SYNTACTIC AND LEXICAL PROCESSING IN HEALTHY AGEING

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ABSTRACT

Successful sentence production requires rapid word retrieval and the generation of an appropriate grammatical structure. In this thesis, I investigated how these lexical and syntactic processes are affected by healthy ageing. In **Chapter 2**, using a structural priming paradigm, I found evidence that the nature of syntactic representations is unaffected by healthy ageing and that global, not internal, structure determined syntactic choices in young and older adults. In **Chapters 3-4**, using adaptations of the planning scope paradigm, I found that young and older adults engaged in a similar phrasal scope of advanced planning. However, I also found evidence of age-related differences in lexical processing in that older adults were less able to manage the temporal activation of lexical items and their integration into syntactic structures. In **Chapter 5**, I investigated sentence comprehension using the neuroimaging technique of MEG. In young adults, I found that the binding of words into a minimal sentence structure was associated with a modulation in alpha power. Overall, the findings of this thesis demonstrate that there is a complex relationship between healthy ageing and language, such that certain features of language may be preserved with age, while others decline.

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PUBLICATIONS

During the course of my postgraduate study, the following articles were accepted for publication in peer-reviewed journals, uploaded to pre-print servers and/or presented at conferences. A number of these publications form the basis of the experimental chapters presented in this thesis. I was the primary author on all publications relating to this thesis, but was advised on study design, data analysis and manuscript revisions by the listed co-authors.

Chapter 2

Hardy, S. M., Wheeldon, L., & Segaert, K. (2019). Structural priming is determined by global syntax rather than internal phrasal structure: Evidence from young and older adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition* (advanced online publication), https://www.ncbi.nlm.nih.gov/pubmed/31545625.

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Hardy, S. M., Wheeldon, L., Segaert, K. (2019*). Structural priming is determined by global syntax rather than internal phrase structure: Evidence from young and older adults.* Poster presented at the 25th Architectures and Mechanisms of Language Processing (AMLaP) conference, Moscow, Russia.

Chapter 3

Hardy, S. M., Segaert, K., & Wheeldon, L. (2020). Healthy ageing and sentence production: Disrupted lexical access in the context of intact syntactic planning. *Frontiers in Psychology*, *11*, 257 https://doi.org/10.3389/fpsyg.2020.00257.

Hardy, S. M., Segaert, K., & Wheeldon, L. (2018). *Ageing and sentence production: Impaired lexical access in the context of intact syntactic planning.* Poster presented at the Experimental Psychology Society (EPS) Spring Conference, Leicester, UK.

Hardy, S. M., Segaert, K., & Wheeldon, L. (2018). *Ageing and sentence production: Impaired lexical access in the context of intact syntactic planning.* Poster presented at the 10th International Workshop on Language Production, Nijmegen, the Netherlands.

Hardy, S. M., Segeart, K., & Wheeldon, L. (2017). *Ageing and sentence production: Effects of syntactic planning and lexical access.* Talk presented at the 23rd Architectures and Mechanisms of Language Processing (AMLaP) conference, Lancaster, UK.

Chapter 4

Hardy, S. M., Segaert, K., & Wheeldon, L. (submitted). Age-related disruption in the use of lexical information during sentence production, despite preserved syntactic planning. *Pre-print available on PsyArXiv*, https://psyarxiv.com/xrbta.

Hardy, S. M., Segaert, K., & Wheeldon, L. (2019). *Age-related disruption in the use of lexical information in sentence production, despite preserved syntactic planning.* Poster presented at the 25th Architectures and Mechanisms of Language Processing (AMLaP) conference, Moscow, Russia.

Additional publications not included in this thesis

Hardy, S. M., Messenger, K., & Maylor, E. A. (2017). Aging and syntactic representations: Evidence of preserved syntactic priming and lexical boost. *Psychology and Aging, 32(6), 588-596,* https://www.ncbi.nlm.nih.gov/pubmed/28891670.

Messenger, K. **Hardy, S. M.,** & Coumel, M. (2020). An exemplar models should be able to explain all syntactic priming phenomena: Commentary on Ambridge (2020). *First Language,* https://doi.org/10.1177/0142723720904479

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CHAPTER 1
General Introduction and Thesis Outline

Successful communication with others is essential for the language-orientated society in which we live. Every day we use words and sentences to convey our thoughts and intentions to others, enabling us to build meaningful relationships with those around us. Nevertheless, producing a fluent and coherent sentence is a complex task, involving the coordination of multiple cognitive and neural mechanisms (Levelt, 1989). Moreover, these processes must be executed quickly and efficiently if a speaker is to maintain an acceptable rate of conversation turn-taking (>200ms gap between speakers; Stivers et al., 2009). As we age, cognitive and neuroanatomical changes occur that can create challenges for language processing, including declines in working memory capacity and inhibitory control, as well as widespread changes in grey and white matter volume (for reviews see, Abrams & Farrell, 2011; Burke & Shafto, 2008; Shafto & Tyler, 2014). However, older adults are often able to adopt effective processing strategies, such as the recruitment of additional brain regions, in order to compensate for lost efficiency elsewhere (see Wingfield & Grossman, 2006, for a review). According to Peelle (2019), this creates a complex balance between processing efficiency and task requirements in older adults, such that language skills may appear preserved in situations in which processing efficiency outweighs task demands, but age-related declines may emerge when the given demands outweigh the available cognitive resources (see **Figure 1.1**). Investigating how different aspects of language processing are affected by healthy ageing is therefore critical for understanding this complex balance between decline and preservation.

With this in mind, the aim of this thesis was to investigate age-related effects on various features of sentence processing, using novel techniques not previously applied to older adults. The elderly are the fastest growing age group worldwide and it is predicted that, by the year 2050, 21% of the global population will be aged 60 and above (Harper, 2014; World Health Organisation, 2011). This further highlights the importance of conducting novel studies into language and ageing in order to better understand the changes that occur during healthy ageing, and to crucially identify the mechanisms that underlie these changes. The following introduction outlines the different processes required for successful sentence production and comprehension, and introduces the experimental techniques used in this thesis (**Chapter 2-5**) to investigate age-related changes in these processes.

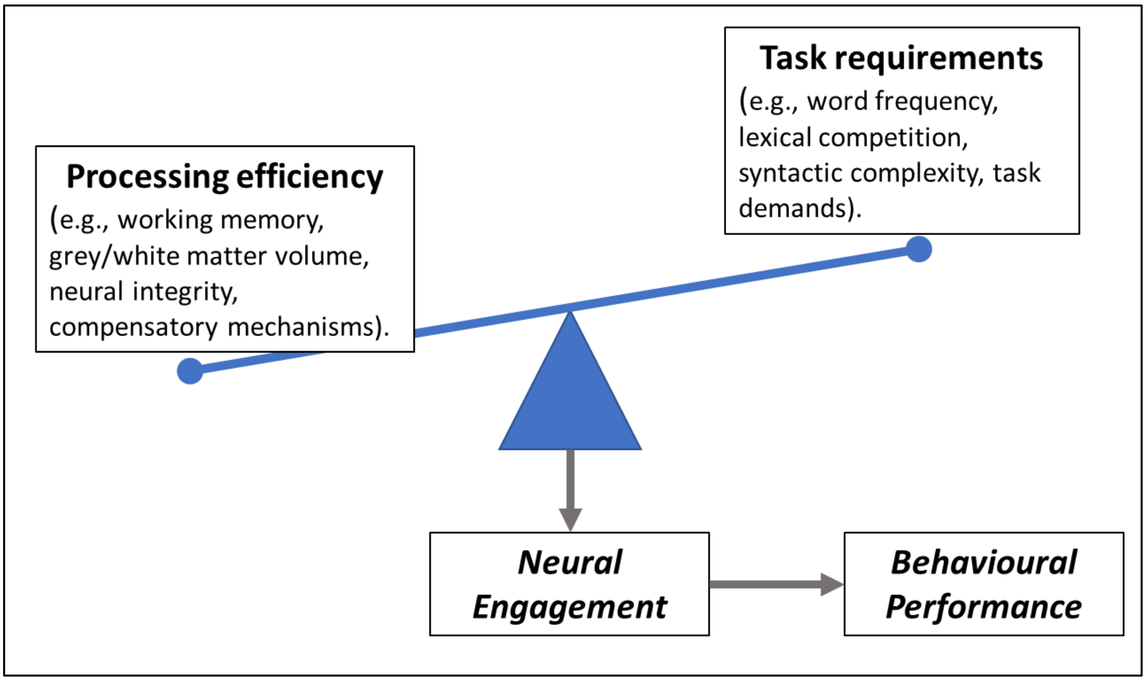

Figure 1.1 *Schematic framework for considering the neural engagement that supports language processing in older adults, adapted from Peelle (2019).*

1.1 The model of the speaker

Sentence production begins with the preparation of a non-linear preverbal message – the exact nature of the message is debated, but it is generally considered to include information relating to conceptual and thematic features within the discourse context (Levelt, 1989). In order to produce a sentence, a speaker must rapidly transform this preverbal message into an articulated utterance; all models of sentence production propose that this translation process occurs in a number of successive steps (Bock & Levelt, 1994; Chang, 2002; Chang, Dell, & Bock, 2006; Chang, Dell, Bock, & Griffin, 2000; Dell, 1986; Dell, Oppenheim, & Kittredge, 2008; Ferreira & Slevc, 2007; Garrett, 1980; Levelt, 1989, 1992; Levelt, Roelofs, & Meyer, 1999; Pickering & Branigan, 1998; Segaert, Wheeldon, & Hagoort, 2016). Broadly speaking, the preverbal message triggers the formulation stage in which the message turned into a set of linguistic representations, or features, that can ultimately be phonologically encoded for articulatory or written output. During the formulation stage, a number of separable sub-processes are executed that deal with formulating the content, or lexical properties, of the sentence and specifying the syntactic (i.e., grammatical) structure of the eventual utterance.

According to lexically driven accounts of sentence production, a speaker must first retrieve the relevant lemma forms from the lexicon, broadly defined as the internal word store that contains information relating to a word's conceptual, syntactic and phonological features; the selection of the lemmas then drives the grammatical encoding stage during which the speaker uses lexical-syntactic information to 'build up' an appropriate syntactic structure or representation (Bock & Levelt, 1994; Levelt, 1989; Levelt et al., 1999; Pickering & Branigan, 1998). In a fixed word-order language, this primarily involves sequentially ordering the words into order to convey their relational meaning (also termed 'constituent assembly'; Bock, 1995); for example, in English (a SVO language), the verb would be placed before the object (*"She chases him"*). Alternatively, more computational models propose that there is a complete dissociation between the formulation sub-processes, such that syntactic structure is derived solely from conceptual structure (i.e., thematic roles) with lexical access occurring independently (Chang, 2002; Chang et al., 2000, 2006). The final step of formulation involves the encoding of the phonological and phonetic features of the speech output prior to articulation (Dell, 1986; Levelt, 1999; Roelofs, 1992, 1997). At this level, the key debate turns to the relationship between grammatical and phonological processing with some models proposing a discrete feed-forward activation (Levelt, 1989; Levelt et al., 1999) and others proposing a more interactive relationship (Dell, 1986; Dell & O'Seaghdha, 1992).

Nevertheless, despite these ongoing debates, the different theoretical models converge on similar processing levels, and all postulate that language processing needs to be executed quickly and efficiently for successful communication to occur. Importantly, in order to achieve the required speed of speech output, all models also assume that processing at each level occurs incrementally, such that speakers do not complete all processes for the whole sentence before beginning articulation, but instead utterances are planned and produced in a more piecemeal fashion. In this way, a speaker may be producing one part of a sentence while simultaneously planning the next part, meaning that various processing components are concurrently active at any one time. An incremental system is beneficial as it allows for the rapid release of parts of the sentence as soon as planning is complete, reducing the demand for storage in working memory (Kempen & Hoenkamp, 1987; Levelt, 1989; Wheeldon, 2013). Nonetheless, debate does exist surrounding the scope of incrementality and the amount of pre-planning that speakers engage in prior to articulation; specifically, whether speakers plan sentences in chunks relating to the clause (Bock & Levelt, 1994), phrase (Smith & Wheeldon, 1999) or word (Griffin, 2001). Moreover, the scope of planning may not always align for the lexical and syntactic features of a sentence, such that lexical planning scope is comparatively more restrictive (Wheeldon, Ohlson, Ashby, & Gator, 2013).

To summarise, the formulation of a fluent and coherent sentence requires a series of successive processes, relating to the lexical, syntactic and phonological features of the sentence, which are executed in an incremental fashion. Within this thesis, I investigated the effect of healthy ageing on three key features of sentence formulation: (1) syntactic representations and grammatical encoding; (2) incrementality in sentence planning; and (3) lexical retrieval. These processes are central to all models of speech production, and while their exact nature is debated, all three features may be considered 'corner stones' of successful sentence production. In what follows, I outline the techniques used in **Chapters 2-4** to investigate these processes in young and older adults.

1.1.1 Structural priming as a window into syntactic representations and grammatical encoding

For some preverbal messages, there may be more than one syntactic structure for conveying the same core meaning. For example, a transitive verb event can either be described using an active or a passive sentence (*"the girl is chasing the boy"* vs*. "the boy is being chased by the girl"*). Which syntactic structure a speaker chooses may be influenced by various factors including the conversational context, the frequency of the structure, and recent syntactic processing. One factor that has been pervasively found to influence syntactic choices is *structural priming* (also referred to as syntactic priming or persistence): the facilitation of syntactic processing that occurs when a structure is repeated across otherwise unrelated utterances (Bock, 1986; Pickering & Ferreira, 2008). For example, a speaker will be more likely to use the passive syntax to describe a transitive verb target if they have recently processed a passive prime sentence, as opposed to the alternative active sentence (see

Mahowald, James, Futrell, & Gibson, 2016, for a meta-analytical review). Models of structural priming propose that priming reflects facilitated linguistic processing when either a speaker is accessing a syntactic structure (Pickering & Branigan, 1998), formulating it (Chang et al., 2006) or a combination of the two (Segaert et al., 2016). Importantly, structural priming occur independently of any lexical overlap, meaning it can provide a window in how speakers represent and encode syntax at a highly abstract level (Branigan, 2007).

In **Chapter 2**, we therefore used the structural priming paradigm to investigate the influence of healthy ageing on syntactic choices. Specifically, we aimed to understand whether young and older adults rely on the same or different processes when selecting a syntactic alternative, and whether both age groups represent syntactic structures in a similar or different way for both global and local features of a sentence. The global feature is defined as the broader syntactic structure of the sentence (e.g., the passive syntax), whereas the local features relate to the more detailed constituent information within the internal phrases of the sentence (e.g., the subject noun phrase). In **Chapter 2**, we examined whether repetition of global and local structures affected the magnitude of the choice structural priming effect in young and older adults (i.e., how likely they were to produce a passive target sentence). The findings of this study also provide insight into the level of specification, or detail, of underlying syntactic structures. The concept of under-specification (the idea that certain features are not expressed within a linguistic representation) can be found at the phonological and lexical-semantic level of processing (for reviews see, Frisson, 2009; Steriade, 1995). We aimed to address a debate within the structural priming literature about whether syntactic representations are highly abstract (i.e., unspecified) in nature (Chang et al., 2006; Pickering & Branigan, 1998) or whether they also encompass some functional lexical content (Ziegler, Snedeker, & Wittenburg, 2017).

In addition to influencing syntactic choice, repetition of syntactic structure has been found to decrease speech onset latencies, indicating a facilitated processing effect of sentence planning and production (e.g., Corley & Scheepers, 2002; Segaert et al., 2016; Smith & Wheeldon, 2001). This onset latency priming effect is stronger for the preferred active syntax, but choice priming effects are stronger for the dispreferred passive syntax (Ferreira & Bock, 2006; Segaert et al., 2016). This highlights how structural priming may have different facilitatory effects at the syntax selection and planning stages (two successive steps within the sentence production process; Segaert et al., 2016). In **Chapter 2**, we therefore also measured how quickly young and older adults produce target sentences following primes of different syntactic and phrasal structure. Specifically, any group age differences in the magnitude of the onset latency priming effects are informative about age-related changes in the time taken to select and plan sentences.

Moving forward to **Chapter 3**, we aimed to probe deeper into age-related differences in grammatical encoding by specifically investigating the processes involved in syntactic planning, but not selection. One way this can be achieved is by removing the choice element from the structural priming paradigm in order to focus on the facilitated speed of speech production that occurs when a structure is repeated (Smith & Wheeldon, 2001; Wheeldon & Smith, 2003). In **Chapter 3 (Experiment 1)**, we therefore instructed young and older adults to describe moving pictures using specific sentence types. Without a choice element, very minimal time is required at the selection stage (as there are no competing syntactic alternatives). Instead, onset latencies are largely determined by processing at the planning stage, thereby providing a more precise window into the effect of healthy ageing on the processes involved in syntactic planning during grammatical encoding.

1.1.2 On-line measures of incremental planning scope during sentence production

I have already touched on the advantages of using speech onset latencies to investigate age-related changes in sentence planning, but here I discuss in more detail the insight to be gained from using on-line measures of production and how such measures were applied in the experiments reported in **Chapters 3-4**. As previously discussed, sentence production occurs incrementally in a chunk-like manner, such that speakers only plan a small amount of what they wish to say before beginning articulation and that planning continues to unfold after speech onset for the remainder of the sentence (Kempen & Hoenkamp, 1987; Levelt, 1989, 1992). Nonetheless, a certain degree of pre-planning is required prior to speech onset to enable fluency during sentence production. Consequently, the amount of time that a speaker takes to initiate a sentence is informative about the amount of planning that has occurred before articulation begins (see Wheeldon, 2013, for a review).

A body of research using onset latency measures have provided evidence consistent with a phrasal scope of advanced planning in young adults (e.g., Allum & Wheeldon, 2007; Levelt & Maassen, 1981; Martin, Crowther, Knight, Tamborello, & Yang, 2010; Smith &

Wheeldon, 1999; Wheeldon et al., 2013). Such studies have found that, all other things being equal, speakers take longer to initiate sentences with a large initial phrase (e.g., a coordinate noun phrase; *"[the dog and the hat move] above the fork"*), compared to a smaller initial phrase (e.g., a simple noun phrase; *"[the dog moves] above the hat and the fork"*). This demonstrates that young speakers are prioritising the generation of syntax and retrieval of lexical items within the first phrase prior to articulation. Another on-line method for investigating planning scope involves eye-tracking (i.e., monitoring speakers' gaze shifts and durations when describing picture arrays). Typically, eye-tracking studies have found that speakers plan in word, not phrasal, units (Griffin, 2001; Zhao & Yang, 2016). This apparent contrast to studies involving onset latencies is likely due to differences in the measurements used: while latency measures provide insight into the preparation time before articulation, eye-tracking measures focus more on the gaze shifts during articulation that are tightly locked to individual word onset (Wheeldon, 2013). For the studies reported in this thesis, we were more interested in age-related changes in the amount of pre-planning that occurs prior to speech onset; hence, onset latency measures were the primary methodologies used in **Chapters 3-4**.

Moreover, there is no research to date investigating planning scope in older adults using latency measures of production. The majority of behavioural studies examining sentence production and ageing have predominantly used off-line measures, involving the assessment and coding of sentences after they have been produced (see Burke & Shafto, 2008, for a review), which, while informative about syntactic choices and errors, cannot provide insight into the time-course of the underlying sentence planning process. Furthermore, age-related changes in the cognitive resources that support language processing, such as working memory, typically decline with age, which may in turn lead to changes in the processes involved in on-line sentence planning and production in older adults (Peelle, 2019). In **Chapter 3 (Experiment 2)**, we therefore used the onset latency planning scope paradigm to investigate the effect of healthy ageing on the amount of pre-planning that occurs prior to articulation. Young and older adults described moving picture displays designed to elicit specific sentence types that varied in the length of the initial noun phrase (simple vs. coordinate). Specifically, our findings will be informative about whether syntactic planning at the phrasal level is preserved with age, or whether older adults adopt a different planning scope in order to compensate for cognitive declines elsewhere.

1.1.3 Manipulating the ease of lexical processing during sentence planning

In **Chapters 3-4**, we also aimed to examine the effect of healthy ageing on the processes involved in lexical selection and retrieval. In the studies reported, we integrated a lexical manipulation into the planning scope paradigm in order to more precisely examine age effects at the lexical level of processing. This is important because fluent sentence production requires successful processing at both the syntactic and lexical level. Nevertheless, lexical retrieval and syntax generation do not rely on the exact same mechanisms (Bock & Levelt, 1994; Levelt, 1989) and may even be entirely dissociated (Chang et al., 2000, 2006). Thus, evidence of age effects in syntactic processing is not necessarily indicative of age effects in lexical processing (or vice-versa). One way to examine the processes involved at the lexical level is by manipulating the ease of lexical processing during sentence planning. For example, Wheeldon et al. (2013) included a picture preview in their sentence production task: they found that previewing an upcoming lexical item decreased speech onset latencies in young adults, particularly when it fell within the initial phrase, indicating a facilitatory effect on lexical processing (see also Allum & Wheeldon, 2009). Thus, in some trials in **Chapter 3 (Experiment 2)**, participants were shown a picture of a to-be-produced lexical item before producing sentences with initial coordinate or simple noun phrases. The magnitude of the preview benefit in older adults will provide insight into age-related changes in lexical retrieval and the integration of lexical item into syntactic structures.

Moving to **Chapter 4**, another way to investigate age-related changes in lexical processing is by manipulating the semantic relationship between words in a sentence. According to the spreading activation theory of sentence production (Dell, 1986; Dell & O'Seaghdha, 1992), when a word is selected for production (triggered by the conceptualisation of the pre-verbal message), lexical representations of semantically similar words are also activated within the lexicon (e.g., cat-dog). In order to maintain fluency, a speaker must prevent interference from a semantic competitor during lexical retrieval and speech production; resolving this competition typically leads to increased speech onset latencies for single words when a distractor is present (Glaser & Düngelhoff, 1984; Schriefers, Meyer, & Levelt, 1990) and for sentences that contains semantically related lexical items (Smith & Wheeldon, 2004; Yang & Yang, 2008). In **Chapter 4**, we therefore used a semantic interference sentence production paradigm (similar to Smith & Wheeldon, 2004) to investigate age-related changes in lexical competition during sentence planning and production. The findings build on **Chapter 3** and provide further insight into the effect of healthy ageing on the processes involved in lexical retrieval and encoding.

1.2 The neurobiology of sentence comprehension

The majority of this thesis is focused on age-related changes in sentence production; however, an equally important part of successful communication is comprehension. During a conversation, individuals must decode the words and sentences of other speakers in order to understand the underlying message. For example, Levelt's (1989) production model also includes a speech-comprehension system, during which the auditory speech is parsed and mapped onto a representation that details the phonological, morphological, syntactic and semantic features of the input. Other models of speech comprehension similarly propose that successful comprehension involves the unification of various components of speech, relating to phonology, syntax and semantics, into a comprehensible message (McClelland & Elman, 1986; Pickering & Garrod, 2013). Such processes are predominantly supported by a left-lateralised network of regions within the human brain (Tyler & Marslen-Wilson, 2008), although there is increased neural activation in the right hemisphere with age (Peelle, 2019; Wingfield & Grossman, 2006). In **Chapter 5**, we investigated the neurobiological processes involved in syntax comprehension.

The main focus of this experimental chapter was a novel neuroimaging study using magnetoencephalography (MEG; discussed in more detail below); however, I also include a preface of a behavioural experiment investigating sentence comprehension in healthy ageing. In **Chapter 5 (Part A)**, we investigated young and older adults' comprehension accuracy and self-paced reading speeds when reading sentences of varying syntactic complexity. Specifically, we aimed to provide insight into the debate about whether syntax comprehension abilities are preserved with age (e.g., Campbell et al., 2016; Davis, Zhuang, Wright, & Tyler, 2014) or decline (e.g., Peelle, Troiani, Wingfield, & Grossman, 2010; Stine-Morrow, Ryan, & Leonard, 2000) by employing a continuum of syntactic complexity that consisted of five levels ranging from very simple to very complex constructions. In **Chapter 5 (Part B)**, we turned to focus on the neural mechanisms that support syntax comprehension by conducting an MEG study.

1.2.1 MEG: A tool for precise oscillatory detection and source localisation

Neuroimaging – the non-invasive recording of the brain's activity or imaging of the brain's structure – is a useful research tool for investigating the neural networks that support different cognitive and behavioural functions, such as language. One functional neuroimaging technique is MEG – the recording of magnetic fields generated by the electrical activity of neurons in the brain (Singh, 2014). While all different neuroimaging techniques have their own advantages and disadvantages, MEG is unique in that it has both high temporal and spatial resolution, particularly when combined with magnetic resonance imaging (MRI) for more detailed source localisation (Lopes da Silva, 2013; Singh, 2014). MEG can therefore be used to provide a precise window into the oscillatory activity involved in syntax comprehension, and to localise this activity to specific regions within the brain (e.g., Bemis & Pylkkänen, 2011, 2013; Harris, Pylkkänen, McElree, & Frisson, 2008).

In **Chapter 5 (Part B)**, we recorded participants' MEG activity while they performed an auditory comprehension task. Specifically, we investigated the neural networks involved in syntactic binding – the combination of multiple words into a larger syntactic structure with more complex meaning (Chomsky, 1995; Hagoort, 2003). Following Segaert, Mazaheri, and Hagoort (2018), we used a minimal sentence two-word paradigm involving pseudo-verbs in order to minimise contributions from semantic and other cognitive resources, such as working memory. In a change to all other experiments in this thesis, we only tested young adults. This was in part due to large costs associated with MEG, but also time constraints of the PhD. Nonetheless, our findings still make a valuable contribution to the current syntactic binding literature. Moreover, through this study, I acquired a variety of new methodology and analytical skills that I plan to continue to use throughout my career in order to investigate age-related effects on syntactic processes at a more neurobiological level.

1.3 Thesis summary

In summary, the main aim of this thesis was to investigate age-related changes in the processes involved in fluent sentence production and comprehension using novel techniques not previously applied to older adults. **Table 1.1** summarises the aims and methodologies of four experimental studies included in this thesis. Lastly, in **Chapter 6**, I bring together all the experimental results of this thesis and discuss the wider implications for theories of language and ageing. To anticipate our key findings, throughout the reported experiments, we find evidence of age effects on the lexical, but not syntactic, processes involved in sentence production. Together, the findings of this thesis highlight that healthy ageing does not affect all features of language processing equally, and that there is a complex balance between what is preserved and what declines with age.

In the interest of clarity, I have also provided a glossary of key terminology used in this thesis in **Table 1.2**. This is important because certain terms, in particular those that refer to elements of planning, are often defined differently within the literature.

Table 1.1 *Summary of the aims and methodologies of the four experimental chapters reported in this thesis.*

Chapter	Aim	Methodology
2	To investigate age-related differences in the level of abstractness of syntactic representation and the ways in which sentences are planned.	Choice and onset latency structural priming.
3	To investigate age-related changes during on-line sentence planning and in the scope of pre-planning that is required prior to articulation.	Onset latency structural priming (Exp 1) and planning scope (Exp 2).
4	To investigate age-related changes into semantic competition during lexical selection and retrieval.	Semantic interference sentence production task.
5	To investigate age-related changes in syntax comprehension and the neurobiology involved in syntactic binding.	Reading comprehension task (Part A) and MEG (Part B).

Table 1.2 *Glossary of key terminology used in this thesis.*

Term	**Definition**
Healthy ageing	The natural cognitive, physical and psychological changes that occur as a person gets older. Ageing is a linear process throughout the lifespan, but 'old age' is generally considered to begin around 65-years-old.
Syntactic priming	The facilitation of syntactic processing that occurs when a syntactic structure is repeated. This facilitation may occur at the syntax selection or planning stage of production.
Syntactic planning	The processing of the features of a syntactic component that occurs prior to articulation of the component (i.e., a phrase or sentence). This processing includes the encoding of the conceptual and functional relationship between words, as well as the linearization of the words into an order suitable for production.
Lexical planning	The processing of the features of a lexical component (i.e., a word) that occurs prior to articulation of the word. This processing primarily involves the retrieval of the word lemma from the lexicon.
Planning scope	The scope, or size, of the planning units that speakers use when incrementally planning parts of a sentence. These units may encompass a syntactic component (i.e., a phrase) or a lexical component (i.e., a word).
Pre-planning	The amount of planning that a speaker engages in prior to beginning articulation of a sentence. The time taken to begin sentence onset is therefore indicative of the minimal amount of time needed to plan the initial part of a sentence.
Semantic interference	When the processes involved in the retrieval of a word lemma from the lexicon are disrupted by the co-activation of a semantically related competitor word.
Syntactic binding	The combination, or unification, of singular words into a larger syntactic structure with more complex meaning.

Note. Throughout the literature, 'syntactic' is sometimes replaced with 'structural' – these two words are largely interchangeable and have the same meaning in the context of the terminology described here.

CHAPTER 2

Structural Priming is Determined by Global Syntax Rather Than Internal Phrasal Structure: Evidence from Young and Older Adults

Structural priming refers to the tendency of speakers to repeat syntactic structures across sentences. We investigated the extent to which structural priming persists with age and whether the effect depends upon highly abstract syntactic representations that only encompass the global sentence structure or whether representations are specified for internal constituent phrasal properties. In Experiment 1, young and older adults described transitive verb targets that contained the plural morphology of the patient role (*"The horse is chasing the frogs/ The frogs are being chased by the horse"*). While maintaining the conceptual and global syntactic structure of the prime, we manipulated the internal phrasal structure of the patient role to either match (plural; *"The king is punching the builders/ The builders are being punched by the king"*) or mismatch (coordinate noun phrase; *"The king is punching the pirate and the builder/ The pirate and the builder are being punched by the king"*) the target. In both age groups, we observed limited priming of onset latencies, but robust effects of choice structural priming – participants produced more passive targets following passive primes – which critically did not vary dependent on whether the internal constituent structure matched or mismatched between the prime and target. Experiment 2 replicated these findings for the agent role: choice structural priming was unaffected by age or changes to the prime noun phrase type. This demonstrates that global, not internal, syntactic structure determines syntactic choices in young and older adults, as predicted by residual activation and implicit learning models of structural priming.

Peer-reviewed publication:

Hardy, S. M., Wheeldon, L., & Segaert, K. (2019). Structural priming is determined by global syntax rather than internal phrasal structure: Evidence from young and older adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition* (advanced online publication), https://www.ncbi.nlm.nih.gov/pubmed/31545625.

Data availability: The full set of stimuli is provided online on the Open Science Framework (https://osf.io/8y5jx/).

2.1 Introduction

To communicate successfully, a speaker must convert a conceptual representation of the information that they wish to convey into an appropriate syntactic structure (Bock & Levelt, 1994; Garrett, 1980; Levelt, 1989). For some messages, more than one syntactic structure can be used to convey the same core meaning; for example, a transitive verb event can either be expressed using an active sentence (*“the girl is chasing the boy”*) or a passive sentence (*“the boy is being chased by the girl”*). In these instances, the syntactic structure that a speaker chooses reflects the relationship between thematic representations of the message to be expressed and the syntactic properties to which they are assigned (i.e., whether the agent or patient of the transitive verb action is assigned to the subject or object position). One factor that has been pervasively found to influence syntactic choices is *structural priming*: the facilitation of syntactic processing that occurs when a syntactic structure is repeated across an otherwise unrelated prime and target pair (Bock, 1986; Pickering & Ferreira, 2008). For example, a speaker will be more likely to use the passive syntax to describe a transitive verb target if they have recently processed a passive prime sentence as opposed to the alternative active sentence (see Mahowald et al., 2016, for a meta-analytical review). Importantly, structural priming can provide a window into how speakers represent syntax independent of lexical content, allowing insight into the abstractness of syntactic representations (Branigan, 2007).

In this study, we used the structural priming paradigm to investigate which factors influence syntactic choices in order to gain insight into the abstractness of syntactic representation and the processes involved throughout the lifespan in syntax generation and planning. Our aims were two-fold. Firstly, we aimed to investigate whether structural priming is determined solely by the repetition of the highly abstract, or global, syntactic structure that lacks phrase structure detail or whether changes to the internal phrasal structure influence the magnitude of structural priming. Changes in the structural priming effect that are dependent on whether global or local structure is repeated across the prime and target can test predictions about the abstraction of syntactic representations made by existing models of structural priming (e.g.. Chang et al., 2006; Pickering & Branigan, 1998). Both structural choice and on-line sentence planning processes are essential for producing a fluent and coherent sentence

(Levelt, 1989). We therefore examined whether repetition of global and local structure affected a speaker's choice to use an active or a passive sentence to describe a transitive verb target, as well as how long they took to begin articulation (a measure of on-line sentence planning). Secondly, we aimed to investigate the effect of ageing on syntactic choices and sentence planning by testing both young and older adults. This is because the processes determining syntactic choices and sentence planning may vary across the lifespan due to the extensive cognitive and neuroanatomical changes that occur with healthy ageing, such as a decline in processing speed and a reduction in grey matter volume (Good et al., 2001; Salthouse, 1996), which may in turn lead to older adults adopting different strategies when processing language (see Peelle, 2019, for a review).

In the following introduction, we first review the current theoretical models of structural priming along with the evidence for the role of constituent phrasal structure in sentence production. We then outline the design and predictions of the current study.

2.1.1 Influence of constituent structure on structural priming

Models of structural priming have tended to postulate that priming reflects facilitated linguistic processing that occurs when either a speaker is accessing a syntactic structure (Malhotra, Pickering, Branigan, & Bednar, 2008; Pickering & Branigan, 1998), formulating it (Chang et al., 2000, 2006; Jaeger & Snider, 2013) or a combination of the two (Reitter, Keller, & Moore, 2011; Segaert et al., 2016). What these models have in common is that they largely assume that the complete syntactic structure is represented in a highly abstract form (i.e., only encompasses the global syntax and is unspecified for detailed constituent information). For example, Pickering and Branigan (1998) propose that syntactic structures are represented by combinatorial nodes within the lexicon which encompass the broader phrasal structure (e.g., that a passive sentence contains a prepositional by-phrase), but are unspecified for more detailed constituent information, such as the internal structure of the constituent phrases. According to the model, processing of a prime structure activates the relevant combinational node to an above-baseline level, and this residual activation drives the repeated selection of the primed syntax when a speaker must then describe a syntactically related target. Importantly, Pickering and Branigan (1998) argue that syntactic representations must be shallow and monostratal in nature (i.e., unspecified for internal phrasal features) in order for abstract representations to be generalisable across multiple utterances (see Branigan & Pickering, 2017, for a more extensive explanation).

A second account of structural priming relates to error-based implicit learning (Chang, 2002; Chang et al., 2000, 2006). According to this more computational model, language users create expectations based on linguistic input, which they use to anticipate upcoming words in a sentence. If a different word is heard to what is expected, this can result in prediction error (e.g., when processing a prime relating to the comparatively less frequent passive syntax). This then leads to a slight change in the mappings between message-level representations and abstract syntactic structures (driven by implicit learning), which biases the speaker toward expressing the syntactically similar target message using the primed syntax. Critically though, Chang and colleagues argue that implicit learning must occur at an abstract level of syntax that is independent of the internal properties of a sentence, such as the sequence of words within constituent phrases. This is because the model's dual-path architecture would become distinctly less effective if syntactic constituents were represented differently depending on their internal features (e.g., separate units for *"I"*, *"the boy"* and *"the old apple"* instead of a singular noun phrase unit), leading to interference during sentence processing and production.

Consequently, both the residual activation (Pickering & Branigan, 1998) and implicit learning (Chang et al., 2006) models predict that structural priming is determined solely by the repetition of the global syntactic structure. If this is the case, the magnitude of structural priming should be unaffected by changes to the constituent phrasal features of the sentence, relating to both the closed-class content (i.e., function words and affixes) and open-class content (i.e., nouns, lexical verbs and adjectives). However, as we now discuss, the evidence for the role of constituent structure on structural priming is not as clear-cut as the models may suggest.

2.1.1.1 Evidence for the role of constituent structure on structural priming

To first consider the effect of closed-class content, Bock (1989) found that dative verb primes with a 'to' or a 'for' in the prepositional phrase (e.g., *"A cheerleader offered a seat to her friend / saved a seat for her friend"*) equally primed production of a target sentence with the preposition 'to' (e.g., *"The girl handed the paintbrush to the man",* instead of the double-object alternative *"The girl handed the man the paintbrush"*). Likewise, dative verb priming is unaffected by whether the prime and target contain the same or different closed-class morphemes in the verb phrase (e.g., *"the teacher [gave/gives/was giving] the homework to the children"*), suggesting that the combinatorial nodes representing syntax are unspecified for verb tense (Pickering & Branigan, 1998). Such evidence may be considered to support the assumption of structural priming models that repetition of global syntactic structure is what drives the priming effect. However, Ziegler et al. (2017) question the complete abstractness of syntactic representations, and instead argue that combinatorial nodes must encompass some functional lexical content at a more internal level since it is possible to prime the use of function words. For example, speakers can be primed to mention or not mention the function word 'that' in an embedded clause sentence (e.g., *"The mechanic mentioned [that] the car could use a tune-up"*); this is despite the fact that the presence or absence of 'that' does not affect the overall meaning or syntactic structure (Ferreira, 2003). Similar priming effects have been found for the use of the optional verb-doubling structure in Chinese (Francis, Matthews, Wong, & Kwan, 2011), and the use of the second determiner in coordinate noun phrases (e.g., *"the cat and [the] dog"*; Temperley, 2005).

To now turn to the role of open-class content, the evidence of their role in structural priming is also mixed. On the one hand, Pickering and Branigan (1998) found that the inclusion of adjectives did not affect dative verb priming (e.g., *"The racing driver showed the manager the torn overall"* primed *"The patient showed the doctor his spots"*), as would be expected if syntactic structures are represented in a highly abstract form. Likewise, the magnitude of structural priming has been found to be unaffected by the addition of a subordinate clause to one of the existing phrases (e.g., *"The professor offered the students his theories [that had insulted many people]"*; Fox Tree & Meijer, 1999) or when the dative structure appears as a complement within an embedded clause sentence (e.g., *"John said that* *[the girl gave the boy the puppy]*; Branigan, Pickering, McLean, & Stewart, 2006). However, Melinger and Dobel (2005) observed structural priming from single verb primes that are restricted to a particular syntactic structure (e.g., in English ‘contribute’ can only occur within a prepositional dative structure); this suggests that structural representation can be accessed via verbs, indicating that priming effects are not always driven solely by repetition of global syntactic structure.

Moreover, structural priming is enhanced when open-class words are repeated between the prime and target (*lexical boost*; see Mahowald et al., 2016, for a review). Pickering and Branigan (1998) account for this effect by proposing that there is an additional lemma node representing the head lexical item (the verb in a dative or transitive sentence) that is activated in conjunction with the relevant combinatorial node. However, this explanation cannot account for why lexical boost has been found for the repetition of non-head lexical items, such as nouns in dative sentences (Scheepers, Raffray, & Myachykov, 2017) or adjectives in relative noun phrases (Cleland & Pickering, 2003). Such findings challenges Pickering and Branigan's (1998) argument that syntactic representations are highly abstract in nature and unspecified for open-class content as they explicitly propose that non-head lexical items are represented within an internal phrasal structure, and thus their repetition should not affect the magnitude of structural priming. By contrast, lexical boost (of both head and non-head lexical items) does not present a challenge for Chang et al.'s (2006) model as they instead propose that lexical boost is driven by explicit memory traces of the prime that are entirely dissociated from abstract syntactic representations (see also Chang, Janciauskas, & Fitz, 2012).

To summarise, although the theoretical models of structural priming postulate that syntactic representations are highly abstract and unspecified for internal phrasal structure, studies investigating the role of closed/open-class content on structural priming have provided conflicting evidence. We aimed to directly address this question by investigating the effect of differences in the complexity of the noun phrase structure between prime and target transitive verb sentences on the magnitude of structural priming. Unlike previous studies, we strove to maintain that all features relating to conceptual and global syntactic structure were equal between the prime and target sentences. Any differences in the magnitude of priming we observed, therefore, relate directly to differences in the complexity of the internal phrasal structure.

2.1.1.2 Influence of constituent noun phrase structure on structural priming

Nouns represent open-class content in a sentence, and while previous studies have focused on the inclusion or omission of adjectives and subordinate phrases (Fox Tree & Meijer, 1999; Pickering & Branigan, 1998), no study to date, to our knowledge, has manipulated the open-class content within the complexity of the noun phrase while maintaining the conceptual and semantic elements of the sentence (e.g., the number of thematic roles). The semantic content of a sentence is largely borne through the noun phrases (Keizer, 2007); hence, structural priming effects may be more sensitive to changes in the noun phrase than in other open-class content. We note that previous studies have demonstrated that it is possible to prime repetition of the noun phrase (Bernolet, Hartsuiker, & Pickering, 2007; Branigan, McLean, & Jones, 2005; Cleland & Pickering, 2003; Melinger & Cleland, 2011). However, these studies have predominantly used simple and relative noun phrases (e.g., *"the red square"* vs. *"the square that is red"*) in which the noun is the head lexical item and the noun phrase also encompasses the complete (i.e., global) syntactic representation of the sentence. Thus, in simple and relative noun phrases, the noun phrase structure is likely to be represented on a more independent level and does not form a constituent part of a larger syntactic structure. By contrast, the noun phrases of a transitive verb sentence each represent one part of the larger syntactic structure, relating to the subject noun phrase at the beginning of the sentence and the object noun phrase at the end of sentence (see **Figure 2.1**). As such, constituent noun phrases are highly likely to be represented differently, and consequently affected differently by structural priming, compared to the more global noun phrase structures.

