LANGUAGE COMPREHENSION IN HEALTHY AGEING AND MILD COGNITIVE IMPAIRMENT

by

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ABSTRACT

Despite structural decline in language relevant brain regions, language comprehension appears to be relatively preserved with age. This raises the question: "*How does the ageing brain maintain the cognitive system*?" In this context, this thesis investigates the behavioural and functional underpinnings of sentence comprehension in healthy ageing and Mild Cognitive Impairment (MCI). Using a minimal phrase paradigm designed to focus on the process of syntactic binding, *Chapter 1* reports a behavioural experiment demonstrating age-related decline in syntactic comprehension that increases in the absence of semantic-contextual information. Extending on these findings, *Chapter 2* reports an electroencephalography (EEG) experiment on the oscillatory mechanisms involved in syntactic processing in older adults, which gives evidence for qualitative differences in the neural signature associated with syntactic binding in older compared to younger adults. *Chapter 3* reports an EEG experiment on oscillatory activity associated with lexical retrieval and semantic processing in MCI. The results indicate subtle, yet clear alterations in the neural signatures associated with these processes in individuals with MCI relative to healthy controls. Collectively, the studies reported in this thesis add to our understanding of the robustness and changeability of the language comprehension system in the face of the wide array of changes that occur with ageing, further constraining neurocognitive theories on this subject.

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Publications

Poulisse, C., Wheeldon, L., Segaert, K. (2019). Evidence against preserved syntactic comprehension in healthy ageing. The influence of ageing on elementary syntactic comprehension. *Journal of Experimental Psychology: Learning, Memory and Cognition*

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Conference talks

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GENERAL INTRODUCTION

Even though the structural morphology of the human brain is mature by birth, growth continues until early adulthood, peaking between 18 and 30 years of age. Throughout this period, the size of the brain quadruples from 400g at birth, to around 1400g at maturity. The postnatal increase in brain weight reflects ongoing elaboration of the system and is largely due to differentiation and maturation of existing neurons (Anderson, Northam, Hendy & Wrennall, 2008). This incredible plasticity enables the development of the cognitive system of the brain. Indeed, even though the mechanisms underlying this relationship are not yet fully understood, we know that cognition and brain are inextricably linked.

At the other end of the lifespan spectrum, *change*, is commonly viewed as decline, rather than development (Strehler, 1997). Starting between 30 and 40 years of age, brain weight progressively declines. By and large, advanced age is characterized by structural alterations in the brain. Importantly, not all brain regions are equally affected. Instead, the frontal and temporal areas appear to be particularly susceptible to structural degradation (Fjell & Walhovd 2010). Likewise, age does not have a homogeneous effect on decline in cognitive functions. General cognitive functions such as working memory, processing speed, perception and attention are subject to age-related decline (Dennis & Cabeza, 2008). On the other hand, language comprehension at first sight appears to remain relatively preserved with age (Burke & Shafto, 2008, Ansado, Marsolais, Methqal, Alary & Joanette, 2013). In view of the fact that cognitive processes depend on the structural and functional properties of the brain, it seems likely that age-related differences in cognitive functions are closely linked to changes in the integrity of cerebral architecture and function (Dennis & Cabeza, 2008). Indeed, there exists fairly extensive literature indicating that age-related changes in brain structure (e.g., white matter hyperintensities and gray matter shrinkage) are associated with declines in cognitive functioning (e.g., Raz, 2004; Grady, 2012). Crucially, however, structural and cognitive age-related changes do not straightforwardly line up. In fact, the relative preservation of language comprehension is in spite of structural changes in language relevant regions of the brain, and in spite of declines in working memory and processing speed (Ansado et al., 2013). This feeds into a fundamental question in the cognitive neuroscience of ageing: *How does the ageing brain maintain the cognitive system?* The aim of this thesis is to contribute to answering this question in the context of language comprehension.

In this thesis, the relationship between ageing and language comprehension is explored by investigating the behavioural (*Chapter 1*) and functional (*Chapter 2 and Chapter 3*) underpinnings associated with processing of syntactic and semantic information during sentence comprehension. In addition, functional change associated with lexical retrieval and processing semantic information is investigated in relation to the evolution of early cognitive impairment due to degenerative disease (*Chapter 3*). The implications of the findings reported in these chapters are further discussed in the *General discussion.* In the remainder of this introduction, I will briefly outline the key issues addressed in the studies reported in this thesis.

Behavioural measures of age-related differences in syntactic comprehension

Language comprehension requires the activation, coordination and integration of different aspects of linguistic knowledge to construct a representation of the sentence meaning (Brown, Hagoort & Kutas, 2000). One of these aspects is syntax. Syntax involves the grammatical arrangement of words within a sentence (Carroll, 2007). Syntactic processes and information are used in sentence comprehension in a number of ways, including structure building (i.e., combining words into larger structures based on grammar rules and word category information); checking agreement (i.e., matching the value of a grammatical category between different constituents of a sentence) and mapping thematic roles (e.g., mapping the agent ('doer') and patient ('doe-ee') onto certain positions in the sentence; Kaan & Swaab, 2002). Age-related differences in sentence comprehension have been extensively studied using paradigms that capitalize on syntactic complexity, for example, by comparing syntactically complex object relative clause sentences to syntactically simpler subject relative clause sentences, or by using sentences that are temporary syntactically ambiguous, as in garden path sentences like "*The experienced soldiers warned about the danger conducted the midnight raid*" (Burke & Shafto, 2008). The weight of the evidence from these studies suggests that sentence comprehension in older adults remains relatively well preserved. Declines in sentence comprehension occur only at increased levels of syntactic complexity.

Crucially, however, sentences with a complex syntactic structure may impose a larger burden on working memory. Given that working memory declines with age (Caplan & Waters, 2005), it is difficult to determine to what extend the age-related changes in syntactic comprehension are accounted for by reductions in working memory capacity. Moreover, in addition to a strong reliance on syntactic information, processing complex syntactic structures involves additional comprehension mechanisms, including semantic and pragmatic processing. Indeed, the multifaceted nature of syntactic comprehension makes it difficult to experimentally isolate the distinct contributions of the different aspects of linguistic information that ultimately guide sentence comprehension. This is a particularly critical issue in research on age-related change in language comprehension, as different aspects of linguistic processing may vary in their sensitivity to ageing.

Moreover, healthy ageing is characterized by a large degree of inter-individual variation. In other words, "ageing" is not a unitary process across individuals. Instead, there exists marked individual variability in both neuroanatomical as well as cognitive age-related change. Understanding what accounts for this variability is a key question in research in the cognitive neuroscience of ageing. This requires research on the effect of age on language comprehension to consider age in a broader, more holistic sense than just chronological age. Both processing speed and working memory capacity decline with age (Salthouse, 1996; Waters & Caplan, 2001; Caplan & Waters, 2005) and are known to contribute to language processing (Wingfield, Peelle & Grossman, 2003; Wingfield & Grossman, 2006). Health characteristics can also explain variability in cognitive ageing (Raz, 2009, Shafto et al., 2019). Physical health in older adults is positively related to general cognitive functioning (Barnes, Yaffe, Satariano & Tager, 2003; Colcombe et al., 2004), brain electrical activity (Sanchez-Lopez et al., 2018) and language processing (Segaert et al., 2018b). In view of these findings, the work reported in this thesis incorporated measures of physical capacity and cognitive functioning. Specifically, a grip strength measurement, as an established marker of physical health (Lara et. al., 2015) and a physical activity questionnaire (New Zealand Physical Activities Survey Short Form; Sport and Recreation New Zealand, 2001) were included (*Chapter 1* and *2*) to measure physical health. In addition, both processing speed (i.e., WISC-IV; Wechsler, 2008) and working memory (i.e., Digit Span; Waters & Caplan, 2003) were included to measure cognitive functioning (*Chapter 1 and 2*). These biomarkers of healthy ageing were included with the aim of identifying factors associated with individual differences in language performance.

As an essential first step, the investigation of cognitive ageing in language comprehension requires behavioural measures of critical mechanisms. In *Chapter 1,* I report an investigation of age-related performance differences in syntactic comprehension. The aim of this study was to minimise the contribution of working memory to syntactic processing by reducing sentence complexity to a minimum of two words: a pronoun and a verb (e.g., "*I cook"*), thereby focusing on the elementary building blocks of syntactic operations. By comparing performance on a syntactic judgement task between young and older adults, I investigated whether syntactic comprehension of simple syntactic structures is indeed preserved with age. Furthermore, I tapped into the relationship between syntax and semantics by comparing comprehension on sentences containing real verbs to sentences containing pseudoverbs (e.g., "*I spuff*"). Individual variation in performance, including ageing effects, is further explained in terms of individual differences in overall cognitive and physical functioning.

Measuring functional mechanisms associated with language comprehension using EEG

In response to the neuroanatomical and cognitive changes that occur in ageing, results of numerous neuroimaging studies suggest that the functional properties of the brain change as well. This phenomenon is commonly referred to as *neurofunctional reorganization* (Ansado et. al., 2013). Therefore, following the investigation of age-related changes at the behavioural level, I investigated the functional properties of language comprehension.

In *Chapter 2* and *Chapter 3,* I report two studies employing Electroencephalography (EEG) to measure the neuronal activity of the brain. This imaging technique measures electrical activity generated by populations of medium (i.e., thousands) to large sized (i.e., millions) populations of neurons. This activity is characterized by coordinated inhibitory and excitatory postsynaptic oscillations (i.e., rhythmic fluctuations) in the membrane potentials of pyramidal neurons in the cerebral cortex (Cohen, 2014). EEG is known for its high temporal precision, making this technique particularly suitable for capturing the fast cognitive dynamics associated with language processing. I used two different EEG analysis techniques. Specifically, I investigated event related potentials (ERPs), which are calculated by averaging the EEG signal over epochs (i.e., experimental trials) time –locked to an external or internal stimulus event (i.e., words in the context of the current investigations; Luck, 2005). ERPs directly reflect neural activity in the brain with millisecond precision, making this method particularly suitable for capturing the fast dynamics associated with language comprehension (Wlotko, Lee & Federmeier, 2010). An alternative approach to investigating event-related changes in the EEG signal, and the main focus in this thesis, is to investigate oscillatory activity. An advantage of investigating neural oscillations relative to ERPs is that this method allows for the investigation of event related changes which are time-locked to the event, but not necessarily phase locked (i.e., when the phase of the event-related response is the same or very similar across all individual trials). Neural oscillations can be characterized as a compilation of sine waves of different frequencies (i.e., the number of cycles per second, or Hertz (Hz)); peak amplitude (i.e., the magnitude of change) and phase (i.e., a specific point in the cycle of the sine wave relative to its origin; Mathalton, Vikaas & Sohal, 2015). The temporal frequencies of neural oscillations are classically divided into five frequency bands: delta (1~2 Hz); theta (3~7 Hz); alpha (8~12 Hz); beta (13~30 Hz) and gamma (30 ~200 Hz). I specifically looked at oscillatory power (i.e., the strength of the signal at a particular time-frequency point; amplitude squared), which has proven a powerful method to investigate language comprehension (Prystauka & Lewis, 2019).

Theoretical perspectives on neurofunctional reorganization

Neuroimaging studies have provided substantial evidence of distinctively different patterns of neural activation between young and older adults under identical task requirements. Older adults generally show a more widespread pattern of activity in relation to young adults (Cabeza et al., 2002; Davis, Dennis, Daselaar, Fleck & Cabeza, 2008). There are two prominent views on the significance of the more diffuse activity in older adults. According to the first view, the appearance of widespread activity in the older brain reflects a general decline in neural efficiency, or reduced cerebral specialization. The term *dedifferentiation* is commonly used to refer to this account (Baltes & Lindenberger, 1997; Wingfield & Grossman, 2006). An alternative interpretation is that the age-related alterations in brain functions reflect focused recruitment as a means to compensate for neurocognitive decline. Consequently, the degree to which an older individual displays certain age-related activity patterns might be associated with better performance. This is commonly referred to as *compensation* (Wingfield & Grossman, 2006).

The two concepts of dedifferentiation and compensation form the basis of a number of theoretical frameworks that have been developed in order to explain patterns of age-related changes in brain activity. The finding of a more bilateral pattern of frontal recruitment in older adults has led to the development of the HAROLD model, *Hemispheric Asymmetry Reduction in Older Adults* (Cabeza, Anderson, Locantore & McIntosh, 2002). The reduction in hemispheric activity has been observed across different cognitive domains and, according to this framework, illustrates a key feature of neural processing in the ageing brain. The age-related decrease in lateralization as proposed by the model may reflect dedifferentiation, as well as compensation processes. Evidence supporting either of the two views can be found in the literature (*compensation:* e.g., Cabeza et al., 1997; Reuter-Lorenz et al., 2000; *dedifferentiation*: e.g., Meunier, Stamatakis & Tyler, 2014; *both:* Burianová., Grady, Moscovitch, 2013.). Another frequently observed pattern of age-related change in brain activity is a relative shift from posterior to anterior involvement, known as the *posterior-anterior shift in aging* (PASA, Grady et al., 1994; Davis et al., 2008). Among studies demonstrating an effect of age consistent with PASA, some find support for a compensatory role, while other studies find negative correlations with performance or non-significant trends (for a review on functional age-related change and cognitive performance with fMRI, see Eyler, Sherzai, Kaup & Jeste, 2010). In an attempt to synthesize the variety of reported activity patterns into one framework, the *Compensation-Related Utilization of Neural Circuits Hypothesis* (Diaz Rizio &

Zhuang, 2016; Reuter-Lorenz & Lustig, 2005), contextualizes age-related differential activity patterns in task difficulty. According to this framework, older adults exhibit patterns of brain activity that may appear compensatory in nature at low levels of task difficulty. However, when task difficulty exceeds the resources available, compensatory mechanisms break down. Consequently, performance declines and evidence for dedifferentiation emerges. Similarly, according to the Scaffolding Theory of Aging and Cognition (Reuter-Lorenz & Park, 2014) an individual's level of cognitive function is determined by a combination of structural change, functional deterioration and compensatory scaffolding, a form of positive plasticity which provides additional support in order to preserve cognitive function through the engagement of supplementary neural circuits. In summary, these different frameworks all share the notion that age-related alterations in brain activity patterns are associated with differences in cognitive performance between young and older adults. However, interpretations vary as to whether this reflects beneficial adaptation, or reduced neural efficiency.

Neurofunctional reorganization in language processing … Compensation? ... Dedifferentiation?

Much previous research on cognitive ageing has focused on syntactic processing, which, in young adults, involves a strongly left lateralized network of inferior-frontal and temporal regions (Snijders et al., Shafto & Tyler, 2014), making this an ideal candidate for examining age-related differences in neural processing. A frequent observation is that, compared to younger adults, older adults show similar, or reduced activity in the regions associated with syntactic processing in young adults, but increased activity in additional regions (Grossman et al., 2002; Peelle, Troiani, Wingfield & Grossman, 2009; Campbell et al., 2016; Peelle, 2019). While some research suggests that the recruitment of additional brain regions serves behavioural preservation of cognitive functioning (e.g., Grossman et al., 2002), other studies do not find a relationship between additional activity and task performance (Peelle et al., 2009). For example, Tyler et al., (2010) found that syntactic processing in older compared to younger adults was associated with increased activity in the right inferior frontal gyrus. However, while this additional activity was associated with decreased gray matter density in the right temporal gyrus, behavioural performance was only associated with left-hemisphere activity.

Beyond observations of increased or decreased activity of individual brain regions, some research suggests that healthy ageing is affected by reduced coherence of functional networks in the brain (Andrews-Hanna et al., 2007, Campbell et al., 2006). In the context of sentence processing, Peelle et al. (2009; mentioned above), found a significant reduction in coordinated activity between the core brain regions supporting sentence comprehension in older compared to younger adults.

In sum, despite ample evidence in the fMRI literature that syntactic processing in the ageing brain is subject to functional reorganization, it is less clear how age differences in brain activity relate to behavioural performance. When the additional activity is not predictive of performance, it is sometimes interpreted as serving a supportive role in working memory related processes or processing demands related to task performance (Peelle et al., 2009, Campbell et al., 2016).

In *Chapter 2,* I further investigate age-related change in syntactic processing using EEG. I examined the oscillatory activity in the EEG during syntactic binding in a group of older adults, as well as the relationship between oscillatory activity and behavioural performance on a syntactic judgement task. At its most fundamental level, syntactic binding refers to the combination of words into larger structures, taking into account features that determine syntactic structure, agreement and tense (Segaert et al., 2018). This elementary computation, otherwise known as *merge* (Chomsky, 1995, Zaccarella & Friederici, 2015) or *unification*

(Hagoort, 2005, 2009, 2016) forms the foundation of structure building of increasing syntactic complexity. Building on the methodology of *Chapter 1,* I investigated syntactic binding by using minimal phrases consisting of a pronoun and a pseudoverb (e.g., "*I dotch*", "*she spuffs*"). The use of pseudoverbs instead of real verbs limits the influence of lexical-semantic content to syntactic binding. Functional neural signatures for syntactic binding were assessed by comparing the oscillatory response to sentences that differentially load on morpho-syntactic binding. I aimed to determine whether the neural signatures associated with syntactic binding relate to behavioural performance in older adults. Evidence of a relationship between successful behavioural performance and a neural signature that deviates from that seen in younger adults would provide initial support for the existence of compensatory mechanisms in syntactic processing in older adults.

Language comprehension in Mild Cognitive Impairment and healthy ageing

In addition to understanding how the brain functionally reacts to structural and cognitive changes that result from healthy ageing, another key question in cognitive neuroscience concerns the effect of neurodegenerative disease on the changing brain. Indeed, ageing is associated with an increased risk of developing a number of neurodegenerative disorders, such as Alzheimer's disease (AD). AD is a progressive neurodegenerative disorder characterized by severe cortical volume loss and disturbance of cognitive functions (Dubovik et. al., 2013). Language impairments are some of the most prominent clinical features of AD and are commonly presented early in the course of the disease. Specifically, previous work reports a decline in semantic abilities and word-finding difficulties in AD (Bickel, Pantel, Eysenbach & Schröder, 2000). The earliest clinically detectable phase of the trajectory toward AD is Mild Cognitive Impairment (MCI; Markesbery, 2010). Consequently, the investigation of language impairments in individuals diagnosed with MCI is of great interest.

In *Chapter 3,* I investigated functional change in language processing in relation to the evolution of early cognitive impairment due to MCI. Using EEG, I investigated the oscillatory dynamics associated with lexical retrieval and semantic processing in language comprehension in individuals diagnosed with MCI and healthy older adults.

Overview of the present thesis

Taken together, the work reported here provides new insights into the dynamics of language comprehension in the ageing brain. In contrast to previous work suggesting preserved syntactic comprehension abilities in older adults, the study reported in *Chapter 1* provides clear evidence of age-related decline in syntactic comprehension performance in a minimal sentence context. In extension of these findings, the study reported in *Chapter 2* suggests the neural signature associated with syntactic binding is qualitatively different in older, compared to younger adults, yet characterized by a large degree of inter-individual variability. Lastly, the study reported in *Chapter 3* finds clear differences in the neural signature associated with lexical retrieval and semantic processing between individuals with Mild Cognitive Impairment and healthy age matched controls. The implications of these findings are brought together in the *General discussion.* Firstly, the evidence provided against preserved syntactic comprehension in healthy ageing in *Chapter 1* has implications for theories in cognitive ageing in general and theories on language comprehension in healthy ageing in particular. *Chapter 2* provides novel evidence on age-related functional change in syntactic processing. Findings from *Chapter 3* suggest the initial breakdown of the language system in Mild Cognitive Impairment can be seen in subtle alterations in neural oscillations.

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CHAPTER 1

EVIDENCE AGAINST PRESERVED SYNTACTIC COMPREHENSION IN HEALTHY AGEING. THE INFLUENCE OF AGEING ON ELEMENTARY SYNTACTIC COMPREHENSION

We investigated age-related differences in syntactic comprehension in young and older adults. Most previous research found no evidence of age-related decline in syntactic processing. We investigated elementary syntactic comprehension of minimal sentences (e.g., "*I cook*"), minimizing the influence of working memory. We also investigated the contribution of semantic processing by comparing sentences containing real verbs (e.g., "*I cook*") versus pseudoverbs (e.g., "*I spuff*"). We measured the speed and accuracy of detecting syntactic agreement errors (e.g., "*I cooks", "I spuffs"*). We found that older adults were slower and less accurate than younger adults in detecting syntactic agreement errors for both real and pseudoverb sentences, suggesting there is age-related decline in syntactic comprehension. The age-related decline in accuracy was smaller for the pseudoverb sentences, and the decline in speed was larger for the pseudoverb sentences, compared to real verb sentences. We suggest that syntactic comprehension decline is stronger in the absence of semantic information, which causes older adults to produce slower responses in order to make more accurate decisions. In line with these findings, performance for older adults was positively related to a measure of processing speed capacity. Taken together, we found evidence that elementary syntactic processing abilities decline in healthy ageing.

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Introduction

Syntactic processing is often discussed in the literature as a key example of a cognitive function that is relatively resilient to age-related decline (Campbell et al., 2016; Samu et al., 2017; Shafto & Tyler, 2014). Studies investigating the effect of age on syntactic comprehension typically use sentences with a complex syntactic structure, such as garden path sentences with a temporary syntactic ambiguity (Samu et al., 2017), or relative clause manipulations that require disambiguation of referential choices (Payne et al., 2014). The interpretation of such complex syntactic structures may not exclusively rely on syntax, but instead, may also require additional comprehension mechanisms including semantic and pragmatic processing. Consequently, such measures of complex sentence processing may not be ideal for measuring syntactic comprehension as an isolated process. Furthermore, complex syntactic structures might impose a larger burden on working memory, as long distance linguistic dependencies must be retained in working memory in order for successful syntactic and thematic integration to take place (Tan, Martin, & Van Dyke, 2017). However, for alternative views on the role of working memory in language processing, see (MacDonald & Christiansen, 2002). Given that age is associated with declines in working memory (Waters & Caplan, 2007), the use of such computationally expensive sentences is problematic. In the present work, we aim to address these issues by reducing the complexity of our stimuli to simple two word sentences, in order to investigate the comprehension of elementary syntactic structures. Consequently, contextual cues and working memory load are kept to a minimum. Moreover, we compare these elementary syntactic operations in real word versus pseudoword sentences, in order to investigate the contribution of meaning to syntactic comprehension. Lastly, we investigate whether individual differences in working memory capacity processing speed and physical health impact on decline in syntactic comprehension in healthy ageing.

Syntactic comprehension

Syntax plays a fundamental role in understanding spoken language. Syntactic information, in addition to other types of information, enables the listener to extract meaning from the incoming speech input. Syntactic processes are used in sentence comprehension in a number of ways, including structure building (e.g., combining words into larger units based on grammar rules and word category information) and checking agreement (e.g., in English, the verb needs to agree in number and person with the subject; Kaan & Swaab, 2002). Furthermore, syntax plays an important role in mapping thematic roles (e.g., mapping the agent ("doer") and patient ("doe-ee") onto certain positions in the sentence). The order of noun phrases to thematic role mapping strongly influences the complexity of the sentence structure and the number of syntactic operations needed to determine the meaning of a sentence. In sum, the level of syntactic processing required to understand spoken language can range from rather simple to very complex.

A considerable amount of research has focused on whether there is age-related decline in sentence comprehension. The emphasis in this line of research tends to be on complex sentence structures. Using a paradigm that capitalizes on syntactic ambiguity, Tyler and colleagues investigated syntactic processing during sentence comprehension in younger and older adults, in sentences varying in the level of syntactic processing required (Campbell et al., 2016; Davis, Zhuang, Wright, & Tyler, 2014; Meunier, Stamatakis, & Tyler, 2014; Samu et al., 2017; Shafto & Tyler, 2014). Specifically, unambiguous sentences have only one possible syntactic interpretation (e.g., "*sneering boys*"), whereas ambiguous sentences have two possible interpretations: an interpretation that, given its higher frequency in the language, is dominant or more expected (e.g., "*cooking apples are*"), or an interpretation that is subordinate or less expected (e.g., "*cooking apples is*"). Participants are asked to indicate whether the disambiguating word (*are* or *is* in the examples) is an acceptable or an unacceptable continuation of the sentence. For individuals without any language disorders, a conventional pattern of responding is to reject more (and respond more slowly to) subordinate sentences compared to dominant and unambiguous sentences, with little difference between the latter two sentences (Campbell et al., 2016). Tyler and colleagues repeatedly found no age-related differences in acceptability ratings (Davis et al., 2014; Meunier et al., 2014), or response times, in which the mean response time difference between the sentences requiring the most and the least syntactic processing (subordinate and unambiguous sentences) was used (Campbell et al., 2016; Samu et al., 2017). Another line of research has measured online syntactic processing with a word-monitoring task to investigate younger and older adults' ability to develop syntactically and semantically coherent representations (Tyler et al., 2010). Participants listened to sentences and were instructed to press a response key whenever they heard a pre-specified target word. Word position of the target word varied from early to late across the sentences. The sentences differentially loaded on syntactic and semantic processing: normal prose sentences had a normal syntactic, semantic and pragmatic structure; anomalous prose sentences had a correct grammatical structure but lacked sentential meaning, and randomly ordered word strings lacked grammatical and sentential meaning. Response times increased at later word positions in both normal and anomalous prose. Comparing a group of young and older adults, this pattern of word position effects showed no age-related performance differences. Taken together, these results suggest that syntactic comprehension is preserved in the late years of adult life. However, all these studies have placed complex syntactic structures at the forefront. Since the manipulations in these studies potentially do not exclusively investigate the contribution of syntactic processes, it is unclear to what extent the performance for processing these sentences also reflects additional (linguistic and pragmatic) comprehension mechanisms.

Moreover, even though in a large number of studies it is concluded that syntactic comprehension performance is preserved in healthy ageing, there are also several studies that have found age-related syntactic comprehension decline. Specifically, older adults tend to be less accurate and slower in answering comprehension questions for syntactically ambiguous sentences (Waters & Caplan, 2001 and Kemtes & Kemper, 1997). Obler, Fein, Nicholas, & Albert (1991) investigated age-related differences in the effect of syntactic complexity and semantic plausibility on sentence comprehension. Participants listened to sentences that were divided into six different syntactic types (active, passive, single negative, double negative, double embedded or comparative). Accuracy showed a general age-related decline and older adults were disproportionally less accurate at the harder sentence types. In a sentence picture matching paradigm with sentences of increasing syntactic complexity, Antonenko et al. (2013) found superior syntactic performance in younger compared to older adults. The paradigm consisted of sentences with three different levels of syntactic complexity. The easiest level did not have hierarchical embeddings (e.g., "*The tiger is crying, pulling the frog, and he is gray.*"), while the other two levels included one or two subordinate clauses (e.g., "*The tiger that is crying and pulling the frog is gray.*" and "*The tiger that is pulling the frog that is crying is gray.")*. A correct picture matching decision required full understanding of the sentence structure. Older adults were less accurate and slower than younger adults in the task, but the effect of syntactic complexity was not different between age groups. The behavioural results were related to brain function and structure. Syntactic abilities of young adults were associated with functional coupling in a dedicated, mainly left hemispheric syntax network. In contrast, the syntax network of the older adults included additional (frontal and parietal) regions supporting working memory as well as semantic processing. Indeed, numerous functional imaging studies have shown that older adults recruit different, or additional brain regions compared to younger adults to perform certain tasks, with some research suggesting these additional activity patterns are compensatory in nature (Cabeza, Anderson, Locantore, &

McIntosh, 2002; Grossman et al., 2002). Crucially, the finding by Antonenko et al. (2003) that syntactic ability in older adults was related to the recruitment of regions supporting working memory as well as semantic processes emphasizes the relevance of a behavioural measure that isolates the syntactic component in sentence comprehension.

The influence of semantic processing on syntactic comprehension

Syntactic comprehension is strongly influenced by semantic information. However, there exists debate with respect to the time course within which the integration of syntactic and semantic information takes place. Serial syntax-first models assume the language processing system initially constructs a simple syntactic structure independent of lexical-semantic information and semantic aspects are integrated at a later stage (Frazier & Fodor, 1978; Kimball, 1973). In contrast, interactive-constraint models assume syntactic and semantic processes interact at any time (Marslen-Wilson & Tyler, 1980; Taraban & Mcclelland, 1988). A third approach, the neurocognitive model of auditory sentence processing (Friederici, 2002) argues that autonomous and interactive processes coexist, but describe different processing phases during language comprehension.

Some research suggests that the interplay between syntax and semantics changes with age. Specifically, older adults rely on morpho-syntactic information to a lesser degree than young adults when other cues for sentence interpretation are available (Bates, Friederici, & Wulfeck, 1987). For example, Obler et al. (1991; mentioned above) did not only investigate age-related decline in processing syntactic complexity, they also investigated whether semantic information can aid in processing syntactically complex sentences. Sentences were either semantically plausible or implausible. Older adults were disproportionately less accurate in acceptability judgements for more syntactically complex sentence types but also for implausible sentences. The authors therefore suggested that older adults come to rely more on processing strategies that stress the plausibility of the semantics of the sentences in terms of their world knowledge rather than on a strict decoding of the syntactic structure. These results are in line with more general findings suggesting that older adults increasingly rely on semantics and world knowledge in auditory sentence processing and reading comprehension (Wingfield et al., 1994; Wingfield, 1996 and Soederberg Miller et al., 2004) as well as in other domains, such as memory (e.g., Castel, 2005; Rowe, Valderrama, Hasher, & Lenartowicz, 2006). In sum, previous findings suggest that non-syntactic components such as semantics and pragmatics facilitate syntactic comprehension and that contextual information in sentence comprehension becomes more important with age.

The moderating effect of individual differences

Although there exists a general picture of cognitive decline in healthy ageing, there is also a large amount of individual variability. In fact, the heterogeneity in performance tends to increase with age (Stones, Kozma & Hanna, 1990). As comprehensibly described in a review by Peelle (2019), an individual's performance on a language task is not only determined by the task requirements, but also by the processing resources available to that individual. The level of resources available varies widely in older adults, with processing efficiency being determined by the person's working memory, attention and processing speed abilities, but also by neuroanatomical features (Peelle, 2019). Neuroanatomical features in turn are related not only to the person's chronological age, but also to other factors such as the person's aerobic fitness level (Hillman, Erickson, & Kramer, 2008; Lazarus, Lord, & Harridge, 2018). Understanding what accounts for inter-individual variability in age-related decline in cognitive tasks is therefore an important issue in ageing research.

It is well known that ageing is associated with decline in working memory capacity and processing speed (Waters & Caplan, 2007); both are known also to contribute to language comprehension (Just & Carpenter, 1992; Salthouse, 1996). A study by Wingfield, Peelle & Grossman (2003) on the effects of speech rate and syntactic complexity in young and older adults established the moderating influence of processing speed on age differences in sentence comprehension. In this experiment, a group of younger and older adults heard short sentences that differed in syntactic complexity by using subject relative clauses (e.g., "*Men that assist women are helpful*") and object relative centre embedded clauses (e.g., "*Women that men assist are helpful*"). Furthermore, speech rate was time compressed to 80%, 65%, 50% or 35% of the original speaking time, varying the processing challenge. Participants were asked to indicate whether the action was performed by either a male or female character. Accuracy was lower for the more complex object-relative clause sentences than for the easier subject-relative sentences for both age groups, with older adults showing disproportionally poorer comprehension accuracy only at accelerated speech rates. While older adults were slower than younger adults at all speech rates, older adults had disproportionately longer response times for accelerated speech rates and more complex syntactic structures. In a similar vein, a number of studies have demonstrated that the influence of working memory capacity on sentence processing is larger among older compared to younger adults. Payne et al. (2014) found that age differences in relative clause comprehension were largely modulated by individual differences in working memory capacity and that this influence was exaggerated among older adults. Specifically, during comprehension of sentences introducing a temporary syntactic attachment ambiguity (e.g., "*The son of the princess who scratched himself/herself in public was humiliated*"), poorer working memory capacity in older adults was associated with increased processing time in sentences in which the reflexive pronoun referred to the object of the modifying prepositional phrase (*herself, the princess*). Payne et al. (2014) suggest that with increasing age, attentional control resources in working memory are recruited at progressively lower levels of difficulty in order to maintain comprehension. These findings illustrate the importance of investigating how individual differences in working memory and processing speed contribute to age-related differences in syntactic comprehension.

Another factor that has gained increasing attention is a person's physical health. Taking into account variability in health characteristics could explain a considerable proportion of variance that would otherwise be ascribed to age (Raz, 2009). In this context, Lara et al. (2015) have proposed a set of biomarkers of healthy ageing, in which healthy ageing was operationalised as preserved physical, cognitive, physiological, endocrine, immune and metabolic functions. Lifestyle variables such as regular physical activity and aerobic fitness have gained much attention in research focused on differential cognitive ageing (Colcombe et al., 2004) and aerobic fitness levels have been shown to be associated with word production in healthy older adults (Segaert et al., 2018). In the current study, we measured grip strength, because it is an established marker of a person's physical health (Lara et al., 2015) and it has previously been related to cognitive decline (Auyeung, Lee, Kwok & Woo, 2011). We will also administered a physical activity questionnaire. Addressing the moderating influence of working memory, processing speed and physical health can leverage the predictive power of research on age differences in syntactic comprehension.

Current study

In the current study we investigated whether there is age-related decline in syntactic comprehension. Specifically, our aims were threefold. Firstly, we aimed to test whether the comprehension of elementary syntactic structure is preserved in older age. Secondly, we aimed to test whether lexical-semantic content aids syntactic comprehension and whether this changes with age. Thirdly, we aimed to investigate whether individual differences in working memory capacity, processing speed and physical health modulate syntactic comprehension and moreover, whether the impact of these increase with age.

We investigated syntactic comprehension in an auditory syntactic judgement task, in a group of younger and older participants. The complexity of our stimuli was reduced to simple two word phrases consisting of a pronoun and a verb (e.g., *"I walk").* Consequently, working memory load for processing these phrases is minimal. A similar task was used in Segaert, Mazaheri and Hagoort (2018). In the present study, lexical-semantic content was varied by using existing verbs versus pseudoverbs. A pseudoword follows the orthographic and phonological rules of a language, but has no meaning in the mental lexicon of that language. The pseudoverbs were used to create phrases of minimal semantic content (e.g., *"she ploffs"*), whereas the existing verbs were used to create semantically meaningful phrases (e.g., *"she cooks"*). The pseudoverbs and existing verbs formed two separate experimental blocks, identical in all aspects but the use of the pseudoverbs versus the real verbs. We refer to these blocks as the "Pseudoverb" and "Real verb" block respectively. The task was to listen to the phrases and indicate whether it was morpho-syntactically correct (yes/no). In addition to accuracy, response time (RT) was measured from the start of the response screen to the button press.

To investigate the impact of individual differences on syntactic comprehension, we measured important biomarkers of healthy ageing (Lara et al., 2005): physical health was assessed using strength grip and a physical activity questionnaire; cognitive functioning was assessed through a working memory capacity, processing speed and verbal IQ measure.

We predicted the following. First, in line with most previous findings of preserved syntactic comprehension in ageing, we predicted that performance on the real verb phrases would be equivalent for young and older adults. Second, we expected reduced performance on the pseudoverb phrases for older adults, compared to young adults, in line with previous findings suggesting that older adults come to rely more on strategies involving semantic processing. We also expected a stronger influence of working memory and processing speed for older compared to young adults. Lastly, if a relationship exists between physical health and syntactic comprehension in older adults, we expected to find that age-related decline in syntactic comprehension would be modulated by physical health, with higher levels of physical health associated with better performance in older adults.

Methods

Participants

50 young university undergraduates (45 women, mean age: 19, SD: 0.92, range 18- 21 years; 5 men, mean age: 20, SD: 0.89, range 19- 21 years) and 50 older adults (28 women, mean age: 71, SD: 5.79, range 60 – 82 years; 22 men, mean age: 72, SD: 5.68, range: 62- 86 years) participated in the study. Participants were recruited via the database of the School of Psychology of the University of Birmingham. All participants were native British English speakers with normal or corrected to normal hearing. Exclusion criteria included bilingualism, neurological disorders, speech or language disorders and dyslexia. To assess general cognitive function, the Montreal Cognitive Assessment test (MoCa; version 7.1) was administered to the elderly participants, resulting in 5 participants being excluded, as their scores were equal to or below the cut-off value of 26. Consequently, 45 older participants (23 women, mean age: 71, SD: 5.66 and 22 men, mean age: 73, SD: 5.61) were included in the analyses. The older participants' education level ranged from Primary School (1 participant); O-levels/GCS2 (11); A levels/Vocational Course (6); Bachelors/Undergraduate level (21) and Master's degree or higher (10). All participants gave informed consent. Students were given university credits as compensation; older adults received monetary compensation. The research was conducted at the University of Birmingham and had full ethical approval.

Materials

A set of 20 English pseudoverbs created by Ullman et al. (1997) served as stimulus materials for the Pseudoverb block: brop, crog, cug, dotch, grush, plag, plam, pob, prap, prass, satch, scash, scur, slub, spuff, stoff, trab, traff, tunch, vask. These pseudoverbs were all monosyllabic with an average word length of four letters and an average phoneme length of 3.7. All pseudoverbs could be inflected according to regular grammar rules for verbs in English. They could be combined with six pronouns (I, you, he, she, we, they) or with 6 adverbs (daily, quickly, safely, early, promptly, rarely). This would yield minimal phrases, such as "*I dotch*", "*he dotches*", "*they dotched*", or "*dotch quickly*". In addition, a set of twenty common English verbs were selected to serve as stimulus material for the Real verb block: chop, cook, cram, bake, drop, flap, skip, brew, rob, rush, scour, move, jog, slam, stir, tug, walk, pull, stack and reap. These were regular monosyllabic verbs, matched in length to the pseudoverbs with an average phoneme length of 3.5. Like the pseudoverbs, these real verbs could be combined with a pronoun, or an adverb to form minimal phrases, such as "*I chop*", "*she chops*", "*they chop*", or "*chop quickly*". The same adverbs were used with both the pseudoverbs and real verbs. The adverbs were all disyllabic and care was taken to ensure that combining them with any of the real verbs would form a semantically meaningful combination.

Digital recordings of all stimuli were made using a male native speaker of English. All verbs were recorded in first, second and third singular and plural present tense. Each stimulus was pronounced three times, after which the clearest recording was selected. In order to equalize the volume of the individual recordings, all audio files in wav format were normalized to 1db using the software program Adobe Audition.

Design

The order of the Real verb and Pseudoverb blocks was counterbalanced across participants. Both blocks consist of the same four conditions (see Table 1). In the *correct syntax condition* a (pseudo)verb was paired with a pronoun, resulting in a morpho-syntactically correct combination (e.g., *"she cugs", "she walks"*). In the *incorrect syntax condition*, integration could be attempted, but the inflection of the verb/pseudoverb did not match the pronoun (e.g., *"she cug", "she walk"*). In addition, two filler conditions were included. For the *no syntax filler condition*, the verb/pseudoverb was paired with another verb/pseudo (e.g., "*dotch cugs*", "*bake walks*"). This combination of stimuli should not trigger integration processes at a morpho-syntactic level. The *no syntax* filler condition was included in the current experiment in order to verify that participants indeed read these phrases as a pairing of two verbs/pseudoverbs and did not attempt to integrate them. The purpose of this condition (merely a filler condition in the present experiment) was to include it as a condition of interest (a baseline condition) in a follow-up EEG experiment. Finally, the *adverb filler condition* consisted of a verb/pseudoverb paired with an adverb (e.g., *"cugs quickly", "walks quickly"*). The purpose of the adverb fillers was to avoid any predictability in the engagement of integration processes for pairs beginning with a verb/pseudoverb. Specifically, a word pair starting with a verb/pseudoverb had an equal chance of forming a syntactically correct or incorrect word pair. To briefly preview the results, participants were highly accurate on the filler trials (above 90% across experimental blocks in both age groups), suggesting participants understood the task. An overview of the stimulus sets for both blocks and examples of all conditions is provided in Table 1.1.

Table 1.1 Example stimuli in each condition for the Pseudoverb and Real verb block with trial numbers per condition

condition [number of trials]		example pseudoverb	example real verb	correct sentence?
correct syntax condition	[36]	I ploff she ploffs we ploffed	I pull she pulls we pulled	Yes
incorrect syntax condition	[36]	I ploffs he ploff	I pulls he pull	No
no syntax filler	[36]	ploffs dotch ploff dotches ploff dotched	walks pull walk pulls walk pulled	No
adverb filler	[36]	ploff quickly ploffs quickly ploffed quickly	walk quickly walks quickly walked quickly	Yes

Task

Participants were tasked with detecting grammatical mistakes. The timing of each component in one trial is illustrated in Figure 1.1. Each trial started with a fixation cross (1000 ms) and a blank screen (1000 ms). Following this, the minimal phrase was presented word by word with a Stimulus Onset Asynchrony of 1200 ms. The Inter Stimulus Interval (ISI) between the first and the second word varied as a function of the duration of the first word and ranged between 300 and 900 ms. A response screen showing the text "*Was this a grammatically correct sentence?*" appeared 805 ms after the onset of the second word and remained on the screen until a button press. The ISI between the second word and the response screen varied between 100 and 505 ms as a function of the duration of the second word. Participants were instructed to indicate whether the word pair they just heard was grammatically correct by clicking the left and right mouse button to respond with 'yes' or 'no' respectively. The response screen was followed by a blank screen for 6 ms. The correct response for each condition is listed in Table 1.1. The experiment was run using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

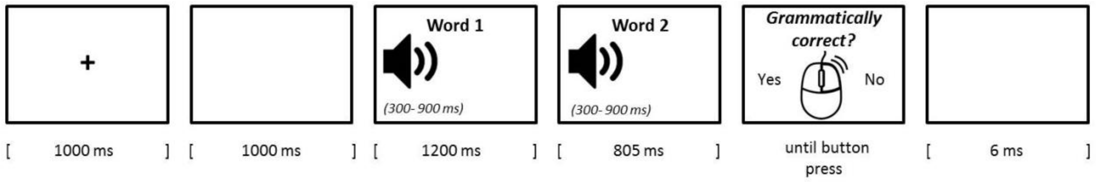

Figure 1. 1 Timing of the components of one trial.

Experimental lists

As can be seen in Table 1.1, the correct syntax condition can be formed with three possible pronoun – verb/pseudoverb combinations. That is, the verb/pseudoverb *stem* combined with either 'I', 'you', 'we' or 'they'; the verb/pseudoverb stem plus *–s* combined with 'he' or 'she', or the verb/pseudoverb stem plus *–ed* combined with each of the six pronouns. Each form occurred 12 times and the possible pronouns within each form occurred an equal number of times. This means that each possible pronoun occurred 3 times in the *stem form*, 6 times in the *–s form* and 2 times in the *–ed form*. The verbs/pseudoverbs were randomly assigned to the pronouns, with the constraint that each verb would occur only once in each form. The incorrect syntax word pairs were formed according to the same criteria. However, as no incorrect combination can be composed with the *–ed form*, only two forms were possible. To ensure an equal number of trials across conditions, both the *stem form* and *-s form* consisted of 18 trials in this condition, again ensuring that the possible pronouns occurred an equal number of times. The no syntax filler condition consisted of three possible forms, such that the second verb could either be *stem-form*, *-s form*, or *–ed form*, with 12 trials per form. To avoid repetition effects, the first word of the pair in this condition could neither be the same verb nor have the same ending as the second word of the pair. Lastly, the adverb filler condition also consisted of three possible forms, with the first word being either in *stem- form*, *-s form*, or *–ed form*, followed by randomly assigned adverbs as the second word. There were 36 trials per condition, resulting in 144 trials in total for both blocks.

A unique randomized stimulus list was created for each participant and divided into three separate sections, separated with self-paced breaks. The order of the Pseudoverb and Real verb block was counterbalanced between participants. Each block was preceded by a unique list of 33 practice trials.

Inter-individual variability markers

A number of individual differences measures were collected to assess the physical health and cognitive functioning of our participants.

Markers of cognitive function: The Backward Digit Span task (Waters & Caplan, 2003) was administered to measure *working memory capacity*. Using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA), participants were instructed to attend to a series of visually presented digits of increasing length. After the presentation of the last digit, participants were instructed to enter the digits in the reverse order by using the numbers on the keyboard. The task began at a length of two digits and went up to seven digits. There were 5 trials at each digit length. No practice trials were included. Span size was defined as the longest digit length at which a participant correctly recalled three out of five trials. If a participant recalled two out of five trials correctly at the longest digit length, half a point was added to the total score. The raw span size scores were used in the analyses.

Using the WISC-IV Coding subtask (WAIS-IV; Wechsler, 2008), *processing speed* was assessed. In this task, the participant is asked to copy symbols that are paired with numbers within 120 seconds. A point is assigned for each correctly drawn symbol completed within the time limit. The total raw score is the number of correctly drawn symbols, with a maximum of 135. The raw scores were converted into age-scaled scores using the WAIS-IV manual.

Verbal IQ was assessed by means of the National Adult Reading Test (NART), based on Nelson and Willison (1991). The NART consists of 50 words with atypical phonemic pronunciation. Participants were instructed to slowly read aloud the list of words. Auditory recordings were made of the responses, which were individually rated by a native British speaker as either correct or incorrect according to the correct pronunciation as given by Google translate (2017, January 18). The NART error score consists of the total number of errors made on the complete NART. The Verbal IQ score that was used for analyses was calculated according to standard procedures: Estimated Verbal IQ = 129.0 – 0.919 X NART error score.

Markers of physical health: We assessed grip strength using a standard adjustable hand dynamometer (Takei Scientific Instruments). Standing in upright position, the participant was instructed to hold the dynamometer towards the ceiling with a completely outstretched arm, so that the shoulder and elbow were fully flexed at 180 degrees, hand palm facing the gaze direction. From this starting position, the participant was instructed to move their arm downwards in three seconds while squeezing the dynamometer with maximum force. A total of three measurements were recorded for the dominant and non-dominant hand, which was preceded by three practice trials for each hand. The highest value of the dominant hand was used for analyses. These raw scores were converted into standardised z-scores within age- and gender groups.

A physical activity questionnaire (New Zealand Physical Activities Survey Short Form; Sport and Recreation New Zealand, 2001) was included as a self-report measure of the participants' habitual practice of physical activity. A composite score, calculated by adding the duration (in minutes) of moderate activity and two times the duration of vigorous activity, was used for analyses.

Procedure

As mild hearing loss is a common condition in elderly people and the ability to clearly hear the stimuli is crucial for the aim of our study, the procedure started with a volume check. Participants listened to 20 randomly selected stimuli (10 real verbs and 10 pseudoverbs) through headphones and were asked to repeat what they heard. The experimenter paid special attention to correct pronunciation of the words' suffices. Volume settings were adjusted if necessary.

Half of the participants started with the Pseudoverb block and the other half started with the Real verb block. Instructions were identical in both blocks. After the participant read the instructions, the experimenter briefly summarized the procedure. Participants wore headphones and used the computer mouse to give their responses. Both blocks started with 33 practice trials, such that each possible word pair combination occurred three times. Participants received verbal feedback on their performance on the practice trials and only proceeded to the real experiment when they had a clear understanding of the task. The same procedure was repeated for the other block. Participants were instructed that the task in the second block was exactly the same as the previous one, only this time with real/pseudoverbs.

Each block took on average 30 minutes to complete, including the practice trials and two self-paced breaks. Participants were then tested on the additional measurements which were conducted in the following order: the Backward Digit Span Task; the Hand Grip Strength; the Physical Activity questionnaire; the Coding task and lastly the NART.

Data analyses

The dependent variables are the accuracy and response time (RT) on the correct syntax and incorrect syntax trials[1]. The RT data for each participant in each condition was subjected to a ± 2 standard deviation trim, resulting in an exclusion of 5% of the data points in both groups. Lastly, one elderly participant was removed from further analyses due to excessively long RTs (mean 2522, sd 1827, compared to the group mean 1164, sd 949)[2]. Only correct responses were included in the RT analyses. We analysed accuracy using a mixed-logit model in R (R Core Team, 2015), using the *lme4* package (Bates, Mächler, Bolker & Walker, 2015). This method is most suitable for analysing categorical responses while excluding the necessity to conduct separate participant and item analyses (Jaeger, 2008). RT was analysed with a linear mixed model. The use of mixed effects models offers the opportunity to estimate effects and interactions of the experimental manipulations, or fixed effects, while simultaneously estimating parameters of the variance and covariance components of individual subjects and items as random effects (Kliegl, Wei, Dambacher, Yan, & Zhou, 2011).

To avoid multicollinearity in the regression models, we computed the Pearson's correlation coefficients and p-values for our predictors using the *corrplot* package in R (Wei & Simko, 2016). Given that all correlations had a Spearman's rank correlation coefficient <0.3, all predictors were included in the models.

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[1] To preview the results, there was no difference in response bias between the two age groups. A response bias would result in a performance difference between the two conditions. For example, a bias towards responding with 'yes' would result in a lower accuracy in the correct syntax condition ('yes' here is a mistake) compared to the incorrect syntax condition ('yes' here is correct). We ran a t-test to verify whether there was a difference in the mean accuracy between the two conditions for both age groups individually. There was no significant difference in accuracy, neither in the younger age group (t(98) = -0.40, p = 0.69), nor in the older age group (t(98) = 0.12, p = 0.91).

[2] However, running the RT model with this outlier participant included did not affect the outcomes.

The regression models for predicting both RT and Accuracy were based on the following predictors: Verb type (Pseudoverb and Real verb); Syntax condition (correct and incorrect); Age group (younger and older); Working Memory capacity; Processing Speed; Hand grip; Physical activity and Verbal IQ. Our categorical predictors verb type, syntax condition and age group were all sum coded, such that the intercept of the model represents the grand mean (across all conditions) and the coefficients can directly be interpreted as main effects. Continuous variables were centred.

We began with a full model and then performed a step-wise "best-path" reduction procedure for the fixed effects to determine the simplest model that did not differ significantly from the full model in terms of variance explained (as described in Weatherholtz, Campbell-Kibler & Jaeger, 2014) using the drop1 function from the *stats* package (version 3.4.2). We used a maximum random effects structure, allowing us to include intercepts for participants and items ("random intercepts"), as well as well as by-participants and by-item random slopes for the fixed effects. When the model did not converge with the fully expressed random effects structure, we simplified the random effects structure removing first the interactions, followed by the slopes which contributed least to the variance explained (Barr, Levy, Scheepers, & Tily, 2013).

Given that we were interested in the relationship between age and syntactic comprehension, the interactions that arose with the predictor age group were further examined in post hoc analyses in which the regression models were applied to each age group individually. Following this, the significant two way interactions in the post-hoc models were probed by testing each of the simple slopes for significance, using the *jtools* package in R (Long, 2018). Because the jtools package does not support lmer objects, we re-estimated the fixed effects using a lm function for our post hoc response time analyses.

Results

A. Group differences on individual differences measures

Table 1.2 provides an overview of the additional measurements for the younger and older age group. In accordance with typical findings, the young participants outperform the older participants in working memory capacity and processing speed. To disentangle the effect of age from processing speed, the scaled scores were used in the analyses. However, for the sake of completeness, the raw scores are reported as well. The older participants performed significantly better in terms of verbal IQ. There was no difference in physical activity or hand grip strength between both groups.

Table 1.2 Means and standard deviations of additional measurements for the young and older age group and the results of comparisons between the age groups (independent samples t-test)

	Younger age group (N=50)		**Older age group (N= 50)**		**Comparison**	
	mean	sd	mean	sd	t	p
Working Memory capacity	5.57	1.57	4.57	1.59	3.1417	0.002
Processing Speed	80.34	14.91	62.92	16.48	5.5424	< 0.001
Processing Speed scaled	11.52	2.91	12.52	16.48	-1.7233	0.088
Verbal IQ	28.08	4.70	39.60	5.32	-11.314	< 0.001
Physical activity	122.28	121.22	131.20	102.49	-0.39736	0.692
Hand grip	25.92	7.54	26.99	8.85	-0.65062	0.517

B. Age differences in response accuracy for syntactic comprehension

We first discuss the main effect of age group and verb type on accuracy in order to answer our first two research questions concerning the effect of age on syntactic comprehension and the influence of semantic information. Following this, we will look at the effect of individual variation in our biomarkers on these results. Table 1.3 presents the results from the final mixed model predicting accuracy. This model was not significantly different from the full model (Full model = AIC: 6601.6, BIC 6915.4; Best model= AIC: 6598.8, BIC: 6897.7, p = 0.5447).

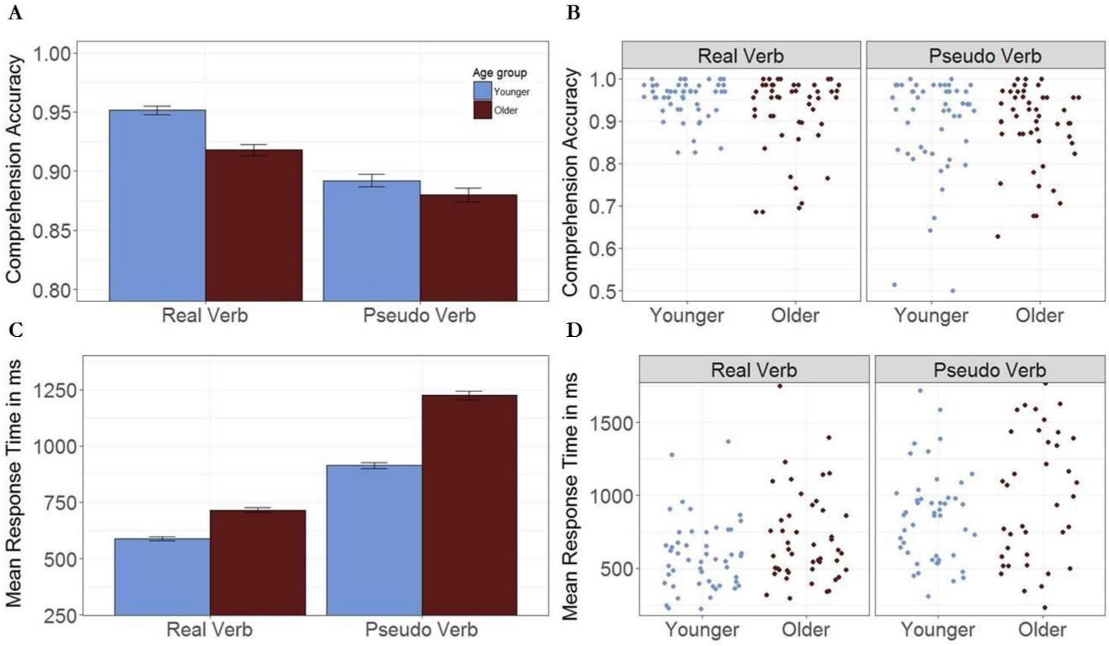

Figure 1.2 Age-related performance differences in accuracy (top row) and speed (bottom row) for syntactic comprehension. Group average proportion of correct comprehension per age group **(A)** and individual means **(B).** Group average response times (RTs) to correct responses for the two age groups **(C)** and individual means **(D).** We have collapsed across the correct integration and incorrect integration condition in these graphs. Error bars are standard errors of the mean.

Figure 1.2 (panel A) shows the group average of the proportion of correct responses given by the younger and the older age group for each of the two blocks. The younger age group obtained a mean accuracy of 95% (sd = 23) in the Real Verb block and a mean accuracy of 89% (sd =31) in the Pseudo Verb block. The older age group obtained a mean accuracy of 92% (sd = 29) and 88% (sd = 31) in the real- and pseudo verb block respectively. The younger age group reached higher accuracy levels compared to the older age group in both the Real Verb and the Pseudoverb block ($p < 0.001$), suggesting that indeed there is age-related decline in syntactic comprehension accuracy. Generally, participants were less accurate in the Pseudoverb block compared to the Real Verb block ($p = 0.001$). The age-related decline in syntactic comprehension was stronger in the Real Verb block than the Pseudoverb block, as revealed by the significant age group * verb type interaction ($p =0.039$).

Table 1.3 Coefficient estimates, standard errors (SE), associated t values and significance levels for all predictors in the generalized mixed model predicting accuracy

Coefficient	Estimate	Std. Error	z value	p	
(Intercept)	**3.07**	**0.18**	**16.63**	**< 0.01**	***
Working Memory	**0.17**	**0.06**	**2.64**	**0.01**	**
Age group	**1.58**	**0.312**	**4.96**	**< 0.01**	***
Verb type	**-0.77**	**0.23**	**-3.29**	**0.01**	**
Syntax condition	**0.29**	**0.14**	**2.07**	**0.04**	*
Processing Speed	0.03	0.03	0.74	0.46	
Handgrip	0.03	0.10	0.34	0.74	
Verbal IQ	**0.11**	**0.02**	**5.56**	**< 0.01**	***
Working Memory * Age group	-0.12	0.13	-0.90	0.37	
Working Memory * Verb type	-0.02	0.05	-0.29	0.77	
Age group * Verb type	**0.58**	**0.28**	**2.06**	**0.04**	*
Age group * Syntax condition	0.26	0.28	0.94	0.35	
Verb type * Syntax condition	0.08	0.27	0.32	0.75	
Working Memory * Syntax condition	0.05	0.05	0.99	0.32	
Age group * Processing Speed	0.01	0.07	0.11	0.91	
Verb type * Processing Speed	**-0.07**	**0.03**	**-2.34**	**0.02**	*
Syntax condition * Processing Speed	**0.07**	**0.03**	**2.53**	**0.01**	*
Age group * Handgrip	0.20	0.21	0.96	0.34	
Verb type * Handgrip	-0.03	0.08	-0.33	0.74	
Syntax condition * Handgrip	-0.00	0.08	-0.02	0.99	
Age group * Verbal IQ	0.03	0.04	0.70	0.48	
Verb type * Verbal IQ	**0.10**	**0.02**	**5.70**	**< 0.01**	***
Syntax condition * Verbal IQ	-0.01	0.02	-0.53	0.60	
Working Memory * Age group * Verb type	**-0.28**	**0.11**	**-2.58**	**0.01**	**
Age group * Verb type* Syntax condition	0.41	0.53	0.77	0.44	
Working Memory * Age group * Syntax condition	**0.41**	**0.10**	**3.95**	**< 0.01**	***
Age group * Verb type * Processing Speed	**0.21**	**0.06**	**3.76**	**< 0.01**	***
Age group * Syntax condition * Processing Speed	-0.06	0.06	-1.07	0.28	
Verb type * Syntax condition * Processing Speed	**-0.12**	**0.05**	**-2.20**	**0.03**	*
Age group * Verb type * Handgrip	0.23	0.16	1.49	0.14	
Age group * Syntax condition * Handgrip	-0.25	0.16	-1.61	0.11	
Verb type * Syntax condition * Handgrip	**-0.60**	**0.15**	**-4.01**	**< 0.01**	***
Age group * Verb type * Verbal IQ	-0.01	0.03	-0.39	0.70	
Age group * Syntax condition * Verbal IQ	0.04	0.03	1.10	0.27	
Verb type * Syntax condition * Verbal IQ	**0.14**	**0.03**	**4.07**	**< 0.01**	***
Age group * Verb type * Syntax condition * Processing speed	0.19	0.11	1.78	0.08	.
Age group * Verb type * Syntax condition * Handgrip	**-0.69**	**0.30**	**-2.28**	**0.03**	*
Age group * Verb type * Syntax condition * Verbal IQ	0.12	0.07	1.77	0.08	.

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 ‘ ’ 1

Model includes a random intercept for items and subjects.

In addition to these group effects, there was individual variation in performance accuracy for both groups (shown in panel 2b)[3]. Of particular interest are interactions between individual difference measures and age group, which were found for processing speed and for working memory capacity. We turn to these next.

Modulating effect of Processing Speed

There was a significant three-way interaction between Age group, Verb type and Processing Speed ($p < 0.001$), suggesting that Processing Speed modulates the effects of Age group and Verb type on the accuracy of syntactic comprehension. To further examine this interaction, we ran a post hoc analysis in which the same model was applied to each age group individually. The results of this post hoc analysis are presented in Table 1.4. Linear regressions were created to visualise the interaction between Verb type and Processing Speed for each age group separately. The left panel of Figure 1.3 shows the average accuracy as a function of Processing Speed in the younger age group for each Verb type separately. Accuracy was higher in the Real verb block compared to the Pseudoverb block. However, this effect of Verb type on accuracy did not depend on processing speed: there was no significant Verb type * Processing Speed interaction in the younger age group ($p = 0.310$). The right panel of Figure 3 shows the average accuracy as a function of Processing Speed for each of the two Verb types in the older age group. Similar to the younger age group, accuracy was higher in the Real Verb block compared to the Pseudoverb block. However, the effect of Verb type on accuracy was qualified by an interaction between Verb type and Processing Speed in the older age group ($p < 0.001$). To determine whether this interaction

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[3] To verify whether the variability in the older age group was larger compared to the younger age group, we performed a Bartlett test between the two age groups for each of the two blocks separately. The results confirm that variability is significantly larger in the older age group, both in the Real Verb block ($\chi2$ (1) = 176.16, p < .001) and the Pseudoverb block $\chi2$ (1) = 20.93, p < .001).

was due to a larger influence of processing speed in the Real Verb block relative to the Pseudoverb block, we ran a simple slope analysis for the influence of Processing Speed on accuracy for each level of Verb type (real versus pseudo). These post hoc z tests revealed the estimated beta coefficient in the Real Verb block was significantly different from zero (B = 0.10; se = 0.06; z = -1.10, p = 0.08). In contrast, the beta coefficient in the Pseudoverb block was not significantly different from zero (B = -0.06; se = 0.06; z = -1.10; p = 0.27). Taken together, the results for older adults indicate that the effect of Processing Speed on accuracy is present in the Real Verb block, but not in the Pseudoverb block. Older adults with higher Processing Speed performed better compared to older adults with lower Processing Speed in the Real Verb block. This suggests that higher processing speed in the older age group decreased the performance gap between younger and older participants in the Real Verb block. Note that we are using scaled Processing Speed scores so these effects cannot be attributed to effects of numerical age.

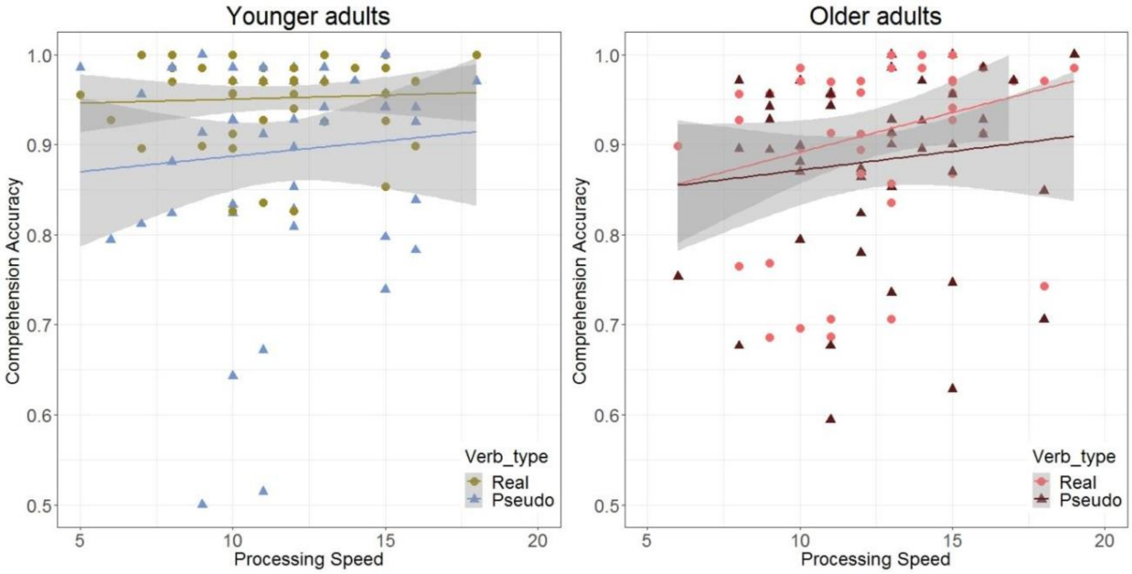

Figure 1.3 Processing speed modulates syntactic comprehension accuracy in the older age group. Three-way interaction between Age group, Verb type and Processing Speed depicted through a linear regression with accuracy as predicted by Processing Speed in the Real Verb and Pseudoverb block for each age group separately. The left panel shows the younger age group, the right panel shows the older age group. Processing Speed influenced the effect of Verb type on accuracy in the older age group, but not in the younger age group.

Modulating effect of Working Memory capacity

To assess whether Working Memory capacity modulates the effect of age group on accuracy, we looked at interactions between Working Memory capacity and age group. There was a significant three-way interaction between Age group, Working Memory capacity and Verb type (p = 0.010), which was further examined in a post hoc analysis by applying the same model to each age group individually (see Table 1.4). The left panel of Figure 1.4 shows the linear regressions of Working Memory capacity predicting accuracy for the two different Verb types in the younger age group. The effect of Verb type on accuracy was influenced by Working Memory capacity, as evidenced by the significant Working Memory * Verb type interaction (p = 0.028). To further interpret this interaction, we performed a simple slopes analysis for the effect of Working Memory capacity in each of the two Verb types. In the Real Verb block the estimated beta coefficient was significantly different from zero (B = 0.19; se = 0.09; z = 2.08; p = 0.04). In contrast, in the Pseudoverb block the beta coefficient was not significantly different from zero (B = 0.04; se = 0.08; z = 0.43; p = 0.67). This suggests that the effect of Working Memory capacity on accuracy was only present in the Real Verb block, such that younger adults with higher Working Memory capacity scores obtained a higher accuracy in the Real Verb block compared to younger adults with lower Working Memory capacity scores. The right panel of Figure 4 shows the linear regressions of Working Memory capacity predicting accuracy for the two different Verb types in the older age group. Working Memory capacity influenced accuracy in the older age group (p = 0.020), such that older adults with higher Working Memory capacity scores performed better than older adults with lower Working Memory capacity scores. However, the effect of Working Memory capacity did not differ across verb type: there was no significant Working Memory * Verb type interaction (p = 0.131). Notably, there was an additional significant three-way interaction between Age group, Working Memory capacity and Syntax condition

($p < 0.001$), which was driven by a significant interaction between Working Memory capacity and Syntax condition in the younger age group ($p < 0.001$), but not in the older age group ($p = 0.057$). The post hoc simple slopes analyses revealed a non-significant effect of Working Memory capacity on accuracy in the correct syntax condition (B = -0.02; se = 0.08; z = -0.19; p = 0.85) and a significant effect of Working Memory capacity in the incorrect syntax condition (B = 0.25; se = 0.09; z = 2.72; p = 0.01). These results indicate that lower Working Memory capacity was associated with lower task performance in the incorrect syntax condition in the younger age group.

Overall, this suggests that in younger adults, a lower working memory span is associated with a relative disadvantage in performance in comprehending real verb phrases and in correctly identifying morpho-syntactically incorrect phrases. In contrast, higher working memory capacity was associated with higher accuracy in the older age group regardless of verb type or syntax condition.

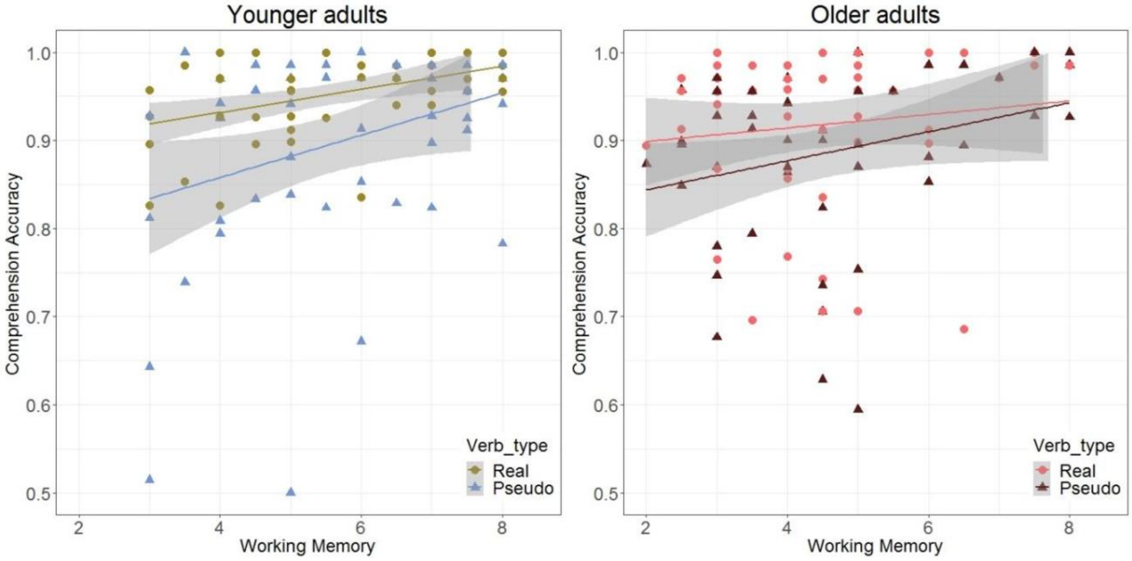

Figure 1.4 Working Memory capacity differentially affects syntactic comprehension accuracy depending on Age group. The three-way interaction between Age group, Verb type and Working Memory capacity, depicted by a linear regression between accuracy and Working Memory capacity grouped by Verb type in the younger age group (left panel) and the older age group (right panel). Lower Working Memory capacity in the young adults was associated with decreased accuracy in the Real Verb block. The relationship between Working Memory capacity and accuracy was not different for the two Verb types in the older age group.

Table 1.4A Coefficient estimates, standard errors, z values and p values of post hoc generalized mixed model predicting accuracy for the young age group. Model includes a random intercept for items and subjects

Coefficient	Estimate	Std. Error	z value	p	
(Intercept)	**3.25**	**0.17**	**19.14**	**< 0.01**	***
Working Memory	0.12	0.08	1.43	<0.16	
Verb type	**-1.19**	**0.26**	**-4.53**	**< 0.01**	***
Syntax condition	**0.49**	**0.12**	**3.93**	**< 0.01**	***
Processing Speed	0.03	0.04	0.68	0.50	
Handgrip	0.134	0.12	1.15	0.25	
Verbal IQ	**0.13**	**0.03**	**4.60**	**< 0.01**	***
Working Memory * Verb type	**-0.16**	**0.07**	**-2.19**	**0.03**	*
Verb type * Syntax condition	**-0.86**	**0.25**	**-3.45**	**< 0.01**	***
Working Memory * Syntax condition	**0.26**	**0.07**	**3.82**	**< 0.01**	***
Verb type * Processing Speed	0.042	0.04	1.02	0.31	
Syntax condition * Processing Speed	0.04	0.04	0.96	0.34	
Verb type * Handgrip	0.08	0.11	0.76	0.45	
Syntax condition * Handgrip	-0.12	0.11	-1.12	0.26	
Verb type * Verbal IQ	**0.09**	**0.03**	**3.19**	**<0.00**	**
Syntax condition * Verbal IQ	0.01	0.03	0.35	0.73	
Verb type * Syntax condition * Processing Speed	-0.02	0.08	-0.27	0.79	
Verb type * Syntax condition * Handgrip	**-0.97**	**0.22**	**-4.42**	**< 0.01**	***
Verb type * Syntax condition * Verbal IQ	**0.20**	**0.05**	**3.75**	**< 0.01**	***

Table1.4B Coefficient estimates, standard errors, z values and p values of post hoc generalized mixed model predicting accuracy for the older age group. Model includes a random intercept for items and subjects.

Coefficients	Estimate	Std. Error	z value	p	
(Intercept)	**2.72**	**0.16**	**17.07**	**< 0.01**	***
Working Memory	**0.23**	**0.10**	**2.32**	**0.02**	*
Verb type	**-0.49**	**0.19**	**-2.63**	**0.01**	**
Syntax condition	0.12	0.10	1.18	0.24	
Processing Speed	0.02	0.06	0.37	0.71	
Handgrip	-0.07	0.17	-0.41	0.68	
Verbal IQ	**0.10**	**0.03**	**3.39**	**< 0.01**	***
Working Memory * Verb type	0.12	0.08	1.51	0.13	
Verb type * Syntax condition	0.24	0.19	1.24	0.21	
Working Memory * Syntax condition	-0.15	0.08	-1.90	0.06	.
Verb type * Processing Speed	**-0.17**	**0.04**	**-4.45**	**< 0.01**	***
Syntax condition * Processing Speed	**0.10**	**0.04**	**2.62**	**0.01**	**
Verb type * Handgrip	-0.14	0.11	-1.24	0.22	
Syntax condition * Handgrip	0.12	0.11	1.10	0.27	
Verb type * Verbal IQ	**0.11**	**0.02**	**5.09**	**< 0.01**	***
Syntax condition * Verbal IQ	-0.03	0.02	-1.33	0.18	
Verb type * Syntax condition * Processing Speed	**-0.21**	**0.07**	**-2.83**	**0.05**	**
Verb type * Syntax condition * Handgrip	-0.27	0.20	-1.32	0.19	
Verb type * Syntax condition * Verbal IQ	0.08	0.04	1.874	0.06	.

*Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 ' ' 1*

Modulating effect of Handgrip strength

We found a significant four way interaction between Age group, Verb type, Syntax condition and Handgrip ($p = 0.027$). Post hoc analyses revealed this effect was driven by a significant interaction between Verb type, Syntax condition and Handgrip in the young age group ($p < 0.001$). There was no significant interaction between Verb type, Syntax condition and Handgrip in the older age group ($p= 0.187$). In the younger age group, accuracy in the incorrect syntax condition of the Pseudoverb block was particularly low and modulated by variability in Handgrip scores.

C. Age differences in response time for syntactic comprehension

Similar to the accuracy results, we will first discuss the overall group differences in response time in relation to Verb type before we discuss how these group differences can be further explained by the inter individual variability markers. Table 1.5 presents the results of the best linear mixed model predicting response times. This model was not significantly different from the full model (Full model = AIC: 183053 BIC 183510; Best model= AIC: 183034 BIC: 183395, $p = 0.902$). Figure 1.2 (panel C) shows the mean response times in ms on the Pseudoverb and Real Verb block for both age groups. The mean response time in the younger age group was 588 ms (sd = 478) in the Real Verb block and 913 ms (sd = 735) in the Pseudoverb block. In the older age group, the mean response time was 716 ms (sd = 735) in the Real Verb block and 1225 ms (sd = 1007) in the Pseudoverb block. The older age group took longer to respond than the younger age group ($p < 0.001$). In addition, response times were significantly longer in the Pseudoverb block compared to the Real Verb block ($p < 0.001$). Age-related decline in response times was larger for the Pseudoverb block compared to the Real Verb block, as revealed by the age group * verb type interaction ($p = 0.008$). Post hoc analyses within each age group revealed that the effect of Verb type exists in both age groups (see Table 1.6). However, as can be seen in Figure 1.2 C, the effect is larger in the older age group.

In addition to these group effects, we were interested in the moderating influence of our cognitive and physical markers, to further explain the individual variation in reaction times that was present in both groups (shown in panel 1.2 D)[4]. Of particular interests are interactions that modulate the effect of age group on response time, which were found for Processing Speed and Working Memory capacity. We turn to a description of these results next.

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[4] To verify whether the variability in the older age group was larger compared to the younger age group, we performed a Bartlett test between the two age groups for each of the two blocks separately. The results confirm that variability is significantly larger in the older age group, both in the real verb block ($\chi 2$ (1) = 264.48, p < .001) and the pseudoverb block $\chi 2$ (1) = 321.8, p < .001).

Table 1.5 Coefficient estimates, standard errors (SE), associated t values and p values for all predictors of linear mixed model predicting response time

Coefficient	Estimate	Std. Error	t value	p value	
(Intercept)	**998.15**	**62.31**	**16.02**	**< 0.01**	***
Working Memory	-14.30	24.97	-0.57	0.57	
Age group	**-527.15**	**126.22**	**-4.18**	**< 0.01**	***
Verb type	**478.64**	**59.24**	**8.08**	**< 0.01**	***
Syntax condition	**78.67**	**27.75**	**2.84**	**0.01**	**
Processing Speed	-23.93	13.88	-1.72	0.09	.
Handgrip	-2.76	41.71	-0.07	0.95	
Physical Activity	0.28	0.34	0.81	0.42	
Verbal IQ	**-23.48**	**8.09**	**-2.90**	**0.00**	**
Working Memory * Age group	-2.67	41.24	-0.07	0.95	
Working Memory * Verb type	-13.92	24.20	-0.58	0.57	
Age group * Verb type	**-328.20**	**122.79**	**-2.67**	**0.01**	**
Age group * Syntax condition	-119.12	77.19	-1.54	0.12	
Verb type * Syntax condition	**100.11**	**45.32**	**2.21**	**0.03**	*
Working memory * Syntax condition	**35.02**	**16.28**	**2.15**	**0.03**	*
Age group * Processing Speed	22.217	27.61	0.81	0.42	
Verb type * Processing Speed	-21.86	13.13	-1.67	0.10	.
Syntax condition * Processing Speed	-7.46	8.01	-0.93	0.35	
Age group * Handgrip	-54.98	69.57	-0.79	0.43	
Verb type * Handgrip	23.28	39.72	0.59	0.56	
Syntax condition * Handgrip	-20.95	27.10	-0.77	0.44	
Age group * Physical Activity	-0.63	0.688	-0.91	0.36	
Verb type * Physical Activity	-0.21	0.33	-0.63	0.53	
Syntax condition * Physical Activity	-0.16	0.20	-0.80	0.42	
Age group * Verbal IQ	**42.47**	**16.11**	**2.64**	**0.01**	**
Verb type* Verbal IQ	-11.05	7.72	-1.43	0.15	
Syntax condition * Verbal IQ	-1.93	4.70	-0.41	0.68	
Age group * Verb type * Syntax condition	-9.16	79.14	-0.11	0.91	
Working Memory * Age group * Syntax condition	**-66.40**	**28.79**	**-2.31**	**0.02**	*
Working Memory * Verb type * Syntax condition	-24.94	24.18	-1.03	0.30	
Age group * Verb type * Processing Speed	**51.28**	**25.42**	**2.02**	**0.04**	*
Age group * Syntax condition * Handgrip	74.76	48.48	1.54	0.12	
Verb type * Syntax condition * Handgrip	**86.39**	**39.94**	**2.16**	**0.03**	*
Age group * Verb type * Physical Activity	-0.99	0.65	-1.53	0.13	
Age group * Verb type * Verbal IQ	20.03	14.99	1.34	0.18	

Model includes a random intercept for items and subjects, a random slope for Integration for both items and subjects and a random slope for Verb type for subjects.

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Note that above results are from a model on untransformed RT values. Because there were differences in response time between the younger and older age group we ran the model also on standardised RT's. This did not affect the outcomes.

Modulating effect of Processing Speed

To assess whether the effect of processing speed on response time was different for younger and older adults, we looked at interactions between Age group and Processing Speed. Similar to our accuracy analyses, we found an interaction between Age group, Verb type and Processing Speed ($p = 0.044$). To investigate the nature of this interaction, we ran a post hoc analysis in which the model predicting response times was applied to each Age group individually. The results of this post hoc analysis are presented in Table 1.6. The left panel of Figure 1.5 shows that in the younger age group, response times were shorter in the Real Verb block compared to the Pseudoverb block. This effect of Verb type on response time did not depend on Processing Speed: there was no significant interaction between Processing Speed and Verb type in the younger age group ($p = 0.559$). In the older age group (right panel of Figure 1.5), response times were shorter in the Real Verb block compared to the Pseudoverb block. However, the effect of Verb type on response times was moderated by Processing Speed: there was a significant Verb type * Processing Speed interaction in the older age group ($p= 0.048$). To investigate this interaction, we tested the slope for the effect of Processing Speed on response time for each Verb type separately. These post hoc t tests revealed the estimated beta coefficient in the Real Verb block was not significantly different from zero ($B = -8.73$; $se = 6$; $t = -1.46$; $p = 0.15$). In contrast, the beta coefficient in the Pseudoverb block was significantly different from zero ($B = -57.89$; $se = 6.15$; $t = -9.42$; $p < 0.001$). This suggests that the relative increase in response time in the Pseudoverb block was elevated in older adults with lower Processing Speed.

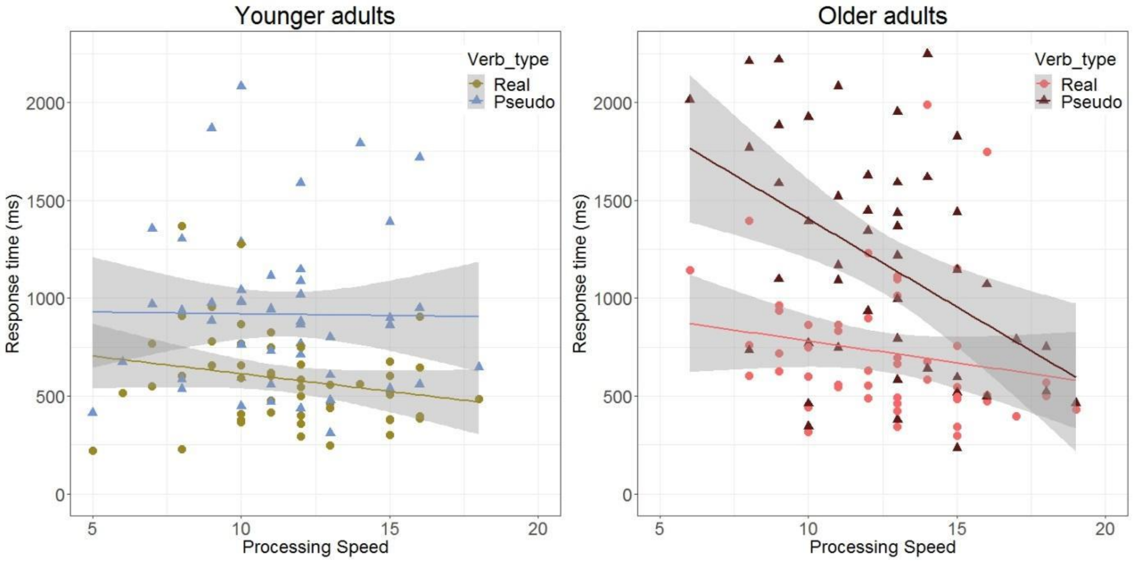

Figure 1.5 Processing Speed differentially effects response time depending on age group. The three-way interaction between Age group, Verb type and Processing Speed, depicted through a linear regression with response time as predicted by Processing Speed in the Real Verb and Pseudoverb block for each age group separately. The left panel shows the younger age group, the right panel shows the older age group. In the younger age group, the effect of Verb type on response time was not influenced by Processing Speed. In contrast, the effect of Verb type on response time was different at different levels of Processing Speed in the older age group.

Table 1.5A Coefficient estimates, standard errors (SE), associated t values and p values for all predictors of a post hoc linear mixed model predicting response time for young adults. Model includes a random intercept for items and subjects, a random slope for Integration for both items and subjects and a random slope for Verb type for subjects

Coefficient	Estimate	Std. Error	t value	p value	
(Intercept)	**745.55**	**43.17**	**17.27**	**< 0.01**	***
Working Memory	-8.624	29.32	-0.29	0.77	
Verb type	**316.61**	**41.10**	**7.70**	**< 0.01**	***
Syntax condition	38.20	27.44	1.39	0.16	
Processing Speed	-11.92	14.96	-0.80	0.42	
Handgrip	-27.14	44.06	-0.62	0.54	
Physical Activity	0.011	0.38	0.03	0.98	
Verbal IQ	-3.66	9.95	-0.37	0.71	
Working Memory * Verb type	-7.50	27.28	-0.28	0.78	
Working Memory * Syntax condition	-11.57	17.14	-0.68	0.50	
Verb type * Syntax condition	82.94	44.30	1.87	0.06	.
Verb type * Processing Speed	8.13	13.90	0.59	0.56	
Syntax condition* Processing Speed	-8.05	7.68	-1.05	0.29	
Verb type * Handgrip	16.10	41.04	0.39	0.70	
Syntax condition * Handgrip	0.047	26.14	0.01	0.99	
Verb type* Physical Activity	-0.52	0.35	-1.47	0.14	
Syntax condition * Physical Activity	-0.21	0.19	-1.11	0.27	
Verb type* Verbal IQ	-5.31	9.28	-0.57	0.57	
Syntax condition * Verbal IQ	1.15	5.12	0.22	0.82	
Working Memory * Verb type * Syntax condition	**-55.37**	**25.34**	**-2.19**	**0.03**	*
Verb type * Syntax condition * Handgrip	31.70	40.18	0.79	0.43	

Table 1.6B Coefficient estimates, standard errors (SE), associated t values and p values for all predictors of a post hoc linear mixed model predicting response time for older adults. Model includes a random intercept for items and subjects, a random slope for Integration for both items and subjects and a random slope for Verb type for subjects.

Coefficient	Estimate	Std. Error	t value	p value	
(Intercept)	**983.85**	**60.71**	**16.21**	**< 0.01**	***
Working Memory	-20.27	42.43	-0.48	0.63	
Verb type	**495.75**	**66.50**	**7.46**	**< 0.01**	***
Syntax condition	**87.71**	**44.59**	**1.97**	**0.05**	*
Processing Speed	-34.83	24.83	-1.40	0.16	
Handgrip	28.78	77.57	0.37	0.71	
Physical Activity	0.60	0.603	0.10	0.32	
Verbal IQ	**-44.54**	**12.85**	**-3.47**	**0.01**	***
Working Memory * Verb type	-24.81	44.42	-0.56	0.58	
Working Memory * Syntax condition	**74.30**	**30.03**	**2.48**	**0.01**	*
Verb type * Syntax condition	113.59	71.53	1.59	0.11	
Verb type * Processing Speed	**-47.26**	**23.89**	**-1.98**	**0.05**	*
Syntax condition * Processing Speed	-7.878	16.43	-0.48	0.63	
Verb type * Handgrip	42.18	80.57	0.52	0.60	
Syntax condition * Handgrip	-46.21	54.64	-0.85	0.40	
Verb type * Physical Activity	0.26	0.58	0.45	0.65	
Syntax condition * Physical Activity	-0.04	0.40	-0.11	0.91	
Verb type * Verbal IQ	-19.99	12.33	-1.62	0.11	
Syntax condition * Verbal IQ	-4.74	8.47	-0.56	0.58	
Working Memory * Verb type * Syntax condition	-14.91	46.20	-0.32	0.75	
Verb type * Syntax condition * Hand grip	136.39	79.56	1.71	0.09	.

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 ‘ ’ 1

Moderating effect of Working Memory capacity

To investigate whether Working Memory capacity differentially affects response times in younger and older individuals, we looked at interactions between Working Memory capacity and age group. There was a significant interaction between Age group, Working Memory capacity and Syntax condition ($p = 0.021$). As can be seen in the left panel of Figure 1.6, the response times in the younger age group did not differ across conditions Working Memory capacity did not influence the response times: there was no significant interaction between Working Memory capacity and Syntax condition in the younger age group ($p = 0.5$; see Table 1.6). As can be seen in the right panel of Figure 1.6, the effect of Syntax condition was moderated by Working Memory capacity in the older age group. Specifically, response times were shorter in the correct syntax condition compared to the incorrect syntax condition, but this difference is driven by older adults with higher Working Memory: there was a significant interaction between Working Memory and Syntax condition ($p = 0.013$). To determine whether the effect of Syntax condition was larger in the correct syntax condition relative to the incorrect syntax condition, we tested the simple slopes of the influence of Working Memory capacity in each Syntax condition against zero. The post hoc t tests revealed the simple slope in the correct syntax condition was significantly different from zero ($B = -58.40$; $se = 10.12$; $t = -5.77$; $p < 0.001$). In contrast, the simple slope in the incorrect syntax condition was not significantly different from zero ($B = 9.51$; $se = 10.02$; $t = 0.95$; $p = 0.34$). Overall, this suggests that for older adults, higher Working Memory capacity was associated with faster response times in the correct syntax condition, while for younger adults, Working Memory capacity did not influence the response times.

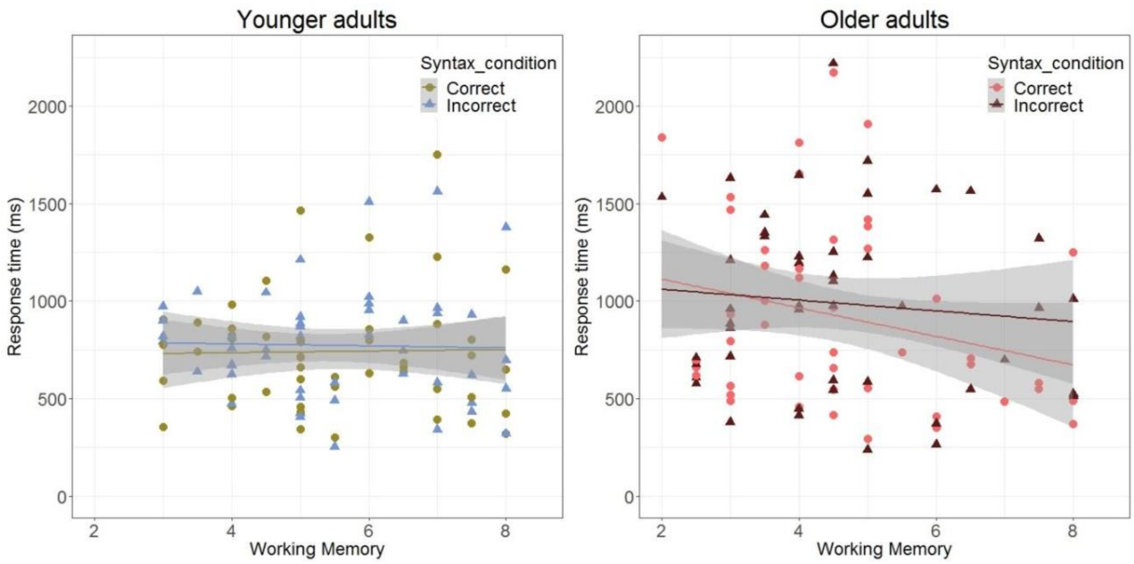

Figure 1.6 Working Memory capacity differentially effects response time depending on age group. The three-way interaction between Age group, Syntax condition and Working Memory capacity, depicted by a linear regression between response time and Working Memory capacity grouped by Syntax condition in the younger age group (left panel) and the older age group (right panel). Working Memory capacity did not differentially affect response times depending on Syntax condition in the younger age group. In the older age group, there was a significant decrease in response time in older adults with high Working Memory capacity in the correct syntax condition.

Moderating effect of Verbal IQ

We found an interaction between Age group and Verbal IQ (p = 0.008), such that a higher Verbal IQ score was associated with faster response times for older adults, but not for young adults.

Discussion

Our study was designed to investigate whether there is decline in syntactic comprehension in healthy ageing. We investigated elementary syntactic comprehension of phrases such as "*I cook*" and "*I spuff*". We demonstrated the following three key findings: 1) there is decline in syntactic comprehension of healthy older adults compared to young adults, in accuracy as well as response times; 2) the age-related decline in the accuracy of syntactic comprehension is stronger for phrases with real verbs, while the age-related decline in the response times of syntactic comprehension is stronger for phrases with pseudoverbs; 3) there is a high degree of individual variation in age-related decline, which is explained in part by differences in working memory capacity and processing speed.

The modulations of processing speed and working memory capacity on syntactic comprehension present a complex picture, which can be summarized as follows. In young adults, performance was not affected by processing speed. This was true for accuracy as well as response time. In older adults, processing speed influenced syntactic comprehension, both in terms of accuracy and response time. However, processing speed differentially influences performance on accuracy and response time depending on the level of lexical-semantic information provided. Specifically, in real verb sentences, processing speed aids accuracy of syntactic judgements, whereas in pseudoverb sentences, processing speed aids response times. The moderating influence of working memory capacity on comprehension performance was different for the two age groups as well. In older adults, working memory capacity aids accuracy, an advantage which was not dependent on the level of lexical-semantic information provided (whereas for young adults it was). Moreover, working memory capacity aids response times in syntactically correct sentences. We discuss these effects below in the context of our key findings.

We have convincingly demonstrated that there is age-related decline in syntactic comprehension when processing two-word phrases with real verbs in our syntactic comprehension experiment. The effects were demonstrated in accuracy as well as response times: older adults were less accurate and slower than young adults. Previous literature on syntactic comprehension in older adults has predominantly used semantically meaningful sentences with complex syntactic structures. Most of these studies did not show age-related decline in processing these sentences (Campbell et al., 2016; Davis et al., 2014; Meunier et al., 2014; Samu et al., 2017; Shafto & Tyler, 2014b; Shafto et al., 2014), although some studies did (Antonenko et al., 2013; Obler, Fein, Nicholas, & Albert, 1991). Our results are in line with the latter set of studies. A new element in the results of the current study is that age related decline in syntactic comprehension was demonstrated in a context where complexity was reduced to the bare minimum: syntactic agreement of pronoun and verb.

A possible explanation for the divergence in results of the current study compared to many previous findings of preserved syntactic comprehension is that the measure of syntactic comprehension used in the current study may draw on a different aspect of syntax. Studies that capitalize on syntactic ambiguity evaluate comprehension by asking questions about the thematic roles assigned to the agent or patient in the sentence (i.e., “who is doing what”, e.g., ‘what is the gender of the agent in the sentence’). A correct response requires comprehension of the full sentence structure, which indirectly requires comprehension of the syntactic structure. In contrast, the measure of syntactic comprehension in the current study focuses on evaluating syntactic agreement. This study thus taps into a different aspect of syntactic processing: grammaticality judgements for minimal phrases with and without meaning. Specifically, in the context of Friederici’s (2000) neurocognitive model of auditory sentence processing, the current study arguably taps into the initial phases of sentence processing of local syntactic structure building and thematic role assignment based on morpho-syntactic information indicating agreement between different elements within a phrase. In contrast, syntactic ambiguity paradigms (as used by Campbell et al., 2016; Davis, Zhuang, Wright, & Tyler, 2014; Meunier, Stamatakis, & Tyler, 2014; Samu et al., 2017; Shafto & Tyler, 2014) tap into later processes of syntactic revision and late integration (although see Antonenko et al., 2013 for a study with a syntactic ambiguity paradigm that did find age-related decline). Different aspects of syntactic processing do not necessarily undergo a similar trajectory of change over the course of ageing. The current study only enables us to draw conclusions on those aspects of syntax that were manipulated in our experiment design. Moreover, our task is a meta-linguistic task that requires post-interpretive processing. For a review on the possible effects of ageing on the added processes involved in post-interpretive tasks, please see a review by Peelle (2019).

Our second key finding is that the pattern and extent of age-related decline is influenced by the level of lexical semantic information provided. The reduction of lexical semantic content by using pseudoverbs instead of real verbs increased the difficulty of the task, as evidenced by the reduced accuracy and increased response times in both age groups. Older adults were slower and less accurate in comprehending both real verb and pseudoverb phrases. In terms of accuracy, this relative performance drop was largest in the real verb phrases compared to the pseudoverb phrases. In terms of response time, the age-related decline was largest in the pseudoverb phrases compared to the real verb phrases. Older and younger adults likely used a different strategy: while younger adults more often adopt a strategy that emphasizes speed, older adults tend to act more error aversive than younger adults (de Jong et al., 2018). Indeed, it has been suggested previously that older adults prioritize accurate responses over fast responses (Forstmann et al., 2011; Starns & Ratcliff, 2010).

One possible interpretation of this pattern of findings is that decline in syntactic comprehension is strongest in the absence of lexical-semantic information, which causes older adults to produce slower responses in order to make more accurate decisions. This interpretation of the results could shed some light on why some previous studies did not show any decline in syntactic processing when syntactic comprehension was probed in the context of full sentence structures. Even when sentence length was deliberately kept short, these sentences were rich in semantic content. This inevitably provides a more extensive context than the two word phrases of the current study. Our findings of reduced syntactic comprehension in a contextually deprived context suggest that the availability of additional lexical-semantic information reduces the decline in syntactic comprehension that comes with ageing.

The absence of semantic information can be considered an increased processing challenge. In this sense, our interpretation that syntactic decline is more pronounced in the absence of semantic information, is in line with Wingfield, Peelle & Grossman (2003). In this study, the influence of varying processing challenges on syntactic comprehension in older adults was investigated in a different way, by measuring syntactic comprehension of subject- and object relative clause sentences at varying speech rates. While older adults were slower than younger adults at all speech rates tested, this age difference became larger with increased speech rates. In other words, older adults took disproportionally longer to give their comprehension responses at an increased level of processing challenge. Likewise, in the current study, the effect of processing challenge resulted in disproportionately increased response times in older adults when contextual constraints were reduced from a two word phrase with a meaningful content to a similar phrase structure without any representation in the mental lexicon. It should be noted that in the Wingfield, Peelle & Grossman (2003) study, comprehension accuracy only decreased in older adults at very fast speech rates, whereas in the current study, accuracy was already lower compared to young adults for the comprehension of real verb phrases, that is, when processing challenge was at relative minimum. However, as argued above, it could be that the minimal phrases used in the current study already provided a higher processing challenge than the semantically richer sentence structures used by Wingfield, Peelle & Grossman (2003).

This leads us to our third key finding that there was individual variation in the age-related decline in syntactic comprehension. Processing speed provided a unique contribution in explaining the individual variation in performance in the older age group. Increased processing speed was associated with higher performance: older adults with a higher processing speed score were more accurate in comprehending real verb sentences compared to their peers with a lower processing speed score. In addition, in the more challenging pseudoverb block where the older participants as a group showed a significant increase in response time, a higher processing speed score was associated with faster responses. Increased processing speed therefore supported syntactic processing in older adults in two ways: it enabled older adults to be more accurate in their overall faster processing of real verb sentences and to respond faster to the more challenging pseudoverb sentences.

The influence of processing speed on syntactic ability is consistent with a large literature suggesting general processing speed impacts language processing (Waters & Caplan, 2007). Notably, this effect was only present in the older age group in our study. These findings are in line with the contention that the general slowing of processing speed that is associated with age impairs cognitive functioning (Salthouse, 1996). Critically, in the experiment that required the least processing load (the real verb phrases) a faster processing speed decreased the performance gap between older and younger adults.

In addition, the influence of working memory capacity on comprehension performance was different for younger and older adults. For our older adults, a higher working memory capacity was associated with increased comprehension accuracy, irrespective of the lexical semantic context and irrespective of the correctness of the phrase. Furthermore, older adults with a higher working memory capacity experienced a relative advantage in response time in the correct identification of morpho-syntactically correct phrases. These results suggest that, even when the complexity of syntactic processing is reduced to its most basic syntactic operation, increased working memory capacity aids syntactic comprehension in older adults. In the younger age group, the influence of working memory capacity on performance was more limited, emerging only in a subset of the conditions. These findings are in line with Payne et al. (2014) who observed that the effect of working memory capacity on language processing was larger in older compared to younger adults. Our research furthermore demonstrates a similar pattern for processing speed.

However, we are cautious about over-interpreting the observed effects of working memory and processing speed, given that only a single measure was used to assess each cognitive function in this study. The composition of the test battery was aimed at investigating a broad range of common cognitive and physical individual differences. This broad approach is, due to the constraints of potential task fatigue from an expanded additional measurements battery, at the expense of a more in depth measurement of the individual components. To further explore the relationship between comprehension of elementary syntactic structures and these individual components, a more comprehensive assessment by using composite scores consisting of multiple measurements would provide a valuable direction for future research.

In terms of the nature of our syntactic comprehension experiment, it should be noted that both stimuli (two word phrases) and task (grammaticality judgement) were specifically chosen to investigate elementary features of syntactic processing while aiming to maximize the isolation of this process in relation to additional processing mechanisms. As a consequence, certain features related to processing real-life connected speech, such as coarticulatory cues, were either absent or very limited in the decontextualized stimuli of our study. Indeed, compared to processing single words or sentences, processing real-life connected speech has been suggested to rely on additional mechanisms (Alexandrou, Saarinen, Mäkelä, Kujala, & Salmelin, 2017). Moreover, sentence comprehension relies on syntactic processes in a number of ways (Kaan & Swaab, 2002). Therefore, our measure of elementary syntactic comprehension inevitably is a limited proxy of syntactic comprehension more generally. In addition, it should be noted that the differences we observed between young and older adults do not in themselves identify the underlying cause of the effect of age on syntactic comprehension. Age-related effects could, in part, be the result of declines in peripheral and central hearing (Rogers and Peelle, submitted) or auditory-motor speech processing (Panouillères & Möttönen, 2017). However, in our study, accuracy across the board was relatively high for the older adults (specifically, the older adults' group average accuracy was above 85% in the experimental conditions and even above 90% in the filler conditions). This strongly suggests that participants were able to differentiate correctly among the different experimental conditions, arguing against a profound effect of hearing loss in the present study. Moreover, while older adults were indeed slower and less accurate than younger adults, they were differentially slower and less accurate in response to different experimental manipulations. Therefore, our data pattern cannot be explained in terms of a monotonic effect of slowing or hearing loss due to age.

Another limitation of the current study is that the younger age group consisted of university students, while the older age group was characterised by a more varied educational background. It is possible that this larger variability in the older age group has influenced our findings and may explain our finding that the influence of superior vocabulary on performance was only present in the older age group.

In summary, the results of the current study shed new light on the decline in syntactic comprehension in healthy ageing. Whereas previous studies have primarily investigated complex syntactic structures and focused on syntactic ambiguity, we investigated syntactic comprehension of the elementary building blocks of syntactic processing: syntactic agreement of pronoun and verb. Older adults were slower and less accurate compared to younger adults. This decline seems to increase in the absence of semantic contextual information, which causes older adults to produce slower responses in order to make more accurate decisions. In line with these findings, accuracy for older adults was positively related to processing speed capacity. Taken together, our results provide very clear evidence that syntactic comprehension declines in healthy ageing.

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Author contributions

C.P, L.W. and K.S. designed the study. C.P was responsible for data collection and assisted by undergraduate students. C.P. analysed the data. C.P wrote the manuscript under the supervision of L.W. and K.S. All authors revised the manuscript and approved the final version of the manuscript.

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CHAPTER 2

BINDING LANGUAGE IN HEALTHY AGEING: THE OSCILLATORY MECHANISMS ASSOCIATED WITH SYNTACTIC BINDING

Older adults frequently display differential patterns of brain activity compared to young adults in the same task, along with widespread neuroanatomical changes. These differing activity patterns in older adults are commonly interpreted as being compensatory (e.g., Cabeza et al., 2002). We examined the relationship between oscillatory activity in the EEG during syntactic binding with behavioural performance on a syntactic judgement task. Minimizing contributions of semantics and working memory, 41 older adults listened to two-word sentences that differentially load onto morpho-syntactic binding: correct syntactic binding (morpho-syntactically correct; e.g., *“I dotch”*); incorrect syntactic binding (morpho-syntactic agreement violation; e.g., “*they dotches*”) and no syntactic binding (minimizing morpho-syntactic binding; e.g., “*dotches spuff*”). Behavioural performance, assessed in a syntactic judgement task, was characterized by high inter-individual variability, with accuracy ranging from 58-100%. Syntactic binding, assessed as the difference between the correct- and no syntactic binding condition, was associated with a smaller increase in theta (4-7 Hz), alpha (8-12 Hz) and beta (15-20 Hz) power in a time window surrounding the second word. This suggest that the neural signature associated with syntactic binding in older adults is qualitatively different from younger adults, who show a larger alpha and beta power increase for binding compared to no binding in the same task (Segaert et al., 2018). However, we found no evidence of a significant association between behavioural performance and the neural signatures of syntactic binding. Our results therefore do not readily support the predictions of compensatory models of language and ageing.

Introduction

There is clear evidence that advanced age, even in the absence of neurodegenerative disease, is associated with structural changes in the brain (Fjell & Walhovd 2010). These structural alterations are accompanied by decline across a number of cognitive domains, including working memory (Waters & Caplan, 2001) and processing speed (Salthouse, 1996). At the same time, there exists evidence that language abilities are generally well preserved across the adult lifespan, (Campbell et al., 2016; Shafto & Tyler, 2014; Peelle, 2019) despite structural changes in language-relevant brain regions (Antonenko et al., 2013; Raz, 2009). Given the structural- and cognitive changes that occur in healthy ageing, it is unlikely that successful performance in older adults is achieved with identical neural processes as young adults (Peelle, 2019). In fact, a differential pattern of brain activity in older compared to younger adults is frequently observed (e.g., Antonenko et al., 2013; Tyler et al., 2010, Wingfield& Grossman, 2006). However, the functional interpretation of these observed differences is not yet well understood. A key question in this context is how mechanisms of neural adaptation and concomitant cognitive change relate to better or worse behavioural performance in older adults. The purpose of the current study was to investigate this question in the context of language comprehension by focusing on a specific fundamental building block thereof: syntactic binding. Syntactic binding refers to the combination of words into lager structures, taking into account features that determine syntactic structure, agreement and tense (Segaert, Mazaheri & Hagoort, 2018). Our first aim was to investigate the oscillatory mechanisms supporting syntactic binding in healthy older adults using a minimal phrase paradigm that minimizes contributions of semantics and working memory load. Our second aim was to investigate whether age-related changes are compensatory by relating the neural signatures of syntactic processing to the degree to which language comprehension is successful within the group of healthy older adults. Lastly, because healthy ageing is characterized by considerable inter-individual variability (Raz, 2009, Peelle, 2019), we incorporated measures of overall cognitive and physical functioning in addition to our neural measure of syntactic processing, to identify factors associated with individual differences in comprehension performance.

Theoretical perspectives on age differences in brain activity

Neuroimaging studies have provided substantial evidence of distinctively different patterns of neural activation between young and older adults under identical task requirements. By and large, the literature shows a more widespread pattern of activity in older (i.e., above the age of 65) relative to younger (i.e., in their 20's) adults (e.g., Cabeza et al., 2002; Davis, Dennis, Daselaar, Fleck & Cabeza, 2008). Different views exist on how to interpret these age-related changes in brain activity. According to one view, the appearance of more diffuse activity in the older brain reflects a general decline in neural efficiency, or reduced cerebral specialization. The term *dedifferentiation* is commonly used to refer to this account (Baltes & Lindenberger, 1997; Wingfield & Grossman, 2006). An alternative (though not mutually exclusive) interpretation is that increased engagement of brain regions in older compared to younger adults reflects focused recruitment as a means to compensate for neurocognitive decline. This is commonly referred to as *compensation* (Wingfield & Grossman, 2006). The term compensation is generally reserved for enhanced activation that is contributing meaningfully to performance (Grady, 2012, Cabeza et al., 2018). However, another possibility is that compensatory mechanisms exist even if performance is impaired (Chastelaine, Wang, Minton, Muftuler & Rugg, 2011; Grady, 2011). According to the partial compensation hypothesis, over-recruitment may reflect adaptive processes that compensate partially, rather than fully.

A growing emphasis in the field of the cognitive neuroscience of ageing is placed on individual differences. Indeed, rather than age per se, age-related performance differences could be better explained by individual differences in neuroanatomical features, cognitive abilities and sensory abilities (Peelle, 2019). Consequently, the characterization of factors contributing to the rate of age-related function decline is an important area of interest (Lara et al., 2015). Both processing speed and working memory capacity decline with age (Salthouse, 1996; Waters & Caplan, 2001; Caplan & Waters, 2005) and are known to contribute to language processing (Wingfield, Peelle & Grossman, 2003; Wingfield & Grossman, 2006). Health characteristics can also explain variability in cognitive ageing (Raz, 2009, Shafto et al., 2019). Physical health in older adults is positively related to general cognitive functioning (Barnes, Yaffe, Satariano & Tager, 2003; Colcombe et al., 2004), brain electrical activity (Sanchez-Lopez et al., 2018) and language processing (Segaert et al., 2018b). These findings highlight the importance of considering healthy ageing in a broader, more holistic sense rather than an exclusive focus on the behavioural and brain decline. In the context of the current study, it seems that examining potential factors contributing to inter-individual variability in comprehension performance and the operations underlying this process could be illuminating in further establishing the conditions under which older adults successfully engage in alternative pathways to language comprehension.

Age differences in brain activity during language comprehension

Functional magnetic resonance imaging (fMRI) studies have yielded evidence that older adults recruit additional brain regions compared to younger adults during syntactic processing (e.g., Grossman et al., 2002; Tyler et al., 2010; Shafto & Tyler, 2014; Peelle, Troiani, Wingfield & Grossman, 2009). This could indicate the existence of compensatory mechanisms, but an explicit relationship between the observed additional activity and successful performance is often missing (for example: Tyler et al., 2010). When additional activity is not predictive of performance, it is sometimes interpreted as exerting a more indirect compensatory influence, by supporting working memory or processing demands related to task performance (Peelle et al., 2009, Campbell et al., 2016).

Electrophysiological (EEG) measurements, which enable the investigation of neural activity that is concurrent with comprehension processes, offer an alternative approach. By and large, ERP components during sentence comprehension show smaller amplitudes and longer latencies in older compared to younger adults (Federmeier & Kutas, 2005; Federmeier, McLennan, De Ochoa and Kutas, 2002; Wlotko, Lee & Federmeier, 2010). Later studies suggest the age-related change in the use of contextual information is associated with a decreased reliance on predictive processing in older adults (Wlotko & Federmeier, 2012; Wlotko et al., 2012). In extension of these findings, research suggests older adults do not seem to engage in mechanisms of binding information the same way younger adults do, as evidenced by age-related deficits in the encoding processes thought to underlie memory binding (Johnson, 1996; Mitchell, Johnson, Raye, Mather & D'Esposito, 2000; Sander, Werkle-Bergner & Lindenberger, 2011). Likewise, the P600, an ERP component sensitive to syntactic violations, is less asymmetric and more frontal in older, compared to younger adults (Kemmer, Coulson, De Ochoa & Kutas, 2004, Leckey & Federmeier, 2017; Alatorre-Cruz et al., 2018). In other words, similar to the age-related increases in bilateral activation patterns observed in the fMRI literature, the changed scalp distribution of the P600 effect suggests a qualitative change in syntactic processing with age, however the functional significance of these changes is still debated.

An alternative approach to investigating event-related changes in the EEG signal, and the one that is our main focus here, is to look at oscillatory activity. An advantage of investigating neural oscillations relative to ERPs is that this method allows for the investigation of event related changes which are time-locked to the event, but not necessarily phase locked (i.e., when the phase of the event-related response is the same or very similar across all individual trials). Sentence comprehension in young adults has been associated with oscillatory changes in the theta (~4- 7 Hz); alpha (8- 12 Hz) and beta band (~13- 18 Hz; Bastiaansen, van Berkum & Hagoort, 2002a; Meyer, 2018; Prystauka & Lewis, 2019). Syntactic processing, particularly the integration of syntactic information across words, has been associated with increased theta power (Bastiaansen, Magyari & Hagoort, 2010). In addition, storing syntactic information in verbal working memory and syntactic binding have been associated a power *increase* in the alpha band (Meyer, Obleser & Friederici, 2013; Bonhage, Meyer, Gruber, Friederici & Mueller, 2017; Segaert et al., 2018). Successful encoding of syntactic information has been linked to a power *decrease* in alpha (Vassileiou, Meyer, Beese, Friederici, 2018; Beese, Vassileiou, Friederici, & Meyer, 2019). Finally, it has been suggested that effects in both the alpha and beta band reflect unification, or binding of semantic and syntactic information in sentences (Davidson & Indefrey, 2007; Lam, Schoffelen, Uddén, Hultén & Hagoort, 2016, Bastiaansen et al., 2010)

Few studies have investigated age-related changes in the oscillatory dynamics associated with sentence processing. However, one study by Beese et al., (2019) reports age differences in the lower alpha-band (~8-10 Hz) in sentence encoding. Specifically, using an auditory sentence comprehension task, oscillatory power differences between correctly and incorrectly encoded sentences were compared across age groups. Interestingly, the authors found an age-related inversion in the alpha band, from a relative *decrease* in correctly remembered relative to later-not-remembered sentences in younger adults, to an *increase* in correctly remembered relative to later-not-remembered sentences in older adults. The authors suggest this shift likely reflects a change from cortical disinhibition to inhibition during sentence encoding.

Isolating syntactic binding in sentence comprehension

In the current study, we use a minimal two-word sentence paradigm to investigate syntactic binding processes in online sentence comprehension. At its most fundamental level, syntactic binding refers to the combination of words into larger structures, taking into account features that determine syntactic structure, agreement and tense (Segaert et al., 2018). This elementary computation, otherwise known as *merge* (Chomsky, 1995, Zaccarella & Friederici, 2015) or *unification* (Hagoort, 2005, 2009, 2016) forms the foundation of structure building of increasing syntactic complexity. Investigating elementary syntactic binding by means of a minimal phrase paradigm offers the advantage of minimizing contributions of other processes involved in sentence comprehension, such as working memory load. This advantage is particularly salient when studying the effect of age on online sentence comprehension, given the large number of factors that are influenced by age.

In a previous study, Segaert et al. (2018) employed a minimal phrase paradigm to investigate the oscillatory mechanisms associated with syntactic binding in young adults. To substantially reduce the infuence of semantic processing on syntactic binding, pseudowords were used instead of existing words. Specifically, participants listened to two-word sentences consisting of a pronoun paired to a pseudoverb (e.g., "*I grush*", "*they dotch*"), forming a morpho-syntactically correct combination (i.e., syntactic binding condition) and to wordlists, consisting of two pseudoverbs paired together (e.g., *"ploffs grush*", "*spuffs dotch*"), eliciting no syntactic binding (i.e., no binding condition). Pseudoverbs, such as "*grush"* and "*dotch",* are present in both conditions, equally eliciting morphological parsing of stems and inflectional affixes, which indicate the number and tense for each instance of a pseudoverb. The two conditions thus differ from each other only with respect to binding taking place. The aspects of syntactic binding that are manipulated in this paradigm are: (1) establishing agreement of number and person between the pronoun and the pseudoverb; and (2) structure building:

‘subject verb’ is a sentence with a syntactic structure, while for wordlists with two verbs, no syntactic structure can be established. The paradigm thus allows us to focus on syntactic binding, with only a minimal contribution from semantics and working memory load. Preceding the presentation of the second word, Segaert et al. (2018) observed a larger increase in alpha and beta power in the syntactic binding condition (relative to the no binding condition) maximal over a cluster of frontal-central electrodes. In addition, a larger increase in alpha power was observed in the syntactic binding condition relative to the no binding condition, which was maximal over a left-lateralized cluster of fronto-temporal electrodes. Using a paradigm similar to the one used in Segaert et al. (2018), the current study aims to investigate the oscillatory mechanisms associated with syntactic binding in older versus young adults.

In another study (Poulisse, Wheeldon & Segaert, 2019), we have used a minimal phrase paradigm to specifically investigate age differences in comprehension performance for elementary syntactic structures. Minimal phrases consisting of a pronoun and a verb were used in an auditory syntactic judgement task to investigate performance differences between young and older adults. The degree of semantic support was varied by comparing sentences containing real-verbs (e.g., “*I cook*”) to sentences containing pseudoverbs (e.g., “*I spuff*”). Older adults were less accurate and slower in detecting syntactic agreement errors than young adults, but this decrease in performance was modulated by the level of semantic information provided. Specifically, the age-related decline in accuracy was smaller for pseudoverb compared to real verb sentences, but this difference was associated with disproportionately slower response times in the pseudoverb compared to the real verb sentence condition. Although older adults as a group showed declined comprehension performance, there was a large degree of inter individual variability, which was partly explained by individual differences in processing speed. Specifically, older adults with higher processing speed abilities performed better in the real verb condition and were faster in the more challenging pseudo verb condition. In addition, performance was moderated by working memory capacity, such that a higher working memory capacity was associated with higher performance in the older age group. These findings on individual differences in performance highlight the importance of adopting an inter-individual variability approach to the investigation of age differences in language performance mentioned previously. In sum, the results of this study show performance in older adults declines even when syntactic constructions are reduced to just two words, thus extending previous work suggesting comprehension performance is particularly vulnerable to age-related decline for the comprehension of syntactically complex sentences (Kemtes & Kemper, 1997; Obler, Fein, Nicolas & Albert, 1991; Wingfield, McCoy, Peelle, Tun & Cox 2006).

Segaert et al. (2018) thus suggest syntactic binding in younger adults is associated with oscillatory power changes in the alpha and beta band. A behavioural study targeting the same fundamental syntactic computation (Poulisse et al., 2019) shows comprehension performance is subject to age-related changes, yet is characterized by a large degree of inter-individual variability. However, no study to date has looked into the oscillatory mechanisms associated with syntactic binding in older adults. This is the motivation for the current work.

Current study

The goal of this study was to investigate the oscillatory mechanisms associated with syntactic processing in healthy ageing. We examined a group of healthy older adults, aged 65 to 80. Secondly, we explored whether age-related changes in oscillatory mechanisms are predictive of performance success in syntactic comprehension. In doing so, we also incorporated factors associated with individual differences in comprehension performance, i.e. working memory, processing speed and indicators of physical healthy (amount of regular physical activity and handgrip strength).

To collect our behavioural and functional measures, we used a minimal phrase paradigm in a separate behavioural and EEG experiment (similar to Segaert et al., 2018 – described above). This paradigm targets elementary syntactic binding operations by using minimal phrases consisting of a pronoun and a pseudo verb (e.g., "*I dotch*", "*she spuffs*"). The use of pseudoverbs instead of real verbs limits the influence of lexical-semantic content to syntactic binding, as pesudoverbs lack a representation in the mental lexicon. In addition, the load on working memory required to process these phrases is kept to a minimum.

We obtained a performance measure for a syntactic judgement task. Participants listened to the minimal phrases and indicated with a button press whether the phrases were morpho-syntactically correct (yes/no). Syntactic comprehension was assessed as the mean accuracy and response time (RT) for correctly rejecting and detecting morpho-syntactic agreement errors.

To obtain our neural measure associated with syntactic processing, EEG was recorded while participants listened to the same minimal phrases. Since we are concerned with syntactic binding, a process that inherently unfolds over time rather than being time locked to a specific event, we especially focused on the oscillatory dynamics related to syntactic binding. Specifically, we compared the oscillatory response to a correct syntactic binding condition (e.g., "*I dotch*") with the response to a no syntactic binding condition (e.g., "*spuffs dotch*"). The analysis focused on power changes surrounding the onset of the *second* word ("*dotch*" in this example). In the correct syntactic binding condition, agreement of number and person is established between the pronoun and the target word "*dotch*", whereas this is absent in the no syntactic binding condition. In addition, the subject-verb combination in the correct syntactic binding condition forms a morpho-syntactic structure. In contrast, in the no syntactic binding condition, a morpho-syntactic structure cannot be established. In other words, the target word in those two conditions differs in terms of syntactic binding taking place. The power difference between the correct syntactic binding and no binding condition served as our neural measure for syntactic processing.

Age-related changes in oscillatory mechanisms (i.e., oscillatory mechanisms supporting syntactic comprehension in older adults) that are predictive of performance success would indicate that these changes are compensatory.

Methods

Participants

A group of 48 older adults participated in the study. All participants were native British English speakers and reported to be in good health with no known history of neurological, speech or language disorders. No participant had audiometer measurements indicating severe hearing impairment [> 70 db or more on the Etymotic Hearing Task (Etymotic Research, Inc.)] on both ears. One participant had an audiometer measurement indicating severe hearing impairment on the left, but mild hearing impairment on the right and was included in the final sample. Furthermore, 7 participants obtained a score below the cut-off value of 26 on the Montreal Cognitive Assessment test (MoCa; version 7.1) and were not included in the analysis. These exclusions resulted in a final sample of 41 participants (26 women, mean age: 69, SD: 3.37, range: 64- 78 years and 15 men, mean age: 69, SD: 5, range: 63- 80 years). All participants had a minimum education level of A levels (or A levels equivalent). Participants were recruited via the database of the University of Birmingham and the Join Dementia Research database. All participants gave informed consent. This research was conducted at the University of Birmingham and had full ethical approval (ERN 15-0866).

Overview of study design

Our study consisted of a behavioural experiment, an EEG experiment (see overview Table 2.1) and a set of biomarker measures of healthy ageing.

A. Behavioural syntactic judgement task: The behavioural experiment served to measure syntactic comprehension performance. Participants were instructed to listen to minimal phrases and were asked to indicate whether the phrase was grammatically correct or not. Performance was measured as accuracy and response time for rejecting and detecting morpho-syntactic agreement errors for respectively correct and incorrect phrases. A mean accuracy and reaction time was calculated for performance on correct and incorrect syntactic binding trials. In other words, this is a measure of participants' ability to perform syntactic binding and serves as a proxy of syntactic comprehension performance.

B. Neural signature of syntactic binding (EEG experiment): To measure the oscillatory mechanisms associated with syntactic binding, the same participants subsequently completed an EEG experiment during which they listened to the same phrases as in the behavioural task. Syntactic binding was measured by comparing the correct syntactic binding to the no syntactic binding condition (Segaert et al., 2018). A reversed speech detection task ensured maximal similarity in the response decision processes between these critical conditions of interest, while keeping the participant focused on the stimuli throughout the task. Note that the contrasts that were used to assess behavioural performance and brain function were specifically chosen to best capture the underlying constructs they were set out to measure. For this reason, a different condition contrast was used for the functional, compared to the behavioural measure.

C. Biomarkers of healthy ageing: Lastly, a set of measures of cognitive processing capacity and physical activity were included to examine individual differences in cognitive and physical decline.

Table 2. 1 Conditions of interest and measures obtained for the behavioural experiment (panel A) and the EEG experiment (panel B)

A. Behavioural experiment

Conditions	*Explanation*	*Example*	*Measurement*
correct or incorrect syntactic binding	Detecting whether a phrase is morpho-syntactically correct or incorrect	correct: I spuff incorrect: I spuffs	**Syntactic comprehension000000 performance:** the mean accuracy and response time (RT) of rejecting and detecting agreement violations

B. EEG experiment

Conditions	*Explanation*	*Example*	*Measurement*
correct syntactic binding	Morpho-syntactically correct phrase	I spuff, they dotched	**Functional neural signature of syntactic binding:** the difference in time frequency power between correct syntactic binding and no syntactic binding
no syntactic binding	No morpho-syntactic binding is possible	plams spuff, grush dotched	

Materials for behavioural experiment and EEG experiment

The stimuli for this experiment were based on a set of 20 non-existent, monosyllabic English verbs created by Ullman et al. (1997): brop, crog, cug, dotch, grush, plag, plam, pob, prap, prass, satch, scash, scur, slub, spuff, stoff, trab, traff, tunch, vask. The words had an average word length of four letters. Despite having no meaning in the mental lexicon, these pseudoverbs can be inflected according to the grammar rules for regular verbs in English. Consequently, combining the pseudoverbs with one of the six pronouns I, you, he, she, we, or they, yields a minimal phrase, for example: "*I dotch*", "*she dotches*", or "*they dotched*". The stimuli were digitally recorded using a male native speaker of English. All pseudoverbs were recorded in first, second and third singular and plural present tense. For each word, the clearest recording out of three attempts was selected. Using the software program Adobe Audition, a reversed speech version of all recordings was created. Lastly, all audio files in wav format were normalized to 1db in order to equalize the volume of the individual recordings.

These stimuli were combined to form three conditions that differentially load on morpho-syntactic binding, serving the basis for our behavioural- and EEG experiment (see Table 2.1). In the correct syntactic binding condition, the pronoun and pseudo verb form a morpho-syntactically correct phrase (e.g., "*I spuff*", "*they dotched*"). In the incorrect syntactic binding condition a pronoun was paired with a pseudoverb, but the inflectional suffix of the verb did not match the pronoun, resulting in a morpho-syntactic agreement violation (e.g., "*I spuffs*", "*they dotches*"). In the no syntactic binding condition, two pseudoverbs were paired together (e.g., "*dotches spuff*"), preventing the establishment of a morpho-syntactic structure.

A potential concern may be that specific combinations in the no syntactic binding condition could be interpreted as noun-verb rather than verb-verb pairings (e.g., in "*dotch spuffs*" and "*dotches spuff*", the first word could be interpreted as a singular and plural noun respectively). However, previous research established that participants do not syntactically bind such pairings (Segaert et al., 2018). Specifically, in this study, 66% of the no syntactic binding trials[5] consisted of pseudoverb combinations in which both verbs were either first, or second person singular (e.g., "*pob grush*" or "*pobs grushes*"). Crucially, if participants would have mistaken the first word for a pseudonoun rather than a pseudoverb, these trials would have been identified as having an agreement mistake in number and person. However, performance accuracy was found to be 97.4% for correctly indicating that there was no mistake in this condition, suggesting participants were not performing syntactic binding in this condition.

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[5] In the original Segaert et al. (2018) paper, the condition in which two pseudoverbs were paired together was called 'wordlist condition', while in the current work, this condition is referred to as 'no syntactic binding' condition.

Behavioural syntactic comprehension experiment

Conditions: Conditions of interest were the correct and incorrect syntactic binding trials; an average performance measure was calculated for 24 trials of each. In addition, there were 48 filler trials: 24 no syntactic binding trials (to ensure similarity to the EEG task), and 24 pronoun filler trials (i.e., two pronouns, e.g., "*we he*", to prevent predictability in the potential engagement of binding processes after the presentation of a pronoun as the first word). Correct syntactic binding trials could be formed with three possible pronoun- pseudo verb combinations. Specifically, the pseudoverb *stem* combined with either 'I', 'you', 'we' or 'they'; the pseudoverb stem plus *–s* combined with 'he' or 'she', or the pseudoverb stem plus *–ed* combined with each of the six pronouns. Each form occurred 8 times and each verb would occur only once in each form. The incorrect syntactic binding word pairs were formed according to the same criteria, but only the *stem* and *-s forms* were possible, as no incorrect combination can be composed with the *–ed form*. The no syntactic binding trials consisted of three possible forms, such that the second verb could either be *stem form*, *-s form*, or *–ed form*, with 8 trials per form. To avoid repetition effects, the first word could neither be the same verb nor have the same ending as the second word of the pair. Lastly, the pronoun filler trials consisted of two possible forms, such that the first word could either be 'I', 'you', 'we' or 'they', or 'he' or 'she', with 12 trials per form. Each participant received a unique randomized stimulus list, which was divided into two blocks, separated with a self-paced break. The experiment had 96 trials in total and was preceded by a practice block of 14 trials.

Trial timing: Each trial started with a fixation cross for 1000 ms, followed by a blank screen for 1000 ms, followed by a word-by-word presentation of the minimal phrase, with a Stimulus Onset Asynchrony of 1200 ms. The Inter Stimulus Interval (ISI) between the first and the second word varied as a function of the duration of the first word and ranged between 300 and 600 ms. A response screen (self-paced) showing the text: *"Did you hear a grammatical mistake?"* appeared 1605 ms after the onset of the second word, followed by an inter trial interval (6 ms).

Performance behavioural experiment: To confirm the overall effectiveness of our experimental manipulation, the results of the behavioural experiment (average for all participants) are reported here. Data points with RTs above or below 2 standard deviations of the participant mean were removed from analyses, resulting in an exclusion of 5% of the data points. The group average performance accuracy for rejecting (correct syntactic binding trials) and detecting (incorrect syntactic binding) syntactic agreement errors was 92% (SD = 27%) and 86% (SD = 35%) respectively. Group average performance was 99% (SD = 12%) for the no syntactic binding condition and 93% (SD = 26%) for the pronoun filler condition. In addition, the group average response time for correct responses was 2734 ms (SD = 1773 ms) for the correct syntactic binding trials; 2977 ms (SD = 1839 ms), for the incorrect syntactic binding trials; 1356 ms (SD =1862 ms) for the no syntactic binding trials and 1111 ms (SD = 1007 ms) for the pronoun filler trials. The overall high performance suggests participants had a clear understanding of the task and could differentiate between the conditions. In the results section we will use a performance measure for individual participants (average of the accuracy / reaction for the correct and incorrect syntactic binding trials) and relate these to our functional neural measures.

EEG experiment: Neural signature of syntactic binding

Conditions: Following the behavioural experiment, participants completed an EEG task in order to collect our functional measure of syntactic processing. This experiment included 72 trials of the correct syntactic binding condition and 72 trials of the no syntactic binding condition. Comparing these two conditions provides a maximum contrast in terms of morpho-syntactic binding and hence served as our measure of syntactic processing. In addition, the EEG experiment included 72 pronoun filler trials and 64 incorrect syntactic binding trials to ensure continuity and similarity with the stimuli from the behavioural experiment. Lastly, 80 reversed speech task trials were added, in which one of the two words was played in reverse.

The experimental lists of the EEG experiment were constructed according to the same criteria as the behavioural task: in both the correct syntactic binding- and the no syntactic binding condition, each possible verb form (*stem form*, *-s form* and *–ed form*) occurred 24 times. Each possible pronoun occurred 6 times in the stem form, 12 times in the -s form and 4 times in the –ed form. In the incorrect syntactic binding condition, both the stem form and –s form trials consisted of 32 trials each, such that each possible pronoun within each verb form occurred an equal number of times. The pronoun filler condition consisted of 40 trials that started with either 'I', 'you', 'we', or 'they' and 32 trials that started with either 'he', or 'she', again ensuring that each possible pronoun occurred an equal number of times within each form. Lastly, the reversed speech task condition consisted of 80 trials, with 20 trials starting with a reversed verb, followed by a pronoun, 20 trials starting with a reversed verb, followed by a pseudo verb, 20 trials starting with a pronoun, followed by a reversed verb and 20 trials starting with a pseudo verb followed by a reversed word. This resulted in a total of 360 trials, divided into 8 blocks and separated by self-paced breaks. The experiment was preceded by a practice block consisting of 30 trials. Each participant received a unique randomised stimulus list.

Trial timing: Each trial started with a fixation cross for 1000 ms, which was followed by a blank screen for 1000 ms, followed by a word- by word presentation of the minimal phrase. The screen remained blank throughout auditory word presentation. The second word was presented 1200 ms after the onset of the first word. A response screen showing the text: "*Reversed?*" was presented 1400 ms after the onset of the second word, to ensure the response screen would not interfere with the processing of the stimuli. The response screen lasted for 4000 ms or until a button press. This was followed by the presentation of a blank screen for 500 ms. A schematic representation of a trial is presented in Figure 2.1.

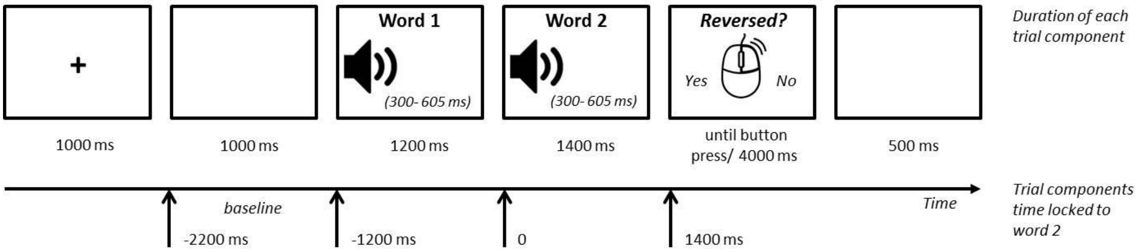

Figure 2.1 Timing of each component in one EEG trial.

EEG recording: EEG recordings were made using a 64 electrode cap-mounted Ag/AgCl electrodes arranged in a 10/10 system layout (including left and right mastoids, CPz as reference and AFz as ground). Recordings were acquired using the EEGO Sports system (ANT Neuro, Enschede, The Netherlands). Horizontal eye movements were monitored by means of two electrodes placed at the outer left and right canthi. The EEG data were high-pass filtered at 0.3 Hz and low-passed at 30 Hz. All impedances were kept below 20 kΩ. Signals were recorded at a 500 Hz sampling rate.

EEG preprocessing: The preprocessing and analyses of the data were performed using functions from EEGLAB (version 13.6.5b; Delorme & Makeig, 2004) and the Fieldtrip software package (Oostenveld, Fries, Maris, & Schoffelen, 2011). The data was average referenced and epoched from -2.2s to 4.5 s, time-locked to the onset of the second word. All reversed speech trials were removed, as well as false positive button presses to non-reversed speech trials and trials containing artefacts (an average of 8 percent per participant). An approximately equal amount of trials was excluded across conditions (an average of 8 percent). Following this, ocular and muscle artefacts were removed using independent component analyses (infomax algorithm) incorporated as the default *runica* function, with the first step of a PCA to reduce the dimensionality of the data, resulting in an average exclusion of approximately 3.5 components per participant. A similar pipeline has been used for data analysis in previous EEG studies (e.g. van Diepen, Miller, Mazaheri, & Geng, 2016; van Diepen & Mazaheri, 2017).

Inter-individual variability measures on cognitive processing, physical capability and physical activity

A number of additional measures were included to examine the effect of individual differences, an overview of which can be found in Table 2.2. All are established biomarkers of healthy ageing (Lara et al., 2015).

Table 2. 2 Overview of additional measurements

Measure	*Task*	*Scoring*
Working memory capacity: Backward Digit (BD) and Subtract 2 (S2) Span task (Waters & Caplan, 2003)	Listening to a series of digits of increasing length, starting with 2 digits, up to 7. There were 5 trials of each digit length. *Task BD*: repeat digits in backward order. *Task S2:* repeat digits after subtracting 2 from each digit.	Span size: longest digit length for which 3 out of 5 trials are correctly recalled; 0.5 point is added if 2 out of 5 is correctly recalled. Composite score: (span BD + span S2) /2.
Processing speed: WISC-IV Coding subtest (WAIS-IV; Wechsler, 2008)	Copying symbols that are paired with numbers within 120 seconds.	One point for each correctly drawn symbol completed within time limit. Total score: number of correctly drawn symbols. Raw scores converted to scaled score equivalents according to age group.
Physical activity: New Zealand Physical Activities Survey Short Form (Sport and Recreation New Zealand, 2001)	A self-report measure of habitual practice of physical activity.	Composite score: adding the duration (in minutes) of moderate activity and two times the duration of vigorous activity.
Handgrip Strength: Hand dynamometer (Takei Scientific Instruments, Japan).	The dynamometer is held towards the ceiling with an outstretched arm whilst standing upright, shoulder and elbow are fully flexed. While the arm moves downwards in 3 sec, the meter is squeezed at maximum force.	Three measurements were recorded for both hands. The highest value of the dominant hand was used for analyses. Raw scores were converted to standardised z-scores within gender groups.

Procedure

The measurements were collected in two separate sessions on different days. Participants were tested in the morning or afternoon. During the first session, the behavioural- and EEG tasks were completed. The procedure was the same for each participant and can be summarized as follows: (1) *Volume check:* Participants listened to 10 randomly selected pseudo verbs through headphones and were asked to repeat what they heard. Special attention was paid to participants' ability to distinguish between words in *stem form*, *-s form* and *–ed form.* Volume settings were adjusted if necessary. (2) *Behavioural task:* During the practice block, participants received verbal feedback on their performance and only proceeded to the real experiment when they had a clear understanding of the task. The behavioural task took on average 30 minutes to complete, including the practice session and a break. (3) *EEG task*: EEG recordings were conducted in a quiet, dimly lit room. After the completion of the capping procedure, participants started with a practice block to familiarize themselves with the task. The experiment was divided into 8 blocks (~5 minutes each), separated by self-paced breaks. The EEG recording lasted around one hour in total. Both the behavioural and EEG experiment were run using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). During the second session, the additional measurements were administered in the following order: Hearing Task, Backward Digit Span Task, Forward Digit Span Task, Hand Grip Strength, Coding, Physical Activity questionnaire and MoCa.

Statistical analyses

Group level statistical analyses: Our first research objective was to establish a neural EEG signature for syntactic binding at the group level. To this end, we examined differences in oscillatory power between the correct syntactic binding and no syntactic binding condition.

Time frequency analyses: Time-frequency representations (TFR) of power were calculated for each condition using the Fieldtrip function '*ft_freqanalysis_mtmconvol*'. Power was analysed from 2– 40 Hz in steps of 1 Hz for every 50 ms. We used sliding Hanning tapers with an adaptive time window of three cycles for each frequency of interest ($\Delta T = 3/f$), utilizing a similar approach as used in previous studies (e.g., van Diepen, Cohen, Denys, & Mazaheri, 2015; Whitmarsh, Nieuwenhuis, Barendregt, & Jensen, 2011). After assessing there were no differences in baseline oscillatory power for the frequency bands of interest between our conditions of interest, power changes in oscillatory activity were expressed in terms of change scores from baseline (ΔPt) using the following formula: $\Delta Pt = (Pt–Pr)/Pr$ where Pr, was the mean power during the baseline period -2200 to -1600 ms before the onset of the second word and Pt was the power at each specific time point. Given the importance of distinguishing between induced responses (i.e., activity that is time-locked but not phase-locked to the event) from evoked responses (i.e., activity that is both time and phase locked to the event), the ERP components were removed from the TFR. First, a time frequency decomposition of the ERP data was performed on each participant for each condition separately, using the approach described above. Following this, the time frequency spectra of the ERPs were subtracted from the time-frequency spectra of the EEG epochs for each condition separately. A similar procedure has been used in previous studies (e.g., Mazaheri & Picton, 2005; Segaert et al., 2018). The resulting subject averaged power changes were subjected to statistical analysis to test for condition differences in the temporal and spectral dynamics of oscillatory modulations induced by the minimal phrases.

To assess the statistical difference between the conditions of interest, while accounting for multiple-comparisons (multiple electrodes and time points), a non-parametric cluster level (over-electrodes) randomization routine (Maris & Oostenveld, 2007) was performed. In this procedure, the power of the frequencies of interest, in each channel and time point within a time window of interest, was clustered depending on if it exceeded a dependent samples t-test threshold of $p < 0.05$ (two-tailed). In doing so, the *triangulation method* was used to determine neighbouring channels. Probability values for the clusters were obtained by a Monte Carlo simulation involving randomly swapping the labels (i.e., conditions) in participants 2500 times and calculating the maximum cluster-level test statistic for each permutation. These analyses were performed by collapsing within the following frequency bands: theta (4-7 Hz), alpha (8- 12 Hz) and low beta (15-20 Hz). The frequencies included in these bands were based on prior literature (Segaert et al., 2018; Mazaheri et al., 2018; Bastiaansen et al., 2010; Shahin, Picton & Miller, 2009). We should note that some previous studies have found that the peak alpha band frequency is reduced in older adults. As such, we ran an additional analysis looking at the individual peak frequency during a baseline pre-stimulus period (-2.2 to -1.2 s), by calculating the mean over the highest amplitude value across all trials and channels for every participant. The individual alpha peak frequencies ranged from 9 to 11 Hz, well within our predefined frequency bandwidth for alpha. In addition, two time windows were selected for the analyses: a large time window from -1.2 to 1.4 seconds surrounding the second word, and a shorter time window starting at the onset of the second word, from 0 to 1.4 s after the presentation of the second word. In sum, this procedure resulted in the identification of a cluster of electrodes that showed the greatest difference in amplitude between the correct syntactic binding and no syntactic binding condition in each of the three frequency bands.

Event Related Potentials: An Event Related Potential (ERP) analyses was performed using the Fieldtrip function '*ft_timelockanalysis*'. ERPs were computed for each individual and for each condition separately. The significance of the difference between the conditions of interest was evaluated by means of a cluster based permutation test.

Individual differences analysis: Our second research objective was to explain the variability among healthy older adults in syntactic performance, as a function of their neural signatures and cognitive and physical biomarkers. We created linear regression models (LM's *lme4* package, version 1.1-10; Bates, Mächler, Bolker, & Walker, 2014) using the *lm* function in R version 3.5.1 (R Development Core Team, 2015). Separate models were created to predict accuracy and response time of syntactic comprehension performance (i.e., dependent variables). The independent variables are the neural signatures of syntactic processing derived from the EEG task and our inter-individual variability measures on cognitive and physical functioning. The neural signatures of syntactic processing were calculated in the following way. First, a power difference TFR was created for each individual participant by subtracting the no syntactic binding condition from the correct syntactic binding condition. Following this, power was averaged over the electrodes and time points that were obtained by the cluster level randomization tests described above, and averaged over the predefined frequency bands that were used in those analyses. This resulted in a power difference value for each individual subject.

We followed two analysis approaches. In our first approach, the selection of independent variables was based on our previous findings suggesting syntactic comprehension performance in older adults is related to processing speed and working memory capacity only (Poulisse et al., 2019). We therefore ran a model with only the neural signatures, working memory capacity, processing speed and age as independent variables (i.e., predictors). In a second analysis approach, hand grip strength and physical activity were included in the models also, guided by previous literature on the influence of these measures on general cognitive ageing. All additional individual differences measures were centred. Table 2.3 provides an overview of group average and standard deviation for each measure. The scaled processing speed scores were used in the analyses, but for the sake of completeness, the raw processing speed scores are reported as well.

In addition to traditional null hypothesis significance testing, we present Bayes factors for any non-significant effects resulting from the regression models in order to quantify the strength of evidence for or against the presence of the effect of a predictor. These values were calculated using the *BayesFactors* package in R (Morey & Rouder, 2018). The strength of evidence for the effect of an independent variable was assessed by comparing a full model excluding the predictor of interest (i.e., H_0) to a full model including this predictor (i.e., H_1). Decision boundaries and interpretation of Bayes factor values were based on the classification scheme by Lee & Wagemakers (2014). Accordingly, an estimated Bayes Factor (BF_{10}; H_1/H_0) between 1 and 3 provides anecdotal evidence for the alternative model (i.e., H_1). On the other hand, a BF_{10} smaller than 1 signifies that the data are more probable under the null model. Specifically, values between 1 and 0.33; 0.33 and 0.10, or smaller than 0.10 provide anecdotal (i.e., weak), moderate or strong evidence for H_0 respectively. A Bayes factor that lies between these boundaries (i.e., around 1) is deemed inconclusive. For example, a hypothetical Bayes factor of 0.25 for the effect of working memory capacity on comprehension performance would indicate the null model is preferred to the model containing working memory capacity by a factor of 4 (1:.25).

Table 2.3 Means and Standard Deviations of predictor variables (N =41)

Measurements	*mean*	*sd*
Working Memory capacity	4.89	0.91
Processing Speed (Scaled)	11.59	2.09
Processing Speed (Raw)	60.00	10.50
Physical Activity	145.98	165.54
Hand grip	30.11	8.62
Age	69.29	3.98

Results

I. Syntactic binding in healthy older adults is associated with an attenuation in theta, alpha and beta power just preceding and after the onset of the 2^{nd} word (group level results).

The group level results are summarized in Figure 2.2. Figure 2.2A and B show the individual grand mean TFRs of the correct syntactic binding and no syntactic binding condition respectively, after removal of the spectral components of the ERP. Qualitatively, in both conditions, the presentation of the first word (at -1.2 s) induced a transient power increase in the theta and alpha range (likely reflecting the sensory responses to the onset of the sound stimuli). Following this, there was a power increase in alpha and low beta activity surrounding the presentation of the second word (at 0 s), followed by a suppression in the alpha and beta range. Figure 2.2C shows the TFR of the correct syntactic binding condition minus the no syntactic binding condition. We first present the results of the cluster based permutation tests using the large time window (i.e., from -1.2 to 1.4s). First, there was a significant difference in theta power (4- 7 Hz) between the correct syntactic binding condition and the no syntactic binding condition, in the time window from -0.25- 0.1s relative to the presentation of the second word ($p = 0.04$). Note, this test was ran with 5000 permutations, as an increased number of permutations was recommended in the fieldtrip output after the initial run with 2500 permutations. Here, power in the theta range returned to baseline in the correct syntactic binding condition during this time window, in contrast to a continued power increase in the no syntactic binding condition. The mean condition difference within this time interval was most pronounced over a cluster of left frontal and left-parietal electrodes for correct syntactic binding compared to no syntactic binding (Figure 2.2D). In addition, a significantly smaller increase in alpha power (8- 12 Hz) was observed in the correct syntactic binding condition from -0.25 to 0.3 s relative to the presentation of the second word ($p = 0.01$). This difference was most pronounced in a cluster of electrodes over left-frontal central and parietal regions (Figure 2.2E). Lastly, there was a significant difference in beta power (15- 20 Hz) in the time window -0.3 to 0.15s around the presentation of the second word ($p = 0.002$), such that the power increase was less sustained in the correct syntactic binding condition, compared to the no syntactic binding condition. This difference was most pronounced in a frontal-posterior cluster of electrodes (Figure 2.2F). Next, using a shorter time window (i.e., from 0- 1.4s after the presentation of the second word), we observed a significantly smaller increase in theta power (4- 7 Hz) in the correct syntactic binding condition in a time window from 0.75- 1s after the presentation of the second word ($p = 0.03$). The mean condition difference within this time interval was most pronounced over a frontal cluster and parietal cluster of electrodes (Figure 2.2G). Using this narrower time window, the same clusters in the alpha (8- 12 Hz) and low beta (15- 20 Hz) bands were observed compared to the larger time window (that is, a cluster from 0- 0.3s post second word in the alpha band and a cluster from 0- 0.15s in the beta band).

To gain insight into the individual variation that underlies the grand average of these significant clusters, we calculated the power difference between the correct and no syntactic binding condition for each individual participant, and averaged the power over the electrodes and time points of each significant cluster. The individual power difference values are shown in Figure 2.2H-K. The participants plotted below the red lines show, in line with the grand mean of all participants, a *smaller* theta, alpha and beta increase for correct compared to no syntactic binding. The participants plotted above the red lines show, in contrast to the grand mean, a *larger* theta, alpha and beta power increase for the correct syntactic binding compared to the no binding condition. The individual participant values suggest there is considerable variability in the magnitude and the direction of the neural signature of syntactic binding.

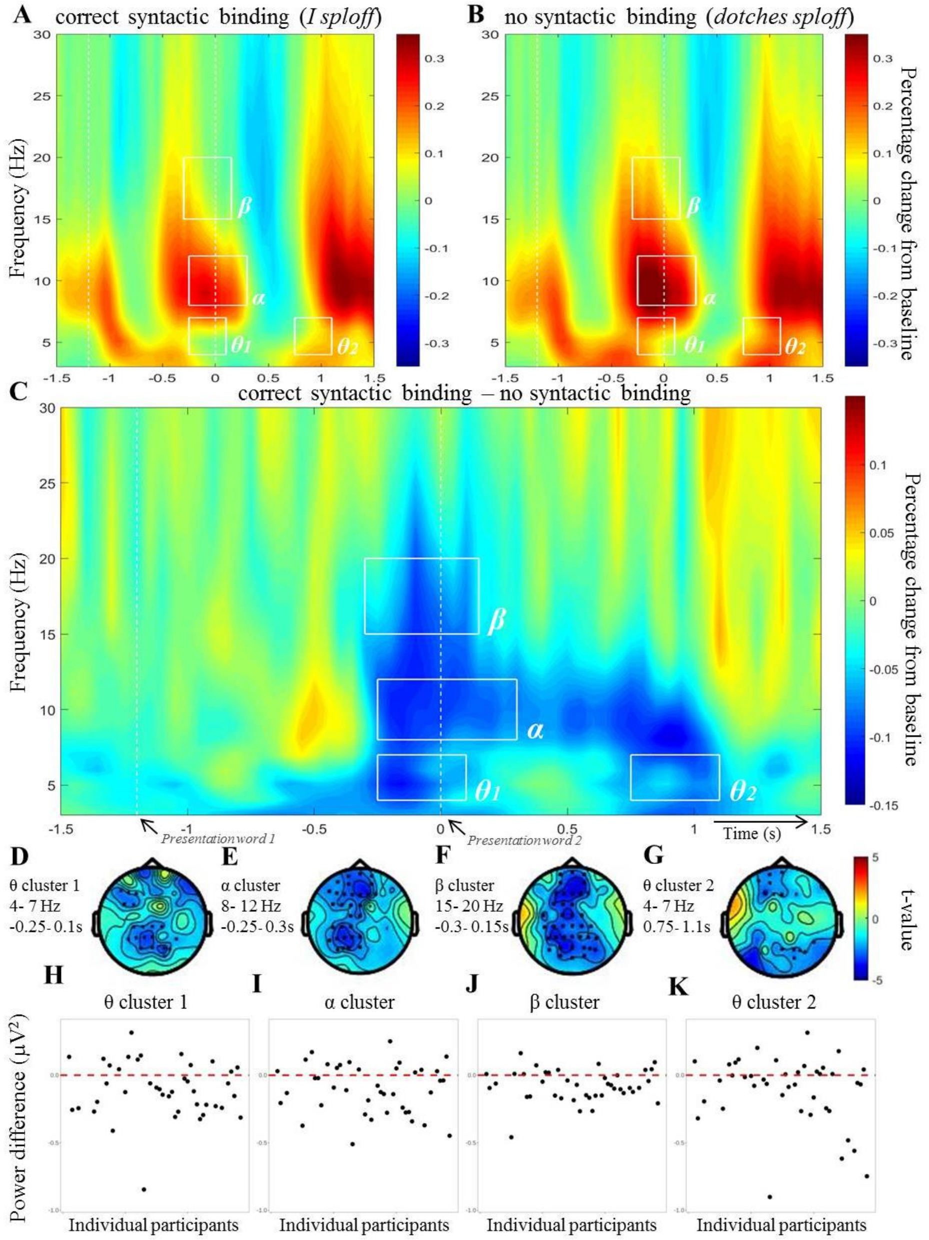

Figure 2.2 Differences in theta (θ), alpha (α) and beta (β) power between the correct syntactic binding condition (e.g. *I sploff*) and the no syntactic binding condition (e.g. *dotches sploff*). (**A-C**) TFR of conditions of interest for all electrodes after removal of the spectral components of the ERP, expressed as a percentage change from baseline (-2s to -1.6s before the onset of word 2) for (**A**) the correct syntactic binding condition; (**B**) the no syntactic binding condition and (**C**) correct minus no syntactic binding. The rectangles indicate the time frequency clusters showing a significant difference between the two conditions. (**D-G**) Head plots illustrating the cluster of electrodes that show the most pronounced mean condition difference. (**H-K**) Individual power differences between the correct syntactic binding and no syntactic binding condition (each dot represents a participant) for the significant clusters i.e. theta (4-7 Hz) cluster 1 for the time window -0.25- 0.1s; alpha (8- 12 Hz) for the time window -0.25- 0.3s; beta (15- 20 Hz) for the time window -0.3- 0.15s) and theta (4-7 Hz) cluster 2 for the time window 0.75- 1.1s. Individuals plotted below the dotted line demonstrate a smaller power increase in the correct syntactic binding condition compared to the no syntactic binding condition, whereas individuals plotted above the line demonstrate a larger power increase in the correct, compared to the no syntactic binding condition. Note, theta cluster 2 is significantly different between conditions only when using the smaller time window from 0 to 1.4s after the presentation of the second word, not when using the larger time window from -1.2 to 1.4 s.

ERP results

Differences in the ERP amplitudes elicited by the target (i.e., second) word comparing the two conditions of interest were assessed by means of cluster based analyses, using a 100-ms pre-stimulus baseline. Based on inspection of the grand average data collapsed across conditions and on previous reports in the literature (i.e., Friederici, 2004 for P1, N400 and P600; Rentzsch, Jockers-Scherübl, Boutros& Gallinat., 2008 for N1), we examined the following latency windows synchronized to the onset of the second word (i.e., at time 0s): 0.1- 0.14s (i.e., corresponding to P1); 0.17- 0.2s (i.e., corresponding to N1); 0.25-0.35s (i.e., corresponding to P300); 0.4- 0.5s (i.e., corresponding to N400); 0.6- 0.7s (i.e., corresponding to the late positivity component/P600). The ERPs for two central electrodes are shown in Figure 2.3A. There was a significant difference in amplitude for the P1; P300 and late positivity (Fig 2.3B), such that the amplitude in the correct syntactic binding condition was more positive compared to the no syntactic binding condition. This overall positivity shift in the first 300 ms post word onset could have been brought about by the difference in amplitude asymmetric (i.e., non-Gaussian) alpha power between the two conditions (Mazaheri and Jensen, 2008, Nikulin et al., 2007, van Dijk, van der Werf, Mazaheri, Medendorp & Jensen, 2010). The ERP differences in the P1 and P300 may therefore not be directly relatable to differences in evoked responses due to the conditions of interest per se. The increased late positivity component for the correct syntactic binding condition however occurs at a time interval in which we do not observe a significant condition difference in alpha power (although we do see a qualitative difference).

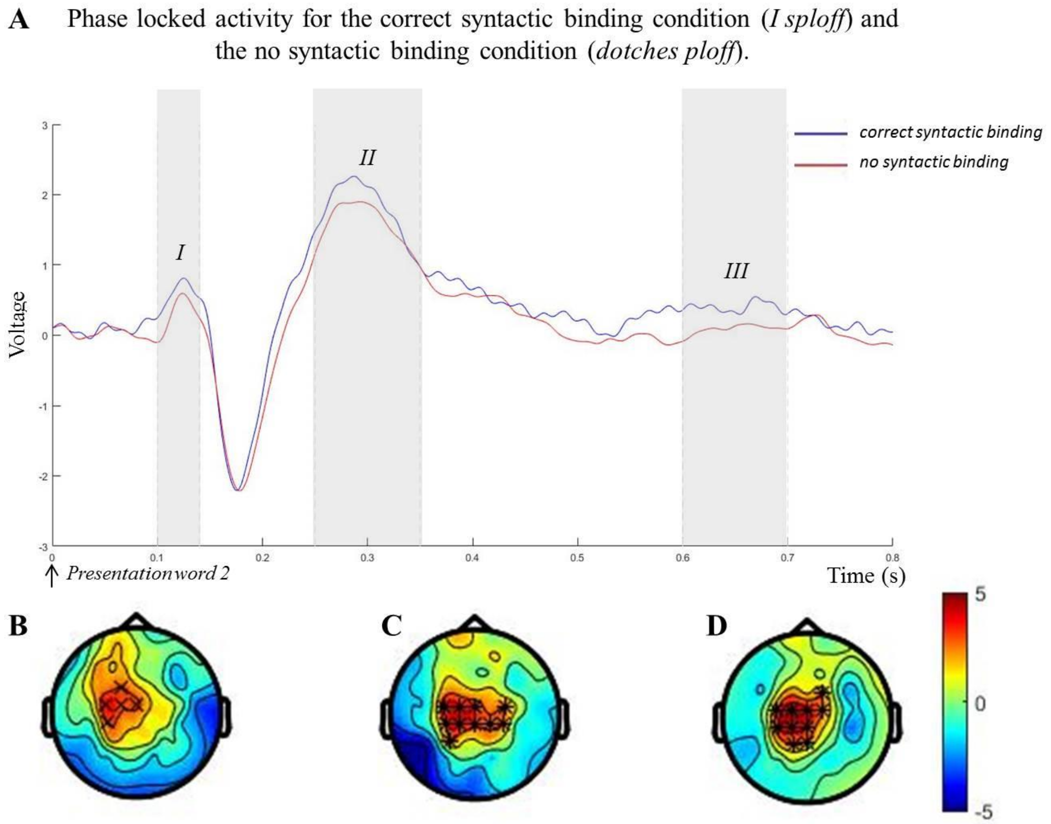
A Phase locked activity for the correct syntactic binding condition (*I sploff*) and the no syntactic binding condition (*dotches ploff*).

Figure 2.3 Phase locked activity. **(A)** The evoked response illustrated for two central electrodes (Cz and FCz) for the correct syntactic binding (in blue) and the no syntactic binding condition (in red) following the presentation of the second word. There was a significantly higher amplitude in the correct syntactic binding condition in the time window 0.10- 0.14 (p = 0.02) *(I);* in the time window 0.25- 0.35 (p < 0.001) *(II);* in the time window 0.6- 0.7 (p = 0.02) *(III).* **(B-D)** Head plots illustrating the cluster of electrodes that show the most pronounced condition difference: **(B)** for the P1 (I in Figure 2.3A); **(C)** the P300 (II in Figure 2.3A); **(D)** the late positivity component (III in figure 2.3A).

II. No evidence for a relationship between syntactic comprehension performance (accuracy and reaction time) and neural signatures associated with syntactic binding.

Individual variability in syntactic comprehension performance is visualised in Figure 2.4. The group average performance accuracy was 89%, with individual accuracy scores ranging from 58% up to 100% (Figure 2.4A). We have used a cut-off score of 50% for accuracy, similar to previous work (Poulisse et al., 2019). However, using a more conservative cut-off of 65% did not affect the outcomes, neither of the accuracy model, nor the response time model. The group average performance response time was 2883 ms, with individual scores ranging from 1145 ms to 6055 ms (Figure 2.4B). Internal consistency estimates for accuracy and response time were calculated as Cronbach’s alpha and as the correlation between an odd/even trial split, utilizing a similar approach as used in previous studies (e.g., Jackson et al., 2006). Both accuracy and response time were found to be reliable measures (α = 0.87 and 0.97 respectively).

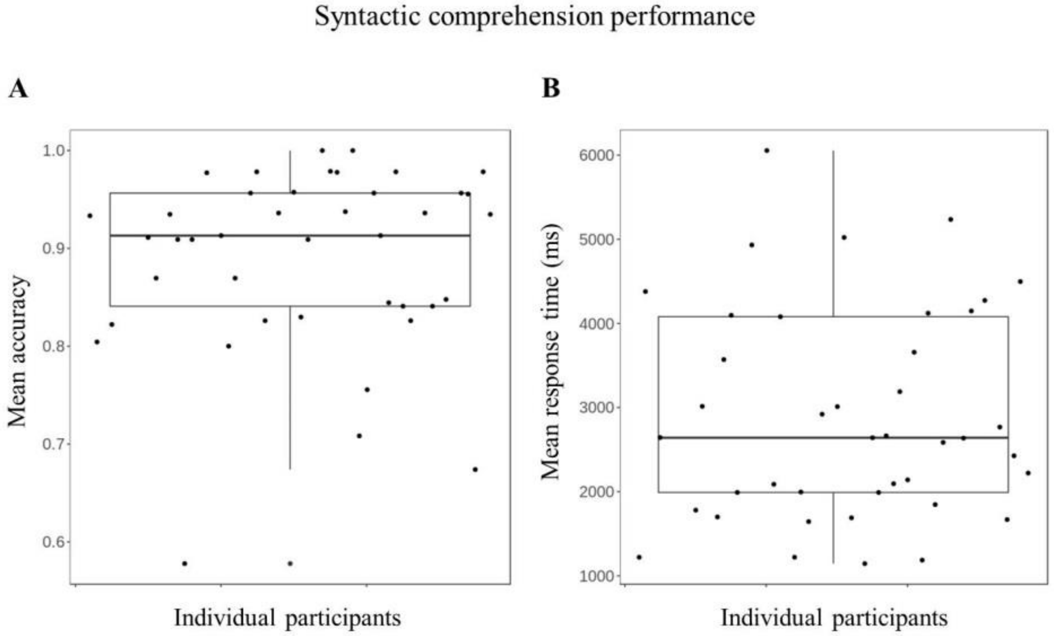

Figure 2.4 Group averages and individual variability in behavioural syntactic comprehension performance, accuracy (A) and reaction times (B). The performance measure is an average score for rejecting (for correct binding, e.g., “*I sploff*”) and detecting (for incorrect binding, e.g., “*I sploffs*”) morpho-syntactic agreement errors.

Visualized in Figure 2.5 is the relationship between syntactic comprehension accuracy on the one hand, and the neural signatures associated with syntactic binding (i.e., the difference in theta, alpha and beta power – see above), working memory capacity, processing speed and age on the other hand. Similarly, the relationship between syntactic comprehension reaction times and each of these variables is visualized in Figure 2.6.

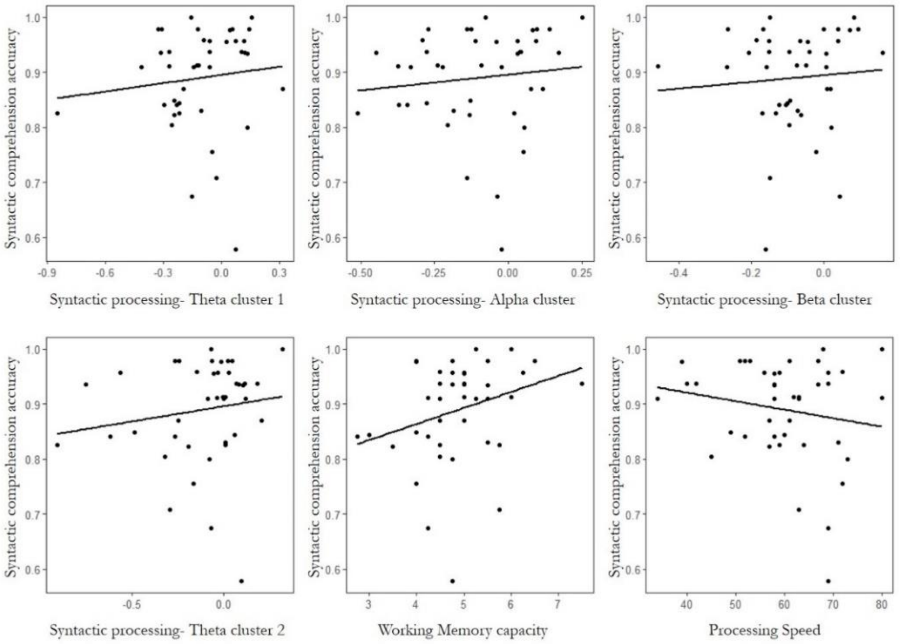

Figure 2.5 A scatterplot matrix of syntactic comprehension accuracy for each participant against each of the independent variables in the regression model including regression lines of best fit. Starting at the top left panel in clockwise direction: the neural signature of syntactic binding in the theta band (cluster 1), in the alpha band; in the beta band; in the theta band (cluster 2); Working Memory capacity and Processing Speed – each in relation to syntactic comprehension accuracy.

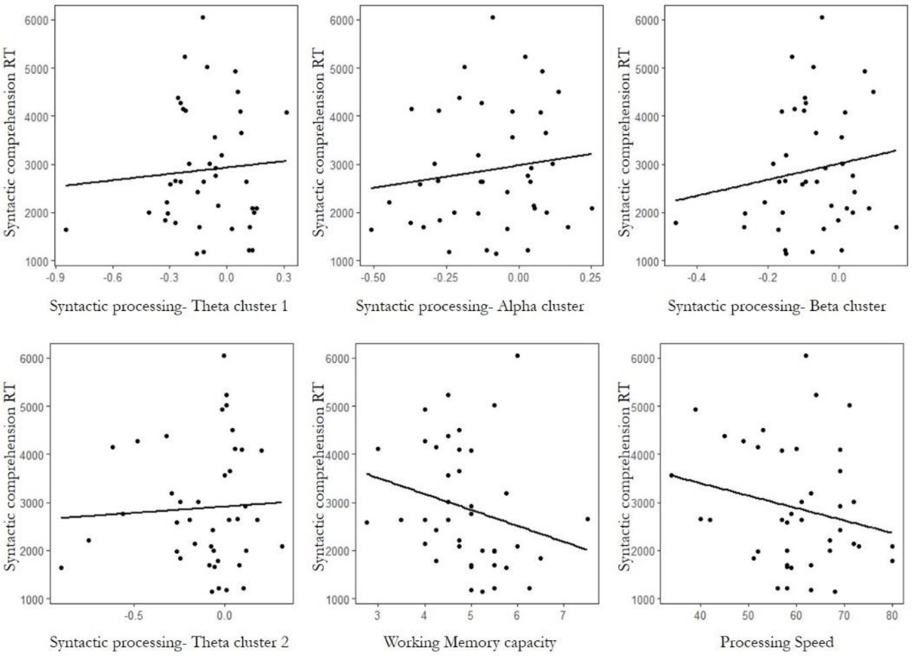

Figure 2.6 A scatterplot matrix of syntactic comprehension response time (RT) for each participant against each of the independent variables in the regression model including regression lines of best fit. Starting at the top left panel in clockwise direction: the neural signature of syntactic binding in the theta band (cluster 1), in the alpha band; in the beta band; in the theta band (cluster 2); Working Memory capacity and Processing Speed – each in relation to syntactic comprehension response time.

We will first turn to the analyses of the relationship between the accuracy data and the neural signatures associated with syntactic binding. Table 2.4A presents the results from the multiple regression model predicting syntactic comprehension accuracy with the neural signatures of syntactic binding (that is, the theta cluster 1; the alpha cluster; the beta cluster and the theta cluster 2), together with processing speed, working memory capacity and age. The overall model fit was R^2 = 0.17. The model did not reach statistical significance (p = 0.47). The included predictors are therefore not able to explain variability in comprehension accuracy.

Likewise, the regression model including all individual variability measures (thus, additionally including hand grip and physical activity) did not reach significance (R^2 = 0.16 p = 0.37; see table 2.4B).

Bayesian analyses showed anecdotal (i.e., weak) support for the effect of the Theta cluster 1 (BF_{10} = 1.71); the Alpha cluster (BF_{10} = 1.55); the Beta cluster (BF_{10} = 1.52) and the Theta cluster 2 (BF_{10} = 1.58). In addition, Bayes factors gave inconclusive evidence for the effect of Processing Speed (BF_{10} = 0.80); Working Memory capacity (BF_{10} = 1.04) and Age (BF_{10} = 1.01), given that all these values centred around 1.

To estimate the statistical power of our model with our available sample size, we ran a post hoc power analysis using the *pwr.f2.test* function for general linear models of the *pwr package* in R (Champ- ley, 2015). This revealed a statistical power of 0.43, given the current sample size (n= 41); the number of coefficients in the model (7) and the effect size (R^2 = 0.17) at an alpha level of 0.05.

Table 2.4A Coefficient estimates, standard errors, t values and p values of the multiple regression model predicting accuracy with Processing Speed and Working Memory capacity as additional predictors

Coefficient	Estimate	Std. Error	t value	p	
(Intercept)	1.248657	0.289578	4.31	< 0.001	***
Theta cluster 1	0.004581	0.120242	0.04	0.97	
Alpha cluster	0.086855	0.167967	0.52	0.61	
Beta cluster	-0.117336	0.208068	-0.56	0.58	
Theta cluster 2	0.037370	0.079344	0.47	0.64	
Processing Speed	-0.002301	0.001558	-1.48	0.15	
Working Memory capacity	0.020429	0.017291	1.18	0.25	
Age	-0.005124	0.004194	-1.22	0.23	

Table 2.4B Coefficient estimates, standard errors, t values and p values of the multiple regression model predicting accuracy with Processing Speed, Working Memory capacity, Handgrip and Physical Activity as additional predictors

Coefficient	Estimate	Std. Error	t value	p	
(Intercept)	1.208e+00	2.974e-01	4.06	< 0.001	***
Theta cluster 1	1.611e-04	1.223e-01	0.00	0.99	
Alpha cluster	6.184e-02	1.724e-01	0.36	0.72	
Beta cluster	-7.119e-02	2.163e-01	-0.33	0.74	
Theta cluster 2	4.306e-02	8.084e-02	0.53	0.60	
Processing Speed	-2.320e-03	1.587e-03	-1.46	0.15	
Working Memory capacity	2.174e-02	1.778e-02	1.22	0.23	
Handgrip	-1.543e-02	1.578e-02	-0.98	0.34	
Physical Activity	9.442e-06	9.304e-05	0.10	0.92	
Age	-4.520e-03	4.309e-03	-1.05	0.30	

*Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 ' ' 1*

Next we turn to the analyses of the relationship between the reaction time data and the neural signatures associated with syntactic binding. Table 2.5A presents the results from the multiple regression model predicting response time on the individual measures on syntactic binding (that is, the theta cluster 1; the alpha cluster; the beta cluster and the theta cluster 2); processing speed, working memory capacity and age. The overall model fit was R^2 = 0.13. The model did not reach statistical significance (p = 0.66); the included predictors are therefore not able to explain variability in comprehension accuracy. Likewise, the regression model including all individual variability measures (thus, additionally including hand grip and physical activity) did not reach significance (R^2 = 0.20, p = 0.58; see table 2.5B).

Bayesian analyses showed anecdotal (i.e., weak) evidence for Age (BF_{10} = 1.67); Theta cluster 1 (BF_{10} = 1.66); Alpha cluster (BF_{10} = 1.59); Beta cluster (BF_{10} = 1.67) and Theta cluster 2 (BF_{10} = 1.65). Bayes factors gave inconclusive evidence for Processing Speed (BF_{10} = 0.99) and Working Memory capacity (BF_{10} = 0.84).

To estimate the statistical power of our model with our available sample size, we ran a post hoc power analysis using the *pwr.f2.test* function for general linear models of the *pwr package* in R (Champely et al., 2018). This revealed a statistical power of 0.32, given the current sample size (n= 41); the number of coefficients in the model (7) and the effect size (R^2 = 0.13) at an alpha level of 0.05.

Table 2.5A Coefficient estimates, standard errors, t values and p values of the multiple regression model predicting response time with Processing Speed and Working Memory capacity as additional predictors

Coefficient	Estimate	Std. Error	t value	p
(Intercept)	2429.000	4008.828	0.61	0.55
Theta cluster 1	-204.298	1664.589	-0.12	0.90
Alpha cluster	862.787	2325.280	0.37	0.71
Beta cluster	391.856	2880.426	0.14	0.89
Theta cluster 2	202.042	1098.417	0.18	0.86
Processing Speed	-26.247	21.570	-1.22	0.22
Working Memory capacity	-337.281	239.373	-1.41	0.17
Age	8.251	58.055	0.14	0.88

Table 2.5B Coefficient estimates, standard errors, t values and p values of the multiple regression model predicting response time with Processing Speed, Working Memory capacity, Handgrip and Physical Activity as additional predictors

Coefficient	Estimate	Std. Error	t value	p
(Intercept)	2022.791	4022.366	0.50	0.62
Theta cluster 1	-139.157	1654.189	-0.12	0.99
Alpha cluster	366.225	2331.412	0.16	0.88
Beta cluster	1028.138	2925.878	0.35	0.73
Theta cluster 2	350.809	1093.322	0.32	0.75
Processing Speed	-24.796	21.469	-1.15	0.26
Working Memory capacity	-349.153	240.541	-1.45	0.16
Handgrip	-205.437	213.430	-0.96	0.34
Physical Activity	1.388	1.258	1.10	0.29
Age	14.363	58.282	0.25	0.81

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 ‘ ’ 1

Discussion

We investigated the oscillatory mechanisms associated with syntactic binding in healthy ageing, and whether these mechanisms are compensatory in nature, supporting behavioural performance. At the group level, we found that syntactic binding, assessed as the difference in oscillatory activity between the correct syntactic binding and the no syntactic binding condition, was associated with a *smaller* increase in theta (4- 7 Hz); alpha (8- 12 Hz) and beta (15- 20 Hz) power in the correct binding relative to the no binding condition. These findings suggest that the neural signature of syntactic binding in older adults is qualitatively different from younger adults, who show a *larger* (instead of smaller) alpha and beta power increase for correct binding compared to no binding in the same task (Segaert et al., 2018). At the individual-level, there was marked variability in the oscillatory signatures for syntactic binding. However, we did not find evidence for a significant relationship between behavioural syntactic performance and the neural signatures of syntactic binding, thereby providing no support for the hypothesis that the changes in the oscillatory signatures for syntactic binding in healthy ageing are compensatory in nature. We expand on the implications of these findings below.

Syntactic binding in older adults is associated with oscillatory activity in the theta, alpha and beta band

We will first discuss the group level results, where we found that correct syntactic binding (relative to no syntactic binding) was associated with a smaller increase in theta (4- 7 Hz); alpha (8- 12 Hz) and beta (15- 20 Hz) power. We will discuss these in turn, starting with the condition effects in the theta band. In sentences for which binding occurs, the theta amplitude rebounds to baseline following a strong increase associated with the presentation of the first word. In contrast, in sentences for which no binding occurs, a prolonged increase in theta power was observed, resulting in a condition difference between -0.25s and 0.1s surrounding the presentation of the second word, which was maximal over a cluster of left frontal-parietal electrodes. The increase in theta power in both conditions fits the general observation that modulations in the theta-band are related to lexical processing (Bastiaansen et al., 2002a; Bastiaansen & Hagoort, 2003; Bastiaansen et al., 2010; Grabner , Brunner, Leeb, Neuper & Pfurtscheller, 2007), although it should be noted that these latter studies used existing words instead of pseudowords.

A potential explanation for the observed early (i.e., between -0.25s and 0.1s surrounding the presentation of the second word) condition differences in theta power may be related to a small difference in the duration of the stimuli. Specifically, whereas the first word in the correct syntactic binding condition is a pronoun, with an average duration of 0.3s (SD= 0.03s), the first word in the no syntactic binding condition is a pseudoverb, with an average duration of 0.4s (SD= 0.07s). However, compared to the correct syntactic binding condition, the prolonged increase in theta power in the no syntactic binding condition is much longer than the 0.1s difference in stimulus length between the conditions. We therefore find it is unlikely that the observed condition differences could be fully explained by the small difference in stimulus duration between pronouns and pseudoverbs.

Alternatively, and in our opinion, more probable, the early condition difference in theta power may be related to prolonged lexical-semantic retrieval operations in the no syntactic binding condition relative to the correct syntactic binding condition. Note that in the correct syntactic binding condition the theta response shows a typical pattern, characterized by an event-related increase in theta power, followed by a return to baseline. Of relevance here is that the first word in the correct syntactic binding condition is a pronoun, i.e., a high frequency word. In contrast, the theta response in the no syntactic binding condition deviates from the typical pattern as the power does not return to baseline until after the presentation of the second word. Here, the first word is a pseudoverb, i.e., a word with no representation in the mental lexicon. However, the fact that no mental representation exists for pseudoverbs does not mean that no lexical-semantic retrieval operations occur. Intuitively, under the assumption that lexical-semantic resources are used for processing the phrases, a failure to match the incoming stimuli to existing stored lexical-semantic templates extends processing time in such instances. A similar interpretation may hold for the second theta cluster that was found from 0.75-1s following the second word. While the second word is a pseudoverb in both conditions, the preceding word in the correct syntactic binding condition contextualizes the second word, whereas the second word in the no syntactic binding condition is a continuation of a meaningless, decontextualized linguistic composition. Taken together, the results in the theta band may suggest that the increased and prolonged power in the no syntactic binding condition is indicative of maintained lexical-semantic processing.

In the alpha band (8- 12 Hz), we observed a smaller increase in the correct syntactic binding compared to the no syntactic binding condition in a time window from -0.25 to 0.3s surrounding the second word over left-frontal central and parietal areas. Using an identical paradigm, Segaert et al. (2018) found a similar, though not identical increase in alpha power for both the correct syntactic binding and no binding condition in younger adults in a time window around the presentation of the second word. (We turn to an in depth discussion of the differences between young and older adults in the next section). This suggests these alpha modulations reflect similar processes, which, in Segaert et al. (2018) were taken to reflect neural signatures for the expectation of binding (i.e., preceding word two) and for binding (i.e., following word two) taking place. Attributing this finding to expectation is in line with observations of Shtyrov, Pulvermuller, Naatanen, Ilmoniemi (2003) and Alexeeva et al. (in prep), who also used a minimal phrase paradigm and measured ERP indexes of combinatorial processing. Their findings suggest that language users pre-activate memory traces of the correct affix, based on information that is available when presented with a pronoun.

Other previous research suggests that an alpha power decrease (instead of an increase) is associated with increased syntactic processing following a syntactic agreement violation (Bastiaansen et al., 2010; Davidson & Indefrey, 2007). The fact that both the current and previous findings by Segaert et al. (2018) found an alpha power increase (instead of a decrease) associated with syntactic binding may suggest a more extended role of alpha oscillations in syntactic processing. Notably, Meyer et al. (2013) also observed an increase in alpha power in auditory sentence processing, although these effects were found in the context of increased storage demands, whereas in our minimal phrase paradigm, working memory demands are deliberately kept low. Alternatively, the observed increase in alpha power in the current and Segaert's et al. (2018) work may be related to specific processing demands required for the contextually deprived stimuli that were used. Specifically, frontal alpha synchronization has been proposed to relate to top-down processing and high internal processing demands (Benedek, Bergner, Könen, Fink & Neubauer, 2011). In a series of studies on the oscillatory mechanisms of creative cognition, or divergent thinking (i.e., tasks in which a person is required to tackle a problem in different, unconventional ways), Fink et al. (Fink, Benedek, Grabner, Staudt & Neubauer, 2007; Fink et al., 2009) suggest that alpha synchronization generally reflects high internal processing demands and states of high internal attention. Processing the pseudoverbs arguably involves high internal processing demands due to the fact that these stimuli do not have a representation in the mental lexicon. The overall task-related alpha increase may therefore be related to high internal processing demands.

Lastly, in the low beta band (15- 20 Hz), there was a smaller increase in power in the correct syntactic binding compared to the no syntactic binding condition in a time window

-0.3 to 0.15s surrounding the onset of the second word. This difference was most pronounced in a large frontal-posterior cluster. While these effects could be related to spectral leakage from neighbouring frequency bands (i.e., the observed power increase in the alpha band), this is unlikely given that the onset of the beta cluster precedes the alpha cluster (by 0.05s). Alternatively, the observed power increase in the beta band could reflect a sustained process related to syntactic binding. Similar to the effects found in the alpha band, the observed increase in beta power is generally consistent with findings from Segaert et al. (2018), but does not straightforwardly fit into the emerging picture from other work suggesting that a beta decrease (rather than an increase) reflects failures of syntactic binding mechanisms (Prystauka & Lewis, 2019, Bastiaansen et al. 2010; Davidson & Indefrey, 2007). However, an important consideration that complicates a comparison of the results from Bastiaansen et al. (2010) and Davidson & Indefrey (2007) on the one hand and the current study and Segaert et al. (2018) on the other hand, is that the former studies focused on syntactic violations, whereas the latter two specifically focused on binding operations at the syntactic level. In addition, the beta effects that were found in the aforementioned studies all started after the onset of the critical word, whereas the overall beta increase that was observed in the current study and Segaert et al. (2018) started before the onset of the critical word. Given the timing of these effects, the observed differences in beta power may be influenced by anticipatory processing mechanisms. Specifically, the beta increase observed here could be in line with accounts proposing that an increase in beta power reflects active maintenance of context, whereas a decrease in beta power signals new processing requirements (Engel & Fries, 2010; Lewis, Wang & Bastiaansen, 2015; Lewis & Bastiaansen, 2015). In a recent study by Armeni, Willems, van den Bosch & Schoffelen (2019) on the oscillatory mechanisms of expectation-based predictive processing in auditory language comprehension, more expected words led to higher beta-band power. In the current study, the inclusion of a filler condition consisting of a pronoun followed by another pronoun eliminated the predictability for the binding condition. However, the no binding condition was predictable prior to the onset of the second word. According to the Engel and Fries (2010) framework, more expected contexts (i.e., in the current study, the no binding condition) would elicit higher beta-band power compared to less predictive contexts (i.e., the syntactic binding condition). The larger beta power increase in the no binding relative to the binding condition could therefore be related to anticipatory processing mechanisms.

Neural signature associated with syntactic binding in older adults is qualitatively different from younger adults

An interesting finding in the present study is that, at the group level, older adults show a qualitatively different neural signature of syntactic binding compared to the previously reported signature in younger adults. We want to emphasize that the comparison between the younger and older age group is indirect. However, the data on young and older adults were collected using the same task and paradigm, both comparing correct syntactic binding to no binding using a minimal phrase paradigm with pseudoverbs, thus warranting a comparison between the two studies.

The most notable difference in the results of the current study and Segaert et al. (2018) is the absence of any theta effects in the younger age group. We argued above that the within group difference in theta power in older adults may be indicative of prolonged lexical-semantic processing in the no syntactic binding condition. The fact that Segaert et al. (2018) did not find any condition differences in the theta band in younger adults suggests that this may in fact be an age-related phenomenon. Specifically, even though the minimal phrases carry limited meaning, older adults may nevertheless continue to recruit semantic resources to process the syntactic information, whereas younger adults may more easily adapt to the greater emphasis on syntactic binding that the experimental manipulation exerts on the processing requirements of the stimuli. A study by Schneider et al. (2016) may further support this interpretation. Specifically, this study investigated the neural oscillations underlying grammatically correct and incorrect sentences in a group of young adults (aged 18- 31). While the integration of semantic information associated with the presentation of each new word in the sentence was expected to elicit a theta increase (i.e., in accordance with Bastiaansen et al., 2002b and Bastiaansen et al., 2010), they observed a decrease in theta power following the critical verb in sentences containing a subject-verb agreement violation. Crucially, an explicit syntactic judgement task was used to assess comprehension performance. The authors speculate that the unexpected theta decrease may reflect that young adults minimized or stopped integrating semantic information after detecting a syntactic violation given that the syntactic error was the primary information required for making a subsequent grammaticality judgement. In other words, these findings tentatively suggest that semantic processing in young adults may halt, or minimize when they are required to explicitly focus on syntactic information. The experimental manipulation in the current study and Segaert et al. (2018) equally forced participants to focus on syntactic information to process the phrases. While the absence of any theta effects in Segaert et al. (2018) indeed suggests that semantic processing in young adults was minimal, we tentatively suggest that the theta effects in the older age group indicate involvement of semantic processing despite the minimal semantic information that could be retrieved. Interestingly, our previous behavioural work has shown that syntactic comprehension performance in older adults was particularly compromised relative to younger adults in pseudoverb sentences compared to real verb sentences (Poulisse et al., 2019). In other words, these behavioural findings suggest that age-related decline in syntactic comprehension is greater in the absence of lexical-semantic information. Supporting evidence for this idea comes from Beese et al. (2019) who found that the use of syntactic constraints in sentence processing was compromised in older compared to younger adults, while the benefit of semantic information was comparable across age groups. The authors propose that the increased reliance on semantic information in older adults may lead to a change in sentence processing strategies toward a semantic approach. The current findings extend this idea by demonstrating alterations in the oscillatory dynamics associated with these processes.

Another noteworthy finding is that the relative alpha and beta power difference between conditions inverts between the two age groups. Specifically, while both the correct binding and no syntactic binding condition was associated with an alpha and beta increase in both young and older adults, the power difference associated with syntactic binding was *negative* in older adults (i.e., there was a *smaller* increase in alpha and beta power in correct relative to no syntactic binding), whereas Segaert et al. (2018) show a *positive* power difference in young adults (i.e., there was a *larger* increase in alpha and beta power in correct relative to no syntactic binding). In both age groups, these differences were observed in a time window surrounding the presentation of the second word (i.e., both preceding and following the onset of the second word). The inverted response pattern cannot be readily reconciled with the proposed idea of increased reliance on semantic processing in older adults. Specifically, semantic (retrieval) processes are commonly associated with a suppression (i.e., a decrease) in alpha power (e.g., Klimesch, Doppelmayr, Pachinger & Russegger 1997; Klimesch, 1999; Mazaheri et al., 2018). Therefore, reasoning based on an age-related increase in semantic processing, would predict a decrease in alpha power in sentences for which binding occurs and a stronger decrease in sentences for which no binding occurs. In contrast we found an alpha increase that was overall stronger in sentences for which no syntactic binding occurs. Indeed, considering these two processes (i.e., lexical-semantic retrieval and syntactic binding operations) in isolation, one would expect the opposite synchronization pattern. However, the evaluation of the sentences in this study likely required both lexical-semantic retrieval as well as syntactic binding processing mechanisms. These coexistent processes may generate oscillations that temporally overlap. From this viewpoint, the observed increase in alpha power may in fact be a summation of heterogeneous oscillatory mechanisms reflecting different, parallel processes. In support of this interpretation, the alpha power modulations were observed over a large cluster of left-frontal central and parietal regions and over a long time window lasting 0.45s. The exact source locations of the different oscillatory activities are difficult to compute due to the low spatial resolution of EEG. In future research, this issue could be clarified by using MEG instead of EEG.

No evidence for a relationship between syntactic comprehension performance and the neural signature associated with syntactic binding

Having established that, at the group level, the neural signature of syntactic binding is qualitatively different in older compared to younger adults, a subsequent question is how age-related changes in neural activity may contribute to successful behavioural performance in old age. The rationale of this research question comes from two key findings in the literature on healthy ageing. Firstly, there have been arguments in the literature that syntactic comprehension in older adults may be subject to neural compensation (e.g., Grossman et al., 2002; Tyler et al., 2010). *Compensation* in this context refers to cognition enhancing recruitment of neural resources that benefits behavioural performance (Cabeza et al., 2018). Secondly, there are individual differences in neural and cognitive functioning; creating individual differences in the supply of resources that is available. These are crucial determinants of an individual's language processing performance (Peelle, 2019).

In the current study, we examined whether there was a relationship between the variability in syntactic comprehension performance and the functional neural signatures of syntactic binding. However, both the regression analyses and the follow up Bayesian Factor analyses generated inconclusive results. Consequently, the absence of a clear, identifiable relationship between syntactic comprehension performance and the neural signatures associated with syntactic binding prevents us from making any further inferences on the presence of neural compensation in this context. In this sense, our results are consistent with Tyler et al. (2010) and Peelle et al. (2009) who observed additional neural activity in older compared to younger adults in the absence of a relationship between the additional activity and behavioural performance. Nevertheless, a few important points should be made regarding our null-findings.

Firstly, the absence of evidence is not equal to evidence of absence. One possibility is that the age-related functional changes that we observed are not compensatory. Instead, they could reflect a general decline in neural efficiency, or dedifferentiation. Alternatively, as is always the case with null-findings, it is possible that a relation between behavioural performance and brain function exists for syntactic processing in healthy ageing, but that we were unable to detect such a relationship.

One possible reason why we may not have observed such a relationship is that our behavioural measure may not have been sensitive enough. However, even though the results of the models relating behavioural performance to the neural signatures were inconclusive, the dependent variables that were used to measure syntactic comprehension performance in this study were reliable measures. Specifically, both measures of syntactic comprehension (i.e., accuracy and RT) were found to have a high level of internal consistency. In addition, the current behavioural findings are consistent with our previous findings showing an average accuracy of 85% (SD = 31%) and an average response time of 1270 ms (SD = 982 ms) for correctly rejecting and detecting morpho-syntactic agreement violations for respectively correct and incorrect phrases (Poulisse et al., 2019).

Alternatively, it may be that the neural dynamics observed for older adults merely reflect generic properties of the neural signature of syntactic binding (i.e., properties that are present in all older individuals, but lacking the specificity to differentiate between sub groups). A critical remark in this connection is the fact that the alpha frequency in particular shows large age-related inter individual differences (Klimesch, 1999). Consequently, it may be that the effect of age on the oscillatory dynamics of syntactic binding can only be observed by discarding fixed frequency bands. While using individual based alpha frequency bands would be a valuable direction for future ageing research on individual variability, it would not be a suitable approach in the current study, given that the changes in the EEG were not limited to modulations in the alpha band. When we did look at the individual peak-frequency of alpha activity, we found it to range between 9 and 11 Hz, which fell within the frequency bands we had previously used to define alpha activity in younger adults. Specifically, syntactic binding is supported by oscillatory activity in the theta, alpha and beta band. Optimizing the alpha band analyses would therefore not sufficiently cover the full range of interest.

Lastly, the post-hoc power analyses using the effect sizes generated by the regression models and the desired power set to 0.8, revealed that a sample size of 69 and 90 is required to relate the neural signatures of syntactic processing to the accuracy and response time for syntactic judgements respectively. This suggests that if a relationship exists between syntactic comprehension performance and age-related functional neural changes, the relationship would be of a weak and complex nature, such that any study aimed at demonstrating a relationship unequivocally would need a very high number of participants.

Limitations and future directions

A number of limitations to our approach deserve to be mentioned.

Firstly, our approach to minimizing the contribution of semantics by using pseudoverbs comes with the constraint that the neural signatures in the time window between the first and the second word may reflect differences between processing an existing word (i.e., a pronoun) and a pseudoverb. However, this is not the most parsimonious explanation given the onset of these condition differences in relation to the first word. Specifically, compared to previous EEG findings on differences between real words and pseudo words (e.g., Münte, Matzke & Johannes, 1997; Shtyrov, Pihko, & Pulvermüller, 2005; Shtyrov & Lenzen, 2017), the observed effects in the current study are relatively late (i.e., both the alpha and beta effects start 0.95s after the onset of word one).

The use of real verbs instead of (or perhaps in addition to) pseudoverbs could further elucidate the exact mechanism behind the observed signatures in the current study. This would be helpful in order to verify whether the observed age differences are indeed related to an increased reliance on semantic information with increasing age. Specifically, this theory would lead us to predict that the neural signature associated with syntactic binding in older adults would show a closer resemblance to the neural signature in young adults for syntactic structures that are embedded in a semantically meaningful context. In line with this interpretation, our previous work showed that age-related decline in syntactic comprehension performance was reduced in real verb sentences compared to pseudoverb sentences (Poulisse et al, 2019).

Furthermore, the predictability of the conditions at the onset of the first word was not ideally controlled in the current design. Similar to our previous behavioural work (Poulisse et al., 2019), the inclusion of a condition in which a pseudoverb is paired with an adjective (e.g., "*cuggs slowly*") could address this issue in future work.

Lastly, the age differences that were observed by comparing the results of the current study with previous findings in young adults (Segaert et al., 2018) motivates a follow up study that would allow a direct statistical comparison between young and old. However, as a critical remark to this point, one should bear in mind that a straightforward comparison between a younger and an older age group will unlikely provide a comprehensive insight into the (potential) role of compensatory mechanisms. After taking into account inter-individual variability in our functional measure, it was evident that only half of the participants responded in a way that was in accordance with the group mean average. Research aimed at understanding what accounts for this inter individual variability will be a critical direction for future research. In this context, it should be noted that the current design only allowed syntactic comprehension effects to be evaluated after averaging over subjects. Experiments specifically designed to allow for mixed effects model fits (i.e., accounting for individual by-subject variation) would be a particularly valuable future direction for estimating inter-individual variation in greater detail (Baayen, Davidson & Bates, 2008).

General conclusions

This study provides novel evidence on age-related functional change associated with syntactic processing. Syntactic binding in older adults is associated with a smaller increase in theta (4- 7 Hz) power; an effect not present in younger adults. In addition, while syntactic binding in older adults is associated with a smaller increase in alpha (8- 12 Hz) and beta (15-20 Hz) power for binding (compared to no binding) conditions, previous work has shown the opposite pattern in younger adults, that is, a larger increase in alpha and beta power for binding (compared to no binding) conditions. Hence, the neural signature of syntactic binding in older adults is qualitatively different from younger adults. We suggest that the observed differences between young and older adults are possibly related to an increased reliance on semantic processing with increasing age. When examining the relationship between these age-related oscillatory changes and behaviour, we found no evidence of a significant association between behavioural comprehension performance and the neural signatures of syntactic binding. Consequently, the absence of an identifiable relationship between behavioural performance and syntactic binding prevents us from making any further inferences on whether these age-related functional changes are indicative of compensation, or dedifferentiation.

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CHAPTER 3

OSCILLATORY MECHANISMS ASSOCIATED WITH LEXICAL AND SEMANTIC PROCESSING IN HEALTHY OLDER ADULTS AND MCI: A MEASURE OF EARLY COGNITIVE IMPAIRMENT?

Previous work suggests that lexical-semantic processing is impaired in Mild Cognitive Impairment (MCI), but mechanisms underlying these alterations are poorly understood. Here, using a flex-printed electrode array placed around the ear (ideal for EEG recordings in a clinical setting) we investigated subtle anomalies in brain activity associated with lexical and semantic processing in individuals with MCI compared to healthy controls. Participants read nouns that were paired with an adjective to form a semantically plausible (e.g., "*sharp knife"*), or implausible (e.g., "*classic snake"*) combination, and nouns that were paired with a letter string, for which minimal semantic binding occurs (e.g., "*snklvwe mother"*). Oscillatory mechanisms associated with lexical retrieval were assessed by comparing adjectives (e.g., "*sharp, classic"*) to letter strings (e.g., "*snklvwe"*). Furthermore, semantic binding was assessed by comparing the semantic binding to the no semantic binding condition around the *second* word. In addition, semantic plausibility was assessed by comparing the plausible and implausible semantic binding condition. In healthy older adults, lexical retrieval was associated with a power increase in the alpha and low beta range in the lexical, relative to the non-lexical condition. Furthermore, semantic binding was associated with a smaller power decrease in the semantic binding relative to the no semantic binding condition. A similar, but attenuated pattern was seen in the MCI group for both lexical retrieval and semantic binding. No within or between group differences were found on semantic plausibility. Taken together, this suggests that oscillatory changes during a simple word processing task delineate important functional differences associated with lexical and semantic processing in MCI.

Introduction

Mild Cognitive Impairment (MCI) is a syndrome characterized by subtle yet clinically established cognitive impairment in the absence of deficits in daily living activities. Although there exists controversy as to whether MCI invariably represents prodromal dementia (Taler & Phillips, 2008), the clinical and pathological characteristics of MCI are thought to represent a point on the continuum of cognitive function that lies between healthy ageing and dementia (Chertkow, 2002; Petersen, 2004). Individuals diagnosed with MCI are at an increased risk of developing Alzheimer's disease (AD): average annual conversion rates from MCI to AD have been found to range between 10- 15%, compared to 1-2% for healthy individuals (Petersen et al., 1997; Petersen, Stevens, Ganguli & Tangalos, 2001; Shah, Tangalos & Petersen, 2000).

Some of the most prominent features of AD pathology are language impairments (Ferris & Farlow, 2013; Vestal et al., 2006; Henry, Crawford & Phillips, 2004). Language abilities commonly deteriorate early in the course of the disease and have been proven to be of particular clinical significance in terms of tracking disease progression (Ferris & Farlow, 2013). Given the urgent need to find markers that indicate subtle anomalies at an early stage of AD, the investigation of language impairments in individuals diagnosed with MCI is of great interest. In this context, the assessment of lexical and semantic processing abilities has been proposed to be a particularly promising approach for better classification of the neuropsychological profile of MCI (Taler & Philips, 2008). The current work aims to contribute to this growing area of research by investigating the oscillatory mechanisms supporting lexical semantic processing in MCI and healthy elderly controls using EEG.

Language impairments in MCI

Accruing evidence suggests that individuals diagnosed with MCI have impairments in naming and verbal fluency (Taler & Phillips, 2008; Thompson, Graham, Patterson, Sahakian & Hodges, 2002; Ahmed, Arnold, Thompson, Graham & Hodges, 2008). While a number of studies have been able to successfully discriminate between healthy control subjects, MCI and AD using naming and fluency tasks (e.g., Bennett et al., 2002; Tabert et al., 2006), other studies have failed to distinguish between either healthy control subjects and MCI (Karrasch, Sinervä, Grönholm, Rinne & Laine, 2005), or between MCI and AD (Vita et al., 2014). A few studies have investigated lexical semantic processing in MCI using non-standardized tests of language function. The limited evidence available suggests this may be a particularly promising approach for characterizing the neuropsychological profile of MCI (Duong, Whitehead, Hanratty & Chertkow, 2006; Taler & Phillips, 2008). Specifically, alterations have been documented in semantic priming (e.g., Duong et al., 2006; Davie et al., 2004), shallow semantic encoding of words (Puregger, Walla, Deecke and Dal-Bianco, 2003) and lexical decision (Taler & Jarema, 2006). In the latter study, on-line processing of differing noun types was investigated in MCI, AD and healthy controls. Using a go/no-go paradigm, participants were instructed to respond to words, but not non-words. Healthy controls were slower to respond to mass nouns (e.g., *honey*) and count nouns (e.g., *table*) compared to dual (metonymic) nouns (e.g., *chicken*). Here, the dual noun category refers to nouns that may both take a mass or a count reading (i.e*., a chicken, many chickens*). The relative advantage of lexical items with multiple related senses (i.e, dual nouns), commonly known as the 'ambiguity advantage' (Kawamoto, Farrar & Kello, 1994) was absent in both the MCI and AD group. In contrast, Duong et al. (2006) found that individuals with MCI were unimpaired on a lexical decision task and semantic priming task, but were impaired on picture naming and semantic probes. The results suggest that intentional, more effortful semantic processing is impaired in MCI, while performance that taps automatic access (i.e., lexical decision and semantic priming) remains preserved. This pattern of result may partly be attributable to differences in task difficulty. However, the authors propose a potential association between executive function and language processing to account for the observed lexico-semantic impairments in MCI. Supporting this assumption, they found that the MCI group also exhibited impairments on tasks relying on executive function.

Further evidence consistent with a semantic processing impairment in MCI comes from Olichney et al. (2002), who investigated event related potentials (ERPs) to single word processing during a word categorization task in individuals with MCI and healthy controls. In this task, participants were auditory presented with category statements (e.g., "*a breakfast food", "a type of wood"*), followed by the visual presentation of either a congruent noun (e.g., '*pancake', 'oak'*), or an incongruent noun (matched in length and frequency to the congruent nouns). The N400, an ERP component that is sensitive to semantic binding operations, is typically smaller for words in a semantically congruous context, compared to words that occur in a semantically incongruous context. The authors found that the difference in the N400 amplitude in response to congruous, compared to incongruous words (i.e., semantic congruency effect) was significantly delayed in the MCI group, compared to healthy controls. In addition, congruent nouns elicited a late positivity component (LPC) around 600 ms in the healthy control group, which decreased in amplitude with repetitive presentation of the word. This effect, known as the 'congruous word repetition effect', was largely attenuated in the MCI group. Interestingly, follow-up comparisons revealed the MCI individuals who subsequently converted to probable AD showed a nearly complete absence of the congruous word repetition effect, suggesting that absence of this effect is indicative of conversion from MCI to AD.

In conclusion, the literature suggests that linguistic impairments in MCI centre around conceptual-semantic and lexical-semantic processing, although there exists some disparity regarding the specific nature of these deficits. Temporally precise experimental methods appear to be particularly sensitive to subtle language impairments in MCI and some may even be of help in predicting conversion to AD.

Oscillatory activity in MCI

An alternative approach to identifying the pathological features of MCI that has gained much recent attention is the investigation of oscillatory brain activity in the time frequency domain. As a complement to the previously mentioned time domain analysis of the EEG signal (i.e., ERP analysis), time frequency analysis allows for the investigation of event related changes which are time-locked to the event, but not necessarily phase locked (i.e., when the phase of the event-related response is the same or very similar across all individual trials). Previous studies on EEG characterization in MCI have predominantly used resting state paradigms, in which participants are instructed to keep still with their eyes closed while the EEG is recorded. Resting state studies have consistently demonstrated an increase in EEG power in the lower frequency ranges (i.e., delta (< 4 Hz) and theta (4~ 7 Hz)), along with a relative decrease in EEG power in the higher frequency ranges (i.e., alpha (8~ 12 Hz); beta (15~ 30 Hz) and gamma (> 30 Hz)) in individuals with MCI and AD relative to healthy age matched controls (Czigler et al., 2008; van der Hiele et al., 2007; Moretti et al., 2010; Babiloni et al., 2016). However, these alterations in resting state EEG have been associated with a variety of neurological disorders; thus, they are not specific to MCI and AD pathology (Klimesh, 1999). In this perspective, research on EEG functional differences between individuals with MCI and healthy controls that is associated with *specific* cognitive functions is desirable to achieve higher specificity. Therefore, the current study aims to gain insight in what oscillatory mechanisms are associated with the lexical and semantic comprehension processing deficits in MCI.

Oscillatory mechanisms of lexical and semantic processing in young and healthy older adults

Studies on language processing in healthy individuals have implicated the involvement of oscillatory activity in the theta (4~ 7 Hz), alpha (8~ 12 Hz) and low beta (15~ 20 Hz) frequency ranges in lexical and semantic processing (e.g., Hagoort, Hald, Bastiaansen & Petersson, 2004; Bastiaansen, Magari & Hagoort, 2010; Davidson & Indefrey, 2007). Specifically, word processing is associated with an increase in theta and low beta power, along with an early power increase, followed by a power decrease in the alpha band (Bastiaansen, Oostenveld, Jensen & Hagoort, 2008; Bastiaansen, van der Linden, Keurs, Dijkstra & Hagoort, 2005). Extending on this, other work has shown that the presentation of words in sentence context is associated with a phasic power increase in the theta band, along with a phasic power decrease in the alpha band (Bastiaansen, van Berkum & Hagoort, 2002). In addition, theta power increase has been associated with lexical ambiguity (Strauss, Kotz, Scharinger & Obleser, 2014) and semantic violations (Davidson & Indefrey, 2007). Moreover, alpha and beta oscillations have been associated with binding, or integration of information and access to stored information (e.g., Klimesch, 2012, Strauss, Kotz, Scharinger & Obleser, 2014 & Segaert, Mazaheri & Hagoort, 2018; Weiss & Mueller, 2012).

The effects of healthy ageing on brain oscillatory responses during language processing are still largely unknown, but some preliminary evidence suggest these dynamics are indeed subject to age-related change. In our previous work (Poulisse, Wheeldon, Mazaheri & Segaert, in prep), we investigated the oscillatory mechanisms associated with syntactic binding in healthy older adults by comparing pseudoverb phrases in a syntactic binding context (e.g., *"they grush", "she grushes"*) to minimal phrases in a no binding context (e.g., '*pobs grush', 'dotched grushes*'). Syntactic binding, relative to no binding, was associated with a *smaller* increase in theta, alpha and beta power in a time window surrounding the onset of the second word. In contrast, using the same condition contrast, earlier work by Segaert, Mazaheri & Hagoort (2018) found that in young adults, syntactic binding (relative to no binding) was associated with a *larger* increase in alpha and beta power. Likewise, Meller, Bastiaansen, Pilgrim, Medvedev & Friedman (2012) investigated the oscillatory dynamics of open class (e.g., nouns, verbs and adjectives) and closed class (e.g., determiners, conjunctions and prepositions) word processing in a group of older adults (mean age 55). Extending on previous work with younger adults (Bastiaansen et al., 2005), the authors additionally investigated how the context surrounding the word influences the oscillatory dynamics underlying retrieval for the two different classes of words. Specifically, the words were either presented in a syntactically correct sentence, or in a scrambled letter order. There was a larger decrease in alpha power for open class, compared to closed class sentences, but only for words that were presented in the scrambled letter context. Furthermore, in contrast to the previous findings in younger adults (i.e., Bastiaansen et al., 2005), no differences in theta power were observed between the open and closed class condition. While in both Meller et al. (2012) and Poulisse et al. (in prep) a comparison of the oscillatory effects between the younger and older age group could only be made in an indirect manner, these findings suggest age-related differences in the neuronal dynamics during word retrieval and binding.

Oscillatory mechanisms of lexical semantic processing in MCI

To our knowledge, only one previous study looked at the oscillatory dynamics of lexical-semantic processing in MCI. Using the same data base as in Olichney et al. (2002), Mazaheri et al. (2018) investigated changes in oscillatory activity in MCI individuals and healthy controls to single words during a language comprehension task. Participants were auditorily presented with category statements (e.g., "*a breakfast food", "a type of wood"*), followed by the visual presentation of either a congruent noun (e.g., "*pancake", "oak"*), or an incongruent noun. While the original Olichney et al. (2002) study was set out to investigate implicit memory, Mazaheri et al. (2018) specifically looked at processes associated with lexical retrieval. The authors found that in both the congruent and incongruent condition, the onset of the word induced a significantly diminished theta increase individuals with MCI who would go on to develop AD (i.e., MCI converters), relative to MCI non converters and healthy controls. These findings reflect impaired lexical and semantic retrieval in MCI. Furthermore, in healthy controls, the semantic processing of congruent, but not incongruent words induced significant coupling between the posterior theta increase and frontal suppression in the alpha and beta band. This effect has been interpreted as indexing the interplay between lexical retrieval processes (i.e., theta activity over temporal regions) and binding of information (i.e., alpha/beta activity over frontal regions). The MCI group did not show this coupling. Taken together, these results suggest that retrieval processes of single word meaning as well as binding processes of multiple words are impaired in individuals diagnosed with MCI. However, a methodological challenge exists in the interpretation of these effects. Specifically, both lexical and semantic processes were assessed in the same sentence context, and semantic processing entailed a manipulation that conflated binding and plausibility processing.

The current study

The current study examined the oscillatory mechanisms supporting lexical and semantic processing in individuals diagnosed with MCI and healthy controls. We specifically focused on identifying the individual contributions of lexical retrieval and semantic binding, with the aim of establishing the specific nature of the linguistic deficits in MCI. We investigated the neurophysiological signature of elementary combinatoric language processing by comparing the oscillatory response to simple adjective-noun word pairs that differentially load on semantic processing (e.g., "*flying eagle*", "*blind couch*") and to adjectives and letter strings that differ in lexical retrieval (e.g., "*iafnxa", "flying")*. EEG was recorded while participants read these minimal phrases on screen.

Three different conditions of adjective-noun pairs were included in the experiment: a plausible semantic binding condition (e.g., *"plastic bucket"*); an implausible semantic binding condition (e.g., *"lively bucket"*) and a no semantic binding condition (e.g., "*iafnxa bucket"*). Lexical retrieval was assessed by comparing the oscillatory response to the semantic binding conditions with the response to no semantic binding condition, following the presentation of the *first word*. In other words, this contrast concerns the comparison of an adjective (i.e., in the semantic binding condition) to a letter string that does not have any meaning representation in the mental lexicon (i.e., in the no semantic binding condition). We thus expected increased lexical retrieval for the existing words, relative to the letter strings. Consistent with previous literature, we expected an increase in theta power in lexical relative to non-lexical retrieval in healthy older adults. In addition, we expected that the theta response to lexical and non-lexical retrieval will be less distinctive in the MCI group. Furthermore, semantic binding was assessed by using the same condition contrast, but focusing on oscillatory changes following the presentation of the *second word*. In the semantic binding condition, a semantic context can be established by binding the first and the second word. In contrast, in the no semantic binding condition the letter string cannot be coupled with the subsequent noun, which would hinder binding processes. In other words, the second word in these two conditions differs in terms of semantic binding taking place. We thus expected that the adjective-noun word pairs in the semantic binding condition would increase semantic binding load relative to the scrambled letter string-noun pairs in the no semantic binding condition. In healthy older adults, we expected semantic binding to be associated with modulations in the alpha and beta band. This effect was expected to be attenuated in the MCI group. Lastly, semantic plausibility was investigated by comparing the oscillatory response to the plausible semantic binding condition with the response to the implausible semantic binding condition. In the plausible semantic binding condition, the adjective-noun word pair forms a semantically likely or congruent combination, whereas in the implausible semantic binding condition, the combination of words forms an unlikely or anomalous context. Consistent with previous findings, we expected a theta power increase for plausible relative to implausible word pairs. We expected that, compared to healthy older adults, individuals with MCI would have an attenuated or abnormal oscillatory theta response.

Methods

Participants

A group of 33 MCI patients and 27 right handed control subjects participated in the experiment. The MCI patients were recruited from the Cambridge University Hospital NHS Trust MCI and Memory Clinics. Of these, 10 patients and 4 control subjects were excluded from the analysis due to extreme noise in the EEG data and signal drop out, resulting in a final sample of 23 MCI patients (mean age: 70 years; SD: 9; range: 51- 86 years) and 23 control subjects (mean age: 72 years; SD: 5, range: 61- 80 years). The two groups were similar in years of education ($t(42) = 1.3$, $p = 0.2$). Healthy controls had an average of 16 years of education (SD: 3), while the MCI group had an average of 14 years of education (SD: 4). MCI was diagnosed by a neurologist according to Petersen's criteria (Petersen, 2004). Specifically, the diagnosis was based on the following criteria: (i) the presence of a complaint of defective memory from the patient (generally corroborated by an informant); (ii) an objective memory impairment for age on formal testing; (iii) relatively preserved general cognition for age; (iv) generally intact activities of daily living; (v) no diagnosis of dementia. All control participants were native British English speakers and reported to be in good health with no history of neurological, or language disorders. Control participants were recruited via the database of the School of Psychology of Birmingham University and were tested at Birmingham University. All participants gave informed consent. Ethical approval was obtained from the NHS Cambridge South Research Ethics Committee; the University of Cambridge Human Biology Research Ethics Committee and by the University of Birmingham Ethical Review (ERN 15-0866).

Materials & Design

A set of 90 high-frequent English nouns were selected to form the basis for three experimental conditions that differentially load on semantic binding. As can be seen in Table 3.1, in the *plausible semantic binding condition,* the nouns were combined with an adjective to form a semantically likely word pair (e.g., "*plastic bucket*"). In the *implausible semantic binding condition,* the adjective and noun formed a semantically unlikely combination (e.g., *"lively bucket"*). Lastly, in the *no semantic binding condition,* the target noun was paired with a string of scrambled letters (e.g., "*iafnxa bucket"*). Given that the letter strings carry no meaning in the mental lexicon, this combination of stimuli should not trigger binding processes at a semantic level. Half of the nouns were animate and the other half were inanimate. Each noun occurred once in all three conditions, resulting in a total of 270 trials. The complete list of stimuli is presented in Appendix A.

The nouns had an average word length of 5.7, an average syllable length of 1.7 and a word frequency index of 28 using the CELEX lexical database (Baayen, Piepenbrock, & van Rijn, 1993). The adjectives in the plausible- and implausible condition had an average word length of 5.9 and 5.7; an average syllable length of 1.7 and 1.8 and an average frequency index of 28 and 28 respectively. Consequently, any effects on plausibility on semantic binding cannot be attributed to the lexical properties of the stimuli.

Table 3.1 Example stimuli of the conditions with trial numbers per condition

Condition	*Explanation*	*Example*	*No of trials*
semantic binding			
plausible semantic binding	semantically plausible word pair	plastic bucket, caring nurse	90
implausible semantic binding	semantically implausible word pair	lively bucket, linear nurse	90
no semantic binding	no semantic binding possible	iafnxa bucket, fdrwea nurse	90

Task

Participants were instructed to carefully read each word pair. To ensure participants remained attentive, they were occasionally required to answer a confirmation (i.e., yes/no) question about the word pair they had read (e.g., *"Did you just read caring nurse?").* As illustrated in Figure 3.1, each trial started with a fixation cross (400 ms), followed by a blank screen (1000 ms). Following this, the word pair was presented on the screen one word at a time. Each word remained on the screen for 300 ms, with an Inter Stimulus Interval of 1500 ms. The second word was followed by a blank screen (2300 ms). In 22% of the trials, this was followed by a response screen showing the text "*Did you just read … …?",* followed with a word pair at the end of the sentence. Participants were informed that the word pair in the sentence was either exactly the same as the word pair of the preceding trial, or one of the two words was slightly different. Consequently, participants were instructed to answer the question by clicking the left and right mouse button to respond with 'yes' or 'no' respectively. The response screen remained visible until a response was given. This was followed by a blank screen (500 ms), to separate one trial from the next. In 78% of the trials, the screen remained blank after the presentation of the second word (for 5100 ms) until the start of the next trial. The experiment was run using the E-prime software (Psychology Software Tools, Pittsburgh, PA).

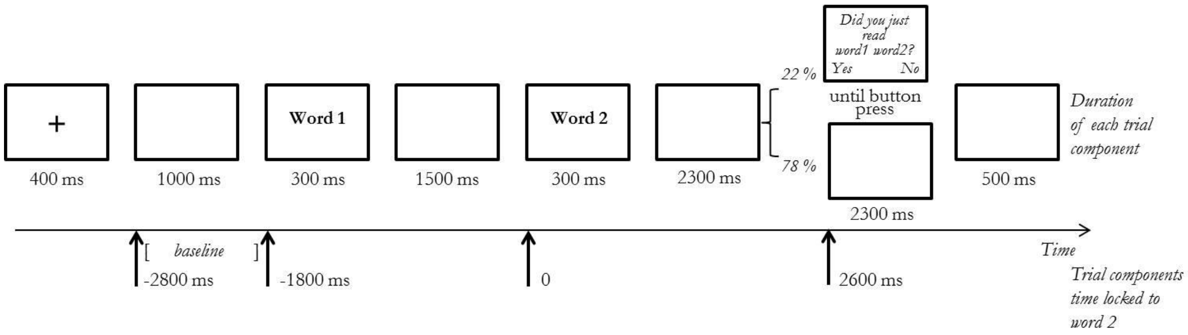

Figure 3.1 Timing of each trial component

Experimental lists

The experiment was divided into three blocks of 90 trials, such that each noun occurred once in every block. The main blocks were further subdivided into three sub-blocks, separated by self-paced breaks, ensuring that each condition occurred an equal number of times in each sub-block. The order of the main blocks was varied to create three different versions of the experiment, which were alternated between participants.

The paradigm intended to present 60 questions (i.e., 22% of 270 trials), however, due to an error in creating the question lists, the number of questions slightly differed across the experimental versions. Specifically, version 1 included 54 questions about a word pair and 7 questions involving a letter string. Of these, 28 questions required a 'yes' response and 33 required a 'no' response. Version 2 included 56 questions about a word pair and 6 questions involving a letter string. Half of these questions required a 'yes' response. Version 3 included 56 questions about a word pair and 4 questions involving a letter string. Of these, 29 required a 'yes' response, whereas 31 required a 'no' response. In case the correct answer was 'no', only one of the two words was different from the presented word pair, with the deviating word being the first or the second word an equal number of times. The deviating word was semantically similar to the corresponding word in the word pair (e.g., the word pair "*fresh bread*", was followed by the question "*Did you just read fresh cake*?"). Each noun occurred once in a question. See appendix B for the complete list of stimuli-question pairings.

Neuropsychological evaluation

Both patients and control subjects underwent a neuropsychological evaluation for the purpose of estimating premorbid intelligence and global cognitive function respectively. An overview of the individual measurements can be found in Table 3.2. All tests were conducted according to standardised procedure.

Procedure

Patients were tested at the Addenbrooke's Hospital in Cambridge. The neuropsychological evaluation was usually performed on a different day from the language experiment. Control subjects were tested at Birmingham University. For both groups, EEG recordings were conducted in the morning or afternoon in a quiet room. After the cEEGrids were applied and a stable EEG signal was established, participants received written and verbal instructions on the language task. The experiment started with a practice block consisting of 30 trials, during which participants received verbal feedback on their performance. Including the practice trials and self-paced breaks, the language task lasted around 30 minutes to complete. Following this, control subjects completed the neuropsychological test battery that was used for neuropsychological evaluation of the patients. The battery was administered in the following order: the MMSE; the ACE-R; the Rey Figure copy and immediate recall; the TMT B; the 4MT; the Digit Symbol task; the Rey Figure delayed recall and the NART. Taken together, the entire session for a control participant lasted approximately two hours.

Table 3.2 Neuropsychological evaluation tests and scoring

Assessment cognitive domain	*Test*	*Description*	*Measure*
Global cognitive functioning	**Addenbrooke's Cognitive Examination-Revised** (ACE-R; Mioshi, Dawson, Mitchell, Arnold, & Hodges, 2006)	A brief cognitive test battery for dementia screening, including five sub-domains: orientation/attention; memory; verbal fluency; language and visuo-spatial ability.	A composite score is calculated by adding the scores of the individual subdomains, with a maximum score of 100. A cut-off of 82 was used to differentiate cognitive impairment from healthy controls (Mioshi et al., 2006).
Global cognitive functioning	**Mini Mental State** (MMSE; subsection of ACE-R)	Measures orientation to time & place; registration; attention and calculation; recall; naming and repetition; comprehension; reading& writing ability and visual construction.	Scores range from 0- 30.
Verbal intelligence	**National Adult Reading Test** (NART; Nelson & Willison, 1991)	Reading aloud a list of 50 words with atypical phonemic pronunciation.	Total number of errors made on the complete NART.
Visuospatial constructional capacity	**Rey Complex Figure Test** (RCFT; Rey, 1941)	Copying the complex figure, followed by immediate recall (i.e. re-drawing the figure from memory), followed by delayed recall (i.e. re-drawing the figure from memory after a 30 min delay).	Task accuracy, based on the quality of the individual components of the figure, resulting in a score ranging from 0-36 for each of the three test phases (i.e. copy, immediate recall and delayed recall).
Attention, executive function	**Trail Making Test B** (TMT B; Halstead, 1947)	Connecting 25 encircled numbers and letters in numerical and alphabetical order while alternating between numbers and letters (for max 300 seconds).	Time in seconds to complete the task.
Processing Speed	**Digit Symbol test** (WAIS-IV; Wechsler, 2008)	Copying symbols that are paired with specific numbers in order, as quickly as possible within 120 seconds.	A point is given for each correctly drawn symbol completed within time limit. Total score: number of correctly drawn symbols. Raw scores converted to scaled score equivalents according to age group
Spatial Memory	**4 Mountains test** (4MT; Chan et al., 2016)	Selecting the image (1 out of 4) of a mountain scenery that shows the same scenery as an image previously shown, but from a different perspective.	Number of accurately selected landscapes, score ranges from 0- 15.

Behavioural analysis

Group differences on accuracy and response time (RT) for answering the confirmation questions were analysed by calculating the mean accuracy and RT for each individual (across conditions), and between group differences were tested for using two-sided t tests at an α of 0.05. The RT data for each participant in each condition were subjected to a ± 2 standard deviation trim. The RT analyses included correct responses only

EEG recordings

EEG recordings were made using the cEEGrid system (Debener et al., 2015), consisting of flex-printed sensor arrays (i.e., grids) that are placed around the ears (see Figure 3.2). Compared to a traditional EEG cap, this system requires less setup time and is more comfortable to wear, making this system particularly suitable for testing in clinical settings. Each grid contains 10 electrodes. One electrode on the right mastoid (i.e., R5) served as the ground electrode and another electrode on the left mastoid (i.e., L6) as the reference. Recordings were acquired using the EEGO Sports system (ANT Neuro, Enschede, The Netherlands), using a sampling frequency of 500 Hz. Care was taken to ensure that the impedance of the ground and reference electrode was below 20 kΩ and at least two other electrodes in each grid were below 40 kΩ.

Figure 3.2 cEEGrids (**A**) Right cEEGrid with ground electrode R5 circled in blue. (**B**) Left electrode with reference electrode L6 circled in green. Image retrieved from: http://ceegrid.com/home/concept/ The image has been modified for illustrative purposes.

EEG preprocessing

The EEG data were preprocessed and analysed using functions from EEGLAB (version 13.6.5b; Delorme & Makeig, 2004) and Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011). The EEG data were high-pass filtered at 0.3 Hz and low-passed at 30 Hz. The data was average referenced and epoched from -2.8s to 1.4s, time-locked to the onset of the second word. Following this, artefact rejection was performed manually to remove muscle artefacts. Data preprocessing revealed high levels of environmental and physiological artefacts. Consequently, it was decided to analyse the data from a single electrode on the left hemisphere that recorded the most stable signal across both groups, specifically electrode L4.

Time-frequency analyses

Frequencies of interest ranged from 2 to 30 Hz. Time-frequency representations (TFR) of power were calculated using the Fieldtrip function '*ft_freqanalysis_mtmconvol*' in steps of 1 Hz for every 50 ms. We applied sliding Hanning tapers with an adaptive time window of three cycles for each frequency of interest ($\Delta T = 3/f$). Power changes in oscillatory activity were expressed in terms of change scores from baseline (ΔPt) using the following formula: $\Delta Pt = (Pt–Pr)/Pr$, where Pt was the power at each specific time point and Pr was the mean power during the baseline period, that is, -2.45s to -1.95 s before the onset of the second word.

Statistical analyses

To statistically quantify differences in power between the different conditions, nonparametric cluster-based permutation tests were performed (Maris & Oostenveld, 2007). Importantly, while nonparametric cluster based permutation tests usually offer the advantage of correcting for multiple comparisons (i.e., across electrodes, time points and, or frequencies), in this case, there was no implemented stats function to perform these corrections, given that the analyses were based on data from a single electrode. For this reason, we refrain from interpreting differences in terms of significance. Instead, we opt for a descriptive interpretation of the results and adopt the conservative criterion that t values higher than 3 are suggestive of oscillatory differences between conditions.

We focus our analyses on a broad, general comparison between conditions. Specifically, all the analyses were performed on the entire frequency range (i.e., from 2 to 30 Hz) and on a time window from -2 to 1.5s relative to the onset of the second word. In addition, all analyses were performed on the grand mean condition averages. In this procedure, for each contrast (e.g., semantic binding versus no semantic binding), power values in every time point were clustered depending on if it exceeded a t-test threshold of p

< 0.05 (i.e., dependent samples t-test for within group comparisons and independent samples t-test for between group comparisons). Although we refrain from interpreting the results in terms of significance, the p values generated by the analyses are reported in the figure captions for the sake of completeness. Given the exploratory nature of our approach (i.e., EEG measurement using electrode arrays around the ear) we did not correct these clusters for multiple comparisons.

Within group analyses: We first assessed the difference in time-frequency power between the different conditions for each experimental group separately. Specifically, for both the healthy control and the MCI group, the following analyses were performed. First, lexical retrieval was investigated by comparing the oscillatory power modulations in the semantic binding condition with the no semantic binding condition following the presentation of the *first word*. Second, semantic binding was investigated by comparing the same condition contrasts following the presentation of the *second word*. Third, we investigated oscillatory changes associated with semantic plausibility by comparing the plausible semantic binding with the implausible semantic binding following the presentation of the second word.

Between group analyses: To compare group differences between MCI patients and healthy controls, we examined between group differences in the oscillatory signature of lexical retrieval, semantic binding and semantic plausibility. Specifically, we computed the power difference between conditions for each individual participant (i.e., semantic binding vs no semantic binding and plausible semantic binding vs implausible semantic binding). The difference values of the MCI patient group were compared to the difference values of the healthy control group

Results

Behavioural results

I.I Neuropsychological evaluation

Table 3.3 presents the results of the neuropsychological evaluation for both the healthy control and the MCI group. The two groups presented significant differences in both tests of global cognitive functioning (i.e., the ACE-R and the MMSE); the Rey figure copy; the TMT B and Processing speed. No group differences were observed in the NART; the Rey figure immediate and delayed recall and the 4 Mountains test.

I.II Language task

We calculated the mean accuracy for the confirmation questions for each subject across the two groups using a Welchs t-test. The mean accuracy for the control group was 98% (SD: 15%); whereas the mean accuracy for the MCI group was 93% (SD: 0.25%). There were no significant differences in accuracy between the healthy control and the MCI group: t(20) -1.96; p= 0.06.

We calculated the median RT for the correct responses to the confirmation questions for each subject across the two groups (Welchs t-test). The median RT for the control group was 1302.5 ms (SD: 475); whereas the median RT for the MCI group was 1837ms (SD: 1116). The control group was significantly faster for correct responses: t(22) -3.6; p = 0.001.

Table 3.3. Means and Standard Deviations of the neuropsychological evaluation for the healthy control and MCI group (Independent Samples t-Test)

	Healthy Controls		*MCI*			*Comparison*		
	N	*mean(sd)*	*N*	*mean(sd)*	*Max*	*t*	*p*	
Global cognitive functioning								
ACE-R	23	95 (4)	22	84 (11)	100	4.44	<0.01	**
MMSE	23	29 (0.8)	16	28 (1.8)	30	2.09	0.05	*
Verbal intelligence								
NART	21	10(7.4)	22	15 (12)	50	-1.75	0.09	
Visuospatial constructional capacity								
Rey Figure copy	23	35 (1.4)	21	32 (5.6)	36	2.38	0.03	*
Rey Figure immediate recall	23	18 (7.7)	21	14 (12.6)	36	1.30	0.20	
Rey Figure delayed recall	23	18 (7.8)	21	13 (12.9)	36	1.58	0.12	
Attention, executive function								
TMT B	23	104 (42.8)	21	144 (80)	300	-2.04	0.05	*
Processing Speed								
Digit Symbol	23	66 (14.7)	21	48 (15)	135	4.03	<0.01	**
Digit Symbol age corrected	23	13.4 (3)	20	48 (15)	135	4.84	<0.01	**
Spatial Memory								
4 Mountains test	20	8 (2.2)	21	8 (3.8)	15	-0.25	0.81	

*Signif. codes: ** 0.01; * 0.05; ‘.’ 0.1. Between group differences were tested with independent t tests assuming unequal variances. Note that higher scores are associated with lower performance on the NART and TMT B test, whereas higher scores are associated with better performance on the other tests.*

EEG results

I Lexical retrieval

First, we will focus on the oscillatory changes associated with lexical retrieval. To this end, we examined the oscillatory power differences between adjectives (e.g., "*sharp", "classic"*) and letter strings (e.g., "*snklvwe", "iafnxa"*; i.e., by comparing the semantic binding and the no semantic binding condition following the presentation of the *first* word). We first present the results for the control and MCI patient group individually.

I.I Lexical retrieval in healthy controls

The left panel of Figure 3.3A (i.e., from -1.8 to 0s) shows the grand mean TFR of lexical retrieval in the control group. Likewise, the left panel of Figure 3.3B shows the grand mean TFR of no lexical retrieval. Qualitatively, the presentation of the first word (i.e., at -1.8s) induced an increase in the high theta range in both conditions. This was followed by a power decrease in alpha and low beta activity, followed by a power increase in the theta range around 0.8 seconds after the onset of word 1 (i.e., around -1 s).

To verify potential differences in lexical retrieval between the two conditions, the t-values of the difference between lexical retrieval and no lexical retrieval are shown in Figure 3.3C (i.e., between -1.8s and 0s). Positive t values indicate more power in the lexical retrieval compared to the no lexical retrieval condition, negative t values indicate less power in the lexical retrieval compared to the no lexical retrieval condition. No differences were observed in the theta band. There was a condition difference in the alpha and low beta range in a time window around 0.55 to 0.75 seconds after the onset of the first word (i.e., between -1.25 and -0.5 seconds relative to the onset of word two; Figure 3.3C). In this time window, alpha and low beta power increased in the lexical retrieval condition, in contrast to a continued power suppression in the no lexical retrieval condition.

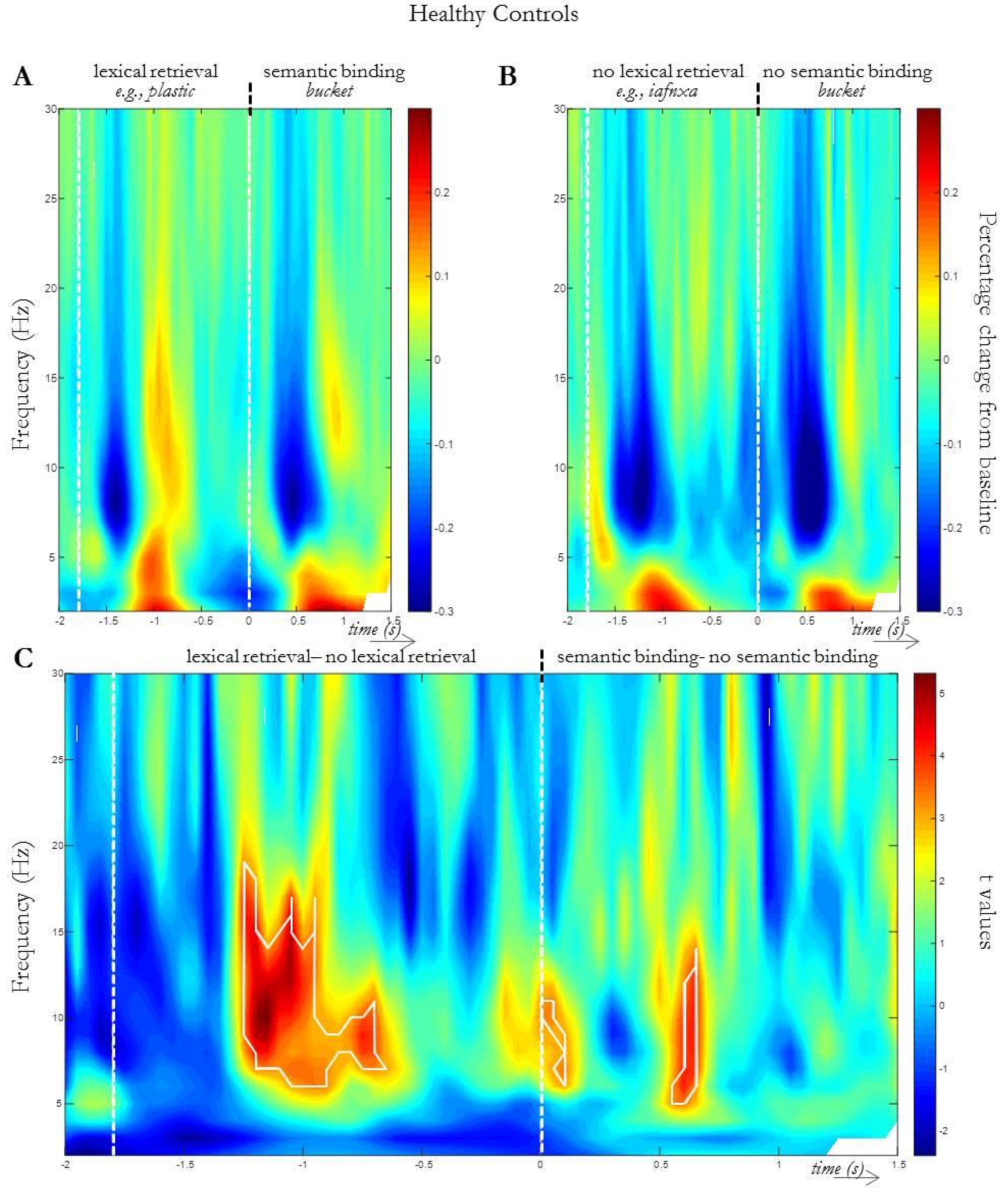

Figure 3.3. Power differences between lexical retrieval and no lexical retrieval following word 1 (i.e., at -1.8s; first white dotted line) and semantic binding and no semantic binding following word 2 (i.e., at 0s; second white dotted line) for channel L4 in healthy controls. (**A-B**) Grand mean TFRs of the conditions of interest, expressed as a percentage change from baseline (-2.45 to -1.95 before the onset of word2), for (**A**) the semantic binding condition; (**B**) the no semantic binding condition; (**C**) Grand mean TFR of the semantic binding condition minus the no semantic binding condition with t-values computed for the difference in power between A and B at each frequency and time point. The white outlined time-frequency clusters have a value > 3 ($p<0.01$ uncorrected), indicating more power in A compared to B.

I.II Lexical retrieval in MCI patients

The first half of Figure 3.4A (i.e., from -1.8 – 0s) shows the grand mean TFR of the lexical retrieval condition in the MCI patient group. Likewise, the first half of Figure 3.4B shows the grand mean TFR of the no lexical retrieval condition. In both conditions, the onset of the first word (i.e., at -1.8s) induced an increase in the (high) theta range, followed by a suppression in the alpha range, followed by a late increase in the theta range. Figure 3.4C shows the difference between lexical and no lexical retrieval (i.e., between -1.8s and 0s). There were no differences in the theta frequency range. As can be seen in Figure 3.4C, there was a tendency for increased power in the alpha range in lexical retrieval compared to no lexical retrieval in a time window around 0.8 s after the presentation of the first word (i.e., around -1s relative to the onset of the second word).

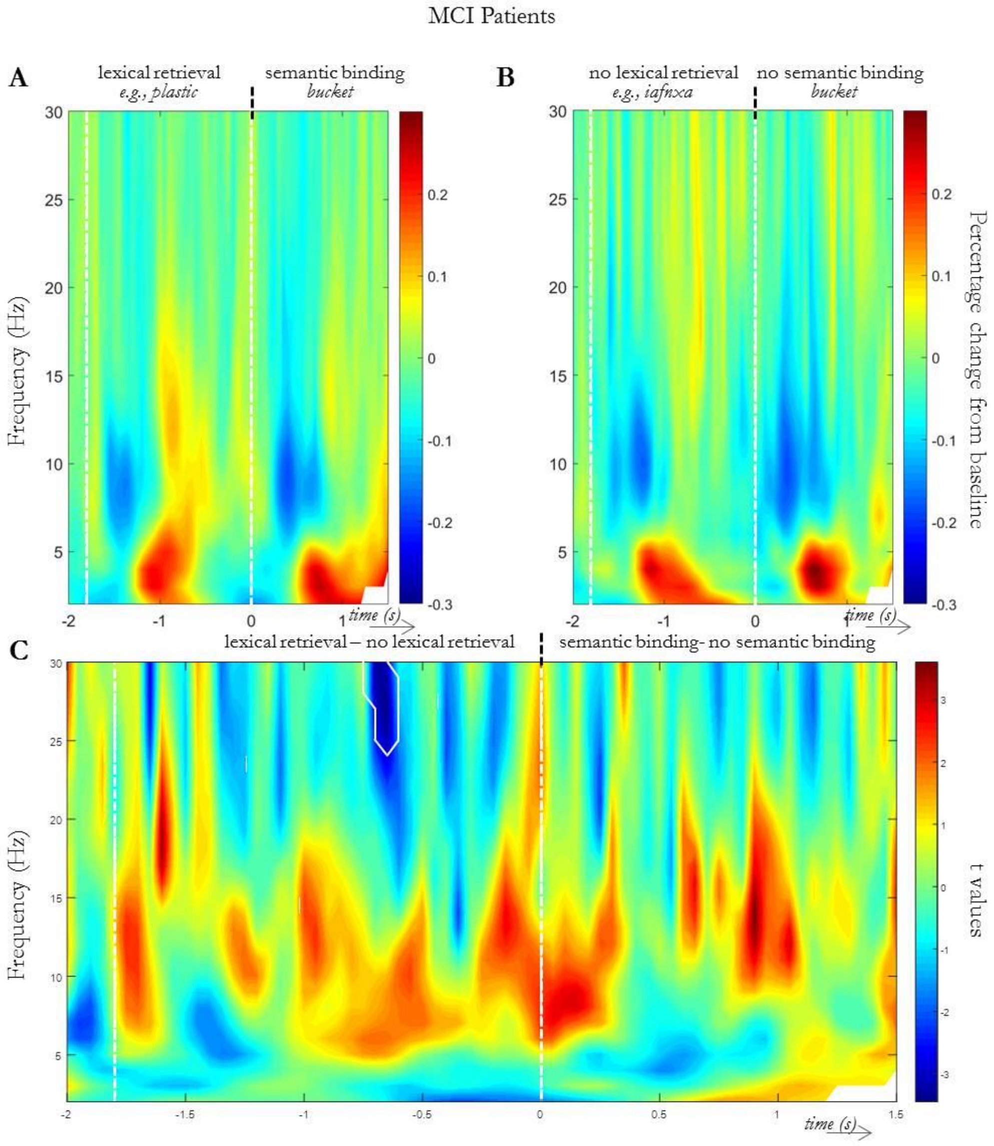

Figure 3.4 Power differences between lexical retrieval and no lexical retrieval following word 1 (i.e., at -1.8s; first white dotted line) and semantic binding and no semantic binding following word 2 (i.e., at 0s; second white dotted line) for channel L4 in MCI patients. (A-B) Grand mean TFRs of the conditions of interest, expressed as a percentage change from baseline (-2.45 to -1.95 before the onset of word2), for (A) the semantic binding condition; (B) the no semantic binding condition; (C) Grand mean TFR of the semantic binding condition minus the no semantic binding condition with t-values computed for the difference in power between A and B at each frequency and time point. The white outlined time-frequency clusters have a t value < -3 ($p<0.01$, uncorrected) indicating less power in A compared to B.

I.III Differences in lexical retrieval between healthy controls and MCI patients

The first half of Figure 3.5A (i.e., from -1.8 to 0 s) shows the TFR of lexical retrieval minus no lexical retrieval for the healthy controls. Likewise, the first half of Figure 3.5B (i.e., from -1.8 to 0 s) shows the TFR of lexical retrieval minus no lexical retrieval for the MCI patients. The comparison of the difference between lexical and no lexical retrieval between healthy controls and MCI patients revealed a tendency towards increased desynchronization in the alpha and low beta band for letter strings compared to words in the control subjects relative to the MCI patients in a time window immediately following the onset of the word (see first half of Figure 3.5C). Following this, there was a larger power increase in the alpha band for words compared to letter strings in healthy controls relative to MCI patients around 0.6s to 0.8s after the onset of the first word (i.e., at -1.2 to -1s relative to word 2 at 0s).

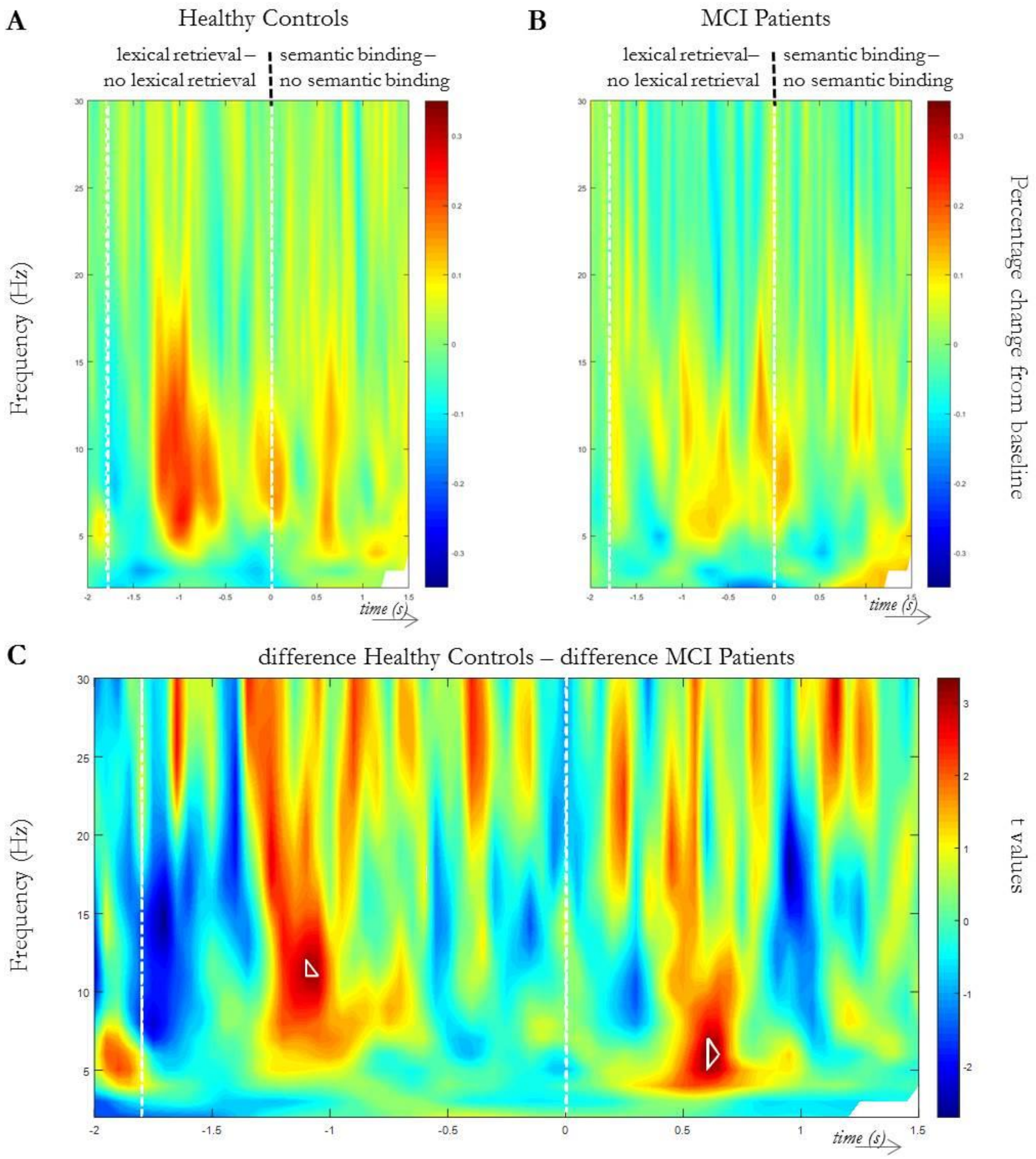

Figure 3.5 TFRs of power for the contrast between lexical retrieval and no lexical retrieval following word 1 (i.e., at -1.8s; first white dotted line) and semantic binding and no semantic binding following word 2 (i.e., at 0s; second white dotted line) for channel L4. (**A-B**) Grand mean TFR for the contrast between semantic binding (*e.g.,"plastic bucket"*) and no semantic binding (*e.g., "iafnxa bucket"*), expressed as a percentage change from baseline (-2.45 to -1.95 before the onset of word2). For the first word, this contrast indicates the difference between lexical and no lexical retrieval. For the second word, this contrast indicates the difference between semantic and no semantic binding. For (**A**) healthy controls and (**B**) MCI patients. (**C**) The difference of semantic binding and no semantic binding in healthy controls minus the difference in semantic binding and no semantic binding in MCI patients with t-values computed for the difference in power between A and B at each frequency and time point. The white outline indicates time-frequency clusters having a $p<0.05$, uncorrected.

II Semantic binding

To investigate the oscillatory changes associated with semantic binding, we focus on the differences in power between the semantic binding and the no semantic binding condition, in a time window surrounding the onset of the *second* word (i.e., a comparison of the degree to which semantic binding occurs). Again, we first report the differences between conditions for the control and MCI group individually, followed by a presentation of the differences between groups.

II.I Semantic binding in healthy controls

As can be seen in Figure 3.3A and B, surrounding the presentation of the second word (i.e., at 0s), there was a power decrease in the theta range in both conditions (along with a power decrease in the alpha and low beta range in the no semantic binding condition). This was followed by an increase in the higher theta range, followed by a power suppression in the alpha and low beta range. Finally, there was an increase in power in the theta range, starting at around 0.5 s after the presentation of the second word. As can be seen in Figure 3.3C, there was a difference between the conditions surrounding the presentation of the second word in the alpha and low beta band. Here, power was at baseline level in the correct semantic binding condition, whereas power decreased in the no semantic binding condition during this time interval. In addition, there was a condition difference in the alpha and low beta range around 0.5 to 0.7 seconds after the presentation if the second word, due to a smaller suppression of power in the correct compared to the no semantic binding condition.

II.II Semantic binding in MCI patients

In the MCI patients, the presentation of the second word (i.e., at 0s) was associated with a decrease in theta power in both conditions (see Figure 3.4A and B). Following this, there was a power decrease in the alpha range, followed by an increase in theta power in a time window around 0.5 – 1s after the presentation of the second word. As can be seen in Figure 3.5C, there was a trend towards an increase in the alpha range in the semantic binding condition relative to the no semantic binding condition surrounding the onset of word two (i.e., at 0s) and around 1s after the onset of word 2. This was due to a reduced decrease in alpha power in the semantic binding relative to the no semantic binding condition.

II.III Differences in semantic binding between healthy controls and MCI patients

The second half of Figure 3.5A and B (i.e., from 0s to 1.5s) shows the TFR of semantic binding minus no semantic binding for healthy controls and MCI patients respectively. The difference of the difference between healthy controls and MCI patients for semantic binding (shown in the second half of Figure 3.5C) shows a larger power increase in the alpha band for semantic binding compared to no semantic binding in healthy controls relative to MCI patients, in a time window around 0.5s to 0.7 s after the presentation of the second word.

III Semantic plausibility

We now report on differential oscillatory power changes for semantically plausible and implausible word pairs. We are specifically focussing on differences in power between the plausible and implausible semantic binding condition after the onset of the second word (i.e., when binding of the two words takes place). Within group condition differences are reported first, followed by between group differences.

III.I Semantic plausibility in healthy controls

The results of the control group are summarized in Figure 3.6. Figure 3.6A and B show the individual grand mean TFRs of the plausible semantic binding and implausible semantic binding condition respectively. In both conditions, the onset of the second word (i.e., at 0s) is associated with a transient power decrease in the theta range. Notably, this power decrease commences before the onset of the second word. Following this, there was a power decrease in the alpha and beta band, followed by an increase in theta power. The difference between the plausible and implausible semantic binding condition in healthy controls is shown in Figure 3.6C. There was a condition difference in beta power in a small time window around 0.5s after the onset of word two, such that there was a stronger decrease in beta power in the plausible, compared to the no plausible semantic binding condition.

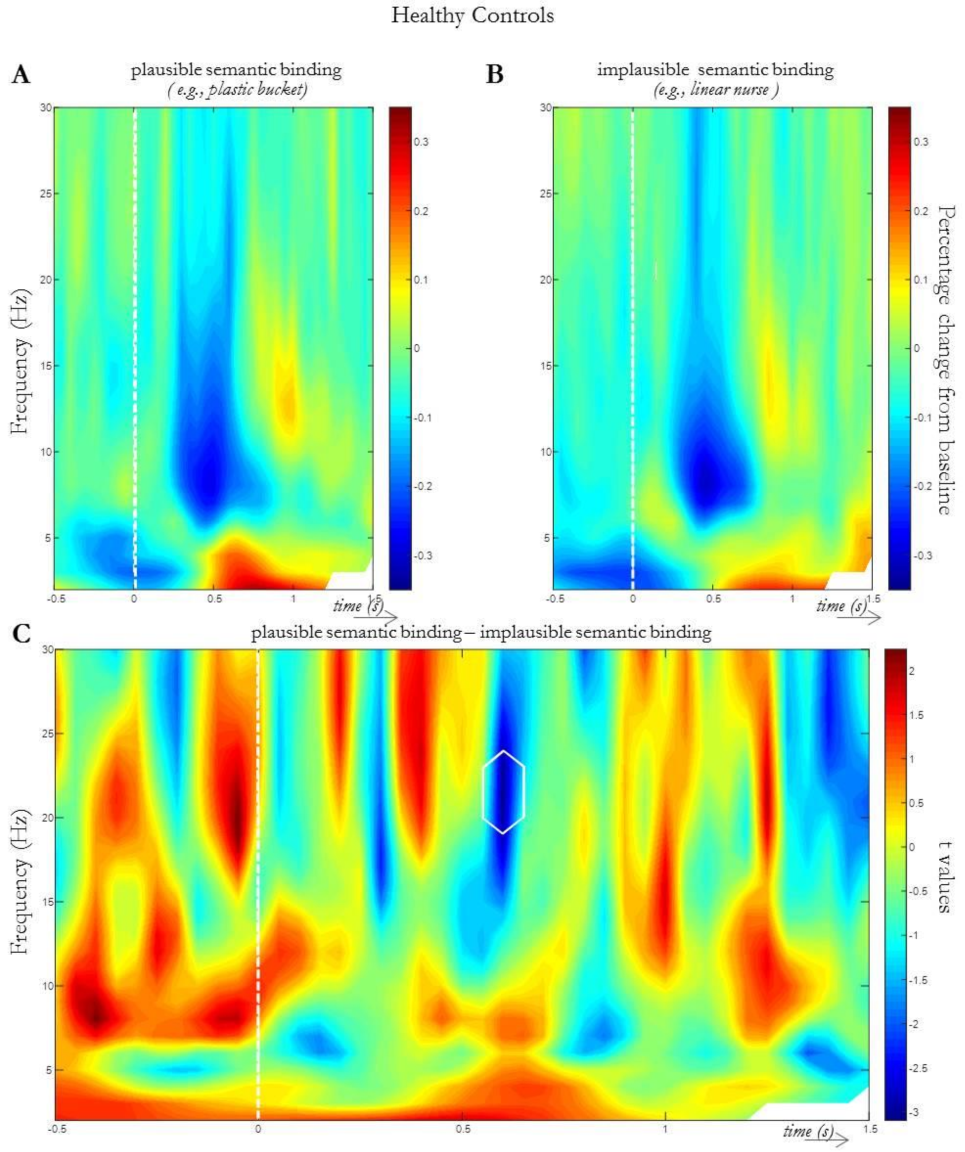

Figure 3.6 Power differences between plausible semantic binding and implausible semantic binding for channel L4 in healthy controls. The white dotted lines in all graphs indicate the onset of the second word (i.e., at 0s). (A-B) Grand mean TFRs of the conditions of interest, expressed as a percentage change from baseline (-2.45 to -1.95 before the onset of word2), for (A) the plausible semantic binding condition; (B) the implausible semantic binding condition; (C) Grand mean TFR of the plausible semantic binding condition minus the implausible semantic binding condition with t-values computed for the difference in power between A and B at each frequency and time point. The white outlined time-frequency clusters have a value (below $p<0.05$, uncorrected) indicating less power in A compared to B.

III.II Semantic plausibility in MCI patients

The individual grand mean TFRs of the plausible and implausible semantic binding condition of the MCI patients are shown in Figure 3.7A and B respectively. In both conditions, surrounding the onset of the second word (i.e., at t 0s) there was a decrease in theta power, as well as a power increase in the higher frequency bands (i.e., alpha and low beta), followed by a power decrease in the alpha band. Finally, there was a power increase in the theta range, starting at around 0,5s after the onset of the second word. As can be seen in Figure 3.7C, there were no condition differences between the plausible and implausible condition after the onset of word two.

III.III Differences in semantic plausibility between healthy controls and MCI patients

Figure 3.8A and B show the TFR of the plausible semantic binding condition minus the implausible semantic binding condition for the healthy controls and MCI patients respectively. The comparison of the difference between plausible and implausible semantic binding between healthy controls and MCI patients, visualized in Figure 3.8C did not reveal any group differences.

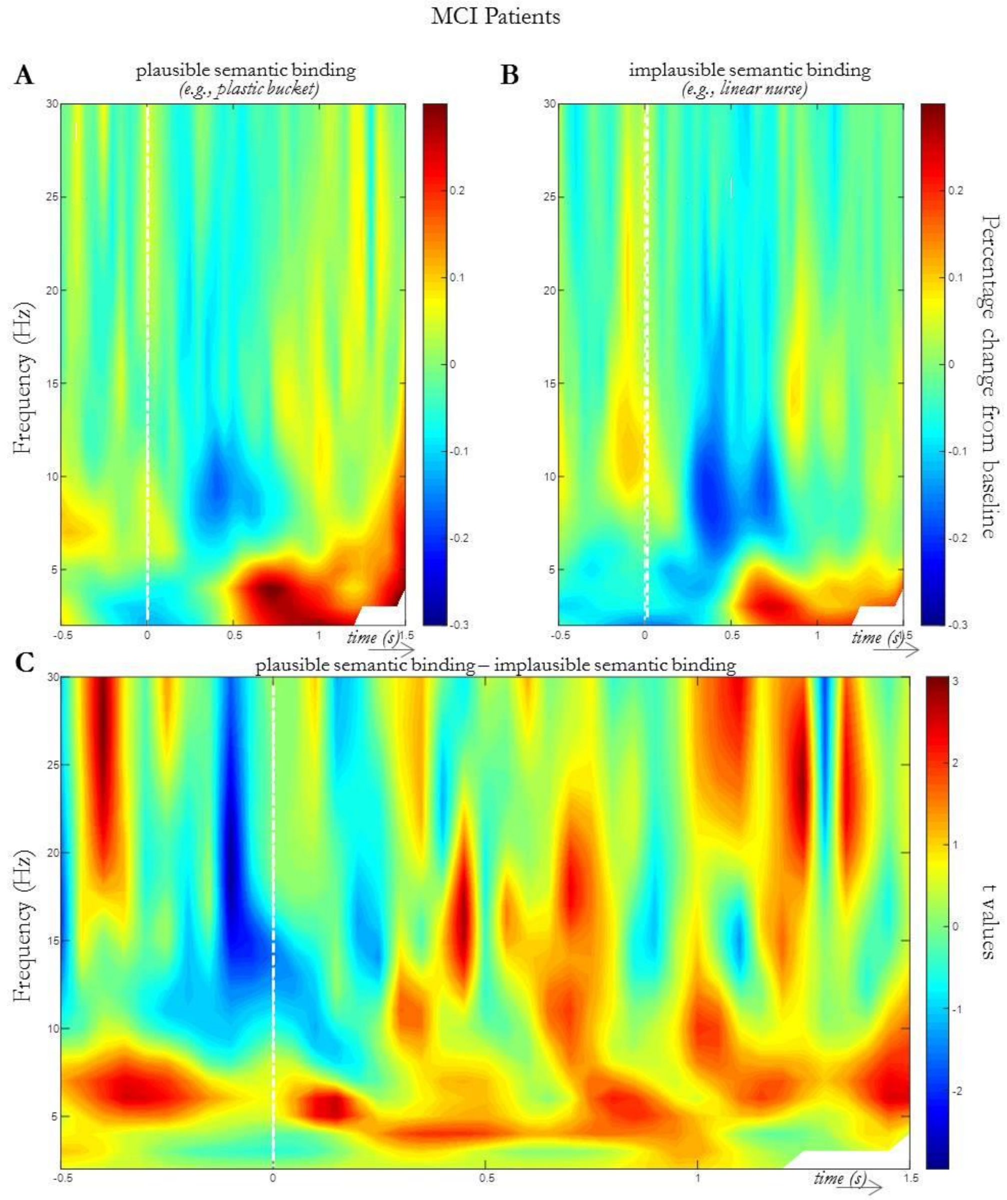

Figure 3.7 Power differences between plausible semantic binding and implausible semantic binding for channel L4 in MCI patients. The white dotted lines in all graphs indicate the onset of the second word (i.e., at 0s). (A-B) Grand mean TFRs of the conditions of interest, expressed as a percentage change from baseline (-2.45 to -1.95 before the onset of word2), for (A) the plausible semantic binding condition; (B) the implausible semantic binding condition; (C) Grand mean TFR of the plausible semantic binding condition minus the implausible semantic binding condition with t-values computed for the difference in power between A and B at each frequency and time point.

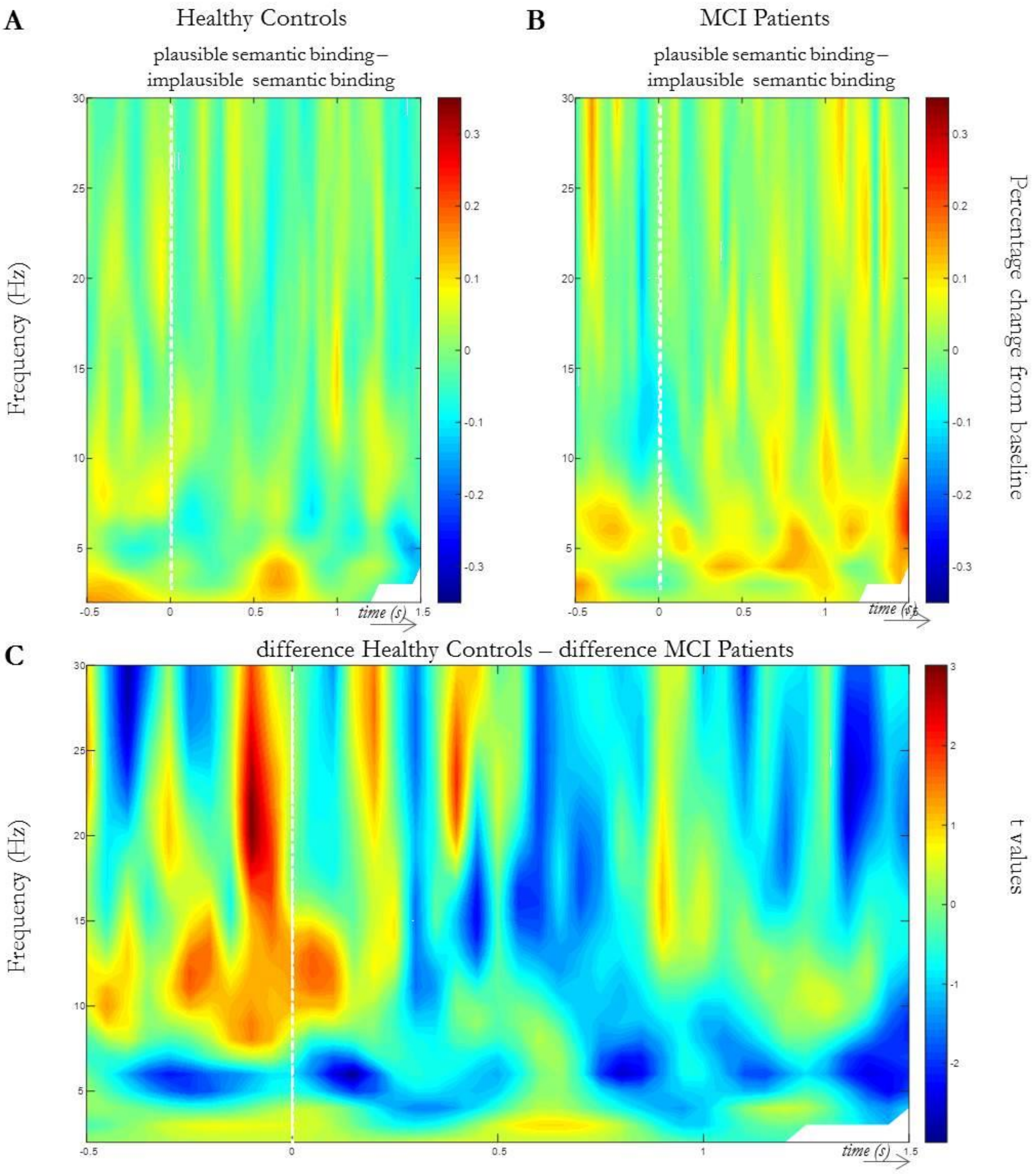

Figure 3.8 TFRs of power for the contrast between plausible semantic binding and implausible semantic binding for channel L4. The two dotted lines in all graphs indicate the onset of the second word (i.e., at 0s). (**A-B**) Grand mean TFR for the contrast between plausible semantic binding (*e.g., "plastic bucket"*) and implausible semantic binding (*e.g., "linear nurse"*), expressed as a percentage change from baseline (-2.45 to -1.95 before the onset of word2). For (**A**) healthy controls and (**B**) MCI patients (**C**) The difference of plausible semantic binding and implausible semantic binding in healthy controls minus the difference in plausible semantic binding and implausible semantic binding in MCI patients with t-values computed for the difference in power between A and B at each frequency and time point.

Discussion

The present study examines the oscillatory mechanisms in brain activity associated with lexical-semantic processes in individuals with MCI and age matched healthy older adults. We investigated oscillatory changes elicited by two-word linguistic expressions that were semantically plausible or implausible and two word compositions in which semantic binding was minimal. Oscillatory mechanisms associated with lexical retrieval were assessed by comparing adjectives (e.g., "*sharp", "classic"*), to letter strings (e.g., "*hwuos", "snklvwe"*). In addition, oscillatory mechanisms associated with semantic binding were assessed by comparing changes in oscillatory power centred around the *second* word between the semantic binding and no semantic binding condition. Lastly, we examined oscillatory mechanisms associated with semantic plausibility, by comparing changes in oscillatory power between the plausible and implausible semantic binding condition. In healthy older adults, lexical retrieval was associated with a shorter suppression in the alpha and low beta power in the lexical, relative to the non-lexical condition following the presentation of the first word. Furthermore, semantic binding was associated with a smaller power decrease in the alpha and low beta band in the semantic binding relative to the no semantic binding condition. Similar, but greatly attenuated effects were found in the MCI group for both lexical processing and semantic binding. Lastly, no within or between group differences were found on semantic congruency. Taken together, we suggest these findings are indicative of subtle alterations in the oscillatory mechanisms associated with lexical and semantic processing in MCI. Implications for each of these findings are discussed below.

Lexical retrieval

In healthy older adults, we found power differences associated with lexical retrieval in the alpha and low beta band. Specifically, comparing the oscillatory patterns to adverbs and letter strings, the duration of alpha and low beta desynchronization following the presentation of the word was shorter for adverbs compared to letter strings. In adverbs, the initial desynchronization was followed by a power rebound, resulting in an increase in alpha and low beta power for adverbs relative to letter strings from around 0.5 to 0.7 s after the onset of the word. While the adverbs carry lexical information, the scrambled letter strings lack a lexical representation. Consequently, lexical search takes longer and requires more effort for the letter strings compared to the high frequent adverbs. The prolonged alpha and low beta desynchronization for letter strings compared to adverbs may be related to this process. This interpretation of this effect is in line with earlier work suggesting extended lexical search in the mental lexicon for pseudo words compared to words (Heim et al., 2005; Heim, Eickhoff, Ischebeck, Supp & Amunts, 2007). In contrast, our finding seems to be inconsistent with Mellem et al. (2012), who found an alpha power *decrease* associated with lexical-semantic retrieval operations in older adults. However, in their study, lexical semantic content was manipulated by matter of degree. Specifically, they compared open class to closed class words, which both carry lexical information but vary in the degree to which they do so (Mellem et al., 2012). In contrast, in the current study, an adjective was compared to a meaningless letter string, that is, a comparison between a lexical and non-lexical item. Note that we did not observe any differences in the theta band between words and letter strings in the current study. Previous studies in younger adults (e.g., Bastiaansen et al., 2005; Bastiaansen et al., 2008) have argued that oscillatory activity in the theta band plays a prominent role in lexical processing. On the other hand, Mellem et al. (2012) did not find any differences in theta power in association with lexical-sematic processing in older adults. The authors have argued that the previously reported theta effects on lexical information may not be a robust effect in older age groups. The results of the current study are in line with these latter findings.

A similar, but greatly attenuated pattern of results was observed in the MCI group. Specifically, there was a tendency towards reduced desynchronization in the alpha and low beta band for adjectives compared to letter strings. In other words, the reduced suppression in alpha and low beta power associated with lexical retrieval was more pronounced in healthy controls relative to the MCI group. In Mazaheri et al. (2018), reading the target nouns induced an increase in theta activity that was significantly reduced in the MCI group relative to healthy controls. This effect was interpreted as being indicative of alterations in lexical processing in MCI. However, the lexical characteristics of the target nouns were not clearly controlled in this study, which challenges an interpretation of this effect in terms of lexical retrieval. In the current design, lexical retrieval was more carefully manipulated by comparing the oscillatory response to adjectives (i.e., for which lexical properties can be retrieved) with the response to letter strings. This comparison did not elicit differences in the theta band in either of the two groups. However, similar to Mazaheri et al. (2018) we find the oscillatory response to words is greatly reduced in the MCI group relative to healthy controls.

Semantic binding and semantic plausibility

In healthy older adults, we observed differences in alpha and low beta power in response to the *second* word of the word pair, depending on whether this noun could be bound together with the preceding item or not. Specifically, both alpha and low beta power were more suppressed in the no semantic binding, relative to the semantic binding condition in a time window surrounding the presentation of the second word and again between 500 to 700 ms after the onset of the second word. This could be interpreted as neural responses associated with semantic binding. These effects appear to be in line with previous research, suggesting alpha power decreases are associated with semantic processing demands (Klimesch, Doppelmayr; Pachinger & Russegger; 1997; Klimesch 1999; Röh, Klimesch; Haider &

Doppelmay, 2001; Mellem et al., 2012).

Similarly, in the MCI group, there was a trend towards a reduced suppression in alpha and low beta power in the semantic binding relative to the no semantic binding condition surrounding the onset of the second word and again around 1000 ms after the onset of the second word. In other words, the MCI group shows a similar, but attenuated response pattern compared to the healthy controls. It follows that the difference (i.e., between healthy controls and MCI) of the difference (i.e., between semantic and no semantic binding), is positive. Specifically, there was a power increase in the alpha band for the healthy controls relative to the MCI group; this effect spanned from around 500 to 700 ms after the onset of the second word. This pattern of results is consistent with reduced semantic binding processes in individuals with MCI compared to healthy age matched controls.

Additionally, we examined oscillatory dynamics of semantically plausible versus semantically implausible word pairs (i.e., semantic plausibility). However, we did not observe any clear condition differences between the plausible and implausible semantic binding condition in either of the two groups. Previous work by Mazaheri et al. (2018) found a transient increase in theta power in congruent relative to incongruent words. This congruency effect was different for the MCI and healthy control group. A potential explanation for the absence of a congruency effect in the current study may be that the semantic context set by the preceding adjectives of the target nouns did not sufficiently differentiate between congruent and incongruent semantic categorization. In other words, the differential sensitivity of congruent and incongruent adjectives in our experimental manipulation may not have been strong enough to elicit a semantic congruency effect.

Limitations and future directions

Despite the potential importance of the findings discussed above, this study has clear limitations. Instead of a conventional, multi-channel EEG system, EEG was recorded using the cEEGrid system. This around-ear system was used due to its suitability for testing in a clinical setting. Even though a number of validation studies established that meaningful continuous EEG as well as ERPs and neural oscillations can be reliably measured using the cEEGrid system (e.g., Bleichner, Mirkovic & Debener, 2016; Bleichner & Debener, 2017; Pacharra, Debener & Wascher, 2017), the recordings in the current study contained fair amounts of biological and non-biological artefacts. Consequently, the analyses were limited to a single electrode and could not be corrected for multiple comparisons. We are therefore slightly cautious about over-interpreting the observed differences in oscillatory dynamics discussed above and want to emphasize that the within and between group comparisons made are exploratory in nature.

Nevertheless, our findings indicate the existence of subtle differences in language processing associated with both lexical retrieval and semantic binding between individuals diagnosed with MCI and healthy age matched controls. Specifically, compared to healthy controls, the oscillatory response associated with both lexical retrieval and semantic binding was attenuated in the MCI group relative to the healthy controls. One could argue that the attenuated response in alpha and low beta power may be a reflection of the more general power reductions in the faster frequency ranges that have been observed in MCI (Czigler et al., 2008; van der Hiele et al., 2007; Moretti et al., 2010; Babiloni et al., 2016). However, the relative decrease in the faster frequency ranges is commonly accompanied by a power increase in the lower frequency ranges. Therefore, if the oscillatory changes reported here are predominately driven by these generic alterations in power, we would have expected to observe stronger theta effects in the MCI group. Given that no group differences in theta power were observed, we believe it is unlikely that this explanation can fully account for the results reported here.

It is noteworthy that there were no significant differences in accuracy on the detection task that participants were performing during the EEG experiment, although the MCI group was slightly slower than the healthy controls. This suggests that the observed group differences in the oscillatory EEG dynamics were not due to reduced comprehension or attention in the MCI group. Taken together, our findings indicate that investigating oscillatory changes during a simple word processing task offers the opportunity to delineate important functional differences associated with diagnostic status (MCI versus healthy control). From a clinical perspective, these differences have the potential to play a role in the development of biomarkers that might in future provide adequate specificity or sensitivity to be used for prognosis of MCI and AD. A useful direction for future research would be to investigate differences in oscillatory dynamics between those individuals with MCI who eventually convert to AD and those who do not. Few studies have investigated differences between converters and non- converters, yet findings by Olichney et al. (2002) and Mazaheri et al. (2018) suggest that these two groups can be distinguished on subtle differences in EEG. From a theoretical perspective, understanding how older brains' process language in relation to the evolution of early cognitive change due to degenerative disease may offer valuable contributions to theories of compensatory mechanisms in the cognitive neuroscience of ageing. In fact, Grady et al. (2003) found evidence for compensatory activity in individuals with mild AD in semantic and episodic memory tasks. Specifically, functional connectivity within a network of left hemisphere frontal and occipital areas associated with both semantic and episodic memory was altered in individuals with mild AD relative to healthy controls. However, the latter group recruited a more extensive network including bilateral prefrontal and temporoparietal areas, which crucially correlated with behavioural performance. Research on the development of compensatory responses at the initial phase of breakdown of the language system would be a valuable focus for future research in this context. Another potential direction for future research would be to investigate how performance on neuropsychological tests that are most frequently used for assessing language deficits in MCI (i.e., verbal and category fluency tasks, the Boston Naming Test), correlates with measurements of oscillatory activity in language processing. In view of the fact that MCI is a heterogeneous condition, the combined assessment of both cognitive and neural alterations associated with language deficits may be helpful in achieving higher specificity that could eventually provide markers at the individual-level.

Conclusions

This study provides preliminary evidence on functional alterations associated with language processing in individuals with MCI relative to healthy age matched controls. Lexical retrieval was associated with a power increase in the alpha and low beta range in healthy older adults, while semantic binding was associated with a reduced power decrease. These effects were greatly attenuated in individuals diagnosed with MCI. The identification of subtle alterations in language processing that are detectable in oscillatory measurements in the EEG provide a promising step towards the development of a tool for early diagnosis of MCI and AD.

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Author contributions

CP, LW and KS designed the study; CP collected the data; CP analysed the EEG data under supervision of AM and KS; CP wrote the manuscript; all authors edited the manuscript.

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GENERAL DISCUSSION

Collectively, the work presented in this thesis is focused on the investigation of language comprehension in the ageing brain. Despite well-documented reductions in the structural integrity of language relevant regions of the brain, language comprehension at first sight appears to be relatively preserved with age. This raises the question: "*How does the ageing brain maintain the cognitive system*?" In this context, I aimed to investigate the behavioural and functional underpinnings of sentence comprehension in healthy older adults. These investigations were all based on minimal sentences designed to focus on the process of syntactic binding, while minimizing the contribution of working memory. A secondary aim in these studies was to identify factors associated with individual differences in sentence comprehension. The rationale for this research objective comes from evidence that healthy ageing is characterized by substantial inter-individual variation in neuroanatomical and cognitive change. For this purpose, I investigated whether individual differences in cognitive and physical functioning impact sentence comprehension in healthy ageing. A third research objective was to investigate subtle functional changes in sentence processing during the initial break down of the language system in Mild Cognitive Impairment (MCI). In doing so, I focused on elementary combinatorial operations supporting lexical and semantic processing in a minimal sentence context. Despite the relative simplicity of the designs employed, my studies have yielded a number of important findings - demonstrating that there is a lot to be discovered with just two words.

Summary of contributions

In the study reported in *Chapter 1,* I investigated the syntactic comprehension of minimal sentences (e.g., "*I cook*") in young and older adults. The results convincingly demonstrate there is age-related decline in syntactic comprehension in a minimal sentence context: older adults were less accurate and slower in correctly detecting and rejecting pronoun-verb agreement violations. This experiment also tapped into the relationship between syntax and semantics, by comparing performance on sentences with real verbs (e.g., "*I cook*", *"they cooks"*) to sentences with pseudo verbs (e.g., "*I grush*", "*they grush*"). The pattern of age-related decline in accuracy and speed was differentially influenced by the level of lexical semantic information provided. Specifically, age-related performance decline was larger for real verb relative to pseudoverb sentences in terms of accuracy, but larger for pseudo verb relative to real verb sentences in terms of speed. In other words, it appeared that older adults produced slower responses in order to make more accurate decisions at an increased level of processing challenge. This implies that age-related decline increased in the absence of semantic contextual information.

Crucially, individual variation in age-related performance decline was partly accounted for by individual differences in processing speed and working memory. Increased processing speed in older adults was associated with higher accuracy in comprehending real verb sentences and faster response times to pseudoverb sentences. In addition, increased working memory capacity was associated with higher accuracy across the board in older adults, whereas working memory capacity in young adults appeared to influence performance in only a subset of the conditions.

A clear strength of this study and improvement in relation to previous literature is that the experimental design specifically targets the process of morpho-syntactic binding. Previous work on syntactic comprehension in older adults has predominantly used semantically meaningful sentences with complex syntactic structures. Most of these studies show sentence comprehension is preserved in older adults and only declines under circumstances of increased syntactic complexity or processing demands (Peelle, Troiani, Wingfield & Grossman, 2009; Meunier et al., 2014; Shafto et al., 2014; Campbell et al., 2016). Crucially, however, the interpretation of such complex syntactic structures may not exclusively rely on syntax, but instead, may also require additional comprehension mechanisms including semantic and pragmatic processing. In other words, the work reported in *Chapter 1* provides an original contribution to this field of research by showing age-related decline in syntactic comprehension in a context where complexity was scaled down to a minimum. Specifically, by isolating the process of morpho-syntactic binding in sentence comprehension, we now have a clearer picture of the effect of age on syntactic comprehension.

Moving from a behavioural to a functional perspective on syntactic comprehension, in the experiment reported in *Chapter 2,* I investigated the oscillatory mechanisms associated with syntactic binding in healthy ageing. Specifically, I compared the oscillatory response elicited by pronouns paired with a pseudoverb, which formed a morpho-syntactically correct combination (i.e., syntactic binding; e.g., *"I dotch"*, *"they grush"*) to two pseudoverbs paired together, for which no syntactic unit could be established (i.e., no syntactic binding; e.g., *"spuffs dotch", "plams grush"*). This was done to isolate the process of syntactic binding to the greatest extent possible while minimizing contributions of semantic binding and working memory load. Syntactic binding was associated with a smaller increase in theta (4-7 Hz); alpha (8-12 Hz) and low beta (15-20 Hz) power in the syntactic binding relative to the no binding condition in a time window surrounding the second word. An additional theta cluster was observed from 0.75- 1s following the presentation of the second word, characterized by a smaller increase in theta power in binding relative to the no binding condition.

The literature on syntactic processing in ageing suggests a change in patterns of neural activity in older compared to younger adults (e.g., Grossman et al., 2002; Peelle et al., 2009; Tyler et al., 2010). However, the functional significance of these changes is not yet clearly understood. On the one hand, these altered patterns of brain activity have been attributed to reduced cerebral specialization, known as *dedifferentiation* (Baltes & Lindenberger, 1997). Alternatively, the engagement of neural networks normally not engaged in a given cognitive task could reflect active recruitment in order to compensate for age-related decline, known as *compensation* (Wingfield & Grossman, 2006). An additional aim of the study reported in *Chapter 2* was to investigate the relationship between brain function and behavioural performance. Unfortunately, there was no relationship between the neural signatures associated with syntactic binding and syntactic comprehension (assessed in a syntactic judgement task similar to the task used in *Chapter 1*). Therefore, this study was not able to further elucidate the significance of the functional mechanisms associated with syntactic binding in terms of compensation, or dedifferentiation. However, these findings do suggest that the neural signature associated with syntactic binding in older adults is qualitatively different from younger adults, who show a larger (instead of smaller) alpha and beta power increase for correct binding relative to no binding in the same task (Segaert et al., 2018). Interesting in this respect is the absence of any theta effects in the younger adults. In older adults, the theta effects that were observed may be related to prolonged lexical-semantic retrieval operations in the no binding condition relative to the correct syntactic binding condition. Specifically, even though the minimal phrases carry limited meaning, older adults may nevertheless continue to recruit semantic resources to process the syntactic information.

While research on syntactic processing in ageing is predominantly based on fMRI, the experiment in *Chapter 2* provides novel insight into age-related functional changes by investigating the oscillatory mechanisms involved in syntactic processing in healthy older adults. In addition, while the investigation of age-related behavioural and functional change has predominantly been carried out independently of each other, this study was set up to investigate the relationship between brain and behaviour. The results suggest that there is a lot more work to be done in this context. However, while the current attempt to relate brain to behaviour yielded inconclusive results, the findings of this study do inform us about important qualitative differences between the neural signature associated with syntactic binding in young and older adults. In addition, in agreement with the behavioural results reported in *Chapter 1,* these findings may reflect an increased reliance on semantic processing in older adults.

Beyond the investigation of the effect of healthy ageing on language comprehension, the results reported in *Chapter 3* inform us about functional change in the context of early cognitive impairment due to degenerative disease. Specifically, I investigated oscillatory changes elicited by two-word linguistic expressions in individual with MCI and healthy age matched controls. In healthy older adults, lexical retrieval, assessed by comparing adjectives (e.g., *"sharp"; "classic"*) to letter strings (e.g., "*hwuos", "snklvwe"*), was associated with a shorter suppression in the alpha and low beta power in the lexical, relative to the non-lexical condition following the presentation of the first word. Furthermore, semantic binding, assessed by comparing nouns paired with adjectives which allowed semantic binding (e.g., "*sharp knife"*; "*classic snake"*) to nouns paired with letter strings which did not (e.g., "*snklvwe mother"; "iafnxa bucket"*) was associated with a smaller power decrease in the alpha and low beta band in the semantic binding relative to the no semantic binding condition. Interestingly, similar, but greatly attenuated effects were found in the MCI group for both lexical retrieval and semantic binding.

Instead of a conventional, multi-channel EEG system, EEG was recorded using the cEEGrid system, consisting of flex-printed sensor arrays (i.e., grids). This novel around-ear system was used due to its suitability for testing in a clinical setting. While follow up studies are necessary to further investigate the feasibility of this system, the current study was an important first step in the use of cEEGrids to investigate fundamental questions in clinical populations. My results indicate the existence of subtle anomalies in brain activity associated with lexical and semantic processing in individuals with MCI compared to age-matched healthy controls.

Theoretical implications

Language comprehension is often cited in the literature as a key example of a cognitive function that remains preserved in old age (e.g., Tyler et al., 2009; Peelle et al., 2009; Ansado et al., 2003), unlike other aspects of language processing such as phonological retrieval (Maylor, 1990; Segaert et al., 2018) and syntactic complexity in spoken and written language production (Kemper, Kynette & Norman, 1992), and unlike cognitive functions which are subject to quite uniform age-related declines, such as working memory; episodic memory and processing speed (Salthouse, 1996; Caplan & Waters 2005; Burke & Shafto, 2008). The results reported in *Chapter 1* convincingly demonstrate comprehension performance on elementary syntactic structures declines with age. Certainly, *relative* to the performance decline observed in other cognitive domains, certain aspects associated with language comprehension may remain at a high level. However, the results of this study do strongly suggest the term '*preservation*' in the context of language comprehension should be used with care.

In *Chapter 1,* I investigated the relationship between syntax and semantics by comparing comprehension on sentences with real verbs to sentences with pseudoverbs.

Performance decline was larger in the pseudoverb, relative to the real verb sentences, suggesting the absence of semantic contextual information increases age-related decline in syntactic comprehension. This interpretation is in line with previous work suggesting successful sentence comprehension is subject to an increased reliance on semantic processing in older age (Obler, Fein, Nicholas & Albert, 1991; Soederbergh-Miller, Kirkorian, Stine-Morrow & Conroy, 2004; Beese, Werkle-Bergner, Friederici & Meyer, 2019). In *Chapter 2*, the experimental design required participants to focus on the syntactic information of the sentence while the influence of semantics was reduced to a minimum by the exclusive use of pseudoverbs. Nevertheless, the EEG results suggest that older adults may continue to recruit semantic resources to process the syntactic information, given the prolonged lexical-semantic processing that was observed in the no binding (e.g., *"spuffs dotch"*) relative to the binding condition (e.g., *"they dotch"*). In other words, the results from *Chapter 2* may provide a functional interpretation for the increased reliance on semantic processing in older adults. Importantly, however, the age-related performance decline in syntactic comprehension reported in *Chapter 1* was not limited to sentences with pseudoverbs, but was observed in sentences with real verbs as well (be it to a lesser degree). This suggests that an age-related increased reliance on semantic information for successful sentence processing can only partially account for the declines in syntactic comprehension.

In *Chapter 3*, I investigated oscillatory mechanisms associated with lexical retrieval and semantic processing in individuals with MCI and healthy age matched controls, two crucial aspects of language comprehension. The contribution of this study lies in the empirical demonstration of subtle, yet clear alterations in the neural signatures associated with these processes in the presence of MCI, that is, at very early stage in the breakdown of the language system. Few studies have previously looked into the oscillatory mechanisms associated with language processing in MCI. From a clinical perspective, the results of this study may provide a careful first step in the development of a tool to measure linguistic impairments in the context of early detection of dementia.

Outlook on the future

An important question left to address in future research concerns the relationship between age-related functional and behavioural change in language comprehension. Specifically, a critical question is whether language comprehension is subject to compensatory mechanisms, that is, whether the relative preservation of behavioural performance that is commonly found in the literature, is related to neural-task related changes in older adults. The study reported in *Chapter 2* could have been informative in this respect. Unfortunately, however, attempts to relate syntactic comprehension performance to the functional neural signatures of syntactic binding yielded *inconclusive* results. This means that the regression models that were used to try to predict behavioural performance were of low predictive value. Note that this is different from a statistically non-significant effect. Future studies will be needed to investigate the relationship between behavioural performance and functional activity more closely. A step forward could be made by designing an experiment that would allow a correlation between brain and behaviour on a trial by trail basis. Note that in the current study, different condition contrasts were selected to assess behavioural performance and functional activity. The condition contrasts for both measures were specifically chosen to best capture the underlying constructs they were set out to measure. However, a consequence of this design choice was that both the behavioural and the functional measure consisted of an average of several data points. Given that this approach proved to be unsuccessful, more closely matched behavioural and functional measurements could be a promising next step. Alternatively, or concurrently, the characterization of a relationship of this complexity may require a measure that combines both temporal and spatial precision. Simultaneous EEG and fMRI recordings that enable the integration of the fast temporal dynamics of EEG with the high spatial precision of fMRI may proof to be a useful tool for this purpose.

In extension of the previous point, a critical piece of the puzzle which was not directly assessed in the current work concerns a measure of the structural integrity of the brain. Crucially, both compensation and dedifferentiation would presumably be a response to alterations in the structural integrity of the brain. However, there exists considerable inter-individual variability in the rate and trajectories of structural brain change (Raz, Ghisletta, Rodrigue, Kennedy & Lindenberger, 2010). Therefore, future studies ideally would include a behavioural, functional and structural measure.

In the context of the findings reported in *Chapter 1 and 2,* further studies are needed to investigate the relationship between hearing loss and auditory sentence comprehension more closely. Age-related hearing loss is a major contributor to difficulties in speech comprehension in older adults (Burke & Shafto, 2008; Peelle, Troiani, Grossman & Wingfield, 2011). Participants with severe hearing impairments (>70 db) were excluded from further analysis in the study reported in *Chapter 2,* and the language tasks reported in *Chapter 1 and 2* were both preceded by a volume check to ensure that participants could hear the stimuli. Nevertheless, the influence of increased effort to process auditory information may have influenced the results (Peelle et al., 2011; Peelle & Wingfield, 2016).

Lastly, the results reported in *Chapter 3* suggest subtle alterations in the neural signature associated with lexical retrieval and semantic processing in individuals with MCI relative to healthy age matched controls. Within five years of MCI diagnoses, around 60% of these individuals will develop Alzheimer's disease (AD; Shah, Tangalos & Petersen, 2000). Previous work has been able to successfully distinguish those individuals with MCI who convert to AD from MCI non-converters and healthy controls based on neurophysiological differences during language processing as measured using EEG (Olichney et al., 2002;

Mazaheri et al., 2018). It would be very interesting to see if, within a few years from now, a similar distinction between MCI converters and non-converters can be established in the current data set.

The outlook on future research suggests there is a lot more work to be done. However, to conclude with a general, yet critical note for future research, a lingering problem in the field of cognitive ageing concerns the confusing terminology of concepts and definitions. Theories on compensation and dedifferentiation are plagued by lack of specification and testable predictions. In fact, a recent review article by Cabeza et al. (2018) emphasised that the ambiguous terminology in the field of cognitive ageing impedes the clear interpretation of findings on age-related differences in brain structure, brain activity and functional connectivity. In an attempt to standardize terminology, the authors aimed to sharpen the definitions of common terms in the field. For example, their proposed definition for compensation can be summarized as "*cognition enhancing recruitment of neural resources in response to relatively high cognitive demand*" (Cabeza et al., 2018). While a uniform terminology and a consensus on classification will most certainly benefit the field, it must be acknowledged that a definition such as the one provided above is not easily translatable to clear, testable predictions, especially for ageing processes which are subject to a complex array of factors. My response to this difficulty was to focus my investigations on a pared down aspect of syntactic processing in ageing. The minimal sentence approach adopted in the current thesis has proven to be a useful tool in identifying the underlying processes that are subject to age-related change and promising approach for future research investigating the link between function and behaviour in ageing.

Concluding words

The ageing brain is characterized by structural, functional and cognitive change, but also by adaptation to change. The experiments presented in this thesis aimed to investigate how the brain maintains the language comprehension system in face of the wide array of changes that occur with ageing. The minimal sentence paradigms that were used to approach this demonstrate that isolating specific processes can provide novel perspectives regarding the behavioural and neural substrates of language comprehension in ageing.

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Appendix A List of stimuli used in the language experiment

Plausible semantic binding	*Implausible semantic binding*	*No semantic binding*
crispy apple	handy apple	snjkwf apple
cotton apron	eager apron	xprtsa apron
pointed arrow	cuddly arrow	ihoaj arrow
quick athlete	loose athlete	jpwdtr athlete
bouncy balloon	braided balloon	qlnea balloon
greedy banker	liquid banker	fwefx banker
wicker basket	fluid basket	mklqkst basket
sweet berries	errect berries	kqott berries
empty bottle	rapid bottle	hjwkwi bottle
fresh bread	sweaty bread	jklajds bread
teasing brother	misty brother	jhfdsdr brother
plastic bucket	lively bucket	iafnxa bucket
prickly cactus	bland cactus	gskqpa cactus
burned candle	silly candle	ldtxb candle
stone castle	thick castle	mlkgft castle
secret chamber	valid chamber	nwpqh chamber
mature cheese	rainy cheese	bjkfw cheese
brick chimney	formal chimney	msqnj chimney
bitter citrus	proud citrus	fstajx citrus
loyal client	oblong client	bpshw client
ticking clock	plump clock	arlexd clock
funny clown	mixed clown	akktr clown
falling comet	knotty comet	kahebtp comet
comfy couch	blind couch	jpdwvj couch
golden crown	baggy crown	jkqwd crown
velvet curtain	mellow curtain	jkpwq curtain
shiny diamond	active diamond	sjwoyl diamond
blank diary	sandy diary	uqhuq diary
smart doctor	medium doctor	sqwfa doctor

Plausible semantic binding	*Implausible semantic binding*	*No semantic binding*
flying eagle	decent eagle	eywnd eagle
wooden fence	wooden fence	njwqk fence
pretty flower	cruel flower	qjkdd flower
fleshy garbage	smelly garbage	amsbs garbage
hairy gorilla	cloudy gorilla	snklq gorilla
grumpygrandpa	basic grandpa	wkdjc grandpa
nervous groom	steep groom	hjwdl groom
melodic guitar	shady guitar	awwkf guitar
muddy hippo	nutty hippo	sdfrews hippo
swift horse	barking horse	swrfeq horse
crying infant	paying infant	qkfhe infant
zooming insect	milky insect	klqkjs insect
padded jacket	steady jacket	klpwqfa jacket
tight jeans	faint jeans	qyuds jeans
boiling kettle	cycling kettle	kyklw kettle
rotten knife	blunt knife	jpwdf knife
crashed laptop	lonely laptop	qkxhwe laptop
rough lawyer	fixed lawyer	zxwlp lawyer
yellow lemon	popped lemon	smsbw lemon
spotted leopard	tender leopard	kwpttbs leopard
noisy lorry	angry lorry	ltrovd lorry
bronze medal	organic medal	lsnksq medal
watery melon	brisk melon	skdwva melon
cracked mirror	fierce mirror	mwhtu mirror
naughty monkey	lavish monkey	mknwkjw monkey
loving mother	blocked mother	snklvwe mother
gnawing mouse	stale mouse	slsjphq mouse
crunchy muesli	legal muesli	mkolwq muesli
caring nurse	linear nurse	fdrwea nurse
black panther	fluent panther	qmabd panther
sharp pencil	heated pencil	jkldq pencil
spicy pepper	minty pepper	aqqlska pepper

Plausible semantic binding	*Implausible semantic binding*	*No semantic binding*
ringing phone	messy phone	jkddlkw phone
famous picture	quiet picture	nklwq picture
greasy pizza	jaded pizza	ftarg pizza
landing plane	singing plane	bknqw plane
metal plate	false plate	hnpwhd plate
curly poodle	harsh poodle	kkajsld poodle
mashed potato	fancy potato	wqosn potato
royal prince	cooked prince	snklgz prince
fuzzy puppy	clear puppy	qvsldj puppy
furry rabbit	closed rabbit	sfgwfj rabbit
creamy sauce	clumsy sauce	kxpwd sauce
woollen scarf	natural scarf	fhdwi scarf
killing shark	kissing shark	kdywt shark
satin sheets	glass sheets	vsppwkd sheets
suede shoes	brief shoes	mklwdvh shoes
slimy snail	noble snail	dsefa snail
hissing snake	classic snake	skldw snake
frozen snowman	tasty snowman	lqbjqq snowman
brave soldier	glossy soldier	hrsca soldier
scary spider	flashy spider	jhhgdh spider
marble statue	fatal statue	nklwq statue
square table	hollow table	nklewf table
strict teacher	crowded teacher	fswra teacher
sleek tiger	complex tiger	hwuos tiger
scaly trout	blond trout	kwjkxk trout
polite waiter	chunky waiter	guwql waiter
creepy witch	gentle witch	kwtlu witch
sailing yacht	elastic yacht	bjkwd yacht
striped zebra	orange zebra	snklve zebra

Appendix B List of questions used in the language experiment

Word-pair	*Question*	*Correct answer*
naughty monkey	Did you just read naughty monkey?	Yes
steady jacket	Did you just read steady jacket?	Yes
stone castle	Did you just read stone castle?	Yes
woollen scarf	Did you just read woollen hat?	No
brick chimney	Did you just hear brick hearth?	No
braided balloon	Did you just read weaved balloon?	No
uqhuq diary	Did you just read uqhuq diary?	Yes
fresh bread	Did you just read fresh cake?	No
classic snake	Did you just read classic snake?	Yes
furry rabbit	Did you just read soft rabbit?	No
bronze medal	Did you just read silver medal?	No
fatal statue	Did you just read fatal statue?	Yes
messy phone	Did you just read messy phone?	Yes
oooorvd lorry	Did you just read ooorvd lorry?	No
velvet curtain	Did you just read lace curtain?	No
flashy spider	Did you just read flashy bedbug?	No
cruel flower	Did you just read cruel flower?	Yes
slimy snail	Did you just read slimy snail?	Yes
muddy hippo	Did you just read dirty hippo?	No
fluid basket	Did you just read fluid basket?	Yes
rotten knife	Did you just read rotten fork?	No
satin sheets	Did you just read satin sheets?	Yes
shiny diamond	Did you just read shiny pearl?	No
cycling kettle	Did you just read walking kettle?	No
heated pencil	Did you just read heated pencil?	Yes
proud citrus	Did you just read proud citrus?	Yes
clear puppy	Did you just read clear puppy?	Yes
grumpy grandpa	Did you just read grumpy granny?	No
spotted leopard	Did you just read spotted lion?	No

Word-pair	*Question*	*Correct answer*
sunny cheese	Did you just read sunny cheese?	No
popped lemon	Did you just read popped lemon?	Yes
fleshy garbage	Did you just read fleshy junk?	No
snklq gorilla	Did you just read snklq gorilla?	Yes
polite waiter	Did you just read polite waiter?	Yes
medium doctor	Did you just read medium dentist?	No
tight jeans	Did you just read straight jeans?	No
nervous groom	Did you just read nervous bride?	No
prickly cactus	Did you just read prickly cactus?	Yes
hollow table	Did you just read hollow table?	Yes
trrra clown	Did you just read trrra clown?	No
knotty comet	Did you just read knotty star?	No
curly poodle	Did you just read curly poodle?	Yes
wooden fence	Did you just read wooden bridge?	No
milky insect	Did you just hear milky insect?	Yes
suede shoes	Did you just read leather shoes?	No
spicy pepper	Did you just read spicy pepper?	Yes
valid chamber	Did you just read lawful chamber?	No
crunchy muesli	Did you just read crunchy muesli?	Yes
crispy apple	Did you just read crispy pear?	No
melodic guitar	Did you just read melodic cello?	No
fluent panther	Did you just read fluent panther?	Yes
lively bucket	Did you just read lively bucket?	Yes
eywnd eagle	Did you just read eywnd eagle?	Yes
eager apron	Did you just read eager apron?	Yes
teasing brother	Did you just read teasing sister?	No
famous picture	Did you just read fabulous picture?	No
silly candle	Did you just read crazy candle?	No
royal prince	Did you just read royal prince?	Yes
loose athlete	Did you just read loose athlete?	Yes