifetime of experience in encountering idiomatic forms has rendered figurative representations overall more accessible for older relative to younger adults.

Study 2 used rTMS to show that idiom comprehension is disrupted when cortical activity is temporarily inhibited in the ventro-lateral prefrontal cortex. Importantly, the effect of cortical stimulation affected only participants with lower levels of cognitive control and was specific to a subset of idioms (low-familiar items), which suggests that listener-inherent and idiom-inherent properties jointly interact and constrain control-related prefrontal demands during idiom comprehension.

In sum, the current findings suggest that an influence of cognitive control on idiom processing may be specific to compromised or impaired processing circumstances, but drawing on cognitive control resources may not be required when such conditions do not exist.

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