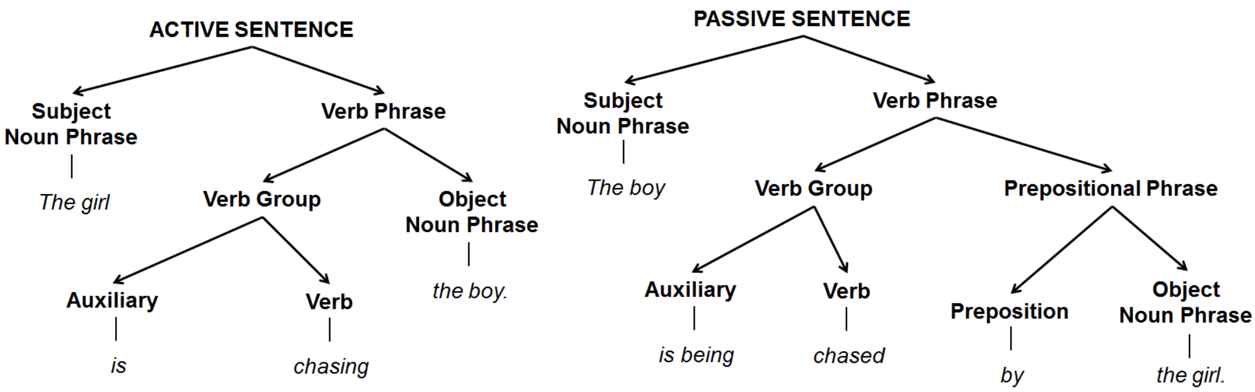

Figure 2.1 *Syntax trees of the structure of an active and a passive transitive verb sentence. In an active sentence, the subject noun phrase refers to the agent of action and the object noun phrase refers to the patient of the action. In a passive sentence, this is reversed and there is an additional prepositional 'by' phrase.*

In this study we specifically investigated the extent to which structural priming persists when the prime contained a coordinate noun phrase structure, but the target contained a plural noun phrase structure. We investigated this at four points in a transitive sentence – at the subject and object noun phrase of both an active and a passive sentence. For example, is a passive target sentence with a plural noun phrase in the patient role (as in 1) primed equally by a prime containing the same phrasal structure as the target (as in 2a) compared to a prime containing a different subject coordinate noun phrase structure (as in 2b)?

(1) Target: *"<u>The frogs</u> are being chased by the horse"*

(2a) Same phrase prime: *"<u>The builders</u> are being punched by the king"*

(2b) Different phrase prime: *"<u>The pirate and the builder</u> are being punched by the king"*

The extent to which structural priming persists when the noun phrase structure differs between the prime and target will be informative about the effect of constituent phrasal structure on primed syntactic choices and the degree of abstractness of the syntactic representations involved. Specifically, our study tests current models of structural priming that propose that syntactic structures are represented in a highly abstract manner. According to the residual activation model (Pickering & Branigan, 1998), we expect to find equal structural priming effects of the passive syntax when the primed syntactic structure both matches (2a) and mismatches (2b) that of the target because combinatorial nodes within the lexicon only represent global syntactic structure and are unspecified for constituent phrasal structure. Likewise, according to the implicit learning model (Chang et al., 2006), we expect equal structural priming regardless of differences in prime noun phrase structure because, within the dual-path model, constituent structures are represented within a single unit irrespective of differences in the internal sequence of words.

2.1.2 Investigating structural priming effects of onset latencies

In addition to syntactic choices, we measured structural priming effects on speech onset latencies. How quickly a speaker begins articulation is informative about the underlying mechanisms at the planning stage of sentence generation (Levelt, 1989; Wheeldon, 2013). Indeed, repetition of syntactic structure has been found to decrease speech onset latencies, indicating a facilitated processing effect, particularly when the preferred alternative, such as the active, is primed (Corley & Scheepers, 2002; Segaert, Menenti, Weber, & Hagoort, 2011; Segaert, Weber, Cladder-Micus, & Hagoort, 2014; Segaert et al., 2016; Smith & Wheeldon, 2001; Wheeldon & Smith, 2003). This positive preference effect on primed onset latencies is in contrast to the inverse preference effect observed for syntactic choices (i.e., greater choice priming of the dispreferred structure; Ferreira & Bock, 2006). This highlights how structural priming may have different effects at the selection and planning stage of sentence production. Moreover, while the selection of a global syntactic structure may occur prior to articulation, the actual planning of the sentence occurs incrementally in smaller more manageable units (Kempen & Hoenkamp, 1987; Levelt, 1989, 1992). An incremental system is beneficial as it allows for the rapid release of parts of the sentence as soon as planning is complete, reducing the demands on working memory. Indeed, evidence suggests that speakers typically plan the first phrase prior to speech onset with planning for the rest of the sentence occurring during articulation (see Wheeldon, 2013, for a review). For example, speakers have been found to take longer to initiate sentences containing larger initial phrases, supporting a phrasal scope of advanced planning (Hardy, Segaert, & Wheeldon, 2020; Levelt & Maassen, 1981; Martin et al., 2010; Martin, Yan, & Schnur, 2014; Smith & Wheeldon, 1999), although the degree and type of pre-planning may vary according to the linguistic structure of a given language (Hwang & Kaiser, 2014, 2015; Myachykov, Scheepers, Garrod, Thompson, & Fedorova, 2013). Taken together, this highlights why it is important to examine choice and onset latency priming effects in conjunction, in order to gain a more complete understanding of the processes involved in fluent sentence production.

Segaert et al.'s (2016) two-stage competition model is the first to account for structural priming effects at both the selection and planning of sentence production (see also Segaert et al., 2011, 2014). According to the model, alternative syntactic structures (e.g., active vs. passive) are represented by competing nodes, with activation levels determined by the relative frequency of the structure. Sentence production begins with construction of the preverbal message and this is followed by two sequential stages. First is the selection stage during which a speaker selects one syntactic structure from competing alternatives, followed by the planning stage during which the selected syntax is incrementally planned and produced. Choice priming effects are determined solely at the selection stage and are a reflection of the activation levels of competing syntactic structures, the levels of which are influenced by the preceding prime (increased activation of the node representing the primed syntactic structure). By contrast, onset latency priming effects are determined by the time taken to complete both the selection and planning stage. While repetition of syntactic structure always reduces time taken at the planning stage, time taken at the selection stage is only reduced for the active prime. This is because processing of the preferred syntactic structure increases the difference in activation levels between the two alternatives, thus reducing selection time. In this way, greater latency priming effects are observed for the preferring syntactic structure. Within our structural priming study, we therefore expect to observe greater latency priming effects when participants choose to use an active sentence to describe the target compared to when they choose to use a passive sentence (similar to Segaert et al., 2011, 2016).

A more interesting and novel prediction though concerns the effect of noun phrase complexity on the magnitude of latency priming. The planning stage of Segaert et al.'s (2016) two-stage competition model is based on Levelt's (1989) principles of incremental planning, meaning that planning of the first unit, likely relating to the initial phrase, is prioritised prior to articulation. Thus, repetition of constituent noun phrase structures may have a different effect on onset latencies dependent on whether the repetition occurs in the initial subject noun phrase or final object noun phrase (see **Figure 2.1**). Specifically, within our study, we may expect to observe facilitatory priming of latencies when the subject phrase is repeated (relating to the agent role of an active sentence, but the patient role of a passive sentence) because this initial part of the sentence is typically planned prior to articulation and therefore any benefits to planning are observable in decreased onset latencies. However, we expect to find no or minimal speed priming benefits when the final object phrase is repeated (relating to the patient role of an active sentence, but the agent role of a passive sentence) because planning for this part of the sentence occurs later during articulation, meaning that any latency benefits are unlikely. Moreover, we may also find differences in the magnitude of the structural priming effect between young and older adults if there are age-related changes in the selection and planning of syntactic structures, as we now discuss.

2.1.3 Influence of ageing on structural priming

There is not a straightforward relation between healthy ageing and decline in language abilities; instead the relationship is more complex as some language skills are more negatively affected by ageing than others (for reviews, Burke & Shafto, 2008; Peelle, 2019). Age-related declines in language production are apparent at both the word and sentence level. Older adults are slower and more error-prone in picture naming tasks (see Feyereisen, 1997, for a meta-analytical review). Similarly, with age, there is a decline in the production of complex syntactic structures, such as embedded clauses, coupled with an increase in syntactic errors, such as the use of the incorrect tense (Kemper, 1987; Kemper, Greiner, Marquis, Prenovost, & Mitzner, 2001; Kemper & Sumner, 2001; Rabaglia & Salthouse, 2011). However, other language skills are characterised by stability with age, such as the ability to switch between the production of different syntactic alternatives (Altmann & Kemper, 2006; Davidson, Zacks, & Ferreira, 2003). Ageing is also associated with certain language improvements, such as increased vocabulary size and knowledge (Verhaeghen, 2003). Age-related declines in language production are likely related to other emerging cognitive deficits, such as a decline in processing speed and working memory (Abrams & Farrell, 2011; Kemper & Sumner, 2001; Salthouse, 1996), and reduced integrity in the brain regions that support language functions, such as the left interior frontal gyrus and the left anterior insula (Peelle et al., 2010; Shafto, Burke, Stamatakis, Tam, & Tyler, 2007). However, older adults are often able to adopt effective processing strategies, such as the recruitment of additional brain regions, in order to compensate for lost efficiency elsewhere, thereby explaining why not all language skills are negatively affected by ageing (see Wingfield & Grossman, 2006, for review).

This contrast between decline and preservation creates a multi-faceted picture of language processing during healthy ageing, which, according to Peelle's (2019) 'supply and demand' framework, can be characterised by the complex interplay between the demands of a given language task and an individual's neurocognitive capacity for the task (see Baltes & Baltes, 1990, for a similar model of gains vs. losses management in psychological well-being in ageing). Within this study, we sought to examine how the processes involved in syntax selection and planning are affected by ageing by comparing groups of healthy young and older adults. Specifically, we aimed to understand whether: (a) young and older adults represent syntactic representations in a similar or different manner for both global and local features of a sentence; (b) both age groups rely on the same processes when selecting a syntactic alternative in a primed situation; and (c) age-related differences exist in the incremental planning of chosen syntactic structures. Answering these questions is important for fully understanding the complex balance between decline and preservation in healthy ageing.

To date, only a few studies have investigated the effect of old age on choice structural priming; however, this has produced mixed results with two studies finding evidence of preserved priming of passives in older adults (Hardy, Messenger, & Maylor, 2017; Heyselaar, Wheeldon, & Segaert, 2018), while others have not (Heyselaar, Segaert, Walvoort, Kessels, & Hagoort, 2017, footnote 2; Sung, 2015).[1] Moreover, all of these studies have only focused on the effect of global syntactic structure (active vs. passive) on the production of passive targets,

[1] Note, other studies have tested non-young adults as controls for clinical patients; however, the samples are often small and the age range large. While three such studies did find evidence of structural priming in controls (Cho-Reyes, Mack, & Thompson, 2016; Ferreira, Bock, Wilson, & Cohen, 2008; Yan, Martin, & Slevc, 2018), a fourth did not (Hartsuiker & Kolk, 1998).

and have not considered the role of internal phrasal structure on the magnitude of structural priming. Manipulating the local, as well as the global, structure of the prime can provide greater insight into age-related changes in syntactic representations, thus helping to clarify the debate within the existing literature. Moreover, including a measure of onset latency priming can help provide a more complete picture of the age-related changes that occur at both the selection and planning stage of sentence production.

Both the residual activation (Pickering & Branigan, 1998) and two-stage competition (Segaert et al., 2016) models include a spreading activation architecture, whereby the node representing the prime syntactic structure is activated to an above-baseline level (which then drives reselection during target processing). However, according to Salthouse's (1996) general slowing model of ageing, declines in processing speed with age can substantially decrease the speed of spreading activation within a cognitive or neural network, a factor which may be related to age-related atrophy of the frontal and cerebellar regions (see Eckert, 2011, for a review). Applied to structural priming, this would predict that, when older adults process a prime sentence, the node representing the structure might not activate quickly enough to a level that could influence syntactic choices on the subsequent target trial or to a level which would benefit the speed of planning of the chosen syntactic structure. In addition, Segaert et al.'s (2016) model includes an element of inhibition as each node representing the syntactic alternatives will inhibit the other node in relation to its own activation level (e.g., hearing a passive prime will increase the activation of the passive node while also inhibiting the activation of the active node). However, according to the transmission deficit model, ageing is accompanied by declines in the strength of positive and negative (i.e., inhibitory) connections among units within a given network (MacKay & Abrams, 1998; MacKay & Burke, 1990). Such an age-related decline in the strength of the connections between syntactic nodes may also result in levels of activation of the syntactic representations that are insufficient for structural priming effects to occur. We may therefore expect to observe less structural priming effects in older speakers compared to young speakers due to age-related differences in processing speed and emerging transmission deficits.

By contrast, the implicit learning model (Chang et al., 2006) would predict similar structural priming effects, at least at the choice level, in young and older adults because implicit learning skills are largely unaffected by healthy ageing (Fleischman, Wilson, Gabrieli, Bienias, & Bennett, 2004; Light & Singh, 1987). As such, both age groups should experience a similar change in mappings between message-level representations and abstract syntactic structures when processing an unexpected passive prime sentence. Notably, all three structural priming models largely predict that any age-related differences or invariance in priming should be equal whether or not the internal phrasal structure matches or mismatches between the prime and target as they assume that abstract syntactic representations only encompass the global sentence structure. However, age group differences in structural priming, particularly relating to onset latencies, may emerge due to differences in the internal phrase structure of the prime if age-related changes exist in the flexibility of sentence planning processes.

The ability to plan sentences incrementally in a chunk-like manner is essential for fluent sentence production (Levelt, 1989). To our knowledge, only one study to date has specifically examined on-line sentence planning processes in older adults. Hardy et al. (2020) found that, although both young and older adults took longer to initiate sentences with a larger initial phrase, there were age group differences in the flexibility of planning scope.[2] Unlike young adults, older adults did not benefit from a preview of lexical information beyond the initial phrase and this premature access to the lexical information (i.e., outside of their preferred phrasal planning scope) actually made them more error-prone. One explanation for this age-related effect on lexical processing may be that older adults' planning scope is more rigidly fixed to phrasal boundaries. Hardy et al.'s (2020) study therefore provides the first evidence that healthy ageing affects some aspects of on-line sentence planning; however, many questions are still to be addressed. Within our study, we aimed to specifically investigate older adults' sentence planning in a task in which syntactic choice was also involved and in which repetition of the global and internal structure was manipulated between the prime and the target. As such, our study will provide added insight into age-related effects on on-line sentence planning. It could be that older adults' increased sensitivity to phrasal boundaries (as found by Hardy et al., 2020) means that they are also more sensitive to the

[2] Note, this study refers to the experiments reported in **Chapter 3** of this thesis.

constituent features within phrases. This may in turn mean that, compared to young adults, the magnitude of the latency priming effects displayed by older adults may be more strongly influenced by whether or not the internal noun phrase structure is repeated between the prime and target.

2.1.4 The present study

In this study, we investigated the effect of global syntactic and internal phrasal structure on the magnitude of choice and onset latency structural priming. Specifically, we aimed to test the predictions of current models of structural priming that syntactic choices are driven by repetition of global, not internal, syntactic structure (Chang et al., 2006; Pickering & Branigan, 1998), and that faciliatory priming effects on sentence planning should be greater when the structure of the initial phrase is repeated (Segaert et al., 2016). Young and older adults completed a structural priming task in which we either manipulated the noun phrase structure of the patient role (Experiment 1) or the agent role (Experiment 2). We conducted the two experiments as we considered that the patient role may be more syntactically important in the production of a passive sentence because it appears in the initial subject phrase, while the agent role may be more conceptually salient because it ranked higher on the thematic hierarchy (Christianson & Ferreira, 2005). Participants described transitive verb targets using either an active or a passive sentence that contained the plural morphology of the patient role (Experiment 1; *"the horse is chasing the frogs"* / *"the frogs are being chased by the horse"*) or the agent role (Experiment 2: *"the horses are chasing the frog"* / *"the frog is being chased by the horses"*). We manipulated whether the preceding active or passive prime contained the same constituent noun phrasal structure as the target or a different coordinate noun phrase structure in the patient or agent role. Crucially, the manipulation of the prime phrasal structure did not affect the global syntactic structure of the sentence or the main conceptual features (always one agent acting on two patients in Experiment 1 and two agents acting on one patient in Experiment 2).

We measured structural priming effects at the choice level of sentence production (the proportion of target passives produced in each prime condition), as well as at the planning level (target onset latencies). The extent to which choice structural priming effects persist when the constituent noun phrase structure differs between the prime and target will be informative about the complete abstractness of syntactic representations. The magnitude of onset latency priming effects when the initial subject phrase structure is repeated between the prime and target, compared to when the final object phrase is repeated, will provide insight into the phrasal scope of planning and how sensitive this is to changes in the constituent phrasal structure. Finally, the extent to which choice and latency structural priming effects differ between young and older adults will be informative about age-related changes in syntax selection and the flexibility of planning scope.

2.2 Method

2.2.1 Experiment 1: Manipulating the patient role

2.2.1.1 Participants

We recruited 40 young adults aged 18-22 from the University of Birmingham student population (compensated with course credits) and 40 older adults aged 62-85 from the departmental Patient and Lifespan Cognition Database (compensated monetarily). All participants were native English speakers with normal or corrected-to-normal vision, and did not report any language disorders. See **Table 2.1** for an overview of the sample characteristics. The study was approved by the University of Birmingham Ethical Review Committee and informed written consent was obtained prior to the test session.

2.2.1.2 Design

Our design featured five different prime conditions (**Figure 2.2**). Each trial consisted of a coloured prime followed by a greyscale transitive verb target. The target could be described using an active or a passive sentence that contained the plural morphology of the patient role (as in 2). In the baseline prime condition (1a), an intransitive verb prime was followed by the transitive verb target (2): this enabled us to directly measure the production of actives and passives that were not primed by a prior transitive verb sentence. In all other prime conditions, a transitive verb prime (1b) was followed by the transitive verb target (2).

Using a colour-coded system for the order of precedence, we were able to manipulate whether participants produced an active or a passive prime sentence (*stoplight* paradigm; Menenti, Gierhan, Segaert, & Hagoort, 2011). We also manipulated whether the patient role of the prime matched that of the target (i.e., also used the plural morphology) or whether the prime patient phrase used a different structure (a coordinate noun phrase). By fully crossing these two manipulations, we created four transitive verb prime conditions (1b) that enabled us to measure the effect of internal constituent noun phrase structure on the magnitude of structural priming in young and older adults.

Table 2.1 *Background characteristics of the young and older adult participant groups for Experiments 1 and 2.*

	Experiment 1		**Experiment 2**	
Characteristic	*Young*	*Older*	*Young*	*Older*
N (Male/Female)	40 (4/36)	40 (20/20)	40 (10/30)	40 (16/24)
Age (years)	19.7 (0.7)	73.9 (6.0)	19.7 (0.9)	72.6 (5.4)
Education[a]	6.0 (0.0)	5.6 (1.6)	6.0 (0.0)	5.7 (1.3)
General cognitive ability[b]	--	27.5 (0.9)	--	28.0 (1.4)

Note. All values are given as means (with standard deviation) except for *N* (Male/Female). [a]Education was scored on a scale of 0 (pre-primary school) to 8 (university doctorate) according to the International Standard Classification of Education (United Nations, 2011). [b]General cognitive ability was measured using the Montreal Cognitive Assessment (Nasreddine et al., 2005): all older adults scored 26 or above (out of 30) indicating that they were currently experiencing healthy ageing (scores < 26 indicate risk of mild cognitive impairment or dementia; Smith, Gildeh, & Holmes, 2007).

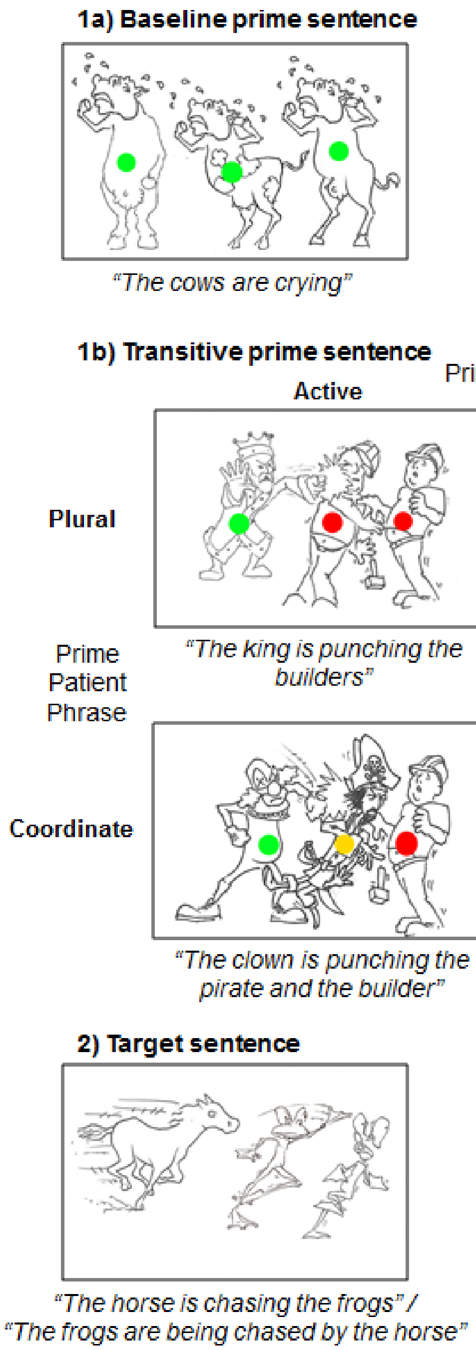

Figure 2.2 *Design of Experiment 1. Prime sentences were elicited using a colour-coding order of precedence system. Baseline primes elicited an intransitive verb sentence (1a). Transitive primes elicited either an active or a passive sentence that contained a plural or coordinate noun phrase structure of the patient role (1b). Each prime was followed by a greyscale transitive target that the participant could choose to describe with either an active or a passive sentence that contained the plural morphology of the patient role (2).*

2.2.1.3 Materials

The experimental stimuli were based on those previously used by Messenger, Branigan, and McLean (2011), but with significant alterations. A full list of stimuli, including all images, is available to download from the Open Science Framework (https://osf.io/8y5jx/). We first created 16 target pictures that were greyscale in colour and depicted transitive verb events involving one agent acting on two patients of the same type (*"The X is verbing the Ys"* / *"The Ys are being verbed by the X"*). The two patients did not look exactly the same (e.g., they had different facial expressions and/or postures), but it was clear that they belonged to the same naming category and occupied the same thematic role within the sentence (see **Figure 2.2**). Eight different transitive verbs (chase, hug, ignore, pat, punch, touch, upset and watch) were each used twice to create the 16 target pictures; half of the target pictures featured human nouns, while the other half featured animal nouns. To control for any potential left-right bias, the agents of the action were depicted an equal number of times on the left and right side of the picture.

Using the same transitive verbs, we then created 16 transitive pictures for the 'plural' prime condition and 16 transitive pictures for the 'coordinate' condition (again, half featured human nouns and half featured animal nouns). The 'plural' prime pictures involved one agent acting on two patients of the same type, whereas the 'coordinate' prime pictures depicted one agent acting on two patients of different types. Critically, this meant that the patient role of the prime and the target were matched in the 'plural' condition, but not in the 'coordinate' condition. We then made an active and a passive version of each prime picture using a 'stoplight' colour-coding system. Participants were instructed to describe the characters in a green-red or green-orange-red order; hence, the strategic placements of coloured dots on the characters were used to elicit the prime sentences. For the 'plural' prime pictures, green and red dots were used to elicit either an active or a passive sentence that contained the plural morphology of the patient role (*"the A is verbing the Cs"* / *"the Cs are being verbed by the A"*). For the 'coordinate' prime pictures, green, orange and red dots were used to elicit either an active or a passive sentence that contained a coordinate noun phrase of the patient (*"the A is verbing the B and the C"* / *"the B and the C are being verbed by the A"*). This created a total of 64 transitive verb primes. We also created 16 baseline primes that depicted intransitive verb events involving three nouns of the same type, all of which were covered with a green dot (*"the Ds are verbing"*). We then prepared 80 experimental items by combining each of the 16 target pictures with a prime picture from each of the five different prime conditions. Within each experimental item, there was no overlap in the verbs or nouns depicted.

Lastly, we created 16 filler items that were greyscale in colour and depicted intransitive verb events involving three nouns of different types (e.g., *"the soldier, the dancer and the king are walking"*). Fillers were used to minimise the possibility that participants would notice the priming manipulation. We then constructed five blocks that each contained 16 experimental items (prime plus target pairs) and 16 filler items. Each block contained the same 16 target pictures, but each target was paired with a different prime condition within each block (i.e., each experimental item only appeared once across all five blocks). The same 16 filler items were repeated across the five blocks. The order of the items within each block was pseudorandomised with the constraint that each block must begin with a filler item. The order of the blocks was then rotated to create five experimental lists; this ensured that each block occurred an equal number of times in each position of the experiment.

2.2.1.4 Procedure and coding

Each participant was randomly assigned to one of the five lists and was tested individually in a quiet testing room. The participant was seated facing a *Dell* 14 inch laptop, and wore a *Sennheiser* headset connected to a *Cedrus* voice key that recorded his/her onset latencies. The presentation of the experiment was controlled using E-prime (Schneider, Eschman, & Zuccolotto, 2002). Audio responses were recorded using an external *Sony* digital voice recorder. Before beginning the structural priming task, the participant was presented with the names and pictures of the 34 animal and human characters than would feature in the priming task. The participant was then tested on the names of the different characters. The aim of this was to ensure that the participant was sufficiently familiar with the characters and that uncertainty about character names would not negatively impact upon their performance in the main priming task. Participants were told that the characters would appear slightly differently in each trial in the priming task (e.g., different postures or facial expressions), but would always be from one of the 34 naming categories.

Following this, the participant was presented with instructions and examples of how to describe the pictures using the colour-coding system. The participant was instructed to use the verb presented below each picture in their sentence, and to begin describing the picture as soon as possible. **Figure 2.3** illustrates the sequence of stimuli presentation per trial. To begin, there were two practice blocks of 24 pictures each. The practices featured 12 filler pictures, four prime pictures from the baseline condition and eight prime pictures from each of four different transitive verb prime conditions. Crucially, none of these practice prime pictures were followed by a greyscale target picture as we wanted to control the number of actives and passives that the participant produced before beginning the experimental blocks. After the practice, the task continued until all five experimental blocks had been completed.

The experimenter manually coded the participant's target responses as either active (*"The horse is chasing the frogs"*) or passive (*"The frogs are being chased by the horse"*). Target responses were only included in the analyses if the participant produced the correct prime sentence (i.e., according to the colour-coding order of precedence system) and if the following was true of the participant's prime and target responses of the relevant experimental item: (1) the correct verb was used; (2) the description was complete; (3) no unnecessary additional information was included; and (4) the participant did not stutter before or during their response.

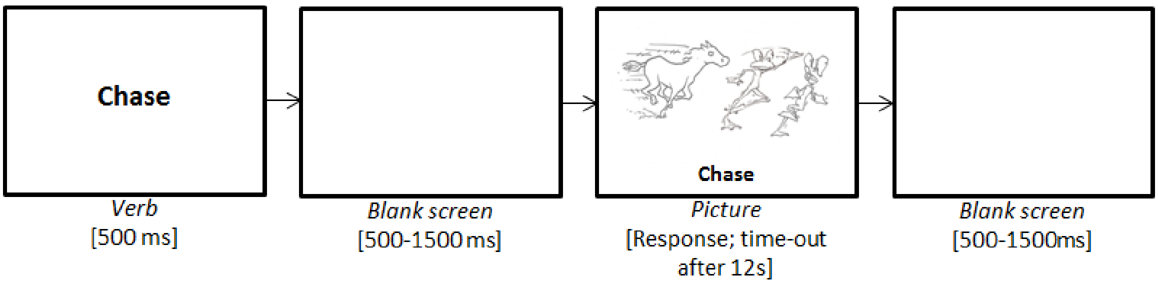

Figure 2.3 *Experiment 1 and 2 stimuli presentation sequence per trial. The sequence presentation event was the same for the prime and target trials, and primes were always immediately followed by the corresponding target. Speech onset latencies on the target trials were recorded from the onset of the picture to when the participant began to speak.*

2.2.2 Experiment 2: Manipulating the agent role

2.2.2.1 Participants

Forty young adults and 40 older adults were recruited from the same sources and compensated in the same manner described in Experiment 1 (see **Table 2.1**). Participants also met the same inclusion criteria and informed written consent was obtained at the beginning of the test session.

2.2.2.2 Design

The design was identical to Experiment 1, with the only difference being that we now manipulated the noun phrase structure of the agent role (**Figure 2.4**).

2.2.2.3 Materials

We created the prime and target pictures using the same transitive verbs and method described in Experiment 1. The main difference, however, was that the pictures depicted two agents and one patient. The target and 'plural' prime pictures depicted two agents of the same type acting on one patient and could be described using a transitive sentence that contained the plural morphology of the agent role (*"the As are verbing the C" / "the C is being verbed by the As"*). The 'coordinate' prime pictures contained two agents of different types acting on one patient and could be described using an transitive sentence that contained a coordinate noun phrase of the agent (*"the A and B are verbing the C" / "the C is being verbed by the A and the B"*). We used the same intransitive baseline pictures (*"the Ds are verbing"*) as Experiment 1. Following the method in Experiment 1, we then created 80 experimental items. Lastly, using the same filler items as Experiment 1, we constructed five blocks that each contained 16 experimental items (prime plus target pairs) and 16 filler items, and rotated the order of the blocks to create five experimental lists.

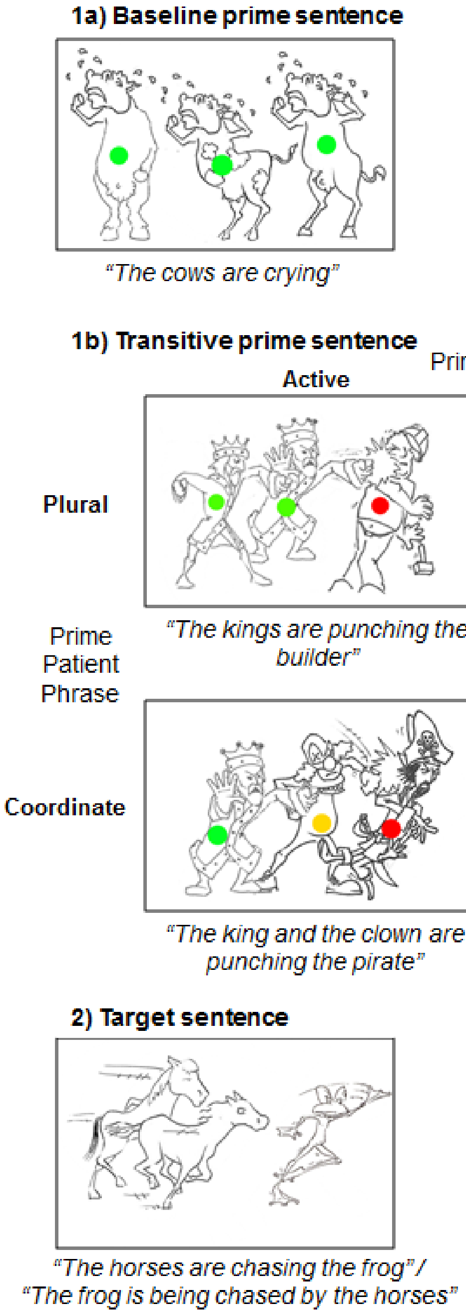

Figure 2.4 *Design of Experiment 2. Prime sentences were elicited using a colour-coding order of precedence system. Baseline primes elicited an intransitive verb sentence (1a). Transitive primes elicited either an active or a passive sentence that contained a plural or coordinate structure of the agent role (1b). Each prime was followed by a greyscale transitive target that the participant could choose to describe with either an active or a passive sentence that contained the plural morphology of the agent role (2).*

2.2.2.4 Procedure and coding

The experimental procedure and coding criteria were identical to Experiment 1. The only difference was that correct target responses must feature the plural morphology of the agent phrase (e.g., *"The horses are chasing the frog" / "The frog is being chased by the horses"*).

2.2.3 Data preparation and analyses

2.2.3.1 Analysis of the choice priming data

In total we recorded 6400 target responses each for Experiments 1 and 2. As is standard in structural priming studies, we first excluded targets for which the corresponding prime was incorrect (i.e., when the participant did not produce an active or passive prime sentence that adhered to colour-coding order of precedence system). This resulted in the discarding of 66 (2.1%) and 171(5.3%) of young and older adults' target responses in Experiment 1, and 191 (6.0%) and 275 (8.6%) of young and older adults' responses in Experiment 2. Next, we excluded target responses for which the participant made an error. A target response was defined as containing an error if: (1) the lexical items were named incorrectly; (2) a different verb was used to the one written beneath the picture; (3) a different syntactic structure was used (i.e., not a complete active or passive sentence); or (4) the participant stuttered before or during their response. In Experiment 1, this resulted in the exclusion of 189 (6.0%) of the young adults' target responses, and 318 (10.5%) of the older adults' responses. In Experiment 2, this resulted in the exclusion of 182 (6.0%) and 230 (8.2%) young and older adults' responses, respectively. Thus, there remained 5656 and 5513 analysable target responses in Experiments 1 and 2, respectively.

The data from the two experiments were analysed separately because the target items were not identical across experiments (i.e., they varied in terms of the number of agents and patients); however, we did follow the same method of analysis. Target responses were coded as 0 for actives and 1 for passives, and we analysed the data using a logit mixed-effects model with the *lme4* package (Bates, Mächler, Bolker, & Walker, 2014) in R (R Core Team, 2015). This is the most suitable way to analyse the data as the dependent variable was categorical (active or passive) and there were repeated observations for participants and items (Baayen, Davidson, & Bates, 2008; Barr, Levy, Scheepers, & Tily, 2013; Jaeger, 2008). We used a maximal random effects structure as this allowed us to include per-participant and per-item adjustments to the fixed interprets (random intercepts) with additional random adjustments to the fixed effects (random slopes).

To examine the effect of structural priming, it is necessary to compare syntactic choices in the different transitive verb priming conditions to the baseline condition (Segaert et al., 2011, 2014, 2016). Using treatment contrast coding, we therefore entered 'Prime Condition' as a fixed effect into the model – this contained five levels in which the baseline condition was the reference level (i.e., included in the intercept of the model), and the four transitive verb prime conditions were directly compared to the baseline condition. To further assess the statistical differences between the Passive Plural and Passive Coordinate conditions, we refitted the model with Passive Coordinate as the reference level. We also entered age group (young vs. old) into the model as a fixed effect, which we sum-coded and transformed to have a mean of 0 and a range of 1 prior to analysis. In each model, we included random intercepts for participants and items, as well as by-participant random slopes for within-participant fixed effects and by-item random slopes for within-item fixed effects. When a model did not converge with the maximal random effects structure, we simplified the random slopes, removing interactions before main effects in the order of least variance explained until the model converged (Barr et al., 2013).

2.2.3.2 Analysis of the onset latency priming data

One young adult and two older adults in Experiment 1 were excluded from the onset latency analysis due to technical issues with the voicekey that meant no latency data were recorded. All baseline responses were also excluded as we were specifically interested in the effect of active and passive primes on the onset latencies of active and passive target responses. We excluded individual target responses for which the voicekey was not triggered (discarding 83 (3.6%) and 256 (12.6%) of young and older adults' responses in Experiment 1, and 69 (3.1%) and 219 (10.4%) of young and older adults' responses in Experiment 2).[3] We further excluded target responses for which the speech onset latency was below 300 ms, above 4000 ms or more than 2.5SDs above/below each participant's mean per condition (discarding 56 (2.5%) and 61 (3.4%) of young and older adults' responses in Experiment 1, and 63 (2.9%) and 55 (2.9%) of young and older adults' responses in Experiment 2). This resulted in a total of 3863 and 3930 analysable targets responses in Experiments 1 and 2, respectively.

In order to examine the effect of syntactic priming on onset latencies, it was necessary to create a post-hoc variable of *'Syntactic Repetition'* with two levels of No Repetition and Syntactic Repetition. The variable captured the relationship between the prime syntactic structure (active or passive) and the chosen structure of the target response (active or passive), such that each prime and target pair could either be coded in the No Repetition or Syntactic Repetition condition.

The onset latency data were again analysed in R using the *lme4* package (Bates et al., 2014). As the dependent variable was continuous, we used a linear mixed-effects model with a maximal random effects structure (as recommended for our design; Baayen et al., 2008; Barr et al., 2013; Jaeger, 2008). For Experiments 1 and 2, we entered age group (young vs. old), prime phrase type of the agent or patient role (plural vs. coordinate), target structure (active vs. passive) and syntactic repetition (no repetition vs. syntactic repetition) as fixed effects into the model. Prior to analysis, all fixed effects were sum-coded and transformed to have a mean of 0 and a range of 1. For both models, we included random intercepts for participants and items, as well as by-participant random slopes for the within-participant fixed effects and by-item random slopes for the within-item fixed effects. When a model did not converge with the maximal random effects structure, we simplified the random slopes following the same method outlined in the analysis of the choice priming data. Significance *p* values were calculated using the *car* package (Fox & Weisberg, 2011).

[3] We speculate that the large number of older adult responses in which the voicekey was not triggered may have been caused by the larger variation in speech volume, frequency and onset typically seen in older adults (Benjamin, 1981; Hooper & Cralidis, 2009; Morris & Brown, 1994).

2.3 Results

2.3.1 Examining the effect of the prime phrasal structure on choice structural priming

2.3.1.1 Manipulating the prime phrasal structure of the patient role

The proportion of passive responses produced by participants in the different prime conditions in Experiment 1, in which we manipulated the prime noun phrase structure relating to the patient role, is shown in **Figure 2.5.A** and the final model of the choice data is summarised in **Table 2.2.A**.

Firstly, the negative intercept of the model indicates that actives were produced more often than passives in the baseline condition (11.8% baseline passive responses). However, as can clearly be seen in **Figure 2.5.A**, there was a significant increase in the proportion of target passives produced, compared to baseline, in both the Passive Plural (19.8% passives, $p < .001$) and Passive Coordinate (17.8% passives, $p < .001$) conditions. By contrast, the proportion of passives produced was not significantly different from baseline in the Active Plural (10.9% passives, $p = .591$) and Active Coordinate (11.2% passives, $p = .889$) prime conditions. This is evidence of the inverse preference effect: syntactic choices are affected by passive, but not active, primes.[4]

To now consider the effect of manipulating the prime patient phrase on choice structural priming, we predicted that, if the internal constituent phrasal structure of the prime was a factor in choice structural priming, then we would observe greater priming in the Passive Plural condition (in which the subject phrasal structure of the prime matched the target) compared to the Passive Coordinate condition (in which the subject phrase of the prime was different to the target). However, we found instead that the proportion of passives produced was not significantly different in the Passive Plural condition compared to the Passive Coordinate condition (Coefficient = 0.08, $z = 0.54$, $p = .586$). Syntactic choices were therefore unaffected by whether the constituent phrasal structure of the patient role was matched or mismatched between the prime and target.

[4] The implicit learning model (Chang et al., 2006) predicts that there is minimal prediction error, and therefore minimal priming effects, when the preferred syntactic alternative (i.e., active) is primed.

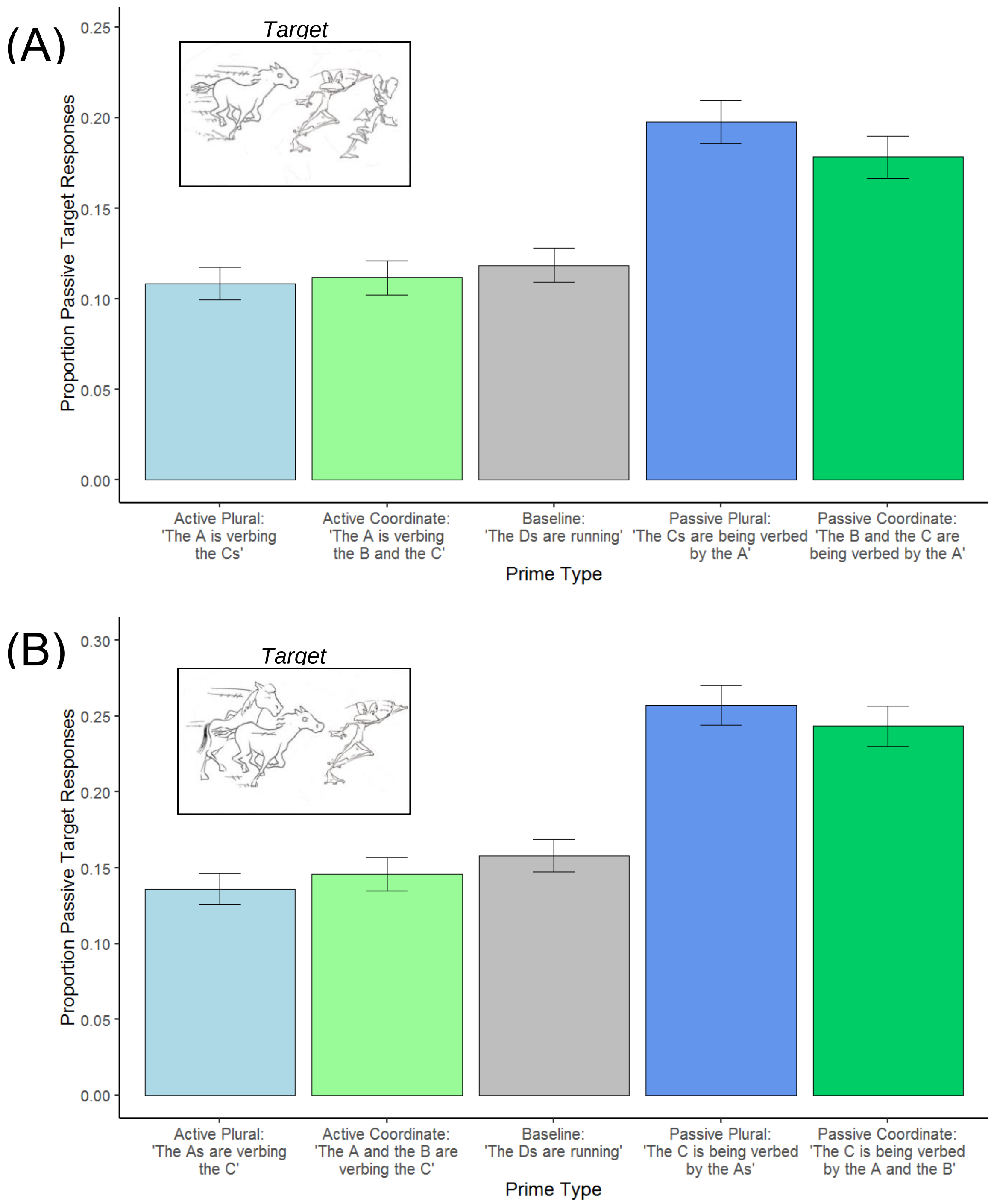

Figure 2.5 *Mean proportion of passive responses produced by participants following the five different prime conditions in Experiment 1 (A) and Experiment 2 (B). Error bars denote ±1 the standard error of the mean. In both experiments, compared to baseline, participants were significantly more likely to produce a passive target following a passive prime, but not following an active prime. Moreover, syntactic choices were affected equally when the prime and the target contained the same or different internal phrasal structure (passive plural vs. passive coordinate conditions).*

Table 2.2 *Summary of the best-fitted mixed-effects models for the choice data of Experiments 1 and 2.*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
A: Experiment 1				
Intercept (Baseline)	-2.66	0.25	-10.43	< .001
Active Plural Prime	-0.08	0.16	-0.54	.591
Active Coordinate Prime	-0.02	0.25	-0.14	.889
Passive Plural Prime	0.72	0.14	4.98	< .001
Passive Coordinate Prime	0.65	0.14	4.53	< .001
Age Group	-0.28	0.35	-0.80	.426
Active Plural Prime * Age Group	0.24	0.29	0.85	.394
Active Coordinate Prime * Age Group	0.31	0.29	1.09	.227
Passive Plural Prime * Age Group	0.28	0.26	1.06	.290
Passive Coordinate Prime * Age Group	0.13	0.27	0.48	.634
B: Experiment 2				
Intercept (Baseline)	-2.13	0.23	-9.14	< .001
Active Plural Prime	-0.28	0.16	-1.74	.082
Active Coordinate Prime	-0.14	0.19	-0.76	.446
Passive Plural Prime	0.62	0.16	3.99	< .001
Passive Coordinate Prime	0.63	0.15	4.11	< .001
Age Group	0.03	0.30	0.09	.936
Active Plural Prime * Age Group	0.33	0.26	1.27	.204
Active Coordinate Prime * Age Group	0.12	0.26	0.47	.641
Passive Plural Prime * Age Group	0.23	0.24	0.97	.331
Passive Coordinate Prime * Age Group	0.03	0.24	0.14	.889

Note. Both models converged with random intercepts for participants and items with an additional by-item random slope for the main effect of prime condition. We also analysed the choice priming data without the baseline condition (instead entering prime syntax and prime phrase type as fixed effects) as this matches the approach used in most other priming studies (see Mahowald et al., 2016). This produced results in line with our primary modelling analysis of Experiments 1 and 2; specifically, we found main effects of prime syntax (*p*s < .001), but not of prime phrase type (*p*s > .15) or any interactions between the two variables (*p*s > .15).

2.3.1.2 Manipulating the prime phrasal structure of the agent role

The proportion of passive responses produced by participants in the different prime conditions in Experiment 2, in which we manipulated the prime noun phrase structure relating to the agent role, is shown in **Figure 2.5.B** and the final model of the choice data is summarised in **Table 2.2.B**.

Similar to Experiment 1, we found that more actives than passives were produced in the baseline condition (15.8% passives, negative intercept the model). We also found evidence of the inverse preference effect: compared to baseline, syntactic choices were significantly affected by passive primes (Passive Plural, 25.7% passives, $p < .001$; Passive Coordinate, 24.3% passives, $p < .001$), but were not affected by active primes (Active Plural, 13.6% passives, $p = .082$; Active Coordinate, 14.6% passives, $p = .446$). Moreover, the proportion of passives produced was not significantly different when comparing the Passive Plural and Passive Coordinate prime conditions (Coefficient = 0.01, $z = 0.15$, $p = .975$). This replicates the findings of Experiment 1, and demonstrates that the invariant effect of prime phrase structure persists even when the more thematically salient agent phrase is manipulated.

2.3.1.3 Examining the effect of age group on choice structural priming

In the choice data analysis of Experiments 1 and 2, we found no main effect of age group or any interactions involving age group and prime condition (all *p*s > .2; **Tables 2.2**). This would indicate that young and older adults were experiencing similar choice structural priming effects. Indeed, the pattern of target passives in the different prime conditions appears similar in both age groups for Experiments 1 and 2 (**Figure 2.6**).

As the effect of age group was critical to our research question, we sought to confirm the similar patterns in young and older adults by modelling the choice data separately for each age and experiment group. We followed the same procedure as described previously: the final models of the choice data for each participant group are summarised in **Table 2.3**. Compared to baseline, both age groups in Experiments 1 and 2 produced significantly more target passives following passive primes (all *p*s < .04), as can clearly be seen in **Figure 2.6**. Moreover, there was no difference in the proportion of passives produced between the Passive

Plural and Passive Coordinate prime conditions for both age groups in Experiment 1 (Young, Coefficient = 0.11, z = 0.20, p = .567; Older, Coefficient = -0.04, z = -0.19, p = .849) and Experiment 2 (Young, Coefficient = 0.08, z = 0.43, p = .669; Older, Coefficient = -0.07, z = -0.38, p = .707). The findings from Experiments 1 and 2 therefore demonstrate that structural priming effects persist with old age, and that neither young nor older adults' primed production of passive sentences were affected by whether the prime constituent phrasal structure matches or mismatches that of the target.

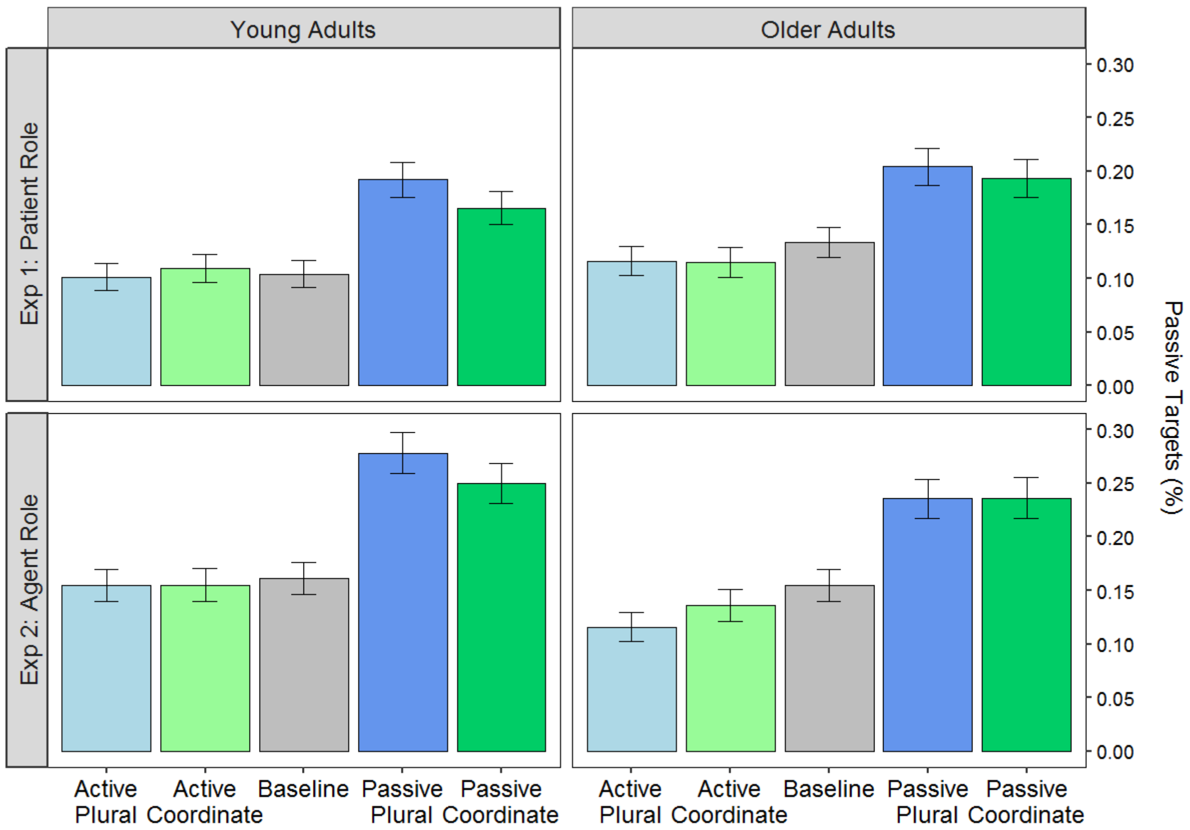

Figure 2.6 *Mean proportion of passive responses produced by young and older adults following the different prime conditions in Experiment 1 (manipulating the patient role) and Experiment 2 (manipulating the agent role). Error bars denote ±1 the standard error of the mean. In all groups, there was significant priming of passives compared to baseline in both the Passive Plural and Passive Coordinate prime conditions.*

Table 2.3 *Summary of the best-fitted mixed-effects models for young and older adults' choice data in Experiments 1 and 2.*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
A: Young Adults Experiment 1				
Intercept (Baseline)	-2.65	0.25	-10.49	< .001
Active Plural Prime	-0.02	0.22	-0.11	.912
Active Coordinate Prime	0.004	0.23	0.02	.983
Passive Plural Prime	0.74	0.22	3.30	< .001
Passive Coordinate Prime	0.63	0.20	3.22	.001
B: Older Adults Experiment 1				
Intercept (Baseline)	-2.75	0.39	-6.97	< .001
Active Plural Prime	-0.14	0.23	-0.61	.540
Active Coordinate Prime	-0.09	0.24	-0.36	.716
Passive Plural Prime	0.60	0.23	2.61	.009
Passive Coordinate Prime	0.64	0.21	3.07	.002
C: Young Adults Experiment 2				
Intercept (Baseline)	-2.25	0.34	-6.58	<.001
Active Plural Prime	-0.05	0.23	-0.22	.829
Active Coordinate Prime	0.08	0.26	0.30	.764
Passive Plural Prime	0.86	0.22	3.91	< .001
Passive Coordinate Prime	0.78	0.24	3.24	.001
D: Older Adults Experiment 2				
Intercept (Baseline)	-2.07	0.25	-8.30	< .001
Active Plural Prime	-0.48	0.22	-2.21	.027
Active Coordinate Prime	-0.28	0.23	-1.23	.218
Passive Plural Prime	0.46	0.22	2.09	.036
Passive Coordinate Prime	0.53	0.20	2.67	.008

Note. All models converged with random intercepts for participants and items with an additional by-item random slope for the main effect of prime condition.

2.3.2 Examining onset latency structural priming effects

The effect of syntactic repetition on the onset latencies of active and passive target responses in Experiments 1 and 2 is shown in **Figure 2.7**. The best-fitting model of the onset latency priming data is summarised in **Table 2.4** for both experiments.

As expected, we found that young adults' speed of sentence production was quicker overall than older adults in both experiments (*p*s < .001).[5] We also found a main effect of target structure (Experiment 1, $p < .001$; Experiment 2, $p = .003$), such that actives were produced significantly quicker overall than passives, as can be clearly seen in **Figure 2.7**. In Experiment 1, we found a main effect of syntactic repetition ($p = .021$), such that target responses were produced quicker following primes of the same structure. However, we did not find an interaction between target structure and syntactic repetition ($p = .310$), as we had expected to if latency priming effects were greater for actives than passives (Segaert et al., 2011, 2016). In Experiment 2, although there was a trend toward an effect of syntactic repetition on target onset latencies, this effect did not pass the significance threshold ($p = .073$). Likewise, we did not observe any interaction between target structure and syntactic repetition in Experiment 2 ($p = .835$).

To now consider the effect of prime phrase type (coordinate vs. plural noun phrase structure) on target onset latencies, we found minimal effects in both experiments. Although the interaction between target structure, syntactic repetition and prime phrase type just reached significance in Experiment 1 ($p = .049$), post-hoc analyses revealed that the interaction between syntactic repetition and prime phrase type was not significant for the production of either active ($\chi^2(1) = 0.24$, $p = .625$) or passive ($\chi^2(1) = 3.22$, $p = .072$) targets.[6] This suggests that the onset latency priming of actives and passives was not significantly

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[5] Due to the large speed differences between young and older adults, we also performed the modelling analysis with age-standardised onset latencies (using z-score adjustments within age groups). This produced the same effects (except for the main effect of age) seen in the non-adjusted onset latencies analyses for both Experiments 1 and 2.

[6] The 'testInteractions' function in the *phia* package (de Rosario-Martinez, 2015b) allows for the direct comparison of the contrasts specified within mixed-effects models. This can be used to investigate the nature of the interactions between the variables entered into the model as fixed effects.

different when the prime and target structure contained the same phrasal structure of the patient role (plural condition) or a different phrasal structure (coordinate condition). Similarly, we did not find any effects or interactions involving prime phrase type in Experiment 2 (all *p*s > .25). Finally, we observed no significant interactions involving age group in either experiment (all *p*s > .2).

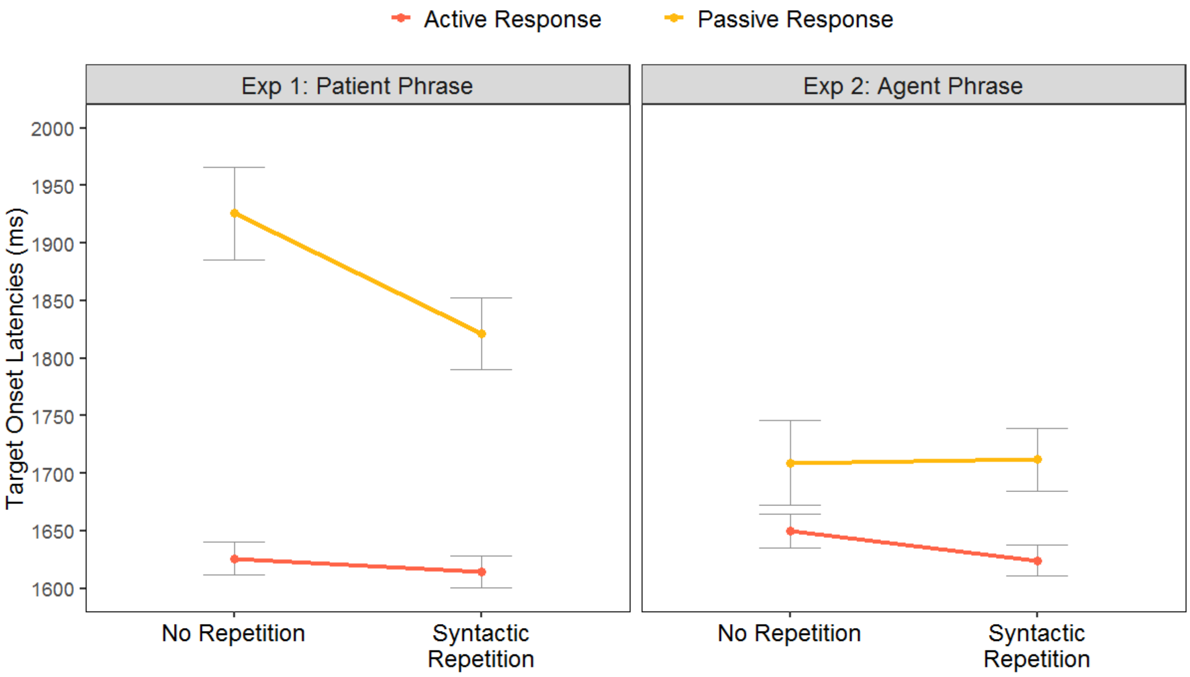

Figure 2.7 *Mean target onset latencies collapsed across age group and prime phrasal structure for Experiments 1 and 2. Error bars denote ±1 the standard error of the mean. In both experiments, active targets were produced significantly quicker than passive targets, and there was a trend toward structural priming of onset latencies (target responses produced quicker following primes of the same structure).*

Table 2.4 *Summary of the best-fitted mixed-effects models for the onset latency data in Experiments 1 and 2.*

Predictor	**Coefficient**	**SE**	***t*-value**	***p***
A: Experiment 1				
Intercept	1810.80	43.38	41.75	<. 001
Age Group	-536.91	74.86	-7.17	< .001
Target Structure	204.24	44.62	4.58	< .001
Syntactic Repetition	-48.99	21.38	-2.29	.021
Prime Phrase Type	25.88	22.80	1.14	.134
Age Group * Target Structure	5.89	64.73	0.09	.751
Age Group * Syntactic Repetition	25.96	42.82	0.61	.581
Age Group * Prime Phrase Type	-5.62	41.02	-0.14	.242
Target Structure * Syntactic Repetition	-44.08	40.90	-1.08	.310
Target Structure * Prime Phrase Type	-9.50	40.81	-0.23	.524
Syntactic Repetition * Prime Phrase Type	-61.36	40.67	-1.51	.961
Age Group * Target Structure * Syntactic Repetition	113.29	82.00	1.38	.175
Age Group * Target Structure * Prime Phrase Type	73.18	81.29	0.90	.498
Age Group * Syntactic Repetition * Prime Phrase Type	-9.93	81.38	-0.12	.331
Target Structure * Syntactic Repetition * Prime Phrase Type	-150.71	81.23	-1.86	.049
Age Group * Target Structure * Syntactic Repetition * Prime Phrase Type	-164.50	162.54	-1.01	.312
B: Experiment 2				
Intercept	1756.06	43.65	40.23	< .001
Age Group	-544.20	70.04	-7.77	< .001
Target Structure	114.53	38.84	2.95	.003
Syntactic Repetition	-27.95	21.52	-1.30	.073
Prime Phrase Type	-10.73	19.46	-0.55	.597

Age Group * Target Structure	-16.59	56.72	-0.29	.683
Age Group * Syntactic Repetition	-13.86	36.83	-0.38	.996
Age Group * Prime Phrase Type	42.13	36.30	1.16	.407
Target Structure * Syntactic Repetition	10.08	37.05	0.27	.835
Target Structure * Prime Phrase Type	-0.92	36.56	-0.03	.986
Syntactic Repetition * Prime Phrase Type	19.18	36.31	0.53	.304
Age Group * Target Structure * Syntactic Repetition	-41.91	73.41	-0.57	.559
Age Group * Target Structure * Prime Phrase Type	69.54	72.71	0.96	.254
Age Group * Syntactic Repetition * Prime Phrase Type	35.88	72.40	0.50	.810
Target Structure * Syntactic Repetition * Prime Phrase Type	-22.46	72.47	-0.31	.814
Age Group * Target Structure * Syntactic Repetition * Prime Phrase Type	68.64	144.68	0.47	.635

Note. The Experiment 1 model converged with random intercepts for participants and items with additional by-participant random slopes for the main effects of target structure, prime phrase type and syntactic repetition, and by-item random slopes for the main effects of target structure, prime phrase type and age group. The Experiment 2 model converged with random intercepts for participant and items with an additional by-participant random slope of the main effect of target structure, and additional by-item random slopes of all main effects.

2.4 Discussion

Using a structural priming paradigm, we investigated the effect of constituent phrasal structure on primed syntactic choices and sentence planning in young and older adults. Our study has three main findings. First, the magnitude of the priming effect on syntactic choices was unaffected by whether the prime and target contained the same or different constituent noun phrase structure in both Experiment 1 (in which we manipulated the phrasal structure of the patient role) and Experiment 2 (in which we manipulated the phrasal structure of the agent role). This suggests that primed syntactic choices are determined by highly abstract representations of the global syntactic structure that are unspecified for constituent phrasal properties, as predicted by both residual activation and implicit learning models of structural priming (Chang et al., 2006; Pickering & Branigan, 1998). Second, we found that all syntactic choice priming effects were similar for young and older participants (i.e., there were no significant differences between age groups). This indicates an age-related preservation of the mechanisms that support choice structural priming and syntax selection across the lifespan. Third, there was a trend toward structural priming in participants' speech onset latencies (i.e., speakers initiated target sentences quicker when the structure was repeated across the prime and target); however, in contrast to the predictions of the two-stage competition model (Segaert et al., 2016) and accounts of incremental planning (Wheeldon, 2013), the magnitude of the latency priming effects were not affected by the target syntactic structure or by repetition of the initial phrase structure.

To first consider the priming effects on syntactic choices, we found robust evidence of the inverse preference effect: there was a significant priming effect for passives (i.e., compared to the baseline condition, speakers produced significantly more passive responses following passive primes), but not for actives, replicating previous production studies (Mahowald et al., 2016). Critically though, our study is the first to demonstrate that choice structural effects persist in equal magnitude when the complexity of the noun phrase structure differs between the prime and target (specifically, when the prime contains a coordinate noun phrase structure, but the target contains a plural noun phrase). Our findings therefore support a model of structural priming in which a syntactic structure is represented in a highly abstract form consisting only of the global relationship between grammatical phrases, but which is unspecified for the internal features within the constituent phrases (i.e., the representation of a passive sentence relates to the broader prepositional by-phrase structure, but the features within the constituent noun phrases are unspecified). This is consistent with both a residual activation account of structural priming which proposed that combinatorial nodes representing syntax within the lexicon only encompass the critical global syntactic structure relating to the transitive verb (Pickering & Branigan, 1998), and an implicit learning account which specifies that the sequence of words within a noun phrase does not affect the broader syntactic representation (Chang et al., 2000, 2006). Indeed, Chang and colleagues claim that this feature is crucial for ensuring optimal efficiency with the language processing network, and that complete syntactic representations can still be activated using missing, but implied, elements (e.g., short passives with an implicit agent; Messenger et al., 2011). Applied to our findings, this suggests that participants encoded the prime syntactic structure within the same abstract representation regardless of whether it consisted of a plural or coordinate noun phrase structure, thus enabling both prime phrase types to equally prime production of a target sentence containing a plural noun phrase structure.

Notably, we found similar choice structural priming effects when we manipulated the noun phrase structure related to both the patient role (Experiment 1) and the agent role (Experiment 2). This is important because it enables us to rule out alternative explanations for our findings relating to conceptual salience and syntactic order. Specifically, the invariant effect of prime phrase type we observed in Experiment 1 cannot be explained by the fact that the patient role (relating to the recipient of the action) may not be conceptually salient enough for changes to the noun phrase structure to affect how syntactic representations are encoded. This is because we observed similar effects in Experiment 2, in which we manipulated the noun phrase structure of the agent role (relating to the more thematically important doer of the action). Likewise, the effects we observed in Experiment 2 cannot be solely attributed to the repetition of initial phrase structure as, if this was the case, we would have expected to observe less passive priming in the Passive Coordinate prime condition in Experiment 1 in which the initial phrase structure was not repeated between the prime and target. Thus, taking both experiments together, our findings indicate that the saliency of thematic role does not affect the encoding of the global syntactic structure of the prime and that the content of the initial phrase is not more heavily weighted when a speaker is choosing whether to use an active or a passive sentence to describe the target. Our study therefore adds to the growing evidence that changes to the internal properties of a sentence, at least at the non-head lexical item level, do not affect structural priming as long as the global syntactic structure remains the same (e.g., Bock, 1989; Fox Tree & Meijer, 1999; Pickering & Branigan, 1998). Importantly, we demonstrated this effect without needing to include additional thematic information when manipulating the open-class content between the prime and target (i.e., all primes and targets conveyed the same thematic event and featured the same number of agents/patients). This is unlike previous studies that have included additional descriptive information relating to the overall thematic event when manipulating the open-class content of the prime and target, either in the form of adjectives (Pickering & Branigan, 1998) or embedded/subordinate clauses (Branigan et al., 2006; Fox Tree & Meijer, 1999). As such, our study provides more decisive evidence that, when the application of a global syntactic structure can be repeated, structural priming effects occur regardless of internal phrasal structure rules that could also be applied.

It is important to note that our findings specifically relate to changes in the internal structure of a non-head noun phrase (i.e., in a transitive verb sentence, it is the verb phrase that corresponds to the head lexical item). In alternative sentence structures in which the noun is the head lexical item, it remains possible that changes to the internal noun phrase structure may have a greater effect on the magnitude of structural priming because, according to the residual activation model, an individual lemma node exists for the head lexical item that is activated in conjunction with the combinatorial node (Pickering & Branigan, 1998). However, such a prediction is not supported by the implicit learning model, which instead predicts that changes to the internal phrasal structure of both head and non-head lexical items should not affect syntactic choices because global syntactic representations are unspecified for the internal sequence of words within all constituent phrases (Chang et al., 2006). Such shallow processing of the internal phrasal structure draws certain parallels with the ‘good-enough’ account of sentence processing (Ferreira, Bailey, & Ferraro, 2002; Ferreira & Patson, 2007): in an attempt to minimise processing load, language users may generate superficial representations of sentences that do not include all constituent features (e.g., whether the noun phrase consists of a plural or coordinate structure). Nevertheless, compared to comprehension, such superficial processing is considerably less likely in situations in which speakers must generate the sentence themselves as they must correctly plan and produce each individual word (Levelt, 1989). As such, in the production-to-production paradigm we used, it is likely that speakers still fully processed the phrasal structure of the prime, but that this information was not encoded within the global syntactic representation.

Applied to sentence production more generally, our robust finding of an invariant effect of prime phrase type on syntactic choices supports a model of sentence generation whereby thematic representations of the message are first assigned syntactic roles (e.g., patient to subject, and agent to object), which then drives the generation of the complete syntactic structure (e.g., a passive sentence) (Bock & Levelt, 1994; Garrett, 1980; Levelt, 1989). In this way, a thematic role is only initially mapped to a broader syntactic role within the sentence and not to a constituent phrasal structure (e.g., plural or coordinate noun phrase); instead, the planning of the internal phrasal structure occurs at a later stage of the sentence generation process (albeit before articulation). Thus, although we only investigated priming from coordinate to plural noun phrase structures in transitive verb sentences, we would expect to see similar choice priming effects from plural to coordinate noun phrases as both involve the same conceptual features (i.e., always two nouns in the critical noun phrase) and the same thematic mapping processes. The only difference we may observe is speakers becoming slightly more error-prone when producing transitive targets that contain coordinate noun phrases as the use of nouns of two different entities (instead of two of the same entity) may elicit more effortful processing. However, we consider that this possible increase in errors would likely arise during the sentence planning and production stage, and not during the actual syntax selection stage (which occurs before any lexical retrieval or incremental planning; Segaert et al., 2016).

The second aim of our study was to investigate the effect of healthy ageing on syntactic choices. We found convincing evidence of structural priming in young and older adults: both age groups produced more passive targets following passive primes (in line with Hardy et al., 2017; but cf. Heyselaar et al., 2017). Moreover, the magnitude of structural priming in both age groups was equally unaffected by changes to the constituent phrasal structure of the prime. Taken together, this suggests that the abstractness of syntactic representations does not change substantially with age (i.e., older adults continue to represent syntactic structures in a highly abstract form that is undetailed for internal properties), and that there is an age-related preservation of the processes that support syntax selection in primed situations. Our finding of an invariant effect of age somewhat contrasts with one of our initial predictions that we expected to observe less structural priming in older adults due to age-related declines in processing speed and transmission strength (MacKay & Burke, 1990; Salthouse, 1996); however, two alternative plausible explanations remain. Firstly, if syntactic choices are predominately driven by implicit learning mechanisms, as suggested by Chang et al. (2006), then a preservation of implicit learning throughout the lifespan (Fleischman et al., 2004; Light & Singh, 1987) will elicit a corresponding preservation of structural priming despite age-related declines in other cognitive functions. Secondly, the general slowing associated with ageing may not affect all cognitive networks equally (Fisher, Duffy, & Katsikopoulos, 2000; Fisk, Fisher, & Rogers, 1992). In this way, despite slowing and transmission deficits in other areas of language processing, such as within the network that supports the retrieval of phonological components of a word (Burke & Shafto, 2004), the spreading activation networks that support structural priming (as in Pickering & Branigan, 1998, and Segaert et al., 2016) may not be so negatively affected by healthy ageing. Indeed, preserved priming effects have been observed in other areas of language processing, such as morphological priming of regularly-inflected words and transparent compounds (Clahsen & Reifegerste, 2017; Duñabeitia, Marín, Avilés, Perea, & Carreiras, 2009; Reifegerste, Elin, & Clahsen, 2018).

Nevertheless, it is important to consider that we found evidence of preserved structural priming effects in older adults in a task in which the demands may not have been great enough to elicit a measurable behavioural difference between age groups. Our task was more difficult than previous ageing priming studies that have included one agent and one patient (Hardy et al., 2017; Heyselaar et al., 2017, 2018; Sung, 2015), since all of our primes and targets consisted of three entities. Nonetheless, active and passive sentences are generally not considered to be the most complex syntactic structures to produce (i.e., they do not contain an embedded clause or a large syntactic operation of movement). Indeed, similar patterns of brain activation have been found in young and older adults when processing passive sentences (Mack, Meltzer-Asscher, Barbieri, & Thompson, 2013), in contrast to the age differences in brain activity during the comprehension of more complex syntactic structures (Peelle et al., 2010; Tyler et al., 2010). As such, within our active and passive production task, the balance between an individual's neurocognitive capacity and the task demands may still have been balanced in favour of 'good' behavioural performance in older adults (i.e., similar structural priming effects to young adults), despite likely declines in overall cognitive capacity (Peelle, 2019). Future work is therefore needed to fully understand the nature of older adults' syntax selection and planning mechanisms in a structural priming task in which the target sentence is syntactically more complex; for example, when the transitive verb sentence is contained within an embedded clause (e.g., *"The teacher saw that [the boy is being chased by the girl]"*) or includes a subordinate clause (e.g., *"The boy is being chased by the girl [who has a bow in her hair]"*) (similar to Branigan et al., 2006, and Fox Tree & Meijer, 1999). The inclusion of individual difference measures, such as processing speed and verbal knowledge, may also help tease apart the predictions about structural priming made by the different models of healthy ageing.

Finally, to consider our onset latency findings, we found that actives were produced significantly quicker than passives in both experiments: this is to be expected as passives are comparatively less frequent in English and therefore take longer to plan and produce (Segaert et al., 2011, 2016). However, we only found a marginal trend toward facilitated effects of target latencies when the prime syntax was repeated, and critically we did not find this effect to vary significantly based on target syntax (active vs. passive) or prime phrase type (whether the prime noun phrase structure matches or mismatches that of the target).[7] Our findings therefore do not confirm our prediction that latency priming effects would be greater for actives than passives (as according to the two-stage competition model, timing at the selection stage should only be reduced for the more frequent active syntax; Segaert et al., 2016).

[7] Importantly, we replicated these null effects across two experiments with similar overall onset latencies (Experiment 1, M = 1653ms, SD = 576 ms; Experiment 2, M = 1650 ms, SD = 569 ms; Coefficient = 19.80, SE = 64.57, t = 0.31, p = .759).

Likewise, our prediction that the latency priming effect would be greater when the initial noun phrase structure was repeated between the prime and target was not found: in line with an incremental scope of advanced planning, we expected speakers to prioritise the planning of the initial phrase prior to articulation, leading to greater speed benefits when it was repeated (Segaert et al., 2016; Wheeldon, 2013). Moreover, we did not find any age group differences in the magnitude of the latency priming effect as we may have expected if age-related differences exist in on-line sentence planning (i.e., older adults' increased sensitivity to phrasal properties and boundaries; Hardy et al., 2020).

While our minimal effects of onset latency priming may appear difficult to reconcile with the incremental framework of the two-stage competition model (Segaert et al., 2016), we consider that a more likely explanation for our lack of latency effects lies in the complexity of our stimuli. We used 34 different human and animal characters in the experimental pictures (this was necessary in order to be able to manipulate the noun phrase structure) and there was no predictability between the nouns featured within a prime and target pair. In contrast, in Segaert et al.'s (2011, 2014, 2016) production priming paradigm, all picture stimuli consisted of either a man and a woman or a boy and a girl; this produced predictability in the characters on the target trials (if the prime featured a man and a woman, the target featured a girl and a boy, and vice-versa). The complexity of the lexical retrieval processes required for our stimuli may therefore have masked effects due to the selection and planning of the target syntactic structure. As such, compared to syntactic choice measures, latency measures of structural priming may be less reliable because they incorporate the time required for lexical retrieval, as well as syntax generation. Further work exploring how latency priming is affected by linguistic factors, in particular the complexity of lexical information, can better inform theories of language production.

In summary, our study is the first to specifically examine the role of constituent phrasal structure, relating to the object and subject noun phrase in a transitive verb sentence, on the magnitude of structural priming. We found robust evidence of structural priming on syntactic choices, which critically did not vary depending on the constituent phrasal structure of the prime. Our findings therefore support models of structural priming that propose syntactic structures are represented in a highly abstract form that is undetailed for internal phrasal structure (Chang et al., 2006; Pickering & Branigan, 1998). Moreover, we observed choice structural priming effects in equal magnitude in both phrase conditions in young and older adults, suggesting that the abstractness of syntactic representations and the mechanisms that support syntax selection are unaffected by healthy ageing.

CHAPTER 3

Healthy Ageing and Sentence Production: Disrupted Lexical Access in the Context of Intact Syntactic Planning

Healthy ageing does not affect all features of language processing equally. In this study, we investigated the effects of ageing on different processes involved in fluent sentence production, a complex task that requires the successful execution and coordination of multiple processes. In Experiment 1, we investigated age-related effects on the speed of syntax selection using a syntactic priming paradigm. Both young and older adults produced target sentences quicker following syntactically related primes compared to unrelated primes, indicating that syntactic facilitation effects are preserved with age. In Experiment 2, we investigated age-related effects in syntactic planning and lexical retrieval using a planning scope paradigm: participants described moving picture displays designed to elicit sentences with either initial coordinate or simple noun phrases and, on half of the trials, the second picture was previewed. Without preview, both age groups were slower to initiate sentences with larger coordinate phrases, suggesting a similar phrasal planning scope. However, age-related differences did emerge relating to the preview manipulation: while young adults displayed speed benefits of preview in both phrase conditions, older adults only displayed speed preview benefits within the initial phrase (coordinate condition). Moreover, preview outside the initial phrase (simple condition) caused older adults to become significantly more error-prone. Thus, while syntactic planning scope appears unaffected by ageing, older adults do appear to encounter problems with managing the activation and integration of lexical items into syntactic structures. Taken together, our findings indicate that healthy ageing disrupts the lexical, but not the syntactic, processes involved in sentence production.

Peer-reviewed publication:

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Data availability: The complete datasets and supplementary measurements of the study are provided online on the Open Science Framework (https://osf.io/wp7dr/).

3.1 General introduction

Producing a fluent and coherent sentence is a complex task involving the coordination of multiple cognitive and neural mechanisms (Levelt, 1989; Mody, 2017). As we age, changes occur that can create challenges for language processing, such as a widespread reduction in grey matter volume (Good et al., 2001) and a decline in working memory capacity (Waters & Caplan, 2003). Nevertheless, older adults have a wealth of experience with language and are often able to adopt effective processing strategies, such as the recruitment of addition brain areas, to compensate for lost efficiency elsewhere (Reuter-Lorenz & Park, 2014; Wingfield & Grossman, 2006). This paints a multifactorial picture of language processing in old age in which some language skills decline because of age-related cognitive changes, but in which others are preserved because of the successful adoption of compensation strategies (for reviews, Burke & Shafto, 2008; Peelle, 2019). Investigating how different aspects of language processing are affected by old age is critical for understanding this complex balance between decline and preservation. In this study, we conducted two novel experiments investigating age-related changes in sentence production; specifically, we investigated the processes involved in syntax generation (Experiment 1), as well as sentence planning and lexical retrieval (Experiment 2). Our findings reveal a contrast between the preservation of syntactic skills, but the disruption of lexical access, in old age; this adds to the growing evidence that healthy ageing does not affect all features of language processing to the same extent.

A number of previous studies have demonstrated age-related decline in language production. To first consider age-related changes at the word level, several studies have found older adults to be slower and more error-prone in picture naming tasks, particularly for low frequency words (see Feyereisen, 1997, for a review), and to experience increased tip-of-the-tongue states, in which a speaker is certain that they know a word but is unable to produce it (Burke, MacKay, Worthley, & Wade, 1991; Segaert, Lucas, et al., 2018; Shafto et al., 2007). This suggests an increased difficulty in retrieving the name of a lexical object and its corresponding phonological form, something which may be attributable to age-related atrophy in the left insula (Shafto et al., 2007). Age-related deficits are also found at the sentence level of production: with age, there is a decline in the production of complex syntactic structures, such as embedded clauses, coupled with an increase in syntactic errors, such as the use of the incorrect tense (Kemper, 1987; Kemper et al., 2001; Kemper, Herman, & Liu, 2004; Kemper

& Sumner, 2001; Rabaglia & Salthouse, 2011). This apparent decline in syntax production is often considered to arise from age-related decreases in the capacity or efficiency of working memory, a cognitive resource that is critical when producing complex sentences that contain multiple clauses and that require greater syntactic operations of movement (Abrams & Farrell, 2011; Kemper & Sumner, 2001; MacDonald & Christiansen, 2002).

In contrast, other aspects of language production are characterized by stability and even improvement with age. Most notably, vocabulary size and knowledge consistently increase with age (Verhaeghen, 2003). Older adults also appear to perform similarly to young adults in tasks where they must switch between formulating alternative syntactic structures, such as dative verb and transitive verb alternatives (Altmann & Kemper, 2006; Davidson et al., 2003). Moreover, in situations in which the task demands are reduced, minimal age differences are found; for example, Kemper, Herman, and Lian (2003) found that young and older adults produced similar responses when asked to incorporate intransitive ('smiled') or transitive ('replaced') verbs into their sentences, and age differences in fluency only emerged when participants were asked to incorporate more complex complement-taking verbs ('expected'). This effect of task complexity on language production skills in old age can be best explained by Peelle's (2019) 'supply and demand' framework, which suggests that behavioural success reflects a complex balance between specific task requirements and the level of cognitive resources available to the speaker; specifically, if task requirements outweigh cognitive resources, processing efficiency will decline leading to poor performance. Due to overall neuroanatomical and cognitive changes that occur during healthy ageing, it is no surprise that older adults' neurocognitive capacity for any given language task is likely to be less than young adults. However, this does not necessarily mean that age differences will always emerge: older adults may still perform similarly to young adults when task requirements are sufficiently low (e.g., when producing simpler syntactic constructions) or they may adopt compensatory processing strategies (e.g., the recruitment of other brain areas). In this way, identical behavioural performance in young and older adults may not always reflect identical neural or cognitive processes.

The idea of neural compensation in ageing has been most studied in terms of language comprehension, in which brain imaging studies have demonstrated that older adults engage additional brain areas in order to maintain high levels of accuracy (see Wingfield & Grossman, 2006, for a review). Likewise, older adults may employ different strategic approaches in order to compensate for processing deficits elsewhere, such as a greater reliance on discourse during reading (Stine-Morrow, Miller, Gagne, & Hertzog, 2008). These same principles of compensation can also be applied to production; for example, Altmann and Kemper (2006) suggested that the minimal age group differences they observed in their sentence generation task were the result of older adults adopting a different strategy to young adults (always assigned the initially presented item to the subject role). Overall, this highlights the importance of continuing to investigate the effect of ageing on different aspects of language processing. Moreover, even when there appear to be no group differences, this does not necessarily mean that young and older adults are engaging the exact same processing networks.

The aim of our study was to investigate how the syntactic and lexical processes involved in sentence generation are affected by healthy ageing using paradigms that have not previously been used with older adults. In both experiments, we employed on-line onset latency measures of sentence production in order to gain information about the incremental fashion in which sentences are planned and produced (see, Wheeldon, 2013, for a review of latency measures of speech production). Most previous studies investigating sentence production and ageing have predominantly used off-line measures, involving the assessment and coding of sentences after they have been produced (e.g., Kemper et al., 2001, 2003; Kemper, Herman, et al., 2004; Rabaglia & Salthouse, 2011), which while informative about syntactic choices and errors cannot provide insight into the time-course of the underlying sentence generation process (Marinis, 2010; Mertins, 2016). To our knowledge, only a handful of studies to date have investigated older adults' sentence production using on-line measures (Griffin & Spieler, 2006; Spieler & Griffin, 2006); hence, there remains a considerable gap in the ageing literature regarding the timing of speech preparation and how different syntactic and lexical processes unfold during the course of sentence production.[8] In Experiment 1, we used a syntactic priming paradigm (as in Smith & Wheeldon, 2001;

[8] We note other studies have employed on-line measures to investigate age-related differences at the single word level (for a review, see Mortensen, Meyer, & Humphreys, 2006). While producing single words requires the retrieval of lexical information, it does not require the incorporation of the lexical items into a syntactic structure for sentence production (Levelt, 1989). Thus, it is difficult to apply these single word findings to age-related effects on sentence production (Kavé & Goral, 2017).

Wheeldon & Smith, 2003) to investigate age-related differences in the speed of syntax generation. In Experiment 2, we used a planning scope paradigm with an embedded picture preview element (as in Smith & Wheeldon, 1999; Wheeldon et al., 2013) to investigate age-related differences in syntactic planning scope and lexical retrieval.

3.2 Experiment 1: Examining the effect of ageing on on-line syntax facilitation

The process of producing a sentence begins with the preparation of a preverbal message – this is a conceptual representation of all the information that the speaker wishes to covey and that will ultimately be formulated into a coherent grammatical structure (Levelt, 1989; Levelt et al., 1999). The exact structure of preverbal messages is debated, but is generally agreed that they minimally contain conceptual category information and a thematic structure with concepts assigned to thematic roles (Wheeldon, 2013). The preverbal message triggers the formulation stage in which the message is turned into linguistic representations, involving both the rapid retrieval of lexical items and the generation of an appropriate syntactic structure, which must be integrated correctly to convey the intended message. More traditional models of sentence production propose that grammatical encoding is lexically driven such that lemmas (representations of the syntactic and semantic properties of a word) are first selected and assigned grammatical roles (e.g., subject or object), which then drives the generation of a syntactic structure (Bock & Levelt, 1994; Levelt et al., 1999; Pickering & Branigan, 1998). Alternatively, computational models postulate that there is a complete dissociation between syntax generation and lexical retrieval, such that syntactic structure is derived solely from conceptual structure (i.e., thematic roles) with lexical access occurring independently (Chang et al., 2000, 2006).

While there remains debate about the exact relationship between syntax generation and lexical retrieval (see Wheeldon, 2011, for a review of the evidence for both lexically mediated and lexically independent models), it is widely agreed that sentence production occurs incrementally, such that only a small amount of planning occurs prior to articulation and that planning continues to unfold after speech onset for the remainder of the sentence (Levelt, 1989, 1992). Consequently, the amount of time that a speaker takes to begin a sentence is informative about the amount of planning that has occurred prior to speech onset in terms of both the retrieval of lexical items and the generation of syntax (Levelt, 1989;

Wheeldon, 2013). On-line onset latency measures can therefore be used to explore age-related differences in the type and amount of advanced planning, or scope, of the sentence generation process.

One paradigm that has been used to explore the processes involved in syntax generation is *syntactic priming*. Broadly speaking, syntactic priming refers to the facilitation of syntactic processing that occurs when a syntactic structure is repeated across an otherwise unrelated prime and target (Bock, 1986; Pickering & Ferreira, 2008). *Choice syntactic priming* is the phenomenon whereby speakers are more likely to repeat a syntactic structure that they have recently processed (see Mahowald et al., 2016 for a meta-analytical review). In our study investigating the speed of syntax generation, we were interested in *onset latency syntactic priming:* the facilitated speed of syntactic processing that occurs when a syntactic structure is repeated across a prime and target (Corley & Scheepers, 2002; Segaert et al., 2011, 2014, 2016; Wheeldon & Smith, 2003). For example, using a picture description task, Smith and Wheeldon (2001) demonstrated that when a speaker must produce a given syntactic structure on a target trial (1a), this was initiated quicker (i.e., decreased speech onset latencies) following recent production of the same structure (1b), compared to when a different structure had just been produced (1c).

(1a) Target: "the spoon and the car move up"

(1b) Related prime: "the eye and the fish move apart"

(1c) Unrelated prime: "the eye moves up and the fish moves down"

This latency priming effect cannot have its source in conceptualisation, lexical access or phonological planning as these factors were tightly controlled within the experimental design (i.e., there was no prosodic, visual or lexical similarity between any of the corresponding primes and targets). Further experiments by Smith and Wheeldon (2001) also ruled out alternative explanations relating to overall sentence complexity (the effect persists when both the related and unrelated prime feature the same number of clauses as the target), as well as to visual perception and picture movement (the effect persists when the related and unrelated primes feature the exact same movement patterns, and when stationary written prime sentences are used). This indicates that the facilitation effect observed is specifically related to the repetition of syntactic structure between the prime and target. Similar facilitation effects have been observed during sentence comprehension – reduced reading times and P600 when a structure is repeated between the prime and target (Tooley, Swaab, Boudewyn, Zirnstein, & Traxler, 2014; Tooley, Traxler, & Swaab, 2009).

The two most common theoretical accounts of structural priming relate to the residual activation of a prime syntactic structure (Pickering & Branigan, 1998) and implicit learning processes that occur when an unexpected prime is heard (Chang et al., 2006). However, these models only provide explanations of facilitation effects relating to syntactic choices and not to the speed of sentence production; thus, the models offer minimal insight into the mechanisms that underlie onset latency syntactic priming. By contrast, Segaert et al. (2016) proposed a two-stage competition model that explains the effect of syntactic priming on both choices and onset latencies (see also Segaert et al., 2011, 2014). According to the model, alternative syntactic structures (e.g., active vs. passive) are represented by syntactic nodes that transmit activation and inhibition (i.e., negative activation) to neighbouring nodes within the network (i.e., to the competing syntactic alternative). The activation levels of each node, and thus how much inhibitory activation is transmitted to the competing node, are determined by the relative frequency of the structure (established through implicit learning). Sentence production begins with construction of the preverbal message and this is followed by two sequential stages. First is the selection stage during which a speaker selects one syntactic structure from competing alternatives. Next follows the planning stage during which the selected syntax is incrementally planned and produced. While syntactic choice is determined solely at the selection stage, production speed is determined by the additive time taken to complete both stages. Consequently, when the choice element is removed (as in Smith & Wheeldon, 2001), onset latencies are largely determined by processing at the planning stage with very minimal processing required at the selection stage as there are no competing syntactic alternatives. In this study, we therefore investigated age-related effects on onset latency syntactic priming without an additional choice element as this allowed us to tap more directly into the processes involved in sentence planning.

The magnitude of the onset latency syntactic priming effects observed in the older adults will be informative about age-related changes in syntactic planning and facilitation that occur during real-time sentence production. While no studies to date have examined age-related effects on onset latency priming, a few studies have investigated age effects on choice syntactic priming. However, this has produced mixed results with two studies finding preserved priming of passives in older adults (Hardy et al., 2017; Hardy, Wheeldon, &

Segaert, 2019) [9], while others have not (Heyselaar et al., 2017, footnote 2; Sung, 2015, 2016).[10] It is therefore difficult to make direct hypotheses about age-related effects on onset latency syntactic priming based on previous evidence. Nevertheless, hypotheses can be made by considering the two-stage competition model in combination with more general models of ageing. The model of Segaert et al. (2016) includes a spreading activation architecture whereby recently processed syntactic structures are activated to an above-baseline level, which contributes to decreased selection and planning speed. However, according to Salthouse's (1996) general slowing model of ageing, declines in overall processing speed with age can substantially decrease the speed of spreading activation throughout a cognitive or neural network. Similarly, the transmission deficit model postulates that ageing weakens the strength of activation of different units and the connections amongst units, both critical for successful spreading activation (MacKay & Burke, 1990). Applied to syntactic priming, this may mean that when older adults' process a prime sentence, the syntactic information relating to the prime does not become available to a central processor quickly or strongly enough to sufficiently excite the representation of the syntactic structure to a level which may influence the speed of syntax selection and planning. If this is the case, we might expect that the magnitude of the onset latency priming effect (i.e., the speed benefit when the syntactic structure is repeated) to be greater for young adults (who possess a faster spreading activation network) compared to older adults (who generally display much slower processing speed; Salthouse, 2004).

[9] Note, this Hardy et al. (2019) study refers to the experiments reported in **Chapter 2** of this thesis.

[10] Note, some other studies tested non-young adults as controls for clinical patients; however, the samples are small and the age ranges are large. While Ferreira et al. (2008, n = 4 aged 50-58) and Cho-Reyes et al. (2016, n = 13 aged 33-76) found evidence of choice syntactic priming in controls, Hartsuiker and Kolk (1998, n = 12 aged ~28-67) did not.

3.2.1 Experiment 1: Method

3.2.1.1 Participants

We recruited 50 young adults (36 female) aged 18-25 (*M* = 19.8, *SD* = 1.1) from the University of Birmingham student population and 56 older adults (37 female) aged 64-80 (*M* = 71.8, *SD* = 4.5) from the Patient and Lifespan Cognition Database. Sample sizes were larger than previous studies investigating latency effects of syntactic priming and planning scope (typically 24-34 participants; e.g., Martin et al., 2014; Smith & Wheeldon, 2001) and the one previous study that has examined age-related effects in on-line sentence production (15-17 participants per age group; Spieler & Griffin, 2006). All older adults scored above 26 out of 30 (*M* = 27.4; *SD* = 1.3) on the Montreal Cognitive Assessment (Nasreddine et al., 2005), indicating that they were currently experiencing healthy ageing (scores < 26 indicate risk of mild cognitive impairment or dementia; Smith et al., 2007). All participants were native English speakers with normal or corrected-to-normal vision, and did not report any language disorders. There was no significant difference in education between age groups.[11] The study was approved by the University of Birmingham Ethical Review Committee and participants provided written informed consent. All participants completed Experiment 1 at an initial test session, followed by Experiment 2 3-7 days later.

3.2.1.2 Design

We used a 2 X 2 mixed design with one between-participant variable of age (young vs. older) and one within-participant variable of prime type (syntactically related vs. syntactically unrelated). Hence, there were two experimental task conditions (**Figure 3.1.A**).

[11] Education was scored according to the International Standard Classification of Education (United Nations, 2011) which classifies education on a scale of 0 (pre-primary school) to 8 (university doctorate). There was no significant difference in scores between young (*M* = 6.0, *SD* = 0.1) and older (*M* = 5.8, *SD* = 1.3) adults, $t(104) = 1.36$, $p = .178$. A score of 6.0 indicates engagement in formal education to an undergraduate bachelor level (approximately equal to 17 years).

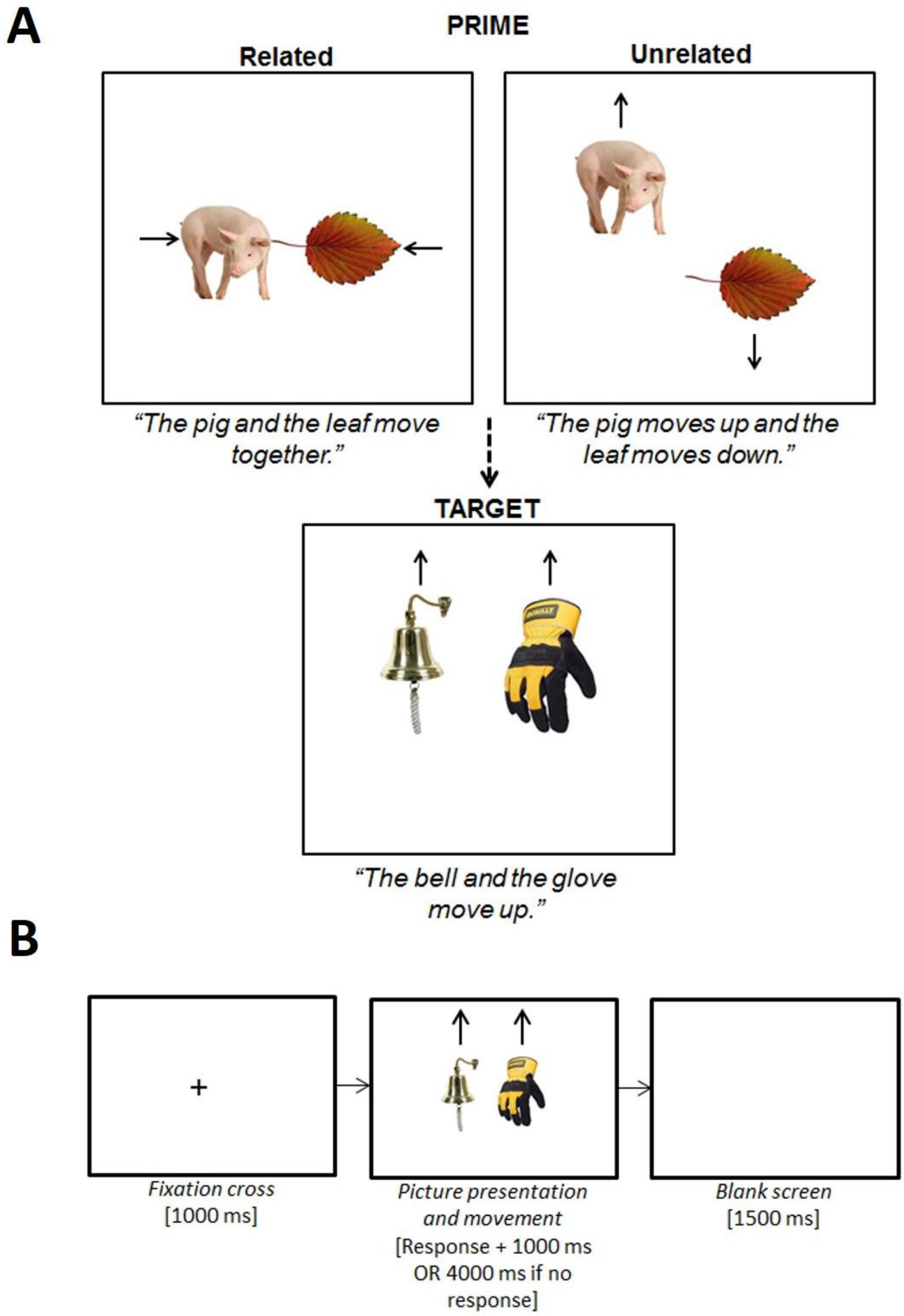

Figure 3.1 *Experiment 1 syntactic priming task design (A) and stimuli presentation events per trial (B). The participant was instructed to begin describing the picture movement as soon as possible using specific sentence types. The stimuli presentation sequence was the same for prime and target trials, and primes were always immediately followed by the corresponding target (i.e., we used a 0-lag delay). Speech latencies on the target trials were recorded from the onset of the pictures to the participant beginning to speak.*

3.2.1.3 Materials

To create the experimental items, we used 80 simple photographic pictures of everyday concrete objects. All picture names were mono- or disyllabic, and when choosing the stimuli, we took care to ensure that the objects could be identified and named quickly and easily. Close attention to participants' performance during the practice sessions also indicated that participants did not have issues with picture naming for our specific stimuli. Forty of the pictures were used to create the 40 picture pairs for the target trials; each picture appeared in two different pairs (once each in the left and right position). Using the same constraints, we constructed 40 picture pairs from another 40 pictures for the prime trials. We then paired each target pair with a prime pair to generate 40 experimental items. We ensured that there was no phonological or conceptual overlap between any of the four pictures within each experimental item (this ensured that any effects we observed were related to syntactic processing, and not to semantic or pragmatic features).

The movement of each picture pair was controlled using E-Prime (Schneider et al., 2002). In all target trials, both pictures moved in the same vertical direction (either up or down). Participants were instructed to describe the picture movements from left to right using specific sentences that they were trained on prior to the beginning the task; hence, the target trials elicited a coordinate noun phrase (*"the A and the B move up/down"*). In the related prime condition, the pictures moved in opposing horizontal directions which elicited a sentence that was syntactically related to the target trials (*"the C and the D move together/apart"*). In the unrelated prime condition, the pictures moved in opposing vertical directions which elicited a sentence that was syntactically unrelated to the target trials (*"the C moves up/down and the D moves down/up"*). We then created two item lists that each contained the same 40 target sentences, but the prime condition matched to each target was rotated such that there were 20 related and 20 unrelated primes per list. Each participant was randomly assigned to one of the two lists and completed 20 experimental items (prime plus target pairs) from each condition (**Table 3.1.A**). A total of 20 items per experimental condition follows the recommendation of Simmons, Nelson and Simonsohn (2011) for conducting a well-powered and reliable study.

Lastly, we used a further 54 pictures to construct 120 filler trials designed to increase the variety of syntactic structures produced by the participant and minimise the risk of them noticing the priming manipulation. We created 96 filler trials that elicited phrases such as:

"there is an X and a Y" (no picture movement); *"the Xs move up"* (two repeat pictures move simultaneously) and *"there are no pictures"* (screen is blank). We also created 24 filler trials that elicited phrases that were syntactically similar to the experimental trials; without such 'decoy' fillers, experimental trials would always occur in pairs (i.e., prime and corresponding target) which may enable the participant to predict the upcoming movement of a target trial. All 120 fillers were added to each of the two items lists. We then divided each list into four blocks that each contained 5 related experimental items, 5 unrelated experimental items and 30 filler items. The distribution of items within each block was pseudorandomised with the constraint that two experimental items never occurred consecutively. The ordering of the blocks was rotated across participants.

3.2.1.4 Procedure

Each participant was tested individually in a sound-attenuating booth facing the screen of a 17 inch *Dell* monitor, in front of which was a *Sony* microphone connected to an amplitude voice key that recorded their responses and onset latencies. **Figure 3.1.B** illustrates the sequence of stimuli presentation per trial. To begin, there were 50 practice trials; the sentences elicited resembled those in the experimental and filler trials and featured all 80 experimental pictures once. If, during the practices, the participant made a lexical error (i.e., used the incorrect picture name) or syntactic error (i.e., used the wrong sentence type), they were corrected by the experimenter. The task then continued until all four experimental blocks had been completed. The experimenter listened from outside the booth via headphones and noted down any errors made by the participant. Errors included: incorrect picture naming (e.g., 'fish' instead of 'shark'); use of a difference sentence structure (e.g., *"the pig moves towards the leaf"* instead of *"the pig and leaf move together"*); and disfluencies, such as stuttering and pausing.

Table 3.1 *Overview of the different items used in the Experiments 1 and 2. Number of items completed by each participant and example stimuli are provided.*

Item Type	**N**	**Example**
A: Experiment 1		
Related	20	Prime: “the pencil and the orange move together” Target: “the clock and the drum move up”
Unrelated	20	Prime: “the cow moves up and the broom moves down” Target: “the apple and the goat move up”
Filler	120	“There are two houses”
B: Experiment 2		
Preview Initial Coordinate	20	Preview: spoon “The trumpet and the spoon move above the crab”
No Preview Initial Coordinate	20	Preview: NA “The skirt and the bell move above the carrot”
Preview Initial Simple	20	Preview: snail “The balloon moves above the snail and the pear”
No Preview Initial Simple	20	Preview: NA “The spanner moves above the monkey and the toaster”
Filler	220	“There are three stars”

Note. The condition to which each experimental item was assigned was rotated across lists (e.g., the picture trio of trumpet-spoon-crab would also have appeared in the three other conditions in Experiment 2 in alternative lists). This meant that, across all participants, each item appeared an equal number of times in each condition; therefore, lexical factors of individual words, such as age of acquisition, were not a concern.

3.2.1.5 Data preparation and analyses

We excluded the data of participants whose error rates were above 50% on the experimental trials; this resulted in the exclusion of five older adults. Of the 4040 target responses, we excluded trials in which the participant made an error on the corresponding prime (170 (8.5%) of young and 301 (14.7%) of older adult trials). Following Ratcliff's (1993) recommendation for dealing with reaction time outliers, we also removed trials for which the target onset latency was below 300ms, above 3000ms or more than 2.5SD above/below the participants' mean per experimental condition (discarding 53 (2.9%) young and 49 (2.8%) older adult trials). All remaining trials were used in the error analyses, but only correct responses (87.4% of trials) were used in onset latency analyses.

All data were analysed in R (R Core Team, 2015) using generalised linear mixed-effects models (*lme4* package; Bates et al., 2014); this was the most suitable way to analyse the datasets as there were repeated observations for participants and items (Barr et al., 2013; Jaeger, 2008). We fitted a binomial distribution to the error data as the dependent variable was categorical (correct = 0; incorrect = 1). Following Lo and Andrews' (2015) recommendation for analysing continuous speed data, we fitted an inverse gaussian distribution to the onset latency data with an 'identity link' function. This model fit is particularly advantageous when comparing groups with large overall speed differences (i.e., young vs. older) as it eliminates the need for data transformation (i.e., logarithmic or z-scores) while still satisfying the normality assumptions of the generalised linear mixed-effect model (Balota, Aschenbrenner, & Yap, 2013; Lo & Andrews, 2015). For both models, we entered age group (young vs. older) and prime type (related vs. unrelated) as fixed effects. We included random intercepts for participants and items, as well as by-participant and by-item random slopes appropriate for the design. Prior to analysis, the fixed effects were sum-coded and transformed to have a mean of 0 and a range of 1. When a model did not converge with the maximal random effects structure, we simplified the random slopes, removing interactions before main effects in the order of least variance explained until the model converged (Barr et al., 2013).

Given that the effect of ageing was critical to our research question, in the case of non-significant interactions involving age group, we sought to quantify the likelihood of this null effect with additional Bayesian analysis. Using the *BayesFactor* package (Morey & Rouder, 2018), we constructed a full model that did include the interaction of interest (H_1) and a null model that excluded the interaction (H_0); we then calculated the Bayes Factor (BF) as H_1/H_0. We interpreted the BF values in line with Lee and Wagenmakers' (2013) classification scheme (see also Schönbrodt & Wagenmakers, 2018). BF values < 0.1 provide 'strong' evidence in support of the null (H_0) hypothesis; whereas, values between 0.1 and 1 are generally deemed inconclusive.

3.2.1.6 Supplementary measurements

All participants also completed a battery of eight additional measures designed to provide an indicator of their current ability across a variety of cognitive and physical domains. Extensive details about these measurements are available online in the ‘Supplementary Measurements’ section of the OSF repository (https://osf.io/wp7dr/) and in the **Appendix** of this thesis.

3.2.2 Experiment 1: Results

Figure 3.2 summarises the target onset latencies and error rates across the two prime conditions for young and older adults.

3.2.2.1 Onset latencies

The best-fitting model of the onset latency data is reported in **Table 3.2.A**. As expected, older adults were significantly slower than young adults (1060ms vs. 898ms, $p < .001$). There was also a main effect of prime type ($p < .001$), such that target responses were produced significantly quicker following related primes (953ms) than following unrelated primes (994ms), indicating an overall syntactic priming effect of 41ms. Most interestingly, there was no interaction between age group and prime type ($p = .746$), indicating that the onset latency priming effect was similar for young (36ms, 3.9% benefit) and older (49ms, 4.5% benefit) adults. Moreover, the additional Bayesian analysis provided ‘strong’ support for the null hypothesis (BF = 0.072) and separate group analyses confirmed that the priming effect was significant for both age groups (**Tables 3.2.B and 3.2.C**).

3.2.2.2 Error rates

The best-fitting model of the error data is reported in **Table 3.3.A**. Although older adults were significantly more error-prone than young adults (16.1% vs. 9.1%, $p < .001$), there was no main effect of prime type ($p = .369$) and no interaction between age group and prime type ($p = .868$; supported by a ‘strong’ BF value 0.060). This suggests that neither young or older adults’ production of errors on the target trials were affected by the syntactic relatedness of the prime (as was confirmed by separate age groups analyses; **Tables 3.3.B and 3.3.C**).

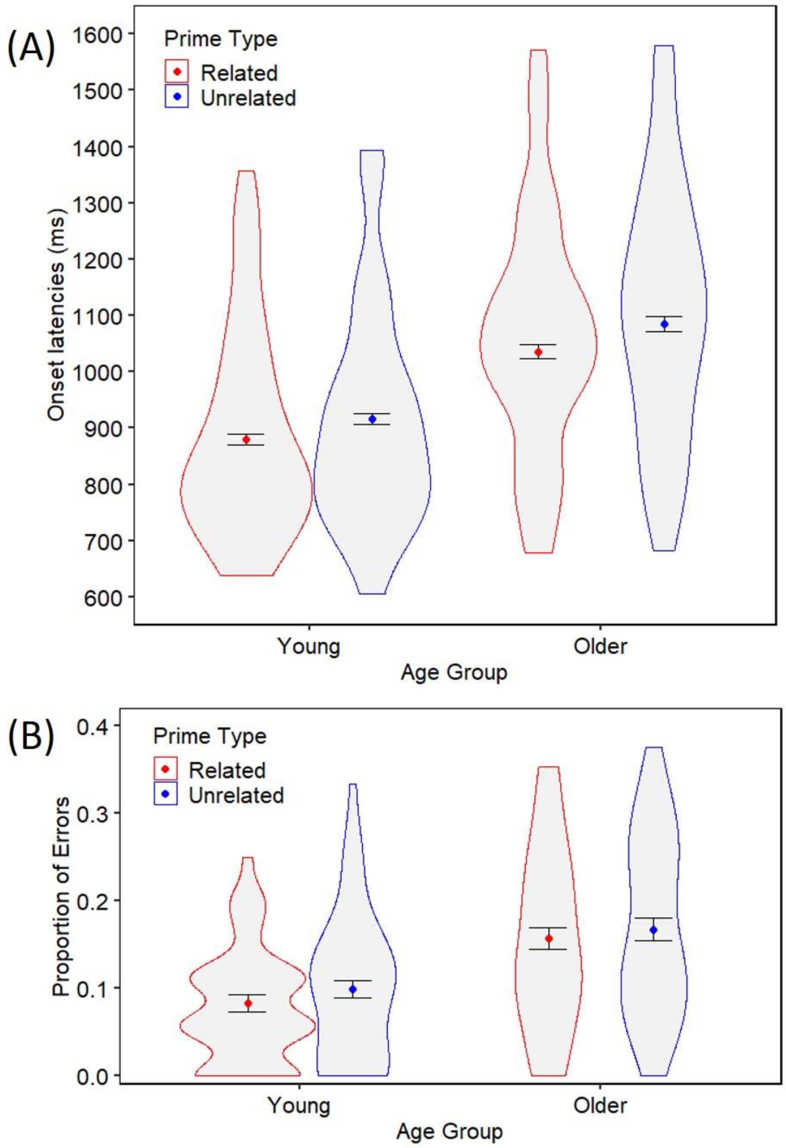

Figure 3.2 *Experiment 1 target onset latencies (A) and errors rates (B) for young and older adults following syntactically related and unrelated primes. The coloured points represent the mean per condition. Error bars denote ±1 the standard error of the mean. Violin spreads represent the distribution of the data across participants.*

3.2.2.3 Summary

The main findings of Experiment 1 are threefold: (1) older adults were slower and more error-prone when producing sentences compared to young adults; (2) our task produced a reliable latency priming effect on the production of target sentences; and (3) there was no age-related effect in the extent to which the speed of syntax generation benefited from repetition of syntactic structure. Together, this suggests that syntactic facilitation effects on onset latencies are preserved with age.

Table 3.2 *Summary of the best-fitted models for the Experiment 1 onset latency data.*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
A: all data				
Intercept	1091.39	22.75	47.97	< .001
Prime type	46.87	12.01	3.90	< .001
Age group	-131.40	29.24	-4.49	< .001
Prime type * Age group	-6.31	19.48	-0.32	.746
B: young adults				
Intercept	981.89	33.63	29.19	< .001
Prime type	34.59	14.22	2.43	.015
C: older adults				
Intercept	1183.26	32.93	35.94	< .001
Prime type	49.11	17.10	2.87	.004

Note. All three models converged with random intercepts for participants and items with additional by-participant and by-item random slopes for the main effects of prime type.

Table 3.3 *Summary of the best-fitted models for the Experiment 1 error data.*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
A: all data				
Intercept	-2.34	0.16	-14.69	< .001
Prime type	-0.14	0.15	-0.90	.369
Age group	-0.76	0.20	-3.74	< .001
Prime type * Age group	0.05	0.28	0.17	.868
B: young adults				
Intercept	-2.69	0.20	-13.70	< .001
Prime type	0.22	0.17	1.34	.181
C: older adults				
Intercept	-1.96	0.18	-10.90	< .001
Prime type	0.10	0.16	0.61	.543

Note. All three models converged with random intercepts for participants and items with additional by-participant and by-item random slopes for the main effects of prime type. The complete dataset model (A) also included a by-item random slope for the main effect of age group.

3.3 Experiment 2: Examining the effect of ageing on on-line planning scope

In Experiment 1, we demonstrated that syntactic processing in both age groups was facilitated by the repetition of syntactic structure, which in turn benefited the speed of sentence production. This is specifically informative about age-related changes in the processes involved in syntactic facilitation at the planning level of sentence generation, as well as the mechanisms that underlie onset latency syntactic priming. In Experiment 2, we investigated older adults' sentence generation in unsupported situations in which sentence production is not primed and the speaker must generate a sentence entirely independently. Moreover, we employed a more complex sentence generation task in which participants produced sentences containing multiple phrases of varying length and complexity (this is in contrast to Experiment 1 where the target sentences all consisted of a single coordinate noun phrase). Within Experiment 2, we were therefore able to investigate age-related changes in incrementality in sentence production – the scope of sentence planning that occurs prior to articulation onset (Kempen & Hoenkamp, 1987; Levelt, 1989).

A number of studies have demonstrated that speakers do not plan all of what they wish to say before beginning speaking, but instead plan and produce a sentence incrementally in smaller word or phrasal units (see Wheeldon, 2013, for a review). An incremental system is beneficial as it allows for the rapid release of parts of the sentence as soon as planning is complete, reducing the demand for storage in working memory. Previous studies have shown that only a small amount of planning is required prior to speech onset, typically the first phrase (Martin et al., 2010, 2014; Smith & Wheeldon, 1999) or even as little as the first word (Griffin, 2001; Zhao & Yang, 2016). Moreover, incremental sentence production enables the processing load to be spread across multiple components and time, thereby further reducing demands on cognitive resources (Levelt, 1989; Wheeldon, 2013). One way to investigate the amount of planning that a speaker engages with prior to articulation is with the *planning scope* paradigm, in which picture displays are used to elicit sentences of different syntactic structures and speech onset latencies are used as an on-line measure of advanced planning. For example, Smith and Wheeldon (1999) found that participants took longer to initiate sentences with larger initial coordinate phrases (2a) compared to smaller initial simple phrases (2b). This suggests that planning scope occurs in phrasal units: when the first phrase (defined as the initial conceptual unit that forms a constituent part of a larger syntactic structure) is larger, speakers need longer to plan the syntax and retrieve the second lexical item before speech onset (see also Levelt & Maassen, 1981; Martin, Miller, & Vu, 2004; Wheeldon et al., 2013).

(2a) “[the dog and the hat move] above the fork”

(2b) “[the dog moves] above the hat and the fork”

Martin et al. (2010, 2014) ruled out an alternative explanation for this effect relating to the visual array (i.e., the grouping of objects moving together) as they found the same phrasal planning scope using stationary pictures arrays (e.g., *“the drum and the package are below the squirrel”*). Moreover, the phrasal planning effect cannot be attributed to the fact that, in English, the second content word in the simple initial phrase (always the verb ‘moves’; 2b) may be easier to retrieve than in the coordinate initial phrase (the second lexical item; 2a) as the effect has been demonstrated when the verb changes from trial to trial (Martin et al., 2010), as well as in Japanese, a head-final language in which the subject and the complement take the first two positions in the sentence regardless of initial phrase type (Allum & Wheeldon, 2007, 2009). A phrasal scope of planning has also been demonstrated for other initial phrase structure, such as adjective-noun phrases (e.g., *"the blue frog is next to the blue mug"*; Wagner, Jescheniak, & Schriefers, 2010). Likewise, speaker have been found to take longer to initiate sentences with more complex initial structures (e.g., *"[the river / the large and raging river / the river near their city] empties into the bay…";* Ferreira, 1991). Nevertheless, the size of speakers' planning scope is not rigidly fixed and can vary due to multiple factors including ease of syntactic processing (Konopka, 2012; Konopka & Meyer, 2014), task complexity (Ferreira & Swets, 2002; Wagner et al., 2010) and cognitive abilities, such as working memory and production speed (Martin et al., 2004; Slevc, 2011; Swets, Jacovina, & Gerrig, 2014; Wagner et al., 2010). Our interest was in whether the scope of advanced sentence planning is also influenced by healthy ageing.

The ageing process is typically associated with an increase in speech dysfluencies during sentence production, such as the use of non-lexical fillers ('uh' or 'um'), word repetitions and unnatural pauses (Bortfeld, Leon, Bloom, Schober, & Brennan, 2001; Horton, Spieler, & Shriberg, 2010; Kemper, Rash, Kynette, & Norman, 1990). One significant factor that has been proposed to account for this age-related increase in speech dysfluencies is a reduction in the capacity and efficiency of working memory (Abrams & Farrell, 2011; Kemper & Sumner, 2001). This is because verbal working memory is essential for being able to successfully prepare more than one word before beginning articulation (Martin et al., 2004; Slevc, 2011) and for temporarily storing information that is needed for later syntactic processing, such as when producing an embedded clause sentence (Kemper, Kynette, Rash, O'Brien, & Sprott, 1989; Rabaglia & Salthouse, 2011). This suggests that incremental sentence planning processes may become less efficient with age (as the result of declining working memory) or that older adults may adopt different processing strategies when planning a sentence in order to compensate for age-related deficits in working memory. We therefore used the planning scope paradigm to investigate age-related changes in the amount of advanced planning that older speakers engage with prior to articulation.

Based on previous literature, we consider that there are two alternative hypotheses for age-related changes in planning scope. Firstly, a decline in working memory with age may disrupt older adults' ability to plan sentences with larger initial phrases. Martin et al. (2004)

found that an aphasia patient with a semantic working memory deficit displayed a greater phrasal complexity effect than controls (i.e., a markedly greater difference in the speed of production of larger, compared to smaller, initial phrases), which they attributed to the patient attempting to plan both nouns in the initial phrase, but having difficulty doing so because of deficits at the lexical-semantic level (see also Lee & Thompson, 2011).[12] Although not as profound as aphasia patients, older adults also experience deficits in working memory (particularly at the verbal level; Bopp & Verhaeghen, 2005). Thus, one hypothesis is that older adults will display a larger phrasal complexity effect than young adults in the planning scope task. Alternatively, to compensate for decline in working memory, older adults may adopt a more extreme word-by-word incremental strategy (i.e., only plan the first word before speech onset regardless of the complexity of the initial phrase). Ferreira and Swets (2002) found that when time pressure was applied, speakers engaged in significantly less advanced planning, suggesting that incremental planning can be strategically controlled by the speaker. This, combined with the evidence that older adults implement various strategies in other areas of language processing (Altmann & Kemper, 2006; Stine-Morrow et al., 2008), may mean that there is a strategic age-related decrease in the amount of advanced planning that occurs prior to articulation.

In Experiment 2 we further aimed to directly investigate age-related changes in the retrieval of lexical items and their integration into syntactic structures. Lexical retrieval and syntax generation do not rely on the exact same mechanisms, and may even be entirely dissociated (Chang et al., 2000, 2006). Thus, evidence of age effects in syntactic processing does not necessarily mean that age effects will also be observed in lexical processing (or vice-versa). One way to examine lexical processing during sentence production is to incorporate a picture preview element into the planning scope paradigm. Wheeldon et al. (2013) required participants to produce sentences similar to (2a) and (2b), but on some trials there was a preview of one of the upcoming pictures. They found that previewing the second to-be-produced lexical item (*hat* for the examples shown in 2) decreased onset latencies more when

[12] We note that both of these studies did include non-young adults as controls for aphasia patients; however, the sample are small and the age ranges large (Lee & Thompson, 2011, n = 9 aged 48-73; Martin et al., 2004, n = 10 aged ~55-66), making it difficult to draw any firm conclusions about age-related effects on incremental sentence planning.

it fell within, rather than outside of, the initial phrase. Moreover, Allum and Wheeldon (2009) observed similar latency preview benefits when the preview was presented either in pictorial or written word form, indicating that preview of pictured objects results in lexical access of the name associated with the picture. Together, these findings suggest that the retrieval of lexical items within the first phrase is prioritised prior to speech onset. Nevertheless, the preview benefit is not reliably maintained when the phrase consisted of three nouns and participants previewed the third lexical item (*"[the drum, the star and the* ***hat*** *move] above the crab"*; Wheeldon et al., 2013). Thus, it appears that advanced lexical planning only encompasses a subset of the required nouns and that this does not always align with scope of syntactic planning.

In Experiment 2 we therefore included a picture preview element within the planning scope task; the magnitude of the preview benefit displayed by older adults will be informative about age-related changes in lexical processing during sentence planning and production. Young adults' preferred scope of lexical encoding appeared to be two items (Wheeldon et al., 2013); however, we speculate that older adults' preferred limit may be less because they have a reduced memory buffer for holding linguistic information (Bopp & Verhaeghen, 2005; Waters & Caplan, 2003). Attempting to retrieve and hold an unmanageable number of lexical items prior to articulation can lead to problems with buffering and maintaining a linearized output (Slevc, 2011; Wheeldon et al., 2013). To overcome this and reduce demands on working memory, older adults may therefore only encode the first lexical item within a phrase prior to articulation; if this is the case, we may expect that, unlike young adults, older adults will not display the preview benefit of the second lexical item even when it falls within the initial phrase.

3.3.1 Experiment 2: Method

3.3.1.1 Participants

The same participants were used as described in Experiment 1.

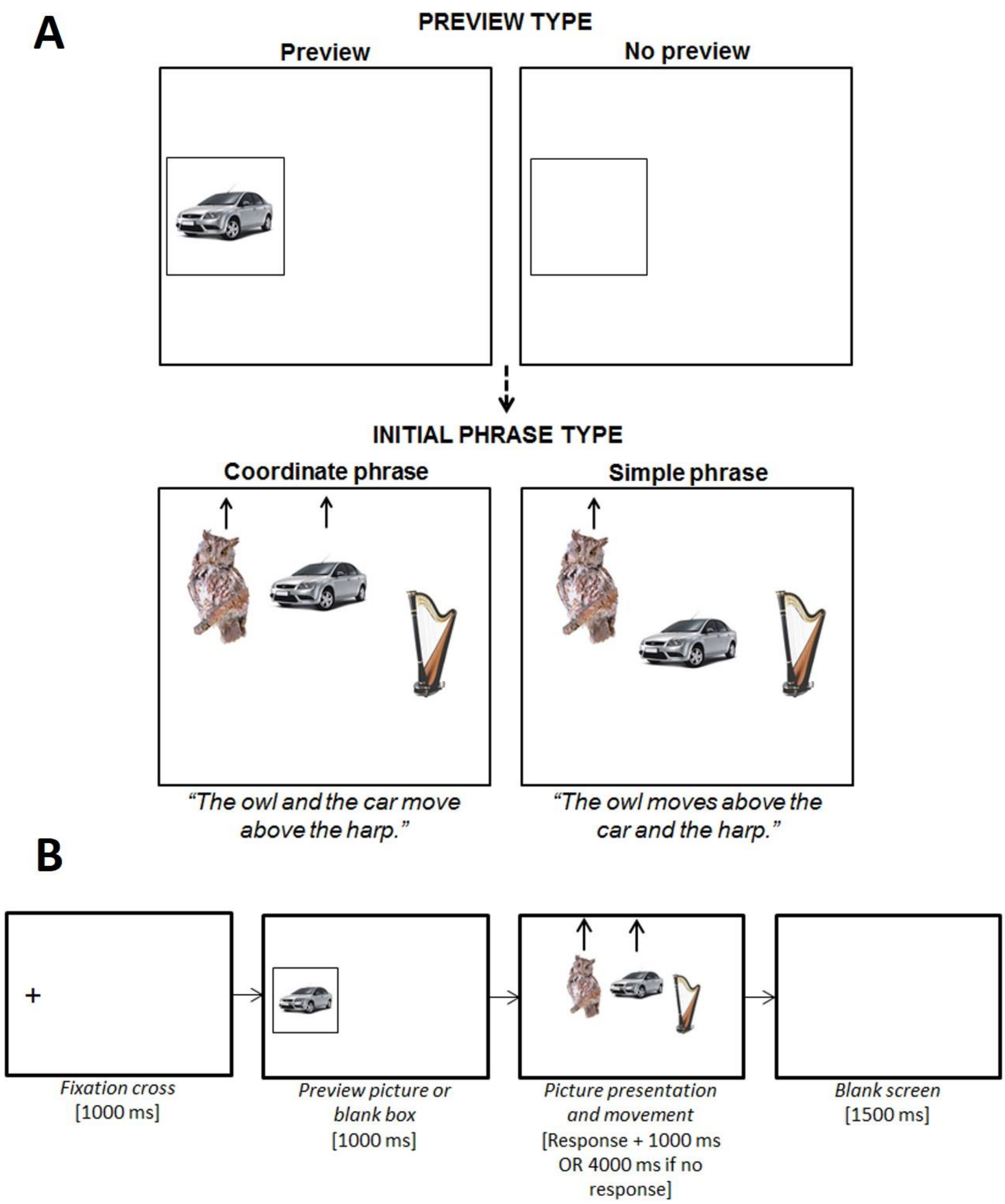

Figure 3.3 *Experiment 2 planning scope design (A) and stimuli presentation events per trial (B). The participant was instructed to pay attention to the preview because it would appear in the upcoming trial, but not to name it aloud. The three pictures then appeared aligned centrally in the horizontal plane (importantly, the leftmost picture did not appear where the preview picture had just been, but in a more right-adjusted position). The participant was instructed to begin describing the picture movement as soon as possible using specific sentence types. Speech latencies were recorded from the onset of the pictures to the participant beginning to speak.*

3.3.1.2 Design

We used a 2 X 2 X 2 mixed design with one between-participant variable of age (young vs. older) and two within-participant variables of preview (no preview vs. preview) and initial phrase type (coordinate vs. simple). Hence, there were four experimental task conditions (**Figure 3.3.A**). Critically, the previewed picture (always of the second upcoming lexical item) fell within the initial phrase in the coordinate condition, but outside of the initial phrase in the simple condition.

3.3.1.3 Materials

To create the experimental items, we used 80 photographic pictures of everyday concrete objects (these were different to those used in Experiment 1, but meet the same criteria). We created 80 experimental items that each consisted of three different pictures that were conceptually and phonologically distinct: each of the 80 pictures appeared in three different experimental items (once in the left, central and right position). As in Experiment 1, the sentence descriptions of the items were elicited by controlling the movement of the pictures (using E-prime) and participants were instructed to describe the picture movements from left to right using specific sentences. In the simple initial phrase conditions, only the left picture moved (either up or down) and the other two pictures remained stationary (*"the A moves above/below the B and the C"*). In the coordinate conditions, both the left and the central picture moved simultaneously (either up or down) and only the right picture remained stationary (*"the A and the B move above/below the C"*). In the preview trials, the preview was always of the central upcoming picture (i.e., object *B*). We created four item lists by evenly rotated the experimental condition assigned to each of the 80 experimental items. Each participant was randomly assigned to one of the four lists and completed 20 experimental items per condition (in line with Simmons et al.'s, 2011, recommendations; **Table 3.1.B**).

Lastly, we used a further 106 pictures to create 220 filler items designed to prevent the participant from anticipating the location of the preview picture and building expectations to guide their response. The fillers elicited some experimental-type sentences and other sentences that differed from the experimental items in terms of the number of pictures and the type of movement, such as: *"there is an X, a Y and a Z"* (no picture movement); *"the Xs move up"* (three repeat pictures move simultaneously); and "*there are no pictures"*.

Importantly, we also varied the position of the preview pictures within the fillers, such that across all the experimental and filler items each screen position was previewed an equal number of times. All 220 filler items were added to each of the four item lists. We then divided each list into five blocks that each contained 44 fillers and 16 experimental items (4 per condition), and pseudorandomised the order of items using the same constraints as Experiment 1. The ordering of the blocks was rotated across participants.

3.3.1.4 Procedure

Each participant was tested using the same equipment set-up described in Experiment 1. **Figure 3.3.B** illustrates the sequence of stimuli presentation per trial. In the preview trials, the previewed picture was presented for 1000ms: the participant was instructed to pay attention to the preview because it would appear in the upcoming trial, but not to name it aloud. To begin, there were 40 practice trials; the sentences elicited resembled those in the experimental and filler trials and featured all 80 experimental pictures once. During the practices, the experimenter corrected the participant if they made a lexical or syntactic error. The task then continued until all experimental five blocks had been completed. Using the same criteria described in Experiment 1, the experimenter noted down any errors made by the participant.

3.3.1.5 Data preparation and analyses

One older adult was excluded from Experiment 2 because of error rates above 50% on the experimental trials. Of the 8400 experimental trials, we applied the same onset latency exclusion criteria described in Experiment 1, resulting in the discarding of 124 (3.1%) young and 166 (3.8%) older adult trials. All remaining trials were used in the error analyses, but only correct responses (81.7% of trials) were used in the onset latency analyses.

The data from Experiment 2 were analysed using the same generalised linear mixed-effects modelling methods described in Experiment 1 (a binomial distribution fitted to the error data and an inverse gaussian distribution fitted to the onset latency data). We entered age group (young vs. older), initial phrase type (coordinate vs. simple) and preview type (no preview vs. preview) into the models as fixed effects. We included random intercepts for participants and items, as well as by-participant and by-item random slopes appropriate for the design. In the case of non-significant interaction involving age group, we used Bayesian analysis to quantify the likelihood of the null effect.

3.3.2 Experiment 2: Results

Figure 3.4 summarises the onset latencies and error rates across the four experimental conditions for young and older adults.

3.3.2.1 Onset latencies

The best-fitting model of the onset latency data is reported in **Table 3.4.A**. As in Experiment 1, older adults were significantly slower than young adults (991ms vs. 843ms, $p < .001$). There was a main effect of initial phrase type, such that sentences with initial simple phrases were produced significantly quicker than sentences with initial coordinate phrases (895ms vs. 935ms, $p < .001$), indicating an overall phrasal planning effect of 40ms (4.5%). Furthermore, the interaction between initial phrase type and age group was not significant (p =. 994), indicating that the incremental planning effect was unaffected by healthy ageing, as was supported by an 'extremely strong' Bayes Factor (BF) value (0.004). Indeed, separate age group analyses confirmed that the phrasal planning effect was highly significant for both young (40ms, 4.6% benefit, $p < .001$) and older (41ms, 4.0% benefit, $p < .001$) adults.

The analyses further revealed a main effect of preview, such that sentences were produced significantly quicker following preview of the second upcoming lexical item compared to no preview (890ms vs. 939ms, $p < .001$), indicating an overall preview benefit of 49ms (5.5%). Interestingly, there was a significant interaction between preview and age group ($p = .036$), such that the preview benefit was larger for young (62ms, 7.6%), compared to older (33ms, 3.4%), adults. Moreover, there was a significant interaction between preview and initial phrase type ($p < .001$): the overall preview benefit was significantly greater when the preview picture fell within the initial phrase (coordinate condition; 74ms, 7.6%) compared to outside of it (simple condition; 26ms, 2.9%).

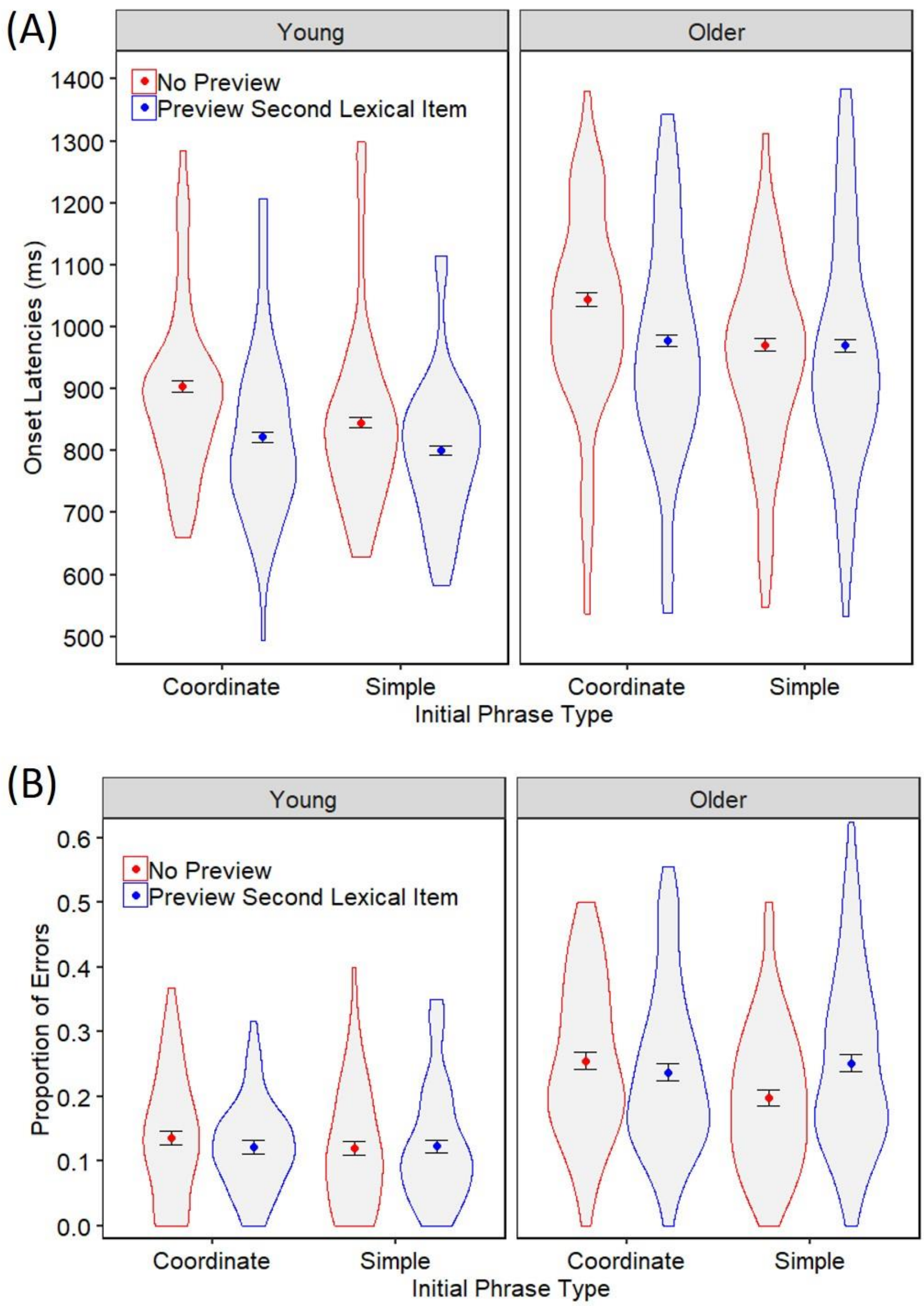

Figure 3.4 *Experiment 2 onset latencies (A) and errors rates (B) for young and older adults when producing sentences with initial coordinate and simple phrases following no preview or a preview of the second upcoming lexical item. The coloured points represent the mean per condition. Error bars denote ±1 the standard error of the mean. Violin spreads represent the distribution of the data across participants.*

Table 3.4 *Summary of the best-fitted models for the Experiment 2 onset latency data.*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
A: All data				
Intercept	1008.53	14.44	69.86	< .001
Preview	-57.60	8.73	-6.60	< .001
Initial phrase type	-43.33	6.91	-6.27	< .001
Age group	-132.07	16.07	-8.22	< .001
Preview * Initial phrase type	51.01	8.77	5.82	< .001
Preview * Age group	-25.26	12.03	-2.10	.036
Initial phrase type * Age group	0.29	11.52	0.03	.980
Preview * Initial phrase type * Age group	-22.09	14.25	-1.55	.121
B: Young Adults				
Intercept	911.75	28.52	31.97	< .001
Preview	-67.95	16.36	-4.15	< .001
Initial phrase type	-44.74	9.49	-4.72	< .001
Preview * Initial phrase type	40.68	16.98	2.40	.017
C: Older Adults				
Intercept	1109.87	21.08	52.66	< .001
Preview	-43.59	18.05	-2.41	.016
Initial phrase type	-39.42	11.66	-3.38	< .001
Preview * Initial phrase type	60.56	14.26	4.25	< .001

Note. All three models converged with random intercepts for participants and items with additional by-participant random slopes for the main effects of preview and initial phrase type, and a by-item random slope for the main effect of preview.

Although the three-way interaction between preview, initial phrase type and age group did not reach significance (p = .121), the Bayesian analysis provided inconclusive evidence in support of the null hypothesis (BF = 0.141). Moreover, separate age group analyses (**Tables 3.4.B and 3.4.C**) suggest that the significant difference in the preview effect for young and older adults may have been driven by more complex effects at the phrase level. Both young (p

= .017) and older (p < .001) adults showed a significant interaction between phrase type and preview; however, this may represent different pattern of effects for each age group (see **Figure 3.4A**). Further post-hoc pairwise comparisons revealed that for young adults there was a significant benefit of preview in both the coordinate (81ms (8.9%), $\chi^2(1) = 18.20$, $p < .001$) and simple (45ms (5.3%), $\chi^2(1) = 9.03$, $p = .002$) phrase conditions, although the magnitude of the effect was distinctly larger when the preview fell within the initial phrase.[13] By contrast, the difference in onset latencies between preview conditions was only significant for the older adults when it fell within the initial phrase (67ms (6.4%) preview benefit; $\chi^2(1) = 15.18$, $p < .001$), but not outside of it (2ms (0.2%) preview benefit; $\chi^2(1) = 0.45$, $p = .502$).

3.3.2.2 Error rates

The best-fitting model of the error data is reported in **Table 3.5.A**. As in Experiment 1, older adults were significantly more error-prone than young adults (23.5% vs. 12.5%, p < .001). While there were no main effects of preview (p = .308) or initial phrase type (p = .097), there was a significant interaction between the two variables (p = .040): the presence of the preview resulted in a 1.6% decrease in participants' errors when producing sentences with initial coordinate phrases, but a 2.9% increase in errors when producing sentences with initial simple phrases. There was no significant interaction between phrase type and age group (p = .747; supported by an 'extremely strong' BF value of 0.009) or between preview and age group (p = .292; supported by an 'very strong' BF value of 0.017). There was also no interaction preview, initial phrase type and age group (p = .295); however, in the case of this 3-way interaction, the Bayesian analysis provided inconclusive support for the null hypothesis (BF = 0.190).

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[13] For the post-hoc analyses, we used the *'testInteractions'* function in the *phia* package (de Rosario-Martinez, 2015a, 2015b), which allows for the direct comparison of contrasts specified within an existing mixed-effect model. Importantly, the *'testInteractions'* function corrects p values for multiple comparisons using the Holm-Bonferroni method (adjusts the criteria of each individual hypothesis), thereby reducing the risk of discovering a false positive result (Aickin & Gensler, 1996; Holm, 1979).

Table 3.5 *Summary of the best-fitted models for the Experiment 2 error data.*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
A: All data				
Intercept	2.02	0.15	13.62	< .001
Preview	-0.07	0.07	-1.02	.308
Initial phrase type	0.12	0.07	1.66	.097
Age group	0.89	0.16	5.70	< .001
Preview * Initial phrase type	-0.28	0.14	-2.06	.040
Preview * Age group	0.14	0.14	1.05	.292
Initial phrase type * Age group	-0.04	0.14	-0.32	.747
Preview * Initial phrase type * Age group	0.29	0.27	1.07	.285
B: Young Adults				
Intercept	-2.50	0.17	-14.65	< .001
Preview	0.06	0.12	0.51	.607
Initial phrase type	-0.14	0.12	-1.16	.245
Preview * Initial phrase type	0.20	0.21	0.93	.352
C: Older Adults				
Intercept	-1.59	0.17	-9.18	< .001
Preview	0.12	0.09	1.42	.154
Initial phrase type	-0.12	0.09	-1.39	.163
Preview * Initial phrase type	0.41	0.17	2.41	.016

Note. All three models converged with random intercepts for participants and items with additional by-participant random slopes for the main effects of preview and initial phrase type. The complete dataset model (A) also included a by-item random slope for the main effect of age group.

Further insight into possible age-related effects may be gleamed from separate age group analyses (**Tables 3.5.B and 3.5.C**). This revealed that the interaction between preview and initial phrase type remained significant for older adults (p = .016), but not for young adults (p = .352). This suggests that young adults' error rates were fairly stable across conditions; whereas, the proportion of errors produced by older adults differed between phrase types dependent on whether the preview was present. Further post-hoc comparisons revealed that there was no effect of preview on older adults' error rates when the it fell within the initial phrase (coordinate condition; $\chi^2(1) = 0.32$, $p = .570$), but that the presence of the preview caused a significant 5.3% increase in errors when it fell outside of the initial phrase (simple condition; $\chi^2(1) = 8.35$, $p = .003$).

3.3.2.3 Summary

The main findings of Experiment 2 can be summarised as follows: (1) as in Experiment 1, older adults were slower and more error-prone than young adults; (2) our task elicited a reliable phrasal planning scope effect that was unaffected by healthy ageing; and (3) while young adults' displayed speed benefit of preview in both phrase conditions, older adults only benefited when the preview fell within the initial phrase and produced significantly more errors when the previewed lexical item fell outside of the initial phrase. Together, this suggests that there are age group differences in lexical processing during sentence planning, which only emerged when the preview fell outside of the initial phrase. It should be noted, however, that a potential caveat of our findings is that we did not find a higher-order interaction between age group, preview and initial phrase type (and the following Bayesian analysis did not provide conclusive support for either the null or the alternative). As such, our post-hoc analyses should be considered somewhat exploratory in nature and we emphasise the need for replication in future studies. Nonetheless, we do still consider our findings to provide a valuable and interesting insight into possible age group differences. Indeed, Fiedler, Kutzner, and Krueger (2012) argue that is important to rigorously explore all possible findings within a dataset, even when they are accompanied by some apparently null results, in order to prevent against the risk of a false negative (the discovery of a false null result) (see also Wei, Carroll, Harden, & Wu, 2012).

3.4 General discussion

Using two on-line experiments, we investigated age-related changes in the syntactic and lexical processes involved in sentence generation. In Experiment 1, both young and older adults produced target sentences quicker following syntactically related primes, demonstrating that speed benefits of syntactic priming are preserved with age, despite older adults' slower and more error-prone production. In Experiment 2, both young and older adults initiated sentences quicker with smaller, compared to larger, initial phrases, suggesting that planning scope, at least at the syntactic level, is unaffected by healthy ageing. Evidence of age-related differences did emerge, however, in the preview conditions, such that young adults displayed a significantly larger preview benefit than older adults (quicker to initiate sentences when there was a preview of an upcoming lexical item). Moreover, post-hoc analyses demonstrated that, while young adults displayed speed benefits of preview when the pictured word fell both within and outside the initial phrase, older adults only displayed speed benefits from the previewed picture when it fell within the initial phrase, and preview outside of the initial phrase caused them to become more error-prone. This suggests that age differences may exist in the flexibility of lexical retrieval during sentence planning and in the ability to integrate lexical information into syntactic structures. Taking both experiments together, our study therefore suggests age-related effects of lexical, but not syntactic, processes on the speed and accuracy of sentence production.

Our robust finding of equal onset latency priming in both age groups in Experiment 1 (supported by both traditional null hypothesis testing and Bayesian analysis) provides the first evidence that syntactic facilitation effects are preserved with age in a task specifically designed to tap into the processes involved in the planning stage of sentence production. Applied to Segaert's et al. (2016) two-stage competition model, this suggests that older adults maintain the ability to quickly and efficiently generate previously activated syntactic structures. This is somewhat contrary to our initial hypothesis that overall decline in processing and transmission speed with age would result in decreases in the spreading activation architecture that supports syntactic priming (MacKay & Burke, 1990; Salthouse, 1996). Instead, the slowing associated with ageing might not affect all cognitive networks equally (Fisher et al., 2000; Fisk et al., 1992). Thus, despite general slowing elsewhere, older adults appear to maintain sufficient cognitive resources to support successful syntactic priming. This is consistent with the evidence of priming benefits in older adults in other areas of language processing, such as semantic priming (Burke, White, & Diaz, 1987; Laver & Burke, 1993) and morphological priming of both regularly-inflected verbs and transparent compounds (Clahsen & Reifegerste, 2017; Duñabeitia et al., 2009; Reifegerste et al., 2018). Together with our findings, this indicates that models of language and ageing should account for the effects of process-specific, rather than general, cognitive slowing (see Laver & Burke, 1993, for a more extensive discussion).

Nevertheless, it is important to consider that we found evidence of preserved latency priming effects in older adults in a task in which the demands were relatively low: participants only needed to dedicate minimal cognitive resources to syntactic selection (because we removed the choice element) and we did not manipulate the ease of lexical encoding. According to Peelle (2019), the relationship between cognitive supply and task demands would still therefore have been balanced in favour of good behavioural performance in older adults, despite likely declines in overall cognitive capacity. It therefore remains unclear whether latency priming effects would continue to be observed in older adults in a task in which demands are increased (e.g., by manipulating the codability of the nouns). Moreover, the consideration of task demands vs. cognitive supply may also be necessary for clarifying the mixed findings within the existing choice syntactic priming and ageing literature (Hardy et al., 2017, 2019; Heyselaar et al., 2017; Sung, 2015, 2016). There are minimal methodological differences between the various studies (all used a picture description production task); however, it remains possible that differences in the characteristics of the samples, such as education level and native language use, may have resulted in differences in processing efficiency between the older adult groups, leading to different behavioural findings between studies (Peelle, 2019). Unfortunately, this information is unavailable for previous studies, meaning such a comparison is not possible. This highlights why it is important for future research to collect individual differences data, as well as age group information, when investigating what determines latency and choice syntactic priming.

Turning now to the findings of Experiment 2, the pattern we observed in the onset latencies is similarly consistent with an age-related preservation of syntactic processing skills as we found robust evidence of a phrasal scope of planning in both age groups: speakers took longer to initiate sentences with larger initial phrases. This replicates previous research in young adults (e.g., Martin et al., 2010, 2014; Smith & Wheeldon, 1999), and suggests that both age groups prioritised the generation of syntax within the first phrase prior to articulation. It is notable that older speakers did not experience disproportionate difficulty in planning the larger initial phrases (as has been observed in aphasia patients; Martin et al., 2004), indicating that although ageing is associated with decline in general cognitive function, this is not substantial enough to cause age-related deficits in incremental sentence production. Moreover, our findings demonstrate that older adults do not actively engage in a more extreme word-by-word planning strategy (if this was the case, latencies would have been similar for simple and coordinate initial phrases), further suggesting that older adults maintain sufficient cognitive capacity to support the planning of an initial phrase containing at least two nouns. Spieler and Griffin (2006) also found no differences in the sentence planning strategy used by young and older adults; however, they found that both age groups planned in single word, not phrasal, units. This apparent contrast to our findings can likely be explained by the different measurements used; specifically, while our use of onset latency measures provided insight into the preparation time before sentence articulation, Spieler and Griffin's (2006) use of eye-tracking focused more on the gaze shifts that occur during articulation and which are tightly locked to individual word onset. Nevertheless, both findings indicate that there are minimal age group differences in on-line syntactic processing, as has been found in other studies in which participants are presented with different words on screen and asked to formulate a sentence (Altmann & Kemper, 2006; Davidson et al., 2003).

An important point to make, however, is that the minimal age group differences we observed in syntactic planning do not necessarily mean that young and older adults were engaging the exact same cognitive networks when performing the task. While young adults may be predominantly relying on activity in the left anterior temporal lobe to support incremental sentence planning (Brennan & Pylkkänen, 2017), older adults may be recruiting additional areas outside of the core language network to support performance (in the same way as has been observed for other aspects of language processing; Peelle et al., 2010; Wingfield & Grossman, 2006). Further work is therefore needed to fully understand the age-related changes in the neural networks that underlie incremental sentence planning. Indeed, evidence of age group differences did emerge due to the picture preview manipulation, suggesting that young and older adults may be adopting different strategies relating to lexical processing, a finding we turn to next.

In Experiment 2, half of the experimental trials were preceded by a picture of the upcoming second lexical item. Overall both age groups were quicker to initiate sentences when there was a preview compared to no preview; however, the magnitude of the preview benefit was significantly greater for young, compared to older, adults. This suggests possible age-related effects in speakers' abilities to incorporate previewed lexical information into their sentence planning. Moreover, further post-hoc analyses suggest that age group differences in the preview benefit may have been driven by more complex effects at the phrase level. To first consider when the previewed picture fell within the initial phrase (*"[the owl and the* ***car*** *move] above the harp"*), we found that both young and older adults were quicker to initiate the sentence when there was a preview, compared to no preview, suggesting that the prior retrieval of the lexical item was significantly benefiting their sentence planning at the lexical encoding level (Allum & Wheeldon, 2009; Wheeldon et al., 2013). However, to now consider when the previewed picture fell outside of the initial phrase (*"[the owl moves] above the* ***car*** *and the harp"*), some interesting age group differences did emerge in participants' onset latencies and error rates. While young adults continued to displayed speed benefit of preview outside the initial phrase (albeit to a lesser extent than when it fell within the initial phrase), older adults did not display any speed preview benefits outside of the initial phrase, and the presence of the picture preview outside their preferred phrasal planning scope caused them to become significantly more error-prone. Importantly, this increase in error rates for the older adults is unlikely to relate to specific issues with picture naming and syntax selection due to the large number of practices completed prior to the experimental task (during which the experimenter corrected the participant if they used an incorrect picture name or sentence type), but more due to disruption during the sentence planning process. Taken together, the onset latency and error data therefore suggest that, unlike young adults, older adults did not benefit from this early access to lexical information and that instead this premature availability had a disruptive effect on their overall fluency.

One explanation for this age group difference relates to age-related differences in the flexibility of the sentence planning process. The fact that young adults displayed significant preview benefits in both phrase conditions, but to a greater extent when the preview fell within the initial phrase, suggests that they prioritised the retrieval of lexical items within the first phrase prior to articulation, but they were also able to successfully manage the early activation of lexical items outside of their usual phrasal planning scope to benefit their overall speed of sentence production. This evidence of adaptability within young adults' planning scope adds to the growing evidence that planning scope is flexible and can be influenced by the ease of syntactic and lexical processing (Konopka, 2012; Konopka & Meyer, 2014; van de Velde & Meyer, 2014). By contrast, older adults' planning scope appears to be a lot more rigidly fixed to phrasal boundaries, such that they are less adaptable when it comes to integrating new lexical information into syntactic structures. Indeed, older adults show less parafoveal preview effects across syntactic pauses than young adults during sentence comprehension, suggesting an age-related segmentation strategy designed to aid syntactic processing (Payne & Stine-Morrow, 2012, 2014; Stine-Morrow & Payne, 2016). This segmentation strategy may also apply to older speakers' sentence production; specifically, in an attempt to decrease processing demands, older adults may strategically choose to only attend to lexical information when it is relevant (i.e., only when it is contained within the next to-be-produced phrase). Thus, older adults are less able to successfully incorporate lexical information outside of the initial phrase into their sentence planning. This contrast between the flexible sentence planning approach observed in the young adults and the rigid approach in older adults further highlights how apparently similar behaviour in both age groups (i.e., both displayed a phrasal scope of planning) may be supported by different cognitive networks and processing strategies.

A second explanation for the age-related difference in lexical processing that we observed involves the executive control required to successfully manage the premature access to lexical information. During picture preview, participants automatically access some lexical information about the pictured item which would be stored in their working memory. Given that young and older speakers display preview benefits within the first phrase, we consider it likely that participants had sufficient time to access the lemma corresponding to the picture name. Critically, participants would have done this for all preview pictures since the syntactic structure and position of the previewed lexical item in the upcoming trial was unpredictable (due to the use of a lot of filler items and stringent counter-balancing). However, if the previewed lexical item does not appear in the first phrase, participants must temporarily inhibit this information in order to prevent it from interfering with the retrieval of the first (unpreviewed) lexical item and planning of the initial phrase. Therefore, when the previewed lexical item falls outside of the initial phrase, there is increased demand on the cognitive resources, in particular inhibitory control, that support the processes involved in maintaining a linearized output. Young adults appear to be very good at coping with this increased demand as they even benefit from the preview information when it is required in the planning of the second phrase.

By contrast, older adults show no speed benefits of the previewed picture when it falls beyond the initial phrase, and instead the presence of the preview caused them to become significantly more error-prone. Theoretical accounts propose that ageing weakens the inhibitory processes that are responsible for regulating what information enters and leaves working memory (Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988). Specifically, if older adults are less able to engage the required level of inhibitory control, the balance between processing efficiency and task demands will move to favour the latter, resulting in increased interference effects and poorer behavioural performance (Peelle, 2019). Indeed, deficits in inhibitory control have been used to explain other age effects on language processing, such as older adults having increased difficulty ignoring distracting or irrelevant information during speech comprehension and production (Britt, Ferrara, & Mirman, 2016; Sommers & Danielson, 1999; Tun, O'Kane, & Wingfield, 2002). Deficits in inhibitory control may therefore offer a possible explanation for our findings as, if the older adults were less able to inhibit irrelevant lexical information during the planning of the first phrase, this would lead to increased problems with formulating a linearized output, resulting in increased errors. Nonetheless, without evidence of a direct link between participants' task performance and individual measures of inhibitory control, such an explanation remains speculative. Within the Supplementary Measurements of this study, we did include eight individual difference measures, such as inhibition, as additional predictors in the two experimental sentence production tasks. However, this do not produce any notable results, something which we likely attribute to our use of a single measurement per construct and the inherent difficulties involved in measuring individual differences within a factorial design (the Supplementary Measurements contain a more in-depth discussion of this point; see **Appendix**). Further work, employing a large battery of inhibition measures, is therefore required to test more directly whether there is a relationship between inhibitory control and lexical planning in healthy ageing.

In summary, our study is the first to examine age-related changes in syntactic and lexical processing during sentence production using on-line onset latency measures. Specifically, our study provides evidence for the age-related preservation of syntactic processing (as evident in the syntactic priming and phrasal planning scope effects we observed in both age groups), but an increased difficulty with lexical retrieval and integration with age (older adults displayed less benefits of preview, particularly when the previewed lexical item fell outside of the initial phrase). We attribute this apparent age-related decline in lexical processing to a decline in the flexibility of sentence planning processes, in particular in speakers' ability to incorporate novel lexical information into their sentence planning. This may be related to older speakers' stronger preference for segmentation at phrasal boundaries when planning a sentence (a strategic approach designed to minimise processing demands) and/or to a decline in executive control making older speakers less able to cope with premature lexical activation beyond the first phrase. Our findings should be considered in parallel with off-line studies of language and ageing in order to gain a more complete picture of language processing in old age, in terms of which processes are preserved and which decline.

CHAPTER 4

Age-related Disruption in the Use of Lexical Information During Sentence Production, Despite Preserved Syntactic Planning

We investigated the effect of healthy ageing on the lexical and syntactic processes of sentence production. Participants produced two-noun sentences that contained semantically related or unrelated lexical items, and initial simple or coordinate noun phrases. Both age groups were slower to initiate sentences with larger initial phrases, indicating a similar planning scope. Young adults displayed similar semantic interference effects in both phrase conditions, whereas older adults displayed larger interference effects when the nouns were in different phrases (initial simple condition). Thus, while syntactic planning appears preserved with age, older adults encounter problems managing the temporal flow of lexical information.

Online publication:
Hardy, S. M., Segaert, K., & Wheeldon, L. (submitted). Age-related disruption in the use of lexical information during sentence production, despite preserved syntactic planning. *Pre-print available on PsyArXiv*, https://psyarxiv.com/xrbta.

Data availability: The complete dataset of the study is provided online on the Open Science Framework (https://osf.io/rwav9/).

4.1 Introduction

Successful communication requires the conceptualisation of a pre-verbal message and the formulation of a corresponding utterance (Bock & Levelt, 1994; Levelt, 1989). At the sentence level, the formulation process involves the rapid retrieval of lexical items and the generation of an appropriate syntactic structure, which must be integrated correctly to convey the intended message. Moreover, the planning of the linguistic output continues to unfold during articulation (Kempen & Hoenkamp, 1987). As we age, cognitive and neuroanatomical changes occur, such as declines in inhibitory control and grey matter volume, which create challenges for language processing (Coxon, van Impe, Wenderoth, & Swinnen, 2012; Good et al., 2001). This may lead to age-related changes in the processes involved in speech planning and production (Peelle, 2019). In this study, we investigated how lexical retrieval and syntax generation are affected by healthy ageing.

When a word is selected for production, lexical representations of semantically similar words (e.g., cat-dog) are also activated (Dell, 1986; Levelt et al., 1999; Rapp & Goldrick, 2000; Roelofs, 1992). The exact nature of this spreading activation architecture is debated (for a recent review, see Roelofs & Ferreira, 2019), but, in order to maintain speech fluency, a speaker must prevent the activation of a semantic competitor from interfering with lexical retrieval and sentence production. Given that the ability to deal with distracting information typically declines with age, possibly relating to a decline in inhibitory control, it follows that older adults may experience increased interference from semantic distractors during speech production (Hasher & Zacks, 1988). However, the evidence is mixed: while some studies have found older adults' speech is slowed due to competition from a near semantic neighbour (Britt et al., 2016; LaGrone & Spieler, 2006) or auditory distractor (Taylor & Burke, 2002), others have found no age differences in semantic interference effects during picture naming (Belke & Meyer, 2007; Burke, 2002; Gordon & Cheimariou, 2013; Mulatti, Calia, De Caro, & Della Sala, 2014; Tree & Hirsh, 2003). Notably, these studies have largely investigating lexical competition effects at the single word level; however, words are rarely produced in isolation, instead they are usually constituent parts of a larger sentence structure. We therefore investigated the effect of lexical competition on older adults' sentence planning in order to provide novel insight into the debate surrounding lexical competition and healthy ageing.

One way to investigate semantic interference at the sentence production level is to use the classic picture-word interference paradigm, in which pictures and words are presented simultaneously (Glaser & Düngelhoff, 1984; Schriefers et al., 1990), but to adapt it to elicit sentences, instead of single words. For example, Smith and Wheeldon (2004) presented participants with moving picture and written word pairs that were either semantically related (watch-clock) or unrelated (watch-hippo) and instructed participants to produce sentence descriptions (e.g., *"the watch and the clock move up"*). The first item to be named was always the picture, but given that reading is such a fast and automatic process (LaBerge & Samuels, 1974; Sadoski & Paivio, 2007), speakers also accessed the lexical information relating to the written word prior to speech onset. The task therefore tests how speakers deal with the concurrent activation of semantic competitors during sentence production. They found that speakers were slower to initiate sentences when the initial phrase contained semantically related, compared to unrelated, nouns. Speech onset latencies are informative about the time-course of the sentence planning process, since speakers take longer to begin speaking when a greater amount of pre-processing is required (Levelt, 1989; Wheeldon, 2013). The findings of Smith and Wheeldon (2004) therefore indicate that semantic competition between lexical items activated in parallel disrupts the sentence planning process, leading to slower onset latencies (see also Sass et al., 2010; Yang & Yang, 2008). At the syntactic level, onset latencies are also influenced by the size of the initial phrase, such that speakers take longer to initiate sentences that contain larger, compared to smaller, initial phrases (Levelt & Maassen, 1981; Martin et al., 2010, 2014; Smith & Wheeldon, 1999). This indicates that speakers engage in a phrasal scope of advanced planning, whereby they prioritise planning the first phrase prior to articulation.

To date, only a handful of studies have investigated on-line sentence planning in older adults. Current evidence suggests that, while older adults plan sentences in a similar incremental fashion to young adults, they are less able to incorporate novel lexical information outside of their preferred phrasal planning scope (Hardy et al., 2020; Spieler & Griffin, 2006). This indicates age-related differences in the management and adaptability of the lexical retrieval processes during sentence planning, and in the ability to integrate lexical information into syntactic structures. However, Hardy et al. (2020) did not manipulate the semantic relationship between the words in the sentence.[14] Therefore, in the present study, young and older adults completed a semantic interference sentence production task (Smith &

[14] Note, this study refers to the experiments reported in **Chapter 3** of this thesis.

Wheeldon, 2004), and we recorded speech onset latencies as a measure of the amount of pre-planning that occurred prior to articulation. If age-related effects in lexical competition exist, we predict greater semantic interference effects in older, compared to young, adults. Moreover, if sentence planning processes become less adaptable with age, we may expect age-related differences in the magnitude of the interference effect dependent on whether the related nouns appear within the same or different phrases. Participants also completed a stop-signal task as a measure of inhibitory control (Logan & Cowan, 1984). If semantic interference is related to an inhibitory control mechanism (Chen & Mirman, 2012; Hasher & Zacks, 1988), then we may predict individual differences in the size of the semantic interference effect to be related to the measures of inhibitory control.

4.2 Method

4.2.1 Participants

We recruited 44 young and 46 older adults: all were healthy native English speakers (**Table 4.1**). The study was approved by the University of Birmingham Ethical Review Committee and informed consent was obtained.

4.2.2 Design

We used a 2 X 2 X 2 mixed design with one between-participant variable age (young vs. older) and two within-participant variables of the semantic relatedness between the picture and word (related vs. unrelated) and the initial phrasal structure (coordinate vs. simple). Crucially, the picture and the word fell within the same phrase in the coordinate condition, but within different phrases in the simple condition (**Figure 4.1.A**).

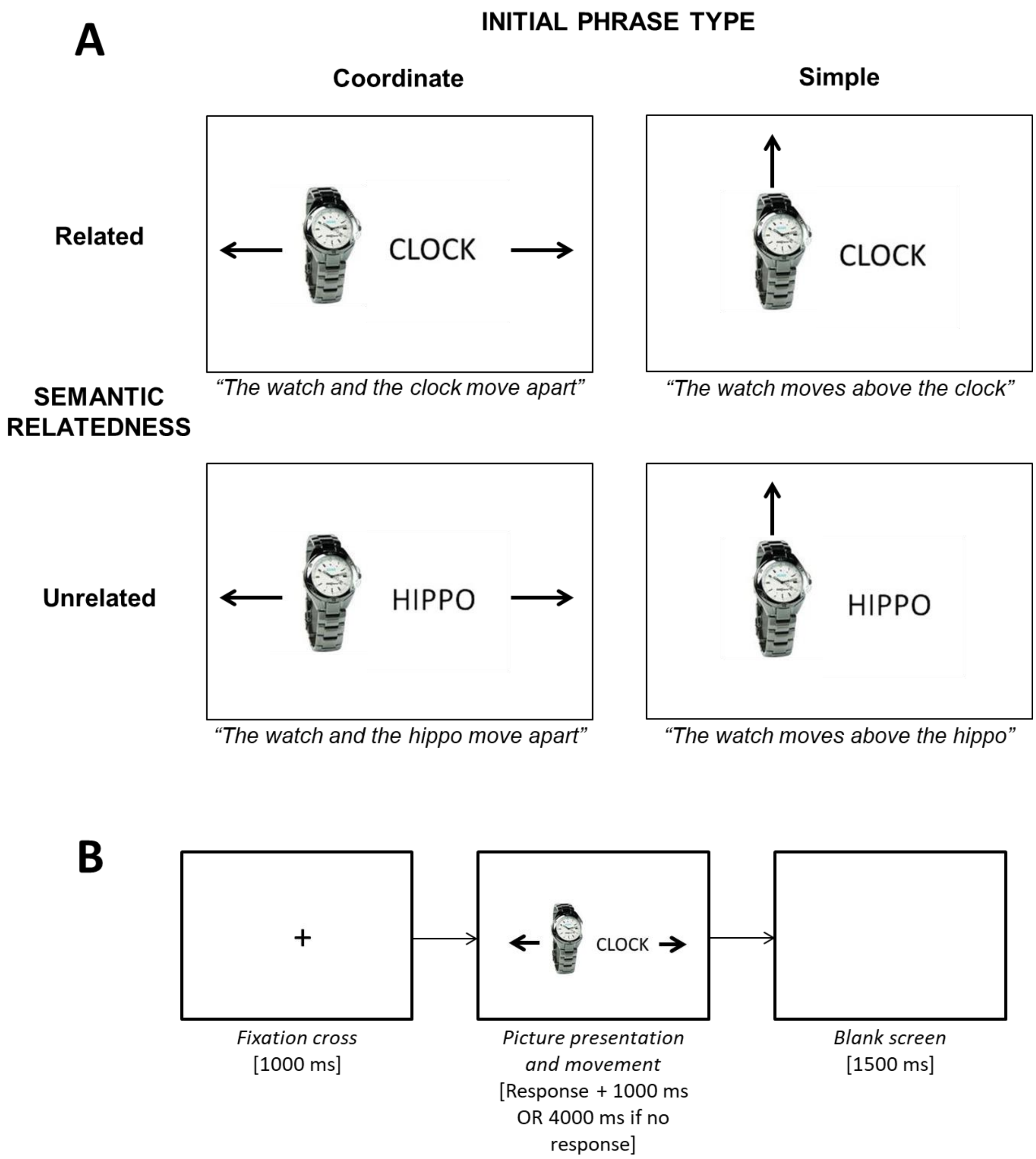

Figure 4.1 *Picture-word interference sentence production task design (A) and trial events (B). The picture and the word appeared simultaneously and aligned centrally in the horizontal plane (the picture was always on the left). The movement of the appropriate items began immediately and was completed in 400ms. Participants were instructed to begin describing the picture/word movements from left to right as soon as possible using specific sentence types. Speech onset latencies were recorded from the onset of the pictures to the participant beginning to speak.*

Table 4.1 *Means and standard deviations of characteristics and stop-signal task measures for young and older adults, and the results of comparisons between the age groups (independent samples t-tests).*

	Young		**Older**		**Comparison**	
Measure	*M*	*SD*	*M*	*SD*	$t(88)$	*p*
Age (years)	19.7	0.8	73.1	4.9	----	----
General cognitive ability[a]	----	----	28.0	1.3	----	----
Education[b]	6.0	0.2	5.7	1.4	-1.64	.104
SSRT[c]	226.8	47.4	266.0	54.7	-3.62	< .001

Note. [a]General cognitive ability was measured using the Montreal Cognitive Assessment (Nasreddine et al., 2005): all older adults scored 26 or above (out of 30), indicating that they were currently experiencing healthy ageing (scores < 26 indicate risk of mild cognitive impairment or dementia; Smith et al., 2007). [b]Education was scored on a scale of 0 (pre-primary school) to 8 (university doctorate) according to the International Standard Classification of Education (United Nations, 2011). [c]SSRT = stop-signal reaction time measure in the stop-signal task. A smaller SSRT indicates better inhibitory control (Bedard et al., 2002).

4.2.3 Materials

The experimental items consisted of 36 photographic pictures and 36 written words of familiar concrete objects. Each picture was paired with a word that was highly semantically related or a near synonym of the corresponding picture name, and with a different word that had no semantic relationship with the picture name.[15] This created 72 picture-word pairs, which each appeared within the two initial phrase conditions, creating 144 experimental items. The movement of each picture-word pair was manipulated using E-prime (Schneider et al., 2002), and participants described the movements from left to right using specific sentence

[15] We ensured that there was no phonological similarity between the picture name and word within each picture-word pair. Of these 72 pairs, 48 matched those used by Smith and Wheeldon (2004). Sixteen additional adults (all native English speakers) who did not take part in this study were asked to rate the relatedness of the 72 picture-word pairs on a scale of 0 (not related at all) to 6 (highly related). The related pairs (M = 4.54, SD = 0.66) were rated as significantly more related than the unrelated pairs (M = 0.31, SD = 0.41), $t(70) = 32.59$, $p < .001$.

types (the picture always appeared in the leftmost position). In the *coordinate* condition, the picture and word moved simultaneously (*The [picture] and the [word] move apart/together"*). In the *simple* condition, only the picture moved and the word remained stationary (*"The [picture] moves above/below the [word]"*).

We also created 120 fillers from a further 15 pictures and 15 words in order to increase the variability of syntactic structures and to reduce predictability about the sentence types. Each filler featured a single picture/word that moved either up, down, left or right (e.g., *"The horse moves up"*). The fillers contrasted the *coordinate* items in terms of the complexity of the initial phrase, and contrasted the *simple* items in the total number of noun phrases.

We constructed four blocks that each contained 30 fillers and 36 experimental items (9 per condition). The order of the items was pseudorandomised with the constraint that two consecutive experimental items always featured different nouns and were never of the same phrasal structure. The order of the blocks was rotated across participants.

4.2.4 Procedure

Participants sat in a quiet testing room, facing a 22-inch monitor, wearing an *OnvianTech* microphone connected to a *Cedrus* voicekey that recorded their onset latencies. **Figure 4.1.B** illustrates the trial events. Before beginning, there were 48 practice trials; the sentences resembled those in the experimental and filler trials and featured all experimental stimuli once. The experimenter listened from outside and noted any errors, including incorrect picture naming (e.g., 'horn' instead of 'trumpet'), use of a different structure (e.g., *"The watch moves up and the clock stays still"* instead of *"The watch moves above the clock"*), and disfluencies, such as stuttering.

Afterwards, participants completed the stop-signal task, in which they were instructed to respond quickly to the 'go' stimuli ('A' or 'Z'), but to withhold their response if the stop signal (a red cross) appeared (**Figure 4.2**). The stop-signal delay (SSD) – the interval between the presentation of the 'go' and 'stop' stimuli – was varied dynamically using an online tracking system. The SSD began at 400ms; it decreased by 16ms if the participant failed to inhibit their response on a 'stop' trial, but increased by 16ms if they were successful. Participants were instructed to continue to respond to the 'go' stimuli as quickly as possible and not to wait for the stop signal as it would occur randomly and infrequently. After training, each participant completed 120 'go' trials and 40 'stop' trials (distributed randomly), divided into four blocks. Each participant's stop-signal reaction time (SSRT), the measure of inhibitory control, was calculated using the block integration method (Verbruggen, Chambers, & Logan, 2013; Verbruggen & Logan, 2009). The SSRT is estimated by subtracting the average SDD from the finishing time of the 'stop' process (this is determined by integrating the reaction time distribution and finding the point at which the integral equals the probability of responding to a specific delay). Moreover, to overcome the issue of progressive slowing (participants strategically becoming slower in an attempt to anticipate the stop signal), we calculated the SSRT within each block (40 trials) and then averaged (Verbruggen et al., 2013).

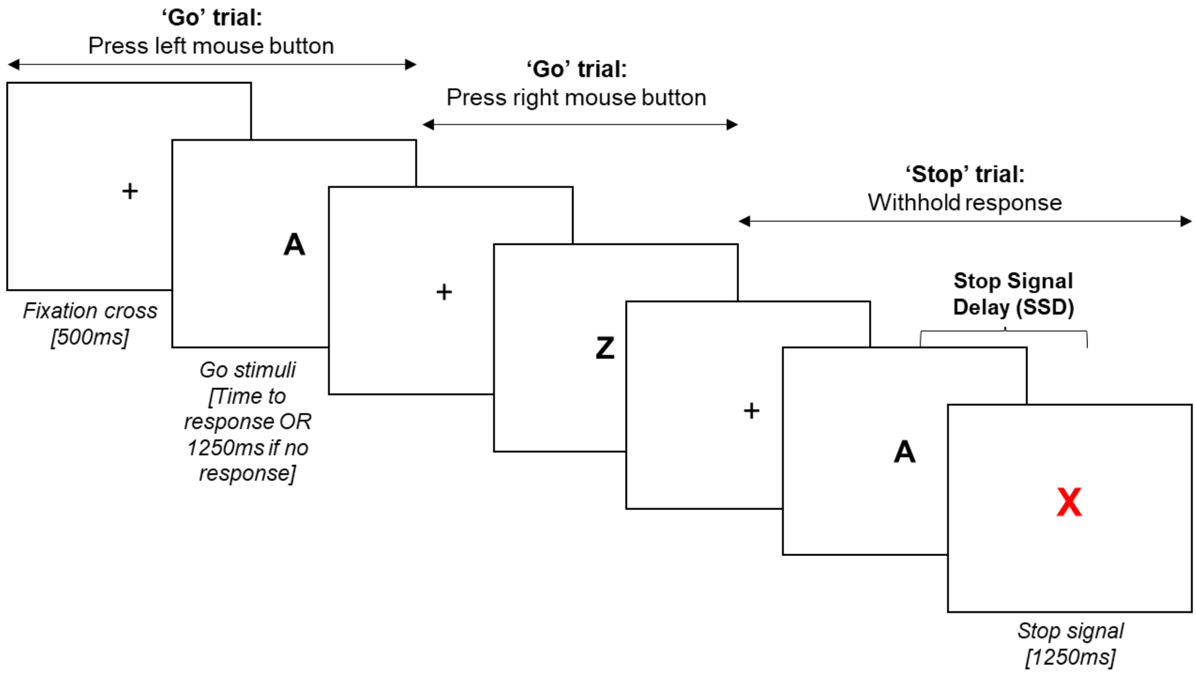

Figure 4.2 *Trial components in the stop-signal task for the 'go' and 'stop' trials. Participants were instructed to press the left mouse button if an 'A' appeared and the right mouse button if a 'Z' appeared, but to withhold their response if the stop signal (a red cross) appeared (25% of all trials). The stop-signal delay (SSD) was varied dynamically according to an online tracking algorithm (controlled using Presentation software). There was an inter-stimulus interval of 1500ms (except for when the SSD occurred).*

4.2.5 Data preparation and analyses

In the stop-signal task, we removed the blocks for which the mean ‘go’ response time was greater than the response time on the failed ‘stop’ trials as this violates the context independent assumption of the SSRT integration method (Verbruggen et al., 2013). Three older adults violated this assumption in all blocks and were removed from the analyses completely. For the remaining participants, we calculated the SSRT over the blocks which did not violate this assumption (removing an average of 1.14 blocks per participant). As expected, we observed a significant age difference in SSRT (**Table 4.1**). Of the 12528 experimental items in the sentence production task, we removed items that contained an error, excluding 329 (5.2%) young and 194 (3.1%) older adult responses. Following Ratcliff (1993), we further excluded responses for which the onset latency was more than 2SD above/below the mean per experimental condition per age group (discarding 310 (5.2%) young and 347 (5.4%) older adult trials).

Data were analyzed in R (R Core Team, 2015) using generalized linear mixed-effects models (*lme4* package; Bates et al., 2014). We fitted a binomial distribution to the error data as the dependent variable was categorical (correct = 0; incorrect = 1). Following Lo and Andrews' (2015) recommendation for analysing continuous speed data, we fitted an inverse gaussian distribution to the onset latencies with an ‘identity link’ function. This model fit is particularly advantageous when comparing groups with large overall speed differences (i.e., young vs. older) as it eliminates the need for data transformation (i.e., logarithmic or z-scores) while still satisfying the normality assumptions of the model (see also Balota et al., 2013). We entered age group, semantic relatedness, and initial phrase type as fixed effects (all contrasted coded as -0.5 vs. 0.5). We included random intercepts for participants and items, as well as by-participant and by-item random slopes appropriate for the design. We entered participants’ SSRT scores as a continuous predictor (centred and standardised). When a model did not converge with the maximal random effects structure, we simplified the random slopes, removing interactions before main effects, until convergence was reached (Barr et al., 2013).

4.3 Results

4.3.1 Onset latencies

Figure 4.3 summarises young and older adults' onset latencies across the four experimental conditions. The best-fitting model of the data is reported in **Table 4.2.A**.

As expected, young adults were quicker than older adults (950ms vs. 1086ms, $p < .001$). Overall participants initiated sentences faster when they began with a simple, compared to a coordinate, initial noun phrase (995ms vs. 1040ms, $p < .001$), indicating a phrasal planning scope effect of 45ms. Participants also initiated sentences faster when they contained semantically unrelated, compared to related, nouns (1004ms vs. 1031ms, $p < .001$), indicating an overall semantic interference effect of 27ms. Interestingly, we found a significant interaction between semantic relatedness and age group ($p = .046$), such that the interference effect was greater for the older (33ms), compared to the young (21ms), adults.

To investigate age group differences further, we modelled the data separately for the young and older adults (**Tables 4.2.B and 4.2.C**). The young adult analyses revealed significant effects of semantic relatedness (interference effect = 21ms; $p = .008$) and initial phrase type (scope effect = 47ms; $p < .001$), but no interaction between the two variables ($p = .225$), indicating that they experienced similar interference effects in both phrase conditions (simple = 25ms; coordinate = 18ms). In the older adult analyses, we found significant effects of semantic relatedness (interference effect = 33ms; $p < .001$) and initial phrase type (scope effect = 43ms; $p < .001$); however, in contrast to the young adults, there was a significant interaction between the two variables ($p = .023$), such that they displayed a significantly larger interference effect when the two nouns fell within different phrases (45ms), compared to within the same phrase (20ms).

Lastly, we found a significant interaction between age group and SSRT ($p < .001$). The separate age group analyses revealed a main effect of SSRT for the older ($p = .004$), but not the young ($p = .663$), adults. Correlational analyses demonstrated that older participants with poorer inhibitory control (i.e., higher SSRT score) were slower to initiate sentences in the production task ($r(41) = .32$, $p = .035$).

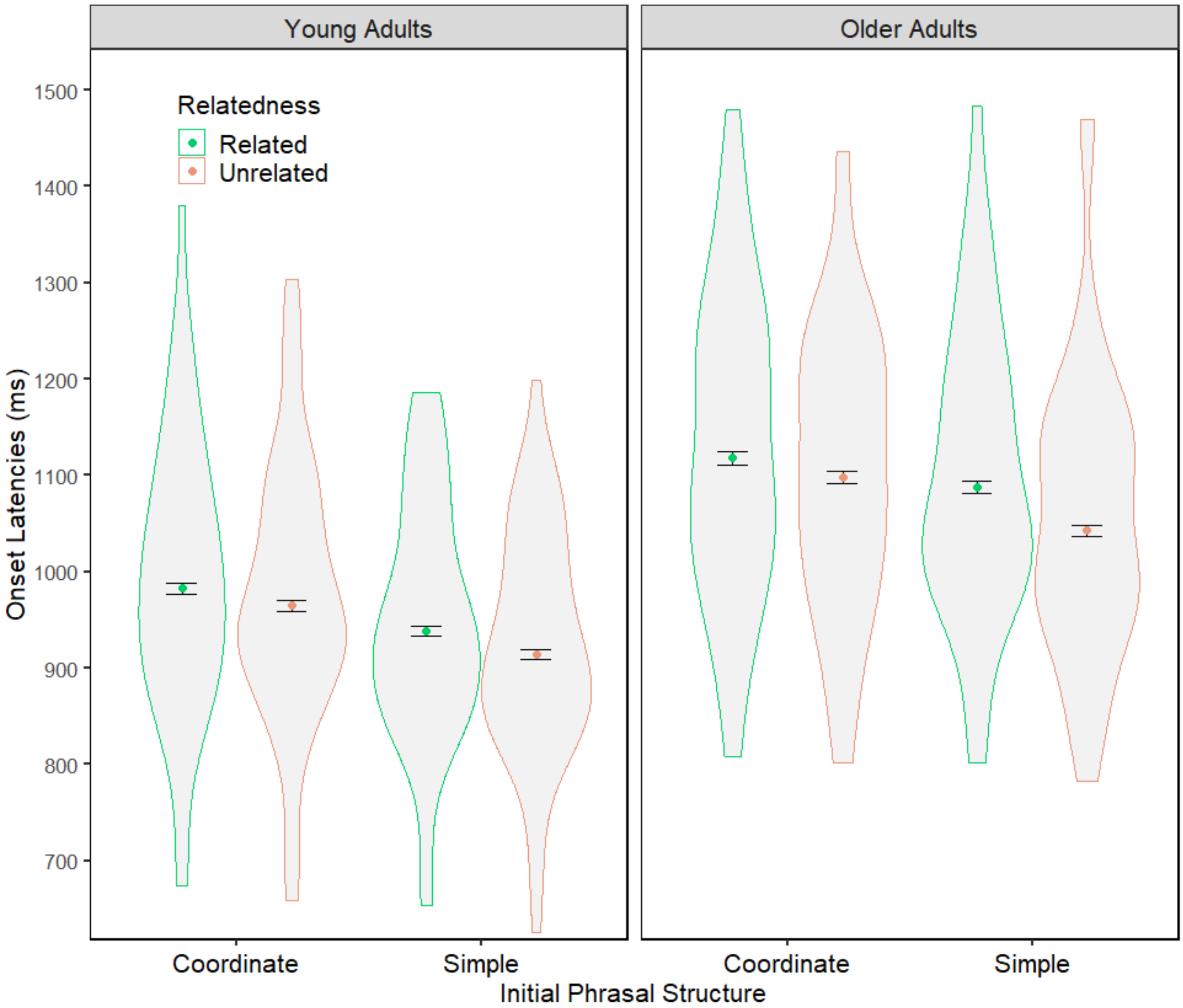

Figure 4.3 *Onset latencies for young and older adults when producing sentences that contained semantically related or unrelated noun pairs that either fell within the same phrase (coordinate initial phrasal structure) or within different phrases (simple initial phrasal structure). The coloured points represent the mean per condition. Error bars denote ±1 the standard error of the mean. Violin spreads represent the distribution of the data across participants.*

Table 4.2 *Summary of the best-fitted generalised linear mixed-effects model for the onset latency data in the sentence production task.*

Predictor	**Coefficient**	**SE**	***t*-value**	***p***
A: All data				
Intercept	1108.52	7.56	146.65	<.001
Semantic Relatedness	28.23	6.13	4.61	<.001
Initial Phrase Type	48.20	4.46	10.80	<.001
Age Group	-103.75	12.93	-8.02	<.001
SSRT	18.86	6.40	2.95	.003
Semantic Relatedness * Initial Phrase Type	-10.25	6.69	-1.53	.125
Semantic Relatedness * Age Group	-16.33	8.18	-2.00	.046
Initial Phrase Type * Age Group	13.06	8.92	1.46	.143
Semantic Relatedness * SSRT	-5.64	4.08	-1.38	.166
Initial Phrase Type * SSRT	8.37	4.44	1.88	.060
Age Group * SSRT	-47.62	12.80	-3.72	<.001
Semantic Relatedness * Initial Phrase Type * Age Group	12.12	13.38	0.91	.365
Semantic Relatedness * Initial Phrase Type * SSRT	3.35	6.72	0.50	.618
Semantic Relatedness * Age Group * SSRT	-0.48	8.15	-0.06	.953
Initial Phrase Type * Age Group * SSRT	-8.36	8.88	-0.94	.347
Semantic Relatedness * Initial Phrase Type * Age Group * SSRT	23.39	13.45	1.74	.082
B: Young Adults				
Intercept	1038.48	8.60	120.76	<.001
Semantic Relatedness	18.40	6.95	2.65	.008
Initial Phrase Type	40.72	3.92	10.37	<.001
SSRT	-3.67	7.68	-0.48	.633
Semantic Relatedness * Initial Phrase Type	-8.94	7.85	-1.14	.255
Semantic Relatedness * SSRT	-4.61	4.68	-0.98	.325
Initial Phrase Type * SSRT	5.00	3.85	1.30	.194

Semantic Relatedness * Initial Phrase Type * SSRT	13.33	7.69	1.73	.083
C: Older Adults				
Intercept	1195.00	14.12	84.62	<.001
Semantic Relatedness	39.32	10.32	3.81	<.001
Initial Phrase Type	42.63	7.16	5.95	<.001
SSRT	39.03	13.43	2.91	.004
Semantic Relatedness * Initial Phrase Type	-19.34	8.49	-2.28	.023
Semantic Relatedness * SSRT	-5.32	6.17	-0.86	.388
Initial Phrase Type * SSRT	12.19	7.27	1.68	.094
Semantic Relatedness * Initial Phrase Type * SSRT	-8.76	8.18	-1.07	.284

Note. SSRT = stop-signal reaction time (the measure of inhibitory control). All models converged with random intercepts for participants and items with additional by-participant random slopes for the main effects of semantic relatedness and initial phrase type, and a by-item random slope for the main effect of semantic relatedness.

4.3.2 Error rates

The best-fitting model of the error data is reported in **Table 4.3**. In general, participants produced very few errors (overall accuracy of 95.8%). Nonetheless, the analyses did reveal a main effect of relatedness (p = .047), such that participants produced more errors when the nouns were related, compared to unrelated (4.5% vs. 3.9%), in line with the effect observed in the latency analyses. There was also a main effect of age group (p = .005), such that young adults produced more errors than older adults (5.2% vs. 3.1%). The direction of this effect is somewhat surprising and may be attributable to older adults paying more attention to the task and/or to a speed-accuracy trade-off (the prioritising of sentence accuracy over a fast response; Forstmann et al., 2011). To investigate this further we calculated the inverse efficiency score (IES) per participant per condition as IES = average onset latency / (1 – proportion of errors) (Townsend & Ashby, 1978). This is a linear integration measure and can be considered the onset latency corrected for the amount of errors committed (Vandierendonck, 2017, 2018). Use of IES can therefore control for possible speed-accuracy trade-off effects in older adult groups (for a similar approach, see Anzures, Ge, Wang, Itakura, & Lee, 2010). Analyses of the IES using mixed-effects models produced the same effects observed in the onset latency analyses. This indicates that the observed positive age effect on errors rates is not the results of a speed-accuracy trade-off and this did not influence the observed onset latency effects.

Table 4.3 *Summary of the best-fitted generalised linear mixed-effects model for the error data in the sentence production task.*

Predictor	**Coefficient**	**SE**	***t*-value**	***p***
Intercept	-3.75	0.15	-25.23	<.001
Semantic Relatedness	0.27	0.14	1.99	.047
Initial Phrase Type	48.20	4.46	10.80	.088
Age Group	0.74	0.26	2.81	.005
SSRT	-0.02	0.12	-0.19	.850
Semantic Relatedness * Initial Phrase Type	-0.24	0.27	-0.89	.372
Semantic Relatedness * Age Group	-0.08	0.23	-0.36	.718
Initial Phrase Type * Age Group	0.23	0.23	1.01	.314
Semantic Relatedness * SSRT	0.04	0.10	0.43	.671
Initial Phrase Type * SSRT	-0.13	0.10	-1.25	.213
Age Group * SSRT	-0.14	0.23	-0.61	.544
Semantic Relatedness * Initial Phrase Type * Age Group	0.13	0.43	0.29	.769
Semantic Relatedness * Initial Phrase Type * SSRT	-0.20	0.19	-1.06	.288
Semantic Relatedness * Age Group * SSRT	0.03	0.21	0.13	.900
Initial Phrase Type * Age Group * SSRT	0.19	0.21	0.93	.352
Semantic Relatedness * Initial Phrase Type * Age Group * SSRT	-0.41	0.38	-1.06	.290

Note. The model converged with random intercepts for participants and items with additional by-participant random slopes for the main effects of semantic relatedness and initial phrase type, and a by-item random slope for the main effect of age group.

4.4 Discussion

We investigated the effect of healthy ageing on the syntactic and lexical processes involved in fluent sentence production in a picture-word interference task. Our main findings are threefold. Firstly, young and older adults initiated sentences faster when they contained smaller, compared to larger, initial phrases, indicating that both age groups were engaging in a phrasal scope of advanced planning. Secondly, the magnitude of the semantic interference effect was larger for older than young adults, indicating an age-related increase in lexical competition during sentence planning. Thirdly, while young adults displayed similar semantic interference effects whether the related nouns fell within the same or different phrases, older adults displayed significantly larger interference effects when the nouns were in different phrases. This suggests that older speakers are more sensitive to phrasal boundaries and that age-related differences exist in how speakers manage the temporal flow of lexical information during sentence production. Taken together, our findings indicate age-related effects on lexical, but not syntactic, processes.

Our robust finding of a phrasal planning scope replicates previous onset latency studies in young (Martin et al., 2010, 2014; Smith & Wheeldon, 1999) and older adults (Hardy et al., 2020). When producing simple syntactic structures, both age groups plan incrementally and prioritise the generation of syntax within the first phrase prior to articulation. Incremental planning allows the processing load to be spread across multiple components and time (Levelt, 1989; Wheeldon, 2013). Thus, despite age-related declines in other cognitive domains, older adults maintain a phrasal scope of advanced planning, ensuring preserved fluency in sentence production. Such an explanation fits within Peelle's (2019) ‘supply and demand’ framework, which suggests that behavioural success reflects a complex balance between task requirements and the level/type of cognitive resources available to the speaker. In the case of syntactic processing, older speakers maintain sufficient cognitive capacity to plan in the same way as young adults. However, when the processing load was increased by the introduction of an added semantic interference component, age-related differences did emerge.

Overall, older speakers were slower than young speakers to initiate sentences containing two semantically related, compared to unrelated, nouns. Our task was specifically designed to tap into how speakers deal with the co-activation of competing lexical items during sentence planning and therefore provides the first evidence that lexical competition increases with age at the sentence level. This finding is consistent with some studies of single word production (Britt et al., 2016; Taylor & Burke, 2002), but not others (Gordon & Cheimariou, 2013; Mulatti et al., 2014). We suggest that these previous mixed findings occurred because producing a single word is often not sufficiently challenging to outweigh older speakers' cognitive resources for a given task (Peelle, 2019). Comparatively greater processing, however, is associated with producing a multi-word sentence. Indeed, while Belke and Meyer (2007) did not find any age differences in semantic interference during single word processing, differences did emerge when participants named multiple objects as part of a list. Together with our findings, this indicates that age-related differences in lexical competition do exist during speech production, but that these may only become apparent during the production of multi-word utterances.

Perhaps most interestingly in our study, the magnitude of the semantic interference effect differed between age groups dependent on whether the related nouns fell within the same phrase or different phrases: while young adults displayed similar interference effects in both phrase conditions, older adults displayed larger interference effects when the nouns were in different phrases. This may seem surprising given that both age groups employed a phrasal planning scope. However, this may be exactly why older speakers experienced increased difficulty because, when the semantic distractor fell outside of the initial phrase, even greater processing was required prior to articulation to prevent the distractor word (which participants would have read rapidly and automatically) from interfering with the planning of the initial phrase. More specifically, our findings may relate to age-related differences in the flexibility of sentence planning. Young adults' planning scope is adaptative as they can incorporate useful information to benefit their speed of sentence production (Hardy et al., 2020; Konopka, 2012; Konopka & Meyer, 2014). Our evidence suggests that this flexibility extends to situations in which unhelpful lexical information is presented, such that young adults can adapt to prevent distracting lexical information from overly disrupting their sentence planning. By contrast, older speakers' planning scope appears less adaptable and more fixed to phrasal boundaries (Hardy et al., 2020). We suggest that this age-related decline in planning flexibility may also mean that older adults are less able to deal with the premature access to lexical information beyond the initial phrase, particularly when it is semantically distracting and designed to interfere with initial planning.

One explanation of the semantic interference effect is that it involves inhibitory control mechanisms to prevent the distractor items from interfering with the production of the target item (Chen & Mirman, 2012), a cognitive resource that is known to decline with age (Coxon et al., 2012). This may predict that our measure of inhibition (stop-signal reaction time) would relate to individual differences in semantic interference; however, we did not find this. One possible reason for this is that measuring individual differences within a factorial design is inherently challenging (Hedge, Powell, & Sumner, 2017), and recent modelling work by Rouder, Kumar, and Haaf (2019) indicates that attempting to correlate individual differences in inhibition is very difficult (if not impossible) due to large amounts of trial noise. Hence, a link between inhibitory control and semantic interference may exist, but our inhibition measure was not sensitive enough to capture this relationship. Alternatively, semantic interference in the picture-word interference paradigm may not involve competition at all and may instead arise at a post-lexical level of processing and reflect the speed with which production-ready representations (i.e., the lexical item relating to the written word) can be excluded as potential responses to the target picture (Finkbeiner & Caramazza, 2006; Mahon, Costa, Peterson, Vargas, & Caramazza, 2007). Our study was not specifically designed to distinguish between these different accounts of semantic interference and both may offer a valid explanation of our findings.

In conclusion, our study provides evidence for an age-related preservation of syntactic planning skills, but an age-related disruption in the management of the temporal flow of lexical information during sentence production. We attribute these ageing effects in lexical processing to age-related declines in the adaptability of sentence planning, such that older speakers are less able to prevent the activation of a distractor lexical item from interfering with their planning of an initial phrase that does not contain the distractor word. Our findings therefore add to the growing evidence that healthy ageing does not affect all features of language equally, and highlights the importance of understanding how and why some aspects of language, such as syntactic planning, are unaffected by age, while others, such as lexical management during sentence production, decline.

CHAPTER 5

Neural Processes of Syntax Comprehension

5.1 General introduction and chapter structure

Production and comprehension often exist as two sides of the same coin since successful communication relies on speakers being sufficiently skilled in both aspects of language processing. In this chapter, we shift to focus on age-related changes during sentence comprehension. The comprehension of a sentence's grammatical structure is generally considered to be relatively well-preserved with healthy ageing (for reviews see, Burke & Shafto, 2008; Shafto & Tyler, 2014). This apparent age-related preservation is often attributed to older speakers' ability to employ effective top-down strategies, such as making use of contextual cues and semantic knowledge, in order to compensate for perceptual and cognitive deficits that may otherwise hinder comprehension (Burke & Shafto, 2008; Thornton & Light, 2006). However, not all studies support the claim that syntax comprehension is unaffected by healthy ageing (e.g., Peelle et al., 2010; Poulisse, Wheeldon, & Segaert, 2019; Stine-Morrow et al., 2000). Moreover, it has been suggested that, in a bid to maintain sufficiently high levels of comprehension accuracy, older adults may recruit additional brain areas to compensate for declines elsewhere (Peelle, 2019; Wingfield & Grossman, 2006).

Taking this into consideration, the aim of this chapter is two-fold. Firstly, to investigate the age-related changes that occur during the comprehension of syntactic structures of varying complexity. Secondly, to gain insight into the neural processes that underlie syntactic processing in young adults – a necessary step prior to studying these processes in older adults. In **Part A** of this chapter, I briefly report a behavioural study in which we measured young and older adults' comprehension accuracy and self-paced reading speeds when reading sentences along a continuum of syntactic complexity. Following this, in **Part B**, I report a study using the neuroimaging technique of magnetoencephalography (MEG) to investigate the oscillatory activity involved in the binding of individual words into larger syntactic structures with more complex meaning. In a change to all other experiments in this thesis, we only tested young adults in the MEG study. This is because it is important to fully understand how young adults perform in a task (both at a behavioural and neurological level) before extending a paradigm to investigate possible age-related effects, particularly when considering the large research costs associated with MEG. The long-term goal is thus to study how the neural processes of syntax comprehension change throughout the lifespan. Nonetheless, even without considering this future goal, the findings of the MEG study make an important contribution to the current literature surrounding the neural processes involved in syntactic binding

CHAPTER 5 (PART A)

Preface on Syntactic Comprehension and Heathy Ageing: A Behavioural Study

Previous studies investigating healthy ageing and sentence comprehension have typically used highly complex syntactic constructions. We investigated which specific aspects of syntactic complexity are most affected by healthy ageing by employing a continuum of syntactic complexity, ranging from very simple to very complex constructions. Young and older adults' self-paced reading times and question response accuracy were measured across five levels of syntactic complexity. While both age groups were slower to read more complex syntactic structures overall, age-related differences did emerge in the comprehension of certain syntactic features. Compared to young adults, older adults' self-paced reading times were more affected by syntactic pauses and the use of the passive syntax (a less frequent structure). This indicates that certain syntactic features are more sensitive to age-related changes than others, and further highlights how healthy ageing does not affect all features of language equally.

5A.1 Introduction

Studies investigating the effect of healthy ageing on syntax comprehension typically use highly complex sentence structures that are often difficult to parse, such as garden path sentences with temporary syntactic ambiguity. For example, Campbell et al. (2016) asked participants to identify whether a disambiguating word in a sentence was an acceptable continuation of the sentence that either developed into an expected dominant structure (e.g., *"In the circus juggling knives <u>is</u> less dangerous than eating fire"*) or an unexpected subordinate structure (e.g., *"In the circus juggling knives <u>are</u> less sharp than people think"*). They found that no age-related differences in acceptability ratings or response times, suggesting similar comprehension abilities (see also Davis, Zhuang, Wright, & Tyler, 2014; Meunier, Stamatakis, & Tyler, 2014; Shafto & Tyler, 2014). However, alternatives studies have found older adults to be slower and less accurate when answering comprehension questions relating to sentences that contain temporary ambiguity and/or complex syntactic structures, such as object-relative clauses (Christianson, Williams, Zacks, & Ferreira, 2006; Obler, Fein, Nicholas, & Albert, 1991; Peelle et al., 2010; Stine-Morrow et al., 2000). Moreover, Poulisse et al. (2019) found older adults were slower and less accurate at detecting syntactic agreement errors in simple two-word sentences (e.g., *"I walks"*), suggesting that age-related declines in syntax comprehension may not just be restricted to highly complex syntactic constructions.

To summarise, due to the mixed findings within the existing literature, two key questions currently remain unanswered: (1) whether syntax comprehension abilities are negatively affected by healthy ageing; and (2) if age-related declines do exist, whether they occur for all syntactic structures or only for the most complex constructions. It is particularly difficult to answer the second question as most studies have tended to focus on either highly complex or highly simple syntactic constructions (e.g., Campbell et al., 2016; Poulisse et al., 2019; Stine-Morrow et al., 2000). It therefore remains unclear which specific aspect of syntactic complexity (if any) poses a challenge for older adults. We aimed to address this issue by examining older adults' sentence comprehension on a continuum of increasing syntactic complexity. In total, we used five levels of syntactic complexity that increased gradually from a relatively simple active sentence to a highly complex sentence that contained multiple embedded clauses (see **Table 5A.1**). Following each sentence, participants were asked a question relating to the identity of the agent or patient described in the sentence.

Participants' comprehension was assessed both in terms of question response accuracy (a measure of their overall understanding of the event; Christianson et al., 2006) and self-paced reading times (a measure of the amount of processing difficulty and reanalysis required; Jegerski, 2014). If age-related differences exist in syntax comprehension, we expect to observe age group differences in comprehension accuracy and self-paced reading times for the syntactic complexity levels that cause the greatest processing difficulties in older adults.

Table 5A.1 *Definitions and example sentences of the different syntactic complexity levels used in the syntax comprehension task.*

	Syntax complexity level	**Example sentence**	**Word count**
1	Two separate active transitive verb sentences.	The girl is confusing the boy. The girl is wrapping a square present.	13
2	Two conjoined active transitive verb clauses.	The girl is confusing the boy and she is wrapping a square present.	13
3	An active transitive verb sentence with a relativized subject noun phrase.	The girl who is confusing the boy is wrapping a square present.	12
4	A passive transitive verb sentence with a relativized object noun phrase.	The boy is being confused by the girl who is wrapping a square present.	14
5	An active transitive sentence with complex centre embedding.	The present which the girl who is confusing the boy is wrapping is square.	14

5A.2 Method

5A.2.1 Participants

The participants described in **Chapter 3** (50 young adults, *M* = 19.8yrs; 56 older adults, *M* = 71.8yrs) also completed this short experiment (see **section 3.2.1.1** for a more comprehensive overview of the sample characteristics).

5A.2.2 Design and materials

We used a 2 X 5 mixed design with one between-participant variable of age (young vs. older) and one within-participant variable of the level of syntactic complexity (1-5).

In order to construct the experimental sentence stimuli, we created a set of 50 unique semantic events that each contained: an animate transitive verb that could plausibly describe an event involving a human agent and a human patient (e.g., 'confuse'); an inanimate transitive verb that could plausibly describe an event involving a human agent and an inanimate patient (e.g., 'wrap'); and an inanimate adjective-noun pair (e.g., 'square present'). For the roles of the animate nouns, the pairs of woman/man and girl/boy were evenly split between the 50 events with each noun being assigned to the agent or patient role an equal number of times. We then generated five different sentence types for each of the 50 semantic events based on the five levels of syntactic complexity (**Table 5A.1**); this created 250 experimental items. The sentences differed minimally in terms of the total number of words (all ranged from 12-14). Lastly, we constructed five lists that each contained 50 experimental items (10 items per syntactic complexity level per list) in a pseudorandomised order (two items of the same complexity level never occurred consequently). Each participant was randomly assigned to one of the five lists.

5A.2.3 Procedure

Participants were seated in a quiet testing room, facing a 14-inch *Dell* laptop. The experimental presentation was controlled using E-prime (Schneider et al., 2002). **Figure 5A.1** illustrates the event timings per trial. Participants were instructed to silently read each sentence and to press the spacebar as soon as they had finished. Each sentence was followed by a comprehension question, relating to either the patient of the animate transitive verb action (e.g., *"Who is being confused?"*) or the agent of the inanimate transitive verb action (e.g., *"Who is wrapping the present?"*). The two animate nouns from the sentence were presented below the question and participants had to select the correct answer (using the left or right mouse button). Before beginning, participants completed 10 practice trials that were syntactically similar to the upcoming experimental items.

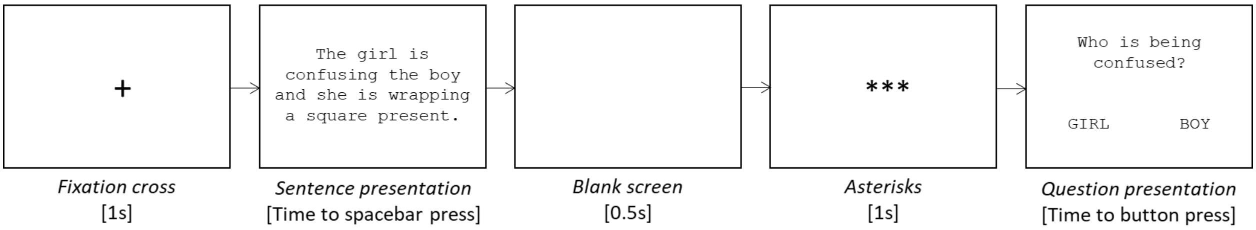

Figure 5A.1 *Syntax comprehension task trial events. Self-paced reading times were recorded from the onset of the sentence to the spacebar press. Comprehension accuracy was measured in terms of participants' response to the question.*

5A.2.4 Data preparation and analyses

Of the 5300 experimental items, we excluded trials for which the reading time was below 1s, above 30s or more than 2.5SD above/below the participants' mean per experimental condition (discarding 70 (2.8%) young and 69 (2.5%) older adult trials). All remaining trials were used in the error analyses, but only correct responses (92.4% of all trials) were used in the self-paced reading time analyses.

The data were analysed in R (R Core Team, 2015) using generalised linear mixed-effects models as there were repeated observations for participants and items (Barr et al., 2013; Jaeger, 2008). We fitted a model with a binomial distribution to the error data (correct = 0; incorrect = 1) and an inverse gaussian distribution to the reading time data as this can account for skewed distribution between age groups without the need for transformation (Lo & Andrews, 2015). Our aim with the analyses was to examine the effect of each incremental increase in syntax complexity on comprehension performance. We therefore entered syntactic complexity level as a fixed effect and used forward difference contrast coding to compare each level to the adjacent level (i.e., L1 vs. L2, L2 vs. L3, L3 vs. L4, L4 vs. L5; see UCLA, 2011). We also entered age group (young vs. older) as a fixed effect, which we sum-coded and transformed to have a mean of 0 and a range of 1 prior to analysis. Lastly, we included random intercepts for participants and items, as well as by-participant and by-item random slopes appropriate for the design. When a model did not converge with the maximal random effects structure, we simplified the random slopes, removing interactions before main effects, until convergence was reached (Barr et al., 2013).

5A.3 Results

Figure 5A.2 summarises young and older adults' mean comprehension error rates and self-paced reading times across the five syntactic complexity levels.

The best-fitting model of the error data is reported in **Table 5A.2.A**. Overall, older adults were marginally more error-prone than young adults (8.5% vs. 6.6%, $p = .057$). Although the error rates followed a similar pattern to the reading times (i.e., increased with each increasing complexity level), we found no main effects of each syntax complexity level comparison or any interactions with age group (all ps > .08).

The best-fitting model of the self-paced reading time data is reported in **Table 5A.2.B**. Older adults were significantly slower overall than young adults (8.6s vs. 5.5s, $p < .001$). Moreover, we found main effects relating to each syntactic complexity level comparison (all ps < .005), as well as significant interactions between age group and each complexity level comparison (all ps < .022). To investigate possible age group differences further, we modelled the data separately for young and older adults (using the same procedure outlined previously): the results of the significance testing for each level comparison per age group are shown on **Figure 5A.2**. For young adults, there was only a significant increase in reading times from Level 2 to Level 3, and Level 4 to Level 5. By contrast, for older adults, reading times significantly differed between all adjacent syntactic complexity levels. Interestingly, this represented a significant decrease in reading times for Level 1 to Level 2, but a significant increase for all other level comparisons.

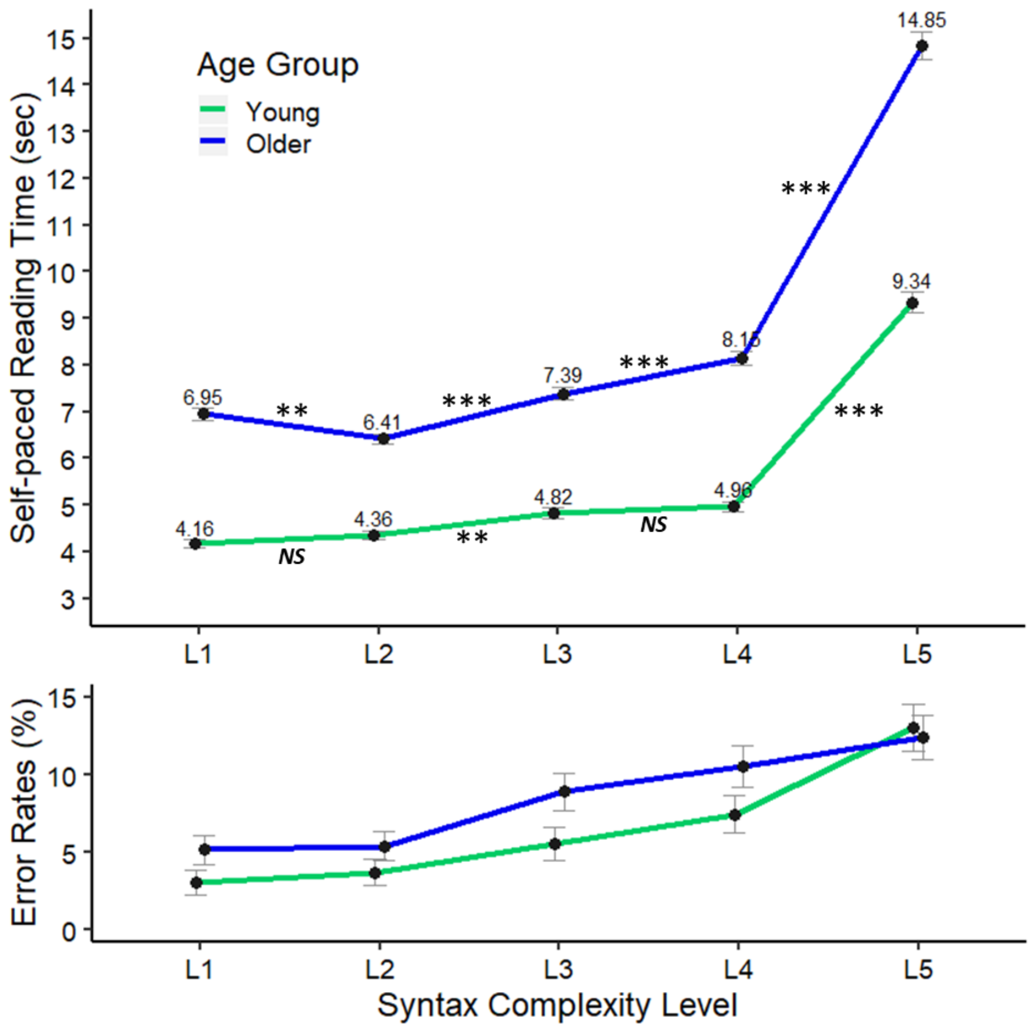

Figure 5A.2 *Mean self-paced reading time and question response error rates for young and older adults when comprehending sentences of different levels of syntactic complexity (Levels 1-5). We found significant differences between adjacent syntax complexity levels for self-paced reading times, but not for question comprehension accuracy. The results of significant testing between adjacent levels on self-paced reading times are shown for young and older adults: ** p < .01; *** p < .001; NS = not significant. Error bars denote ±1 standard error of the mean.*

Table 5A.2 *Summary of the best-fitted generalised linear mixed-effects model for the question comprehension accuracy data (A) and the self-paced reading data (B).*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
A: Comprehension Accuracy				
Intercept	-3.13	0.14	-21.90	< .001
Age Group	-0.47	0.25	-1.90	.057
Level 1 vs. Level 2	-0.10	0.32	-0.31	.758
Level 2 vs. Level 3	-0.49	0.28	-1.75	.081
Level 3 vs. Level 4	-0.46	0.23	-1.81	.087
Level 4 vs. Level 5	-0.14	0.22	-0.64	.519
Age Group * (Level 1 vs. Level 2)	-0.13	0.46	-0.28	.777
Age Group * (Level 2 vs. Level 3)	0.09	0.41	0.23	.820
Age Group * (Level 3 vs. Level 4)	-0.16	0.36	-0.44	.659
Age Group * (Level 4 vs. Level 5)	-0.54	0.35	-1.53	.127
B: Self-paced Reading Time				
Intercept	7.98	0.28	28.15	< .001
Age Group	-3.05	0.49	-6.24	< .001
Level 1 vs. Level 2	0.19	0.07	2.89	.004
Level 2 vs. Level 3	-0.48	0.07	-6.69	< .001
Level 3 vs. Level 4	-0.41	0.09	-4.75	< .001
Level 4 vs. Level 5	-5.18	0.20	-25.27	< .001
Age Group * (Level 1 vs. Level 2)	-0.69	0.13	-5.23	< .001
Age Group * (Level 2 vs. Level 3)	0.44	0.14	3.11	.002
Age Group * (Level 3 vs. Level 4)	0.40	0.17	2.30	.021
Age Group * (Level 4 vs. Level 5)	2.20	0.41	5.36	< .001

Note. The comprehension accuracy model converged with random intercepts for participants and items as well as a by-participant random slope for the effect of syntactic complexity level. The reading time model converged with random intercepts for participants and items. Overall, including syntactic complexity level as a fixed effect significantly improved the fit of both the accuracy model ($\chi^2(8) = 31.7$, $p < .001$) and the reading time model ($\chi^2(8) = 2454$, $p < .001$).

5A.4 Discussion

We investigated the effect of increasing syntax complexity on young and older adults' comprehension accuracy and self-paced reading times. Overall, we found minimal effects relating to comprehension accuracy; however, we did find evidence of age group differences in reading times. Young adults displayed a significant increase in reading times from Level 2 to Level 3 (when the relative clause was introduced), and Level 4 to Level 5 (when a highly complex embedded structure was used). By contrast, older adults displayed a significant difference in reading time with each increasing level of syntactic complexity. This represented a significant decrease in reading times from Level 1 to Level 2 (when a conjunction was introduced), but then a significant increase in reading times for all other complexity levels increases thereafter. Taken together, our findings suggest that different syntactic features may induce more effortful processing in young and older adults.

Perhaps our most surprising finding is that, unlike young adults, older adults showed decreased self-paced reading times when two active sentences (Level 1: *"The girl is confusing the boy. The girl is wrapping a square present."*) were transformed into a conjoined two-clause sentence (Level 2: *"The girl is confusing the boy and she is wrapping a square present."*). This difference occurred even though the total number of words did not change (both contained 13 words), suggesting that the effect was driven by differences at the syntactic processing level. This decrease in reading times may at first seem odd, given that the addition of a conjunctive word ('and') may be expected to require more effortful processing since a relationship between the two clauses is now inferred (Rudolph, 1989). However, an alternative explanation is that the use of two individual sentences at Level 1 may have led to older adults pausing more at the gap between the sentences. Payne and Stine-Morrow (2012, 2014) found that older adults show less parafoveal preview effects at syntactic pauses, such as sentences gaps, during comprehension, suggesting a possible age-related segmentation strategy designed to aid syntactic processing. If this is the case, it follows that older adults may pause for longer at sentence boundaries in order to fully process what they have read so far, leading to greater reading times for Level 1 compared to Level 2.

Beyond Level 2, older adults showed the more expected increases in self-paced reading times for each incremental increase in syntactic complexity. This suggests that, in order to fully comprehend the sentence, older adults engaged in increased processing when a relativized clause was introduced (Level 3), when the sentence was transformed into the passive syntax (Level 4) and when two embedded clauses were included (Level 5). The increases in reading time for each level were greater than those observed in the young adults (as evident in the significant interactions). Our findings therefore suggest that age-related differences in syntactic processing do exist during the processing of complex syntactic structures (in line with Christianson et al., 2006; Peelle et al., 2010; Stine-Morrow et al., 2000).

Notably, unlike older adults, young adults did not show a significant increase in self-paced reading times when the passive syntax was introduced (Level 4); this indicates that the passive, a fairly infrequent structure in English, may be particularly sensitive to age-related changes in syntactic processing. This finding does align with previous evidence that older adults' comprehension of passive sentences declines with age (Obler et al., 1991); however, it is somewhat at odds with our previous findings that the primed production of passives is preserved with age (Hardy et al., 2017, 2019). A possible explanation for this may be related to the fact that passive sentences in this experiment also included a relativized object noun phrase that served to increase the overall length and complexity of the sentence (*"The boy is being confused by the girl [who is wrapping a square present]."*), whereas the sentences used in our previous priming experiments did not (see **Figure 2.2** in **Chapter 2** for an example). This combined complexity load of both the passive syntax and a late subordinate clause may therefore have led to increased self-paced reading times for older, but not young, adults. It is also likely that large methodological differences between such studies (a comprehension reading task here vs. a primed production task in other chapters) may contribute toward different age-related findings.

To summarise, we found age group differences in self-paced reading times at both ends of the syntactic complexity continuum. At the lower end, older adults' preference for greater segmentation at sentence boundaries may have led to increased reading times of simpler two-sentence stimuli, compared to a more complex two-clause sentence. Further up the complexity continuum, we found that, unlike young adults, older adults required increased time to read and process passive sentences that contained a subordinate clause, suggesting that the infrequent passive syntax may be particularly sensitive to age-related changes in comprehension. Nevertheless, self-paced reading times specifically relate to the end of the processing stage (i.e., once participants have resolved any parsing difficulties); in order to gain more detailed insight into any age-related syntactic processing difficulties, an on-line measure, such as eye-tracking, would be required. Eye movements and fixation patterns provide insight into the time-course of the reading process, including predictions about upcoming words and sentence reanalysis (e.g., Frisson, Rayner, & Pickering, 2005; Pickering & Frisson, 2001; Vasishth, von der Malsburg, & Engelmann, 2013). Indeed, compared to young adults, older adults have been found to made more regressions back to the disambiguating word when reading garden path sentences (Kemper, Crow, & Kemtes, 2004). Use of eye-tracking measures may therefore provide detail about which aspect of a complex syntactic structure it is that older adults experience difficulty processing.

Another important question for future research is to identify whether these observed age-related differences in syntax comprehension (at the behavioural level) are underlined by differences at the neural level. Current evidence indicates that, during sentence comprehension, older adults recruit additional brain areas and engage in qualitatively different oscillatory behaviour compared to young adults (e.g., Beese, Vassileiou, Friederici, & Meyer, 2019; Peelle et al., 2010; Tyler et al., 2010). However, it remains unclear whether such age-related changes reflect a general decline in neural efficiency and specialisation (the *dedifferentiation* hypothesis) or whether specific regions are intentionally recruited to compensate for atrophy elsewhere (the *compensation* hypothesis); see Peelle (2019) for a review of the current debate. Neural imaging studies using EEG and fMRI are typically employed to investigate age-related changes in syntax comprehension; however, these two techniques are somewhat limited by either poor spatial resolution (EEG) or poor temporal resolution (fMRI). Use of MEG, however, can overcome such limitations because the use of magnetic, as opposed to the electric, signals means that there is minimal spatial smearing; thus, MEG is unique in that it maintains relatively high levels of both spatial and temporal accuracy (Lopes da Silva, 2013). In **Part B** of this chapter, we therefore investigated the neural processes involved in syntax comprehension. As previously discussed, we first aimed to identify the neural processing involved in syntactic binding (the combination of words into larger syntactic structure with more meaning) in healthy young adults, with the eventual aim to extend the paradigm to older adults. Unfortunately, I did not manage to conduct an MEG study with older adults within the timeframe of my PhD, but I hope to continue with this research line later in my academic career.

CHAPTER 5 (PART B)

An MEG Study of the Neural Processes Involved in Syntactic Binding

Successful sentence processing requires the binding, or integration, of multiple words into larger syntactic structures to establish meaning. We investigated the neural processes specifically involved at the syntactic level of binding by employing a minimal sentence paradigm involving pseudo-words. We compared participants' MEG activity during the comprehension of two-word sentences that required binding (a pronoun combined with a peusdo-verb with the corresponding morphological inflection; *"she grushes"*) to wordlists that did not require binding (two pseudo-verbs; *"cugged grushes"*). We found that, compared to the no binding wordlist condition, syntactic binding in the sentence condition was associated with a smaller increase in alpha power around the presentation of the target word that required binding. The condition difference was most prominent over sensors in the left-frontal region of the brain. We suggest that this modulation in alpha power reflects an expectation of binding to occur and the increased engagement of task-relevant brain regions involved in language comprehension and syntactic binding.

Pre-registration: Prior to beginning data collection, we pre-registered the rationale, stimuli and planned analyses of the study on the Open Science Framework (https://osf.io/6zxsm/).

5B.1 Introduction

Successful language processing requires two key components: memory to store the linguistic properties of words (often referred to as the mental lexicon); and binding to combine multiple words into larger syntactic structures. It is our ability to combine a limited set of individual words into a potentially infinite number of novel sentences that creates the expressive power of language – a skill unique to humans. This binding, or compositional, process is often referred to as *Merge* (Chomsky, 1995; Zaccarella & Friederici, 2015; Zwart, 2011) or *Unification* (Hagoort, 2003, 2005, 2016; Hagoort & Indefrey, 2014). Given that most human language production and comprehension goes beyond the single word level, understanding the cognitive processes that support binding is a central topic in sentence processing research (for recent reviews, see Hagoort, 2019; Pylkkänen, 2019).

Broadly speaking, binding at the sentence level involves two essential elements: (1) semantic binding of the meaningful relationship between words in a phrase or sentence; and (2) syntactic binding of the grammatical relationship between multiple words in a structure, accounting for features that mark tense, aspect and agreement. At its most basic level, binding involves the combination of two words into a minimal phrase or sentence (e.g., *"she walks"*, *"muddy dog"*). Investigating binding at this level is appealing for two reasons: firstly, because the minimal processing of just two words means that contributions from other cognitive resources, in particular working memory load, are minimised; and secondly, because the binding that takes place when processing a two-word sentence is the foundation for the processing of more complex sentences (Hagoort, 2003; Pylkkänen, 2019). For example, in order to fully understand the meaning behind the phrase *"she walks"*, a person must process the syntactic relationship between the two words (i.e., a pronoun and a verb that form a compositional phrase), as well as the semantic properties of the individual words and how they intertwine to form a novel conceptual representation that combines the features of both words. This is akin to the type of processing that is required for the understanding of much more complex sentences; hence, characterising the neural processes involved in the binding of minimal phrases is the first step towards understanding the brain regions implicated in the processing of full sentences.

In this study, we investigated the neural processes specifically involved in the syntactic aspect of binding by using a minimal two-word paradigm involving pseudo-words (Segaert, Mazaheri, et al., 2018; Zaccarella & Friederici, 2015). Pseudo-words follow the orthographic, phonological and syntactic rules of a given language, but have no semantic meaning, so are therefore a useful tool for isolating the syntactic binding process. In order to fully understand the rapid temporal features of syntactic binding, as well as precisely locate the brain regions involved, we employed magnetoencephalography (MEG) – the only non-invasive neuroimaging technique that offers comparatively high temporal and spatial resolution (Gross, 2019; Lopes da Silva, 2013). In the following introduction, we first review the current evidence for the neural networks associated with binding, before outlining the design and predictions of the current study.

5B.1.1 The neurobiology of binding

A number of studies have investigated the neurobiology of binding by comparing short adjective-noun phrases with non-binding wordlists (e.g., *"red boat"* vs. *"cup boat"*). Although it is not possible to disentangle semantic and syntactic binding when examining such adjective-noun phrases, valuable insight can still be gained into the brain regions involved in the binding process. The first of such studies was by Bemis and Pylkkänen (2011) who compared participants' MEG responses when visually presented with a two-word adjective-noun phrase within a binding context (*"red boat"*), a non-binding wordlist (*"cup boat"*) or a non-binding list containing a letter-string (*"xkq boat"*). They found that binding was associated with increased activity in the left anterior temporal lobe (LATL) around 200-250ms after the noun onset, followed by increased activity in the ventromedial prefrontal cortex (vmPFC) about 200ms later. In noun-adjective languages (e.g., Arabic), similar effects are observed following the adjective, demonstrating that the binding process relates to whether the two words can be combined together, not to any specific properties of word order (Westerlund, Kastner, Al Kaabi, & Pylkkänen, 2015). Moreover, the LATL and the vmPFC have been found to be important loci of composition effects during auditory comprehension (Bemis & Pylkkänen, 2013) and sentence production (Blanco-Elorrieta, Ferreira, Del Prato, & Pylkkänen, 2018; Del Prato & Pylkkänen, 2014; Pylkkänen, Bemis, & Blanco-Elorrieta, 2014), demonstrating that basic binding effects are largely modality-independent. Overall, these findings suggest that the LATL and vmPFC play a fundamental role in basic syntactic and semantic composition processes, consistent with neurobiological models of language within a left-lateralised network (Friederici, 2011; Hagoort, 2003; Tyler & Marslen-Wilson, 2008).

Functional MRI studies employing a minimal phrase paradigm have also found binding to be associated with increased activity (in terms of the hemodynamic response) in left-lateralised brain regions. For example, Schell, Zaccarella, and Friederici (2017) found that, compared to a baseline condition with no binding (*"ship"*), there was increased engagement of left interior frontal gyrus (LIFG) and the left angular gyrus during the comprehension of adjective-noun phrases (*"blue ship"*). They also included a determiner-noun condition in which the relationship between the two words was more syntactically driven (*"this ship"*); here, they found increased engagement of the ventral part of the LIFG and left posterior middle temporal gyrus (LpMTG), suggesting that these regions are more strongly implicated in the processes involved in syntactic, as opposed to semantic, binding. Moreover, Zaccarella, Meyer, Makuuchi, and Friederici (2017) found similar effects during the comprehension of three-word sentences (*"the ship sinks"*) and prepositional-determiner phrases (*"on the ship"*), demonstrating that the compositional effects persist beyond the two-word level. Engagement of such brain regions has also been observed during the comprehension of more complex sentence stimuli (Meltzer, McArdle, Schafer, & Braun, 2010; Segaert, Menenti, Weber, Petersson, & Hagoort, 2012; Snijders et al., 2008; Uddén et al., 2019).

Taken together, the existing fMRI and MEG evidence strongly implicates a number of brain regions within the binding process. The exact function of each of these regions is perhaps less well understood, but it is generally suggested that the role of the LpMTG relates to the retrieval and storage of lexical-syntactic information, whereas the LIFG is more involved in managing the assembly of words into a coherent structure (Hagoort, 2005; Snijders et al., 2008). Alternatively, the role of LATL may be more conceptual in nature, such that it serves to combine the semantic properties of the words on a non-syntactic level (Pylkkänen, 2019; Westerlund & Pylkkänen, 2014). Moreover, a central aspect of language processing is bidirectional communication between specialised brain regions (Tyler & Marslen-Wilson, 2008), suggesting that functional connectivity between the different regions is another important feature of successful binding during sentence processing (Hagoort, 2005, 2019). However, from the studies discussed so far, it is unclear whether activity in these regions relates to semantic or syntactic binding (or a combination of the two). This is because in the stimuli used, such as the adjective-noun phrases, compositional processes would have occurred at both the semantic and syntactic level since each word also contains its own semantic properties.

One way to disentangle the neural networks involved in semantic and syntactic binding, and to more specifically isolate the processes involved in syntactic binding, is to use pseudo-words. One such study was by Zaccarella and Friederici (2015) who compared participants' hemodynamic responses during the comprehension of determiner-noun phrases involving pseudo-nouns (*"this flirk"*) to wordlists that contained one pseudo-noun (*"apple flirk"*). They found syntactic binding to correspond to increased activity in the anterior part of the left pars opercularis (Brodmann Area 44; part of the LIFG). Alternatively, Pallier, Devauchelle, and Dehaene (2011) investigated syntactic binding using jabberwocky sentences, in which all content words are replaced with pseudo-words but the syntactic features required for parsing are maintained (e.g., *"he hates this colour"* becomes *"he futes this dator"*). They found that activity in the left inferior frontal and temporal regions was sensitive to constituent size effects, indicating that activity in these areas relates more specifically to syntactic processing (in the absence of meaningful content). Nonetheless, because of the nature of fMRI, these two studies do not inform us about the ongoing oscillatory modulations involved in binding.

In order to investigate the evoked and oscillatory activity associated with syntactic binding, Segaert, Mazaheri et al. (2018) also employed a pseudo-word paradigm, but measured participants' neural activity using EEG (instead of fMRI). Specifically, they compared participants' EEG responses when auditorily presented with either a minimal sentence consisting of a pronoun paired with a pseudo-verb with the correct morphological Dutch inflection (*"zij terst"* ['she grushes' in English]) or a wordlist of two pseudo-verbs (*"cil terst"* ['cug grushes']). By contrasting the two conditions, they found syntactic binding to be associated with power increases in the alpha (8-12 Hz) and beta (15-30 Hz) ranges, centralised over the frontal-central area shortly before the presentation of the target word that required binding, followed by an increase in alpha power over the left frontal-temporal region once the word had been presented. These findings are consistent with the notion that oscillatory activity in the alpha and beta frequencies are crucial for successful linguistic concatenation and high-order linguistics functions (Meyer, 2018; Murphy, 2015; Weiss & Mueller, 2012), and that language processing is supported by communicating regions in a left-lateralised network (Friederici, 2011; Tyler & Marslen-Wilson, 2008). Indeed, studies using more complex sentence stimuli have similarly found power modulations of the alpha and beta frequency bands to be associated with syntactic processing (Beese et al., 2019; Bridwell, Henderson, Sorge, Plis, & Calhoun, 2018; Lewis, Schoffelen, Schriefers, & Bastiaansen, 2016; Meyer, Obleser, & Friederici, 2013; Piai, Roelofs, & Maris, 2014; Rommers, Dickson, Norton, Wlotko, & Federmeier, 2017; Vassileiou, Meyer, Beese, & Friederici, 2018; Wang, Hagoort, & Jensen, 2017). Furthermore, inter-regional connectivity between language-relevant brain regions may be supported by rhythmic synchronisation between different frequencies, including alpha and beta (Schoffelen et al., 2017).

However, despite the wealth of evidence for changes in the alpha and beta frequencies during syntactic processing, the exact role of the different frequency bands and how they interact is less well understood. Most notably, the direction of the alpha power modulation remains unclear. Some studies have found syntactic processing to be associated with an increase in alpha power (Krause et al., 1994; Meyer et al., 2013; Segaert, Mazaheri, et al., 2018). Alternatively, other studies have found evidence of a decrease in the alpha band when greater syntactic processing is required (Bridwell et al., 2018; Davidson & Indefrey, 2007; Vassileiou et al., 2018; Wang et al., 2017). This may potentially relate to a gated inhibition mechanism designed to aid syntactic processing in task-relevant brain regions, such that alpha power decreases play a functional role in inhibiting activity in task-irrelevant regions (Jensen & Mazaheri, 2010; Klimesch, 2012). Further work is therefore needed to: (1) better understand the power modulation associated with syntactic binding (and syntactic processing more generally); and (2) to identify the regional source of these oscillations within the brain and how they interact. Thus, within this current study, we investigated syntactic binding using a minimal pseudo-verb sentence paradigm that minimises contributions from semantics and working memory, but, unlike Segaert, Mazaheri et al. (2018) who used EEG, we measured the neural activity using MEG. In contrast to EEG, MEG has both high temporal and spatial resolution (Gross, 2019), thereby enabling us to characterise the rapid time-frequency modulations of the brain's neural activity associated with syntactic binding, and to precisely identify specific cortical regions involved in the task, as well as the connectivity between these regions.

5B.1.2 The current study

We investigated the neural networks involved in syntactic binding; specifically, using MEG, we compared participants' neural activity when comprehending a minimal sentence involving a pronoun and a pseudo-verb (*"she grushes"*) to the comprehension of a wordlist involving two pseudo-verbs (*"cugged grushes"*). Syntactic binding occurred in the sentence condition (but not the wordlist condition) because the correct morphological inflection cued binding with the corresponding pronoun. Behavioural evidence has shown that participants judge sentences with the incorrect morphological inflection to be syntactically unacceptable (e.g., *"she grush", "I grushes"*), but judge wordlists (e.g., *"cugged grushes"*) and sentences with the correct inflection to be acceptable (Poulisse et al., 2019; Segaert, Mazaheri, et al., 2018); this demonstrates that listeners are engaging in syntactic binding when a minimal sentence is presented, but not when a wordlist is presented. Unlike previous MEG minimal binding studies that have focused on participants' evoked responses (e.g., Bemis & Pylkkänen, 2011, 2013; Pylkkänen et al., 2014; Westerlund et al., 2015), we also investigated oscillatory changes in the time-frequency power domain in order to gain a more complete understanding of the dynamic neural patterns and underlying networks (as recommended by Bastiaansen, Mazaheri, & Jensen, 2012). Moreover, we collected anatomical T1 brain scans from participants in order to localise the oscillatory effects during the binding process to specific cortical regions within the brain, and to investigate how these regions interact. With this in mind, the aim of this study can be broken down into three key questions with the following hypotheses.

Firstly, what frequency power modulations are involved in syntactic binding? We primarily expect power changes in the alpha and beta bands to be associated with syntactic binding as these frequencies are proposed to play a critical role in supporting linguistic functions (Meyer, 2018; Murphy, 2015; Schoffelen et al., 2017). However, based on existing research, the exact nature of these oscillatory changes is less clear. Since we are also using a minimal sentence paradigm, we may expect to see similar effects to those observed by Segaert, Mazaheri et al. (2018) – greater increases in alpha and beta power in the syntactic binding sentence condition, compared to the non-binding wordlist condition. However, it is also reasonable to predict that the added syntactic processing involved in syntactic binding (compared to no binding) may mean that we observe less alpha and beta power in the sentence condition, either in terms of a lesser power increase or a more extreme suppression effect (Bridwell et al., 2018; Davidson & Indefrey, 2007; Vassileiou et al., 2018; Wang et al., 2017).

Secondly, in which brain regions do these oscillations originate? In line with various theoretical frameworks of language, we expect successful syntactic binding to rely on a left-lateralised network of frontal-temporal brain regions (Friederici, 2011; Hagoort, 2003; Tyler & Marslen-Wilson, 2008). In particular, we may predict increased activation of the LIFG during syntactic binding as this region is proposed to be heavily involved in the assembly of words into a coherent phrase or sentence at the syntactic level (Schell et al., 2017; Segaert et al., 2012; Snijders et al., 2008; Uddén et al., 2019; Zaccarella et al., 2017). We may also observe some minor effects within other regions considered to be involved in the binding process, such as the LpMTG (Schell et al., 2017; Snijders et al., 2008) and the LATL (Bemis & Pylkkänen, 2011, 2013; Westerlund et al., 2015; Westerlund & Pylkkänen, 2014). However, compared to the LIFG, we would most likely expect to observe a less pronounced difference between the sentence and wordlist conditions in the LpTMG and the LATL since these regions relate more to the lexical-semantic and conceptual aspects of language processing, two features which we sought to minimise within the design of our study by using pseudo-verbs.

Thirdly, how do these regions interact? Given that successful language processing relies on bidirectional communication between different brain regions (Schoffelen et al., 2017; Tyler & Marslen-Wilson, 2008), we would predict that inter-regional connectivity will likely be observed between the brain regions involved in syntactic binding. The rhythmic synchronisation supporting these inter-regional connections may emerge as between or across frequency interactions between the different brain regions (Brookes et al., 2016; Schoffelen et al., 2017).[16]

[16]*A note for this thesis.* Within the timeframe of my PhD, I was only able to complete the oscillatory analyses to answer the first of the three research questions outlined here, and not the beam-forming and connectivity analyses required for answering questions (2) and (3). The rest of this chapter will therefore focus on the results of the oscillatory analyses, but the eventual aim is to complete all three analyses (as is discussed in more detail in the discussion of this chapter).

5B.2 Method

5B.2.1 Participants

We recruited 25 healthy participants (13 female / 12 male, *M* = 24.0yrs, *SD* = 4.2yrs): all were right-handed and native monolingual British-English speakers. All participants provided written informed consent and were compensated monetarily. Anatomical T1 brain scan (for source localisation purposes) was acquired for 22 of the participants (two participants did not attend the second MRI session, and another did not complete the MRI session due to unexpected discomfort). This study was approved by the University of Birmingham Ethical Review Committee.

5B.2.2 Design and materials

We employed a simple design consisting of two experimental conditions: the sentence condition, consisting of a minimal two-word phrase (pronoun plus pseudo-verb) for which syntactic binding occurred (*"she grushes"*); and the wordlist condition consisting of two pseudo-verbs for which no syntactic binding occurred (*"cugged grushes"*).

To construct the experimental items, we used a set of 20 pseudo-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). All pseudo-verbs were monosyllabic and could be inflected according to the grammatical rules of regular English verbs. We combined each pseudo-verb with three different morphological affixes (no affix; +s; +ed) to create 60 possible pseudo-verb-affix combinations.

In English, only certain pronouns may be combined with certain affixes (e.g., *"she grushes"* is acceptable, but *"I grushes"* is not). Using a list of six pronouns (I, you, he, she, they, we), we created 120 sentence items by pairing each pseudo-verb-affix with two different pronouns that were syntactically appropriate for the corresponding affix, such that syntactic binding may plausibly occur (e.g., *"I dotch", "she grushes", "they cugged"*). To create the wordlist items, we paired together two different pseudo-verb-affix stimuli for which syntactic binding could not plausibly occur (e.g., "*cugged grushes", "dotch traffed"*). Each pseudo-verb-affix stimulus occurred twice as the first word in a pair and twice as the second word in a pair, creating a total of 120 wordlist items. We ensured that the two words within each wordlist pair always consisted of a different pseudo-verb and a different affix.

We also created 120 filler items. Sixty of the fillers consisted of reversed speech and were included as a detection task for the participants. Using PRAAT software (Boersma, 2001), we created a reversed speech version of each of the 60 pseudo-verb-affix combinations. We then paired each reversed speech stimulus with either a non-reversed pseudo-verb-affix or a pronoun (half as the first word of the pair and half as the second word). A further 60 filler items were included to minimise the possibility of participants forming expectations about when syntactic binding will occur based on the first word. Thirty such items consisted of two pronouns for which binding could not plausibly occur (*"she I"*). The other 30 items consisted of a pseudo-verb-affix stimulus followed by one of five possible adverbs (early, promptly, quickly, rarely, safely) for which syntactic binding could plausibly occur (*"cugged quickly"*).

All auditory stimuli were spoken by a native English male speaker and normalised to 1db volume. A full list of the stimuli is available to download online on the Open Science Framework (https://osf.io/6zxsm/).

5B.2.3 Procedure and MEG data acquisition

In line with the paradigm developed by Segaert, Mazaheri et al. (2018), the participants' task was to detect the reversed speech (which only occurred on filler trials). On each trial, participants were auditorily presented with a two-word phrase (see **Figure 5B.1**). Participants were instructed to press a button if part of the speech was reversed (half of the participants used their left index finger, and half used their right index finger), but to do nothing if the speech was not reversed. This ensured that participants paid close attention to the stimuli throughout the experiment, while also ensuring that there was no difference in response decision processes between the critical experimental conditions of interest (sentence vs. wordlist). Each participant completed 360 trials (of which 240 were experimental) in a unique randomised order, divided into six blocks of 60 trials each. Before beginning the task, participants completed 23 practice trials that were similar to the experimental and filler items used in the main task.

During the task, ongoing MEG data were recorded using the TRIUXTM system from *Elekta* (Elekta AB, Stockholm, Sweden). This system has 102 magnetometers and 204 planer gradiometers. These are placed at 306 locations, each having one magnetometer and a set of two orthogonal gradiometers. The data were collected using a sampling rate of 1000 Hz and was stored for offline analyses. Prior to sampling, a lowpass filter of ~250 Hz was applied. Scalp surface data were acquired using a *Polhemus* 3D digitiser to facilitate later co-registration with anatomical brain scans. Additional electrooculography (EOG) and electrocardiogram (ECG) data were collected using methods compatible with the TRIUXTM system.

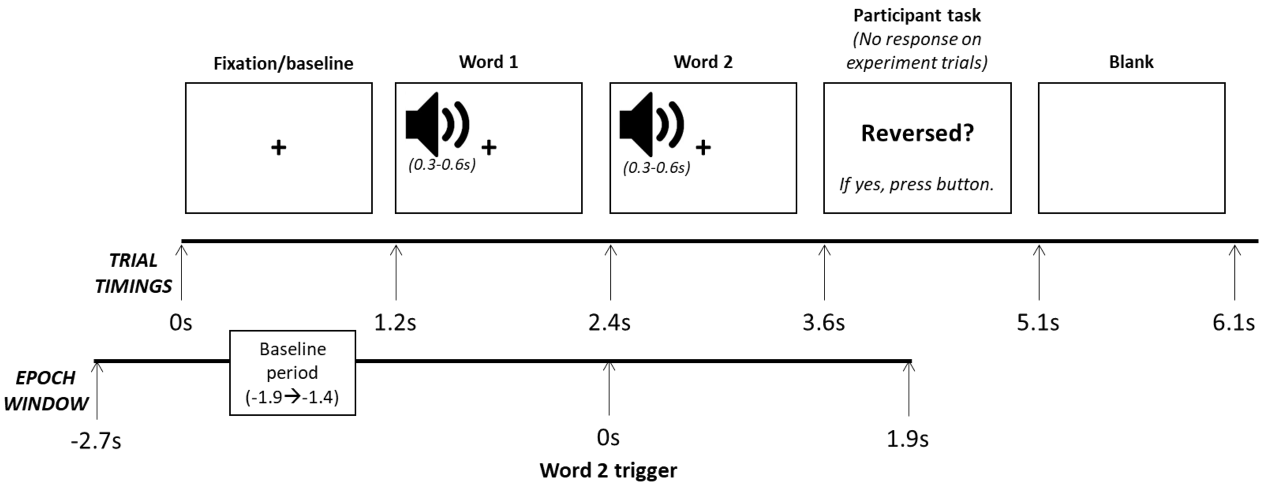

Figure 5B.1 *Stimuli presentation timings per trial and the related epoch window. Stimuli presentation and trigger signals were controlled using E-Prime (Schneider et al., 2002). Visual stimuli were presented using a PROPixx projector, and auditory stimuli were presented using the Elekta audio system and MEG-compatible ear plugs. Participants' motor responses were recorded using a NAtA button pad.*

5B.2.4 MEG pre-processing

The offline processing and analyses of the data were performed using functions from the *Fieldtrip* software package (Oostenveld, Fries, Maris, & Schoffelen, 2011) and custom scripts in the MATLAB environment. First, we applied a 0.1 Hz high-pass filter to remove frequency drift in the data. The data were then epoched to the onset of the presentation of the second word from -2.7s to +1.9s (see **Figure 5B.1**). We corrected the delay between the trigger and the auditory signal for each individual trial by adjusting the 0 of the epoch to match the exact onset of the auditory stimuli. We visually inspected the waveforms of each trial and removed trials that contained excessive signal artefacts (e.g., large sensor jumps or gross motor movement by the participant). We also removed any persistently poor channels (i.e., excessive noise or flatline). We then used a spline interpolation weighted neighbourhood estimate to interpolate across the removed channels per participant. Ocular and cardiac artifacts were removed from the data using an independent component analysis (ICA). We identified these components from their stereotypical topography and time course, as well as by comparisons with the recorded ECG and EOG time courses.

Following this, we removed all filler trials as we are specifically interested in the difference in neural responses between the experimental sentence and wordlist conditions (i.e., our contrast of interest). We further removed trials for which the participant incorrectly responded with a button press (i.e., indicated that the speech was reversed when it was not) and trials during which the participant made an accidental button press before the response screen.

We applied the following participant rejection criteria, as outlined in our pre-registration: (1) failure to perform the task (0 participants); (2) participant-induced artefacts, such as excessive head motion or eye movements, in more than 50% of the trials (1 participant removed); and (3) equipment-related failures (0 participants). The data of the remaining 24 participants were included in the analyses (12 female / 12 male, *M* = 24.2yrs, *SD* = 4.1yrs). Per participant, there was an average of 101 sentence trials and 100 wordlist trials that were usable for analysis (out of a possible 120 per condition).

5B.2.5 Analyses

The aim of our analyses was to investigate the oscillatory activity involved in syntactic binding and to establish from which brain regions the activity originates. To this end, we examined differences in oscillatory power between the sentence and wordlist conditions.

5B.2.5.1 Time-frequency

Identical to Segaert, Mazaheri et al. (2018), for the frequency range 1-30 Hz, the *Fieldtrip* function 'ft_freqanalysis_mtmconv' was used to obtain time-frequency representations (TFRs) of power for each trial using sliding Hanning tapers with an adaptive time window of three cycles for each frequency (ΔT = 3/f). This approach has also been used in a number of previous studies (e.g., van Diepen, Cohen, Denys, & Mazaheri, 2015; van Diepen & Mazaheri, 2017; Whitmarsh, Nieuwenhuis, Barendregt, & Jensen, 2011). For each participant, the data for the planar gradiometer pairs was combined using the *Fieldtrip* function 'ft_combineplanar' (creating a 102-channel combined planar map in sensor space) and we baseline-corrected the data using the oscillatory activity in a 0.5s period of the fixation cross presentation (specifically, -1.9s to -1.4s in the epoch window). We used an absolute baseline correction, which has the advantage of being comparable with the baseline correction used in the phase-locked analyses. We calculated the TFRs separately per condition for each participant and then averaged across all participants.

We assessed the statistical differences in time-frequency power between the sentence and wordlist conditions across participants using a cluster-level randomisation test (incorporated in the *Fieldtrip* software), which circumvents the type-1 error rate in a situation involving multiple comparisons (i.e., multiple channels and time-frequency points; Maris & Oostenveld, 2007). This approach first clusters the data in channel space depending on whether the contrast between the two conditions exceeds a dependent samples *t*-test threshold of $p < .05$ (two-tailed). In line with Segaert, Mazaheri et al. (2018), we used the following pre-defined frequency bands: alpha (8-12 Hz); low-beta (15-20 Hz) and high-beta (25-30 Hz). We considered a cluster to consist of at least two significant adjacent electrodes. A Monte Carlo *p*-value of a cluster was then obtained by calculating the number of times the *t*-statistics in the shuffled distribution is higher than the original *t*-statistic obtained when contrasting conditions. We performed the analyses within the main time window of interest, centred around the presentation of word 2 (-0.5s to 1s of the epoch), and across the complete timeframe of the trial (-1.3s to 1.2s of the epoch).

5B.2.5.2 Event-related fields (ERFs)

We also conducted a comparison of the ERFs (i.e., phase-locked activity) in the sentence and wordlist conditions. For each participant, we performed an absolute baseline correction for the 0.1s just prior to word 1 (-1.3s to -1.2s of the epoch). We then computed the ERFs per participant for each condition across the complete timeframe of the trial using the *Fieldtrip* function 'ft_timelockanalysis' and then averaged across all participants. The statistical difference in the evoked fields between the sentence and wordlist conditions was assessed using a cluster-based permutation test and Monte Carlo calculation, as described previously.

5B.3 Results

5B.3.1 Behavioural

The participants' task was to detect the reversed speech (on filler trials only). The average group accuracy for correct detection was high (*M* = 94.6%, *SD* = 2.3%, *Range* = 82-98%). This indicates that participants were paying attention to all auditory stimuli presented on both filler and experimental trials as they did not know when the reversed speech would be presented (i.e., the order of items was randomised).

5B.3.2 Time-frequency

The group averaged time-frequency representations of power (TFR) averaged across all sensors for the time window of interest (i.e. -0.5 to 1s of the epoch) are summarised in **Figure 5B.2**. The grand mean TFRs are shown separately for the sentence condition, in which syntactic binding occurred (e.g. *"she grushes";* **Figure 5B.2.A**), and the wordlist condition, in which no binding occurred (e.g. *"cugged grushes";* **Figure 5B.2.B**). **Figure 5B.2.C** shows the TFR of the sentence condition minus the wordlist condition. To first describe the qualitative features of the data: in both conditions, there are power increases in alpha and low beta surrounding the presentation of the second word (at 0s; *"grushes"*). Following this, approximately 0.5s after the second word presentation, there is a slight decrease in alpha and low beta power in both conditions. Descriptively, alpha power appears to be generally higher in the wordlist, compared to the sentence, condition throughout the time period of interest (i.e. -0.5s to 1s; **Figure 5B.3.A**).

We now turn to describe the statistical results of the cluster-based permutation tests. Firstly, we consider the effects within the alpha frequency range (8-12 Hz). When we analysed the data within the time window of interest (-0.5s to 1s), we found a significant condition difference in alpha activity surrounding the presentation of the second word (-0.05s to 0.1s, p = .025). Specifically, during this time period, alpha power was higher in the wordlist, compared to sentence, condition (see **Figure 5B.3.A-C**). The sensors showing a significant difference within this time interval were predominantly over the left-frontal region (**Figure 5B.3.B**). When we analysed the data across the complete timeframe of the trial (-1.3s to 1.2s), the condition difference surrounding the second word remained significant (p = .035), while we observed no other significant differences in the alpha range.

Secondly, we consider the effects of low beta (15-20 Hz). When we analysed the data within the time window of interest (-0.5s to 1s), we found a significant condition difference in low beta activity -0.35s prior to the onset of the second word (i.e., 0.85s following the first word, p = .043). Specifically, at this timepoint, low beta power was higher in the sentence, compared to wordlist, condition (see **Figure 5B.3.D-F**). The sensors showing a significant difference at this timepoint were predominantly over the right-temporal region (**Figure 5B.3.E**). However, when we analysed the data across the larger timeframe of the entire trial (-1.3s to 1.2s), this effect of low beta was no longer significant (p = .072).

Lastly, we found no significant condition differences in oscillatory activity within the high beta range (25-30 Hz) within any of the analyses.

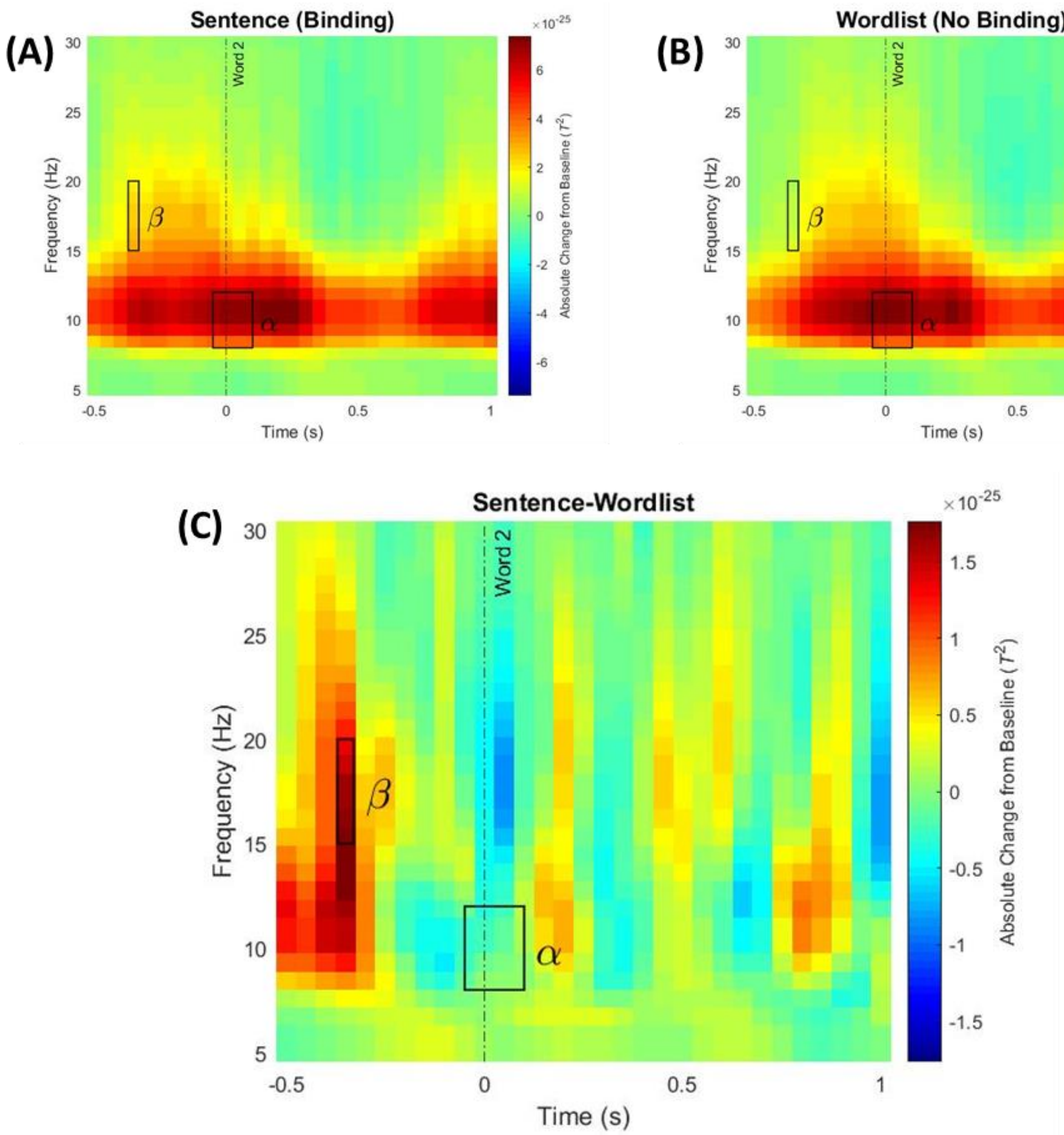

Figure 5B.2 *Time-frequency representations (TFRs) of power averaged across all sensors, expressed as an absolute change from the baseline period (i.e., -1.9s to -1.4s before the onset of the second word) for* ***(A)*** *the Sentence condition, in which syntactic binding occurred (e.g. "she grushes");* ***(B)*** *the Wordlist condition, in which no binding occurred (e.g., "cugged grushes"); and* ***(C)*** *Sentence minus Wordlist. Time relates to the main time period of interest, epoched around the onset of the second word (presented at 0s). The rectangles highlight the time frequency clusters showing a significant difference ($p < .05$) between the two conditions.*

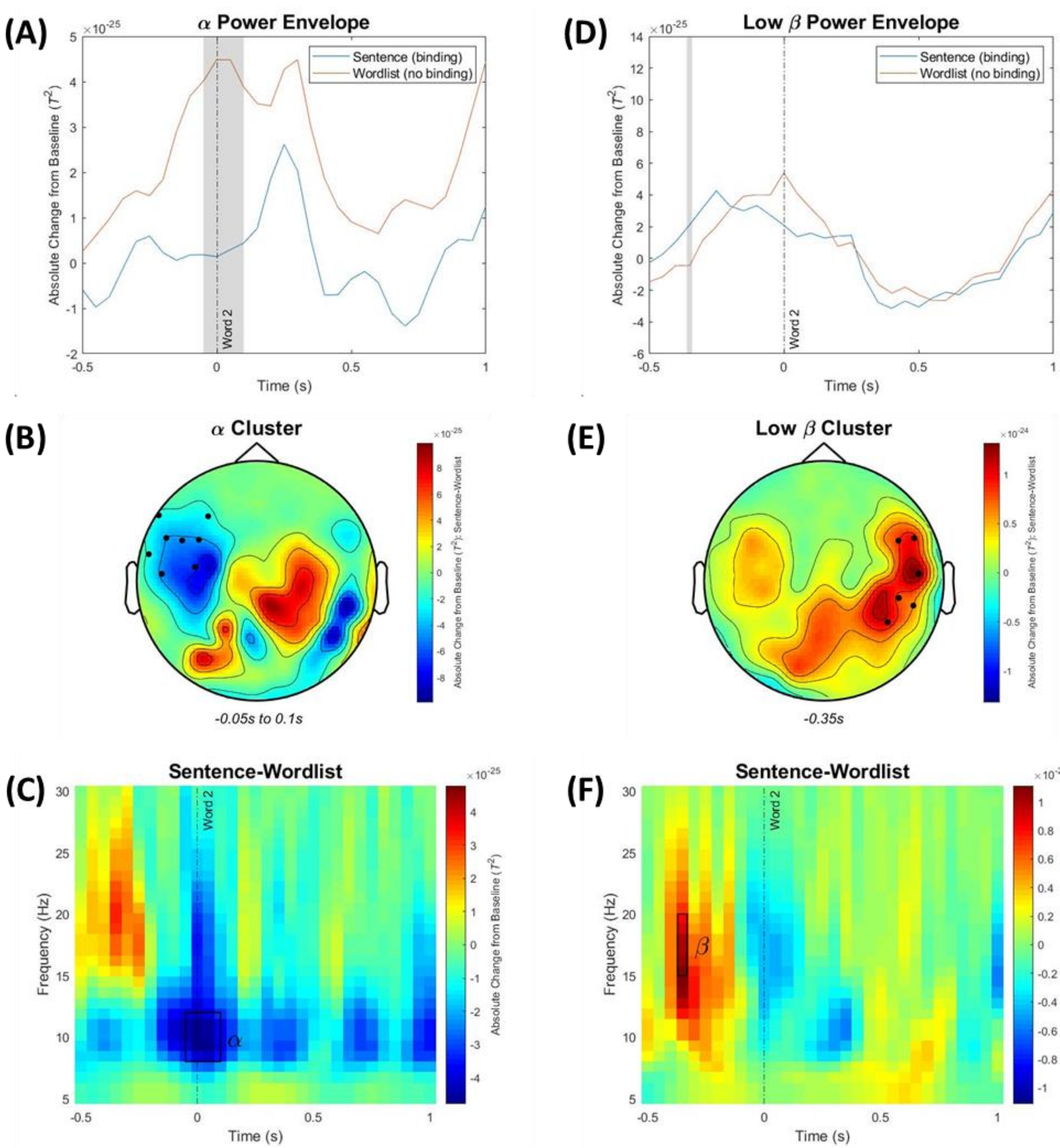

Figure 5B.3 ***(A)*** *The time course of the alpha (8-12 Hz) power envelope for the sensors showing a significant difference in power between the Sentence (i.e., binding) and Wordlist (i.e., no binding) conditions. The shaded grey area indicates the time window in which the difference between conditions is significant (p = .025), centred around the presentation of the second word (-0.05s to 0.1s).* ***(B)*** *The scalp topography of the average activity in the time window showing a significant difference in power between conditions (i.e., the grey shaded area in panel A). The locations of the sensors showing a significant difference (p = .025) during this time interval are marked with black dots.* ***(C)*** *The time–frequency spectra* *averaged across the significant sensors highlighted in the topoplot in panel B.* ***(D-F)*** *Power envelope, scalp topography and time-frequency spectra of the sensors showing a significant condition difference in low beta (15-20 Hz) power: a significant cluster (p = .043) was found -0.35s prior to the onset of the second word (shaded grey area in panel D). Note, when we analysed the data across a larger time window (-1.3s to 1.2s of the epoch), the alpha cluster remained significant (p = .043), but the low beta cluster did not (p = .072).*

5B.3.3 Event-related fields

The group averaged ERFs locked to the onset of the second word averaged across all sensors for the sentence and wordlist conditions are shown in **Figure 5B.4.A**. First, we assessed whether there was a difference in ERF amplitudes between the two conditions across the entire timeframe of the trial (-1.3s to 1.2s of the epoch) when the data was baseline-corrected to a 0.1s period preceding the first word (-1.3s to -1.2s). We found a significant condition difference in ERF amplitude between 0.55s and 0.79s following the presentation of the first word (-0.65s to -0.41s of the epoch, $p < .05$). Specifically, during this time period, ERF amplitude was higher in the wordlist, compared to sentence, condition (**Figure 5B.4.A**). The sensors showing a significant difference within this time interval were predominantly over the left-frontal region (**Figure 5B.4.B**).

Within these analyses, we did not find any condition differences in ERFs following the presentation of the second word; however, this may be because the data were baseline-corrected to just prior to the first word, and not the second word. We therefore analysed the time period following the second word (0s to 1s) using a baseline correction period just prior to the second word presentation (-0.1s to 0s). Again, this did not produce any significant differences in ERFs between the sentence and wordlist conditions.

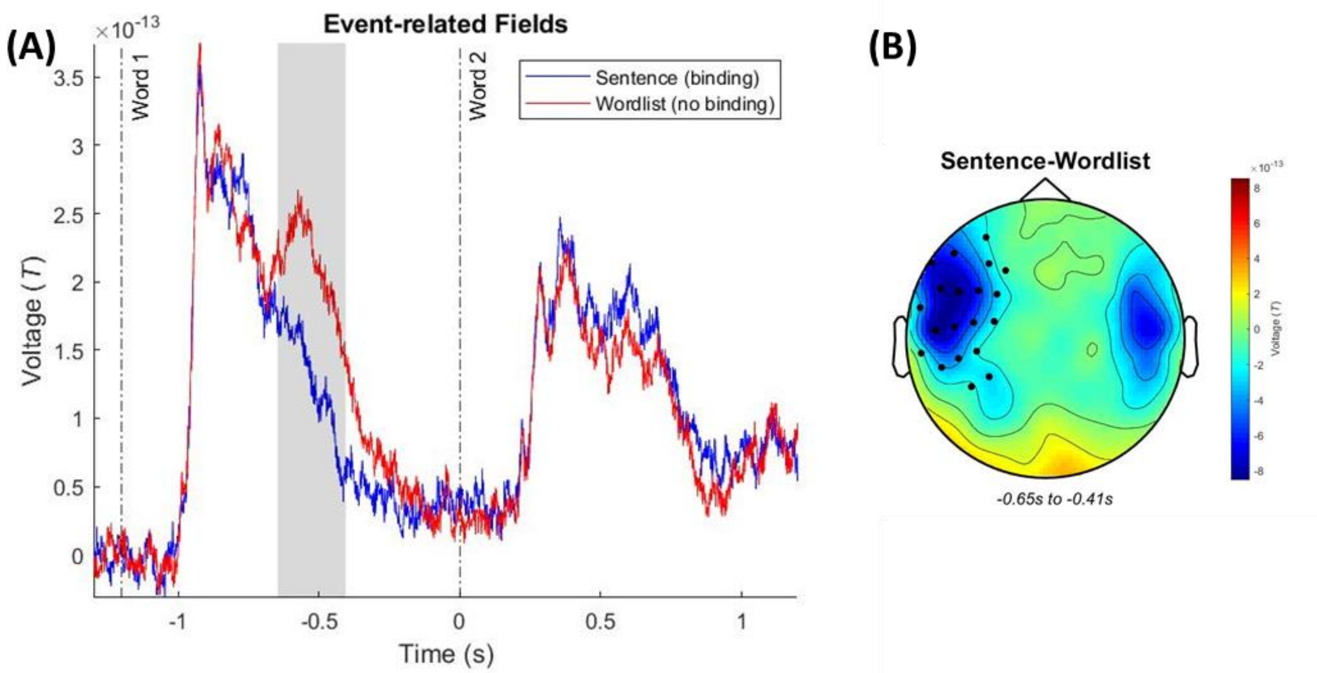

Figure 5B.4 ***(A)*** *The event-related fields (ERFs), locked to the onset of the second word, averaged across all sensors for the Sentence condition (i.e., binding) and Wordlist condition (i.e., no binding), with absolute baseline correction (-1.3s to -1.2s; i.e., 0.1s prior to the onset of word 1). The grey shaded area indicates the time window in which we observed a significant difference in amplitude between the two conditions (p < .05), occurring 0.55s to 0.79s after the onset of word 1.* ***(B)*** *Scalp topography of the average activity in the time window showing a significant difference in amplitude between conditions (i.e., the grey shaded area in panel A). The locations of the sensors showing a significant difference during this time interval are marked with black dots. Note, we did not find any significant differences in the ERFs following word 2, including when we baseline-corrected the data to just prior word 2 (-0.1s to 0s).*

5B.4 Discussion

In this MEG study, we investigated the neural processes involved in syntactic binding using a minimal pseudo-word paradigm. Specifically, we compared evoked and oscillatory activity during the comprehension of minimal sentences involving pseudo-verbs for which syntactic binding may plausibly occur (e.g., *"she grushes"*) to neural activity during the comprehension of pseudo wordlists for which no binding occurs (e.g., *"cugged grushes"*). The time-frequency and event-related field analyses revealed three main findings. Firstly, alpha (8-12 Hz) power was significantly greater in the wordlist (i.e., no binding) condition, compared to sentence (i.e., binding) condition, -0.05s prior to the presentation of the second word to 0.1s after presentation, and this effect was centralised over the left-frontal region of the brain. This suggests that syntactic binding was associated with oscillatory power changes in the alpha band around the time that the target binding word was presented. Secondly, low beta (15-20 Hz) power was greater in the sentence, compared to the wordlist, condition -0.35s prior to the presentation of the second word, and this effect was centralised over the right-temporal region of the brain; however, this effect was only significant when we analysed the time window of interest, and not the complete timeframe of the trial. Thirdly, 0.55s to 0.79s after the presentation of the first word, the ERF amplitude was significantly greater in the wordlist, compared to the sentence, condition, and this effect was centralised over the left-frontal region of the brain. This suggests that differences in the first word between the sentence and wordlist conditions elicited changes in the phase-locked activity. Taken together, these findings provide important insights into the neural networks associated with syntactic binding, as well as the role of different oscillatory frequencies during sentence comprehension, as we now discuss.

5B.4.1 Modulation in alpha power reflects expectation of binding

Perhaps our most surprising finding was that a greater increase in alpha power was associated with no syntactic binding (i.e., the wordlist condition) as this contrasts with Segaert, Mazaheri et al. (2018) previous finding of greater alpha power increase in the sentence binding condition (although interestingly, the topography of their effect was also maximal of the left-frontal area of the brain). This difference in findings is not what we expected given that we employed a very similar paradigm to Segaert, Mazaheri et al. (2018). However, possible explanations for this difference may relate to differences in the languages used (English vs. Dutch), the demographic of the participant samples (monolingual English speakers vs. the more diverse language abilities of most Dutch speakers) and the neuroimaging techniques employed (MEG vs. EEG). In particular, differences in spatial coherence between EEG and MEG may lead to differences in detectable power (Bénar, Grova, Jirsa, & Lina, 2019). For example, EEG and MEG differ in their level of sensitivity to the radical and tangential components of the dipolar sources in the brain, as well as their sensitivity to activity in deeper brain tissues (Lopes da Silva, 2013). In other areas of cognition, distinct EEG/MEG differences have been found in an auditory paired stimulus task examining the P50/M50 component (Edgar et al., 2003), and in the location, phase and amplitude of sleep spindles (Dehghani et al., 2010). It is therefore possible that these measurement differences between our study and Segaert, Mazaheri et al. (2018) may have led to diverging results despite our use of a similar paradigm.

Nonetheless, the findings of our study are still consistent with alpha oscillatory activity playing an important role in higher-order linguistic functions (Meyer, 2018; Murphy, 2015). Importantly, the observed modulations in alpha power occurred independent of phase-locked activity since we did not find any significant difference in ERFs between the sentence and wordlist conditions around or following this presentation of the second word. This indicates that our oscillatory results are specifically informative about the role of the alpha frequency band in the syntactic binding process, and are very unlikely to be driven by changes in the ERFs. Another important feature to highlight is that we found an increase in alpha power (relative to baseline) in both the wordlist and sentence conditions (as clearly shown in **Figure 5B.2.A-C**). This demonstrates that the processing of the syntactic stimuli was not associated with an alpha suppression effect in either condition (i.e., we did not observe decreased alpha power compared to baseline). Instead, the distinction between the two conditions lies in the amount of alpha increase, such that we observed a smaller increase in alpha power in the binding, compared to the no binding, condition.

One explanation for our finding that syntactic binding is associated with a modulation in alpha power relates to predictive processing. Qualitatively, alpha power appears higher in the wordlist condition throughout the time period of interest (see **Figure 5B.3.A**); however, the condition difference was only statistically significant within a 0.15s time window surrounding the presentation of the second word (-0.05s to 0.1s). This significant time window occurred before the second word has been fully presented (all auditory stimuli were at least 0.3s in length), suggesting that the alpha power modulation effect may be related to an expectation that binding will occur. When comprehending a phrase or sentence, we build expectations in order to predict upcoming words (Chang et al., 2006; Kuperberg & Jaeger, 2016); thus, if the first word is a pronoun, as opposed to a pseudo-verb, the participant may reasonably expect that binding is more likely to be required. Although we did attempt to minimise the possibility of participants forming expectations about binding by including filler trials consisting of two pronouns (e.g., *"she I"*), prediction is such an integral part of successful language comprehension that it is impossible to entirely prevent participants from using their existing knowledge about pronouns to predict the likely function and properties of the upcoming word (i.e., that a pronoun will likely be followed by a verb that needs binding).

Predictive top-down processing is beneficial during language comprehension because, given the speed of linguistic input in a dialogue setting, it provides the most efficient solution for fast and accurate comprehension (Kuperberg & Jaeger, 2016). Moreover, modulations in alpha power has been found to play an important role in predictive processing, such that individuals display a greater alpha suppression effect (i.e., decreased alpha power compared to the baseline level) when comprehending a highly predictive, compared to a less predictive, sentence (Piai et al., 2014; Rommers et al., 2017; Wang et al., 2017). In particular, alpha power decreases have been proposed to control the allocation of the brain's resources, such that there is increased engagement of task-relevant regions along with the inhibition of task-irrelevant regions (Jensen & Mazaheri, 2010; Klimesch, 2012). Although we did not observe a strong alpha suppression effect in our study, we did find a smaller increase in alpha power in the sentence, compared to the wordlist, condition. We therefore suggest that less alpha power in the sentence condition around the presentation of the target word may reflect the initiation of anticipatory binding, or unification, processes, along with the increased engagement of the brain regions involved in syntactic binding. The reason why we did not observe a stronger decrease in alpha power (i.e., to below baseline level) may be because we used very simple two-word phrases with minimal semantic meaning (e.g., *"she grushes"*). By contrast, previous studies that have found evidence of more complete alpha suppression during sentence comprehension used more complex sentence stimuli in high or low constraining contexts (e.g., *"To see the [cells/objects], he used a microscope"*; Wang et al., 2017). Compared to our simple stimuli, these sentences would have induced more effortful processing at the lexical, conceptual and syntactic levels.

In line with our interpretation of alpha power modulation reflecting an expectation of binding to occur, the observed effect was predominantly over sensors in the left-frontal area of the brain (as shown in **Figure 5B.2.B**). This is where we would expect the source of linguistic functions, such as syntactic binding and prediction, to originate according to a theoretical framework of linguistic processing within a left-lateralised network of brain regions (Friederici, 2011; Hagoort, 2003; Tyler & Marslen-Wilson, 2008). In particular, within this area of the brain is the LIFG – the region that we predicted would be most strongly associated with syntactic binding given its proposed role in managing the combination of words into a coherent syntactic structure (Hagoort, 2005; Snijders et al., 2008; Uddén et al., 2019). The LIFG and other regions within the left-frontal area of the brain are also involved in predictive processing during the comprehension of real and jabberwocky sentences (Bonhage, Mueller, Friederici, & Fiebach, 2015; Willems, Frank, Nijhof, Hagoort, & van den Bosch, 2016), supporting our explanation that expectation is involved. Nevertheless, because we have not yet performed the source localisation analyses, we cannot precisely identify the different regions involved at this time – this is therefore an important next step for this study (as we consider in more detail later in the discussion).

5B.4.2 ERF differences reflect real vs. pseudo word processing

We now turn to consider the result of our phase-locked analyses. Here we found that the ERF amplitude was significantly greater in the wordlist condition (*"cugged grushes"*) than the sentence condition (*"she grushes"*) 0.55s to 0.79s after the presentation of the first word. This observed ERF condition difference was predominantly over the left-frontal region of the brain (as shown in **Figure 5B.4.B**), suggesting that it may be best interpreted as a late frontal negativity effect. We did not necessarily expect to find a difference in the ERFs, given that Segaert, Mazaheri et al. (2018) found no phase-locked effects; however, an explanation for our observed effect, relating to linguistic processing, still exists. Notably, the effect occurred long before the presentation of the second word (always presented 1.2s after the first word), suggesting that the condition difference in ERFs is unlikely to relate to the binding of the two words. Instead, the condition difference most likely relates to difference in the properties of the first word: in the sentence condition, the first word is always a recognisable pronoun (e.g., *'she', 'I'*), whereas in the wordlist condition, it is one of many possible pseudo-verb-affix combinations (e.g., *'cugged', 'dotch'*). The first word in the two conditions therefore differ on a number of features, relating to ease of lexical access, semantic meaning and frequency, all of which may have led to differences in the observed ERF amplitude.

To consider the existing evidence relating to lexical access, Holcomb and Neville (1990) found that the duration and size of the late negativity effect was greater when pseudo-words were auditorily presented compared to real words, beginning around 0.3s after word onset and persisting until about 1s (see also Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Holcomb, 1993). One interpretation of this result is that the word-like characteristics of pseudo-words mean that they still elicit lexical activation (unlike non-word letter strings), but since there is no actual matching lexical item in the lexicon, a greater amount of post-lexical activation is elicited compared to a recognisable word with a straightforward matching lexical entry. Notably, we observed a similar time-course of the late negativity effect (0.55s to 0.79s) to that found by Holcomb and Neville (1990); hence, one explanation for the difference in ERFs in our study may be that participants were engaging in increased lexical activation in the wordlist condition in a failed attempt to match the initial pseudo-word to an existing lexical item.

5B.4.3 Summary and next steps

In summary, we investigated the neural processes involved in syntactic binding using MEG and a minimal two-word paradigm involving pseudo-words. At the oscillatory level, we found syntactic binding to be associated with a smaller increase in alpha power around the presentation of the second word that requires binding (relative to when the word appears within a non-binding wordlist). We interpret this modulation in alpha power to reflect an expectation of binding to occur, leading to the initiation of anticipatory binding processes and the increased engagement of task-relevant brain regions. At the phase-locked level, we found the ERF amplitude to be greater 0.55s to 0.79s after the presentation of the first word when it was a pseudo-word compared to a pronoun. We interpret this difference in the late frontal negativity effect to reflect differences in the properties of real, compared to pseudo, words, most likely relating to ease of lexical access. Taken together, the findings of this study provide an insight into the time-frequency and phase-locked activity involved in the binding process at the syntactic level. Our finding should therefore be considered alongside studies investigating the evoked and hemodynamic activity involved in binding (e.g., Bemis & Pylkkänen, 2011, 2013; Schell et al., 2017; Zaccarella & Friederici, 2015) in models describing the neurobiology of sentence unification processes.

Nonetheless, certain research questions of this study still remained unanswered, and we plan to address these with future analyses. For example, we found that both the observed alpha power and ERF effects were most prominent over sensors in the left-frontal area of the brain, indicating that activity in this region is crucial for successful language comprehension and syntactic binding (Friederici, 2011; Hagoort, 2003; Tyler & Marslen-Wilson, 2008). However, in order to gain greater understanding of the neural processes involved, it is also necessary to identify the specific cortical regions in which our oscillatory and phase-locked activities originate. The next step for this study therefore involves performing source-localisation analyses on the observed alpha power and ERF effects. Indeed, MEG is ideally suited for localising rapid oscillatory activity to specific cortical structures due to its high temporal resolution and limited spatial smearing (Lopes da Silva, 2013). These characteristics will enable us to bridge the gap between previous EEG and fMRI syntactic binding pseudo-word studies that have only been able to reliably identify either the time-locked or spatial features of the binding process, but not both (Pallier et al., 2011; Segaert, Mazaheri, et al., 2018; Zaccarella & Friederici, 2015). In brief, we plan to use a frequency-domain beam-forming approach to localise power in the brain to specific cortical locations (i.e., voxels), which we will estimate using participants' individual anatomic MRI scans (Gross et al., 2001). We would primarily expect the modulation in alpha power to be localised to structures that have previously been found to be involved in syntactic binding and prediction during language comprehension, such as the LIFG, the LpMTG and the LATL (Bemis & Pylkkänen, 2011, 2013; Schell et al., 2017; Snijders et al., 2008; Zaccarella et al., 2017).

Moreover, MEG not only enables the localisation of the oscillatory activity to cortical regions, but also the investigation of the dynamic interactions between different brain regions and systems that underlie a cognitive process (Lopes da Silva, 2013). Following the beam-forming analyses, we therefore also plan to perform inter-regional connectivity analyses in which we use the oscillatory power envelopes (identified in the time-frequency analyses) to quantify the connectivity between spatially distinct brain regions (Brookes et al., 2016; Schoffelen et al., 2017). Identifying the relationship between the different regions involved in syntactic binding will provide additional insight into the dynamic interaction between different cortical structures within the language processing neural network.

On a final note, we encourage future replication and extension of minimal sentence pseudo-word paradigm in order to gain deeper understanding of the neural processes involved in syntactic binding. Use of the paradigm is advantageous since it enables the isolation of the syntactic binding process at its most basic level with minimal contributions from semantic or working memory. However, given our contrasting findings in the direction of the alpha power modulation to Segaert, Mazaheri et al. (2018), more work is needed to fully understand the exact role of different frequencies within the binding process. We also believe that the paradigm would be a useful tool for investigating syntactic binding processes in older adults given the existing evidence of age-related declines during the comprehension of simple and complex syntactic structures (Beese et al., 2019; Christianson et al., 2006; Peelle et al., 2010; Poulisse et al., 2019; Stine-Morrow et al., 2000). Specifically, investigating the oscillatory signatures and cortical structures associated with syntactic binding, while the contributions from semantic and working memory are kept to a minimum, can lead to a more precise understanding of the effect of healthy ageing on the combinatorial features of syntax comprehension.

CHAPTER 6
Thesis General Discussion

The aim of this thesis was to investigate age-related effects on various features of sentence processing using novel techniques not previously applied to older adults. Specifically, across four experimental chapters, I sought to better understand which aspects of sentence processing are preserved with age, and which decline. In this final chapter, I first summarise the main findings of the thesis, I then discuss the broader theoretical implications of the findings, before considering potential limitations and directions for future research.

6.1 Summary of findings

A summary of the main findings and implications of each experimental chapter is shown in **Table 6.1**.

In **Chapter 2**, we used a structural priming paradigm to investigate the effect of constituent phrasal structure on primed syntactic choices in young and older adults. The primary aim of the study was to determine the level of abstractness of syntactic representations and whether this is affected by healthy ageing. Across two experiments, we found robust evidence that the magnitude of the choice priming effect was unaffected by changes to the internal phrasal structure of the prime. Young and older adults were just as likely to produce a passive target sentence when the preceding passive prime also contained a plural noun phrase or contained a different coordinate noun phrase. This demonstrates that global, not internal, syntactic structure determines syntactic choices in young and older adults, indicating an age-related preservation of the mechanisms that support choice structural priming and syntax selection across the lifespan.

Table 6.1 *Summary of the main findings and implications of the experimental chapters reported in this thesis.*

Chapter	Main Findings	Implications
2	Choice structural priming was unaffected by age or changes to the internal phrasal structure of the prime.	Global, not internal, syntactic structure determined syntactic choices in young and older adults.
3	Both age groups benefited from syntactic repetition and employed a phrasal planning scope; however, young and older adults showed different lexical preview benefits depending on the position of the lexical item in the sentence.	While syntactic planning skills are relatively preserved with age, older adults encounter problems managing the activation of lexical items and their integration into syntactic structures.
4	Older, but not young, adults displayed larger semantic interference effects when two related nouns fell within different phrases in a sentence, compared to when they fell within the same phrase.	Age-related differences exist in managing the temporal flow of lexical information during sentence production.
5 (Part A)	Compared to young adults, older adults self-paced reading times were more affected by syntactic pauses and the passive syntactic structure.	Certain syntactic features are more sensitive to age-related changes in comprehension than others.
5 (Part B)	In young adults, syntactic binding in a minimal sentence (compared to a wordlist) was associated with a smaller increase in alpha power around the presentation of the target word that required binding.	Modulation in alpha power reflects the expectation of binding to occur.

In **Chapter 3**, we further investigated the effect of healthy ageing on sentence production by employing on-line speech onset latencies measures. In **Chapter 3 (Experiment 1)**, we found that both young and older adults were quicker to initiate sentences following syntactically related primes. This finding is consistent with an age-related preservation of the processes involved in syntactic facilitation during sentence planning. In **Chapter 3 (Experiment 2)**, we investigated the effect of healthy ageing on incremental planning during sentence production. Specifically, we used speech onset latencies as a measure of the amount of pre-planning that a speaker engages in prior to beginning articulation. At the syntactic level, we found that young and older adults took longer to initiate sentences with larger, compared to smaller, initial phrases, indicating that both age groups were engaged in a phrasal scope of advanced planning (i.e., prioritising the generation of syntax within the initial phrase prior to speech onset).

Within **Chapter 3 (Experiment 2)**, we also included a lexical manipulation in order to investigate age-related differences in lexical retrieval and integration; interestingly, this did produce age group differences. Previewing an upcoming lexical item benefited young adults' sentence planning (in terms of decreased onset latencies) when the previewed item fell both within and outside the initial phrase. By contrast, older adults only displayed speed preview benefits within the initial phrase, while preview outside the initial phrase caused them to be significantly more error-prone. This suggests that, unlike syntactic processing, lexical processing is more vulnerable to the effects of healthy ageing. Specifically, age-related differences may exist in the flexibility of lexical retrieval during sentence planning and in the ability to integrate lexical information into syntactic structures.

In **Chapter 4**, we aimed to further investigate age-related effects on lexical processing by employing a semantic interference sentence production task. At the syntactic level, we again found that young and older adults engaged in a phrasal scope of advanced planning. This replicates the findings of **Chapter 3** within a different paradigm and robustly demonstrated that syntactic planning skills are preserved with age. However, while young adults displayed interference effects (i.e., slower to initiate sentences when the nouns were related) of similar magnitude when two related nouns fell within the same or different phrases, older adults displayed significantly larger interference effects when the nouns were in different phrases. This provides further evidence for age effects at the lexical level, and indicates that older adults experience increased difficulty in managing the temporal flow of lexical information during sentence production.

Finally, in **Chapter 5**, we turned to the other side of successful communication: sentence comprehension. In **Chapter 5 (Part A)**, we employed a comprehension reading task to investigate which syntactic complexity features are most affected by healthy ageing. We found that, compared to young adults, older adults self-paced reading times were more affected by syntactic pauses and the use of the passive syntax (a less frequent structure in English), suggesting that these syntactic features are particularly sensitive to age-related changes in sentence comprehension.

In **Chapter 5 (Part B)**, we investigated the oscillatory activity involved in the binding of individual words into larger syntactic structures with more complex meaning using the neuroimaging technique of MEG. Using a minimal sentence pseudo-word paradigm, we found that, in young adults, syntactic binding was associated with a smaller increase in alpha power around the presentation of the second word that required binding (compared to when the word appears within a non-binding context), and that this effect was most prominent over sensors in the left-frontal area of the brain. This suggests that expectation of binding to occur leads to a modulation in alpha power, reflecting the initiation of the binding process in task-relevant regions within the brain's left-lateralised language network. The long-term goal of this study is to investigate how these neural processes involved in syntactic binding may be affected by heathy ageing by also testing older adults.

In summary, across the four experimental chapters, I found evidence that healthy ageing does not affect all features of language equally. At the sentence production level, the findings of this thesis demonstrate that, while syntactic skills are preserved with age (in terms of both syntax selection and planning), lexical processes are more vulnerable to age-related effects, particularly in the management of lexical items into syntactic structures. At the sentence comprehension level, I found that certain syntactic features are more sensitive to the effect of healthy ageing than others. Taken together, these findings have important implications for theories of sentence processing, theories of language and ageing, and neurobiological models of language, as I now discuss.

6.2 Theoretical implications

6.2.1 The nature of syntactic representations

In **Chapter 2**, we robustly demonstrated that primed syntactic choices are determined by highly abstract representations of the global syntactic structure that are unspecified for constituent phrasal properties. This provides decisive support, for the first time, for models of structural priming which propose that properties relating to internal phrasal structure are not encoded within abstract syntactic representations. Our findings may be explained under a residual activation model of priming, which proposes that combinatorial nodes within the lexicon only encompass the critical global features of a sentence (Pickering & Branigan, 1998), or an implicit learning account, which argues that the internal sequence of words within a noun phrase must not be specified if a language processing network is to be optimally efficient (Chang et al., 2006). Our findings add to the growing evidence that manipulating the internal phrasal properties of a sentence does not affect the magnitude of structural priming (Bock, 1989; Branigan et al., 2006; Fox Tree & Meijer, 1999; Pickering & Branigan, 1998). Most importantly, we build on these previous studies as we are able to rule out alternative explanations for the effect relating to conceptual salience and thematic order; this is because we found similar priming effects whether we manipulated the noun phrase structure relating to patient role (the initial phrase in a passive sentence) or the agent role (the more thematically salient entity).

6.2.2 Structural priming across the lifespan

Within **Chapter 2** and **Chapter 3 (Experiment 1)**, we found that syntactic facilitation is preserved with age at both the choice and planning level: young and older speakers showed comparable effects of priming, both for syntactic choice and the speed with which they initiated target sentences. Taken together, these findings have important implications for how well models of structural priming are able to account for speakers across the lifespan. Neither the residual activation model (Pickering & Branigan, 1998), implicit learning model (Chang et al., 2006) or two-stage competition model (Segaert et al., 2016) were explicitly designed with older speakers in mind; however, a complete model of language processing should be able to account for speakers of all ages and abilities. Indeed, much effort has been made to apply the principles of these models to young children (Branigan & Messenger, 2016; Messenger et al., 2011; Rowland, Chang, Ambridge, Pine, & Lieven, 2012) and to patients with memory deficits (Cho-Reyes et al., 2016; Ferreira et al., 2008). However, the studies reported in this thesis are among the first to investigate structural priming in older speakers and, therefore, provide novel insights into the application of the models across the lifespan.

To first consider models with a spreading activation architecture (Pickering & Branigan, 1998; Segaert et al., 2016), our findings indicate that, despite general age-related declines in processing speed and transmission strength (MacKay & Burke, 1990; Salthouse, 1996), the nature of this spreading activation network, and how information is transmitted between nodes within the network, is relatively well-preserved with age. Indeed, it is generally considered that once abstract syntactic representations are established in the lexicon (i.e., as combinatorial nodes), they become immediately susceptible to priming effects (Rowland et al., 2012). Thus, given that syntactic representations do not disappear with age (assuming healthy ageing), the residual activation model explains structural priming in speakers of all ages with the application of the same principles. Moreover, our findings suggest that the nature of these syntactic representations does not change with age as we found that both young and older adults' syntactic choices were primed by the repetition of global, but not local, syntactic structure.

Turning now to the implicit learning model (Chang et al., 2006), our findings can also be explained under this account of structural priming. Unlike the residual activation model, the implicit learning model has already integrated developmental and adult processing predictions within a connectionist network since the error-based implicit learning processes that a child uses to learn syntactic structure are the same processes that drive structural priming effects in adult speakers. Our findings indicate that these same implicit learning principles may also be applied to older speakers. This is perhaps not surprising given that implicit learning skills tend to be fairly well-preserved with age (Fleischman et al., 2004; Spaan & Raaijmakers, 2011). However, a note of caution is required regarding *lexical boost* (the increase in the magnitude of the priming effect when there is lexical overlap between the prime and target; Pickering & Ferreira, 2008). Although lexical boost was not investigated in this thesis, Chang et al. (2006, 2012) argue that lexical boost is entirely dissociated from abstract structural priming, and is instead driven by explicit memory traces of the prime. This predicts that lexical boost should decrease with age due to age-related declines in explicit memory (Fleischman et al., 2004; Waters & Caplan, 2003); however, in two recent ageing studies, lexical boost of the passive syntax has been found to persist in older adults (Hardy et al., 2017; Man, Meehan, Martin, Branigan, & Lee, 2019). Thus, while the implicit learning model may explain the findings of this thesis (in which we investigated priming without lexical overlap), it may not offer such a harmonious account of structural priming across the lifespan when the related phenomenon of lexical boost is also considered.

6.2.3 Language and ageing: A complex balance of decline and preservation

Unlike other cognitive functions, there is not a straightforward relationship between healthy ageing and language abilities (Burke & Shafto, 2008). This has always presented somewhat of a puzzle for theories of language and ageing since a complete model must be able to convincingly explain why some language skills decline with age, while others are preserved. Within this thesis, I provide further evidence that healthy ageing does not affect all features of language processing equally. On the one hand, I demonstrate that syntax production skills are relatively preserved with age as I found no effect of age on syntactic facilitation (**Chapters 2-3**) or on the scope of syntactic planning (**Chapters 3-4**). On the other hand, I found that the skills involved in managing the retrieval and integration of lexical items are negatively affected by the ageing process (**Chapters 3-4**). Thus, there exists a dichotomy between the effect of healthy ageing on the syntactic and lexical processes involved in fluent sentence production. The real question though is how can these findings be explained within one complete model.

One theoretical approach to our findings is to consider process-specific mechanisms, whereby some language features may be more vulnerable to the effect of ageing than others (Burke & Shafto, 2004; Laver & Burke, 1993). Such an explanation does fit with our contrasting findings between syntactic and lexical processing in old age; however, this would only make sense under a model of language in which there is a complete dissociation between syntax generation and lexical retrieval (Chang et al., 2000, 2006). Such a dichotomy between lexical and syntactic processing is somewhat harder to explain within models that propose syntactic encoding is lexically driven since this requires a far more interactive relationship between the two processes (Bock & Levelt, 1994; Levelt, 1989; Levelt et al., 1999; Pickering & Branigan, 1998). A better explanation of our findings must, therefore, be one that considers the complex interplay between the functionality of cognitive resources and the linguistic demands of a given task. Throughout this thesis, I have made reference to Peelle's (2019) 'supply and demand' model when explaining the ageing effects that we observed; I will now attempt to more completely assess the findings from **Chapters 2-4** within this model (see **Figure 6.1**). In Peelle's (2019) schematic framework, behavioural performance reflects the complex balance between an individual's processing efficiency (in terms of neurocognitive capacity) and the requirements of the given language task, which will consist of many challenges, relating to both perceptual and metalinguistic processing. If an individual's processing resources are sufficient for a task, good behavioural performance will be observed, but if task demands outweigh these resources, behavioural performance will become poor.

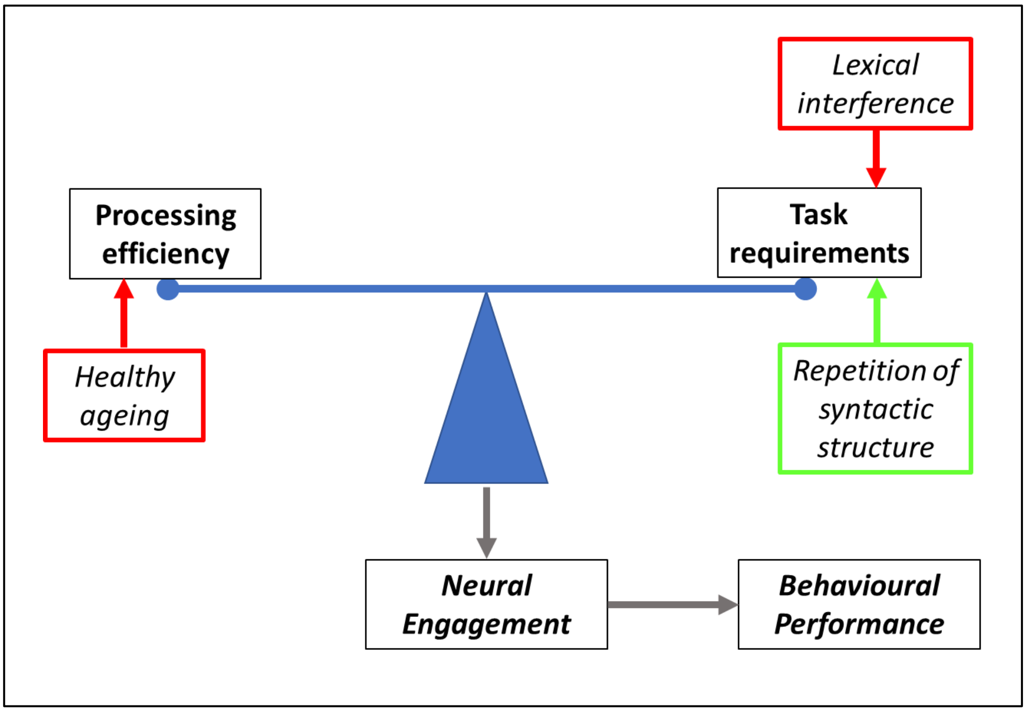

Figure 6.1 *Peelle's (2019) 'supply and demand' framework of language processing, adapted to explain the findings of this thesis. The balance between processing efficiency and task requirements may be shifted by various factors, relating to the healthy ageing process and the syntactic/lexical demands of a given task.*

Due to overall cognitive and neuroanatomical changes that occur with healthy ageing, it is highly likely that an older speaker's processing efficiency will be less than that of a young speaker as there are less resources available to support linguistic processing. However, this decline in processing efficiency does not necessarily mean that age group differences will always be observed. Specifically, good behavioural performance will still be observed in older adults as long as processing efficiency continues to outweigh task demands. I argue that this may explain our findings of preserved syntactic planning in **Chapter 3 (Experiment 2)** and **Chapter 4**. Even though older speakers' processing efficiency is less than young adults, they still possess sufficient cognitive resources to support the planning of sentences containing initial simple or coordinate noun phrases. Moreover, once syntactic repetition is introduced into the task, age group differences are even less likely to be observed because the task demands become easier. Thus, the imbalance between processing efficiency and task demands will shift in favour of good behavioural performance to an even greater extent. This can explain why we observed an age-related preservation of choice and latency structural priming in **Chapter 2** and **Chapter 3 (Experiment 1)**.

However, this balance between processing efficiency and task requirements can easily be swayed in the direction of poor behavioural performance if the task demands are increased. In **Chapter 3 (Experiment 2)** and **Chapter 4**, we increased the lexical demands by introducing an 'unhelpful' lexical preview (outside of speakers' preferred planning scope) or by including a semantic interference element. This makes the task of producing a fluent and coherent sentence more challenging since a speaker now has to employ increased cognitive resources in order to prevent the distractor from interfering with their planning of the initial phrase. For all speakers (young and older), this decreases the relative difference between processing efficiency and task requirements. However, because of existing age-related differences in processing efficiency, the negative effect of increasing the task load is greater for older adults since the scale is already more vulnerable to tip in favour of poor behavioural performance. Moreover, compared to syntactic processing, lexical processing may be generally more susceptible to the effects of increased task demands during healthy ageing due to existing age-related difficulties with word finding and the management of lexical items (Burke et al., 1991; LaGrone & Spieler, 2006; Segaert, Lucas, et al., 2018; Taylor & Burke, 2002). Taken together, this can explain why we observed age group differences in **Chapters**

3-4, such that older adults become slower and more error-prone when they had to inhibit a lexical distractor that was not required in the planning of the initial phrase.

In summary, in the absence of a more reliable model that can comprehensively and completely explain the variable effect of ageing on different aspects of sentence production, Peelle's (2019) 'supply and demand' framework serves as a useful tool for understanding the findings of this thesis (i.e., the evidence that some aspects of sentence production are preserved with age, while others decline). Nonetheless, it is important to note that this is a conceptual framework designed to provide connectivity among different ideas and possible outcomes – it is not an in-depth model of the underlying cognitive and brain mechanisms. This framework may therefore best be considered as a starting point for future research to develop a falsifiable model of language and ageing that can comprehensively explain, through the implementation of mechanistic operations, why healthy ageing has a variable effect on different features of language processing. At present the framework has minimal predictive value, however, if it was developed into a more falsifiable model, this would enable more explicit predictions to be made, which could be tested through well-designed experiments.

6.2.4 Comparing production and comprehension

Across **Chapters 2-4**, we observed robust evidence of preserved syntactic processing during sentence production; however, this seems somewhat at odds with our findings of **Chapter 5 (Part A)** that age-related differences exist in young and older adults' self-paced reading times (a measure of syntax comprehension). One explanation for this apparently contrasting effect of production and comprehension may again relate to Peelle's (2019) model. Specifically, existing age-related declines in processing efficiency may make older adults more susceptible to the effect of increasing task demands. Our evidence indicates that certain syntactic features (namely, syntactic pauses and the passive syntax) are likely to have a greater influence on older adults' behavioural performance in a sentence comprehension task. Moreover, the stimuli used in **Chapter 5 (Part A)** were more complex than those used in the other experiments reported in this thesis (i.e., they contained multiple embedded clauses and large syntactic operations of movement). This may explain why we did not observe any age-related effects on syntactic processing during production because the task requirements (at least at the syntactic level) were not sufficiently taxing to outweigh older adults' processing efficiency. To investigate this further, it is necessary to investigate older adults' syntactic processing during production using more complex stimuli (as we discuss in more detail in **section 6.3.2** below).

However, such an explanation cannot so readily explain why Poulisse et al. (2019) found evidence of age-related decline in syntax comprehension for very simple structures – older adults were slower and less accurate at detecting syntactic agreement errors for two-word sentences that contain either real or pseudo verbs (e.g., *"I cooks" / "I spuffs"*). In order to reconcile these findings with our evidence of preserved syntactic processing during production, it is important to consider the different methodologies. Poulisse et al. (2019) presented the stimuli auditorily at set time intervals and, immediately following this, participants had to indicate whether the sentence was grammatically correct or incorrect. This contrasts with the more self-paced nature of the sentence production task employed throughout this thesis, whereby there were no external pressures on participants' speed of sentence initiation (in **Chapters 3-4** the screen did time-out after four seconds if the participant did not begin speaking, but this is a very generous time period considering that onset latencies were rarely greater than 1500ms). This meant that participants could take as long as they needed to plan and produce their sentence. This differs from Poulisse's et al. (2019) task in which participants had to engage in syntax comprehension processes immediately as the stimuli were presented if they were to answer the grammatical question correctly. Thus, age-related differences in syntactic processing may be more likely to occur in situations in which older adults must immediately process and respond to the stimuli, rather than in situations when they have sufficient time to engage with syntactic processing at their own rate.

6.2.5 The neurobiology of syntactic binding

In **Chapter 5 (Part B)**, we found evidence that binding during sentence comprehension (i.e., the combination of individual words into a larger syntactic structure with more meaning) is associated with oscillatory changes in the alpha frequency band in young adults. In contrast to the majority of previous neuroimaging binding studies, we isolated the neural networks involved in the syntactic aspect of binding by employing a pseudo-word paradigm that minimises contributions from semantics. We therefore consider that the main theoretical contribution of this study is in highlighting that binding at the syntactic level is associated with changes in the time-frequency power spectra (specifically, in terms of the modulation of alpha power). This is only the second study to investigate the non-phase-locked activity associated with binding at a minimal two-word level (see also Segaert, Mazaheri, et al., 2018) and should be considered along with studies that investigated the evoked and hemodynamic activity (e.g., Bemis & Pylkkänen, 2011, 2013; Schell et al., 2017; Zaccarella & Friederici, 2015) when hypothesising about the neurobiology of binding. In particular, while it is generally undisputed that binding originates within a left-lateralised network of brain regions (Hagoort, 2005; Pylkkänen, 2019), the exact role of different frequencies within the binding process and how they contribute to the dynamic interaction between different cortical regions is currently less well understood. The findings of our study shed some light on this as we suggest that modulation in alpha power may reflect an expectation of binding to occur, leading to the initiation of anticipatory binding processes and increased engagement of task-relevant brain regions. We strongly encourage further investigation of the time-frequency activity involved in binding, both at the syntactic and semantic level, in order to more precisely understand the underlying oscillatory mechanisms, and where they originate in the brain, in young and older adults.

6.3 Outlook to the future

6.3.1 Looking deeper into sentence planning

Throughout this thesis, I predominantly used latency measures of speech production in order to investigate the scope of advanced planning. The findings of **Chapters 3-4** in particular revealed interesting age group differences in the time taken to plan sentences of varying syntactic and lexical structures. However, a potential limitation of using speech onset latencies is that they only provide a measure of the end point of the initial planning process (i.e., the time taken to complete the advanced planning required for fluent sentence production), and do not provide any measure of the incremental planning that continues to unfold during articulation. One way to investigate age-related differences in ongoing sentence planning is to use eye-tracking. Measures of gaze fixations and eye movements are useful because they are informative about what speakers attend to prior to and during speech production (Griffin & Bock, 2000). Moreover, eye movement patterns are directly linked to incremental sentence processing since, when comprehending or describing visual scenes, people will tend to move their gaze to the entity that they predict will be referred to next (Altmann & Kamide, 1999) or are planning on saying next (Griffin, 2001; Griffin & Bock, 2000). Various syntactic and lexical factors have been found to influence participants' eye movement patterns, including repetition of syntactic structure (Konopka & Meyer, 2014) and context predictability (Frisson et al., 2005), as well as the phonological and orthographic similarities between words (Frisson, Koole, Hughes, Olson, & Wheeldon, 2014).

Only one previous study has investigated incremental sentence planning in older adults using eye-tracking. Spieler and Griffin (2006) asked participants to describe visual displays containing multiple items (e.g., *"The clock and the television are above the needle"*). They found that young and older adults followed similar patterns during sentence production, in terms of the time spent gazing at an object relative to the onset of the object being named in the utterance. However, Spieler and Griffin (2006) did not vary the syntactic complexity of the sentences that participants produced: all items contained an initial coordinate noun phrase and there were no filler items of a different structure. This predictability in the structure of the sentences means that any difference in eye movement patterns are more likely to relate to lexical factors (e.g., the codability of the item) and not to actual syntactic planning mechanisms. With this is mind, a novel future study would be to incorporate eye-tracking measures into an ageing study in which speakers produce sentences of varying structures (as we did in **Chapters 3-4**). It may be that once the predictability element is removed, age group differences do emerge in the speakers' fixation and gaze patterns during sentence production. In particular, it would be interesting to see whether the increased lexical interference effects we observed in **Chapters 3-4** are in part caused by older speakers initially fixating on the distractor item, causing them to fixate less reliably on the initial to-be-produced item. Related to this, when the lexical distractor appears outside of the planning of the initial phrase, older adults may need to fixate for longer on the initial lexical item in order to resolve any interference effects.

6.3.2 Moving up the scale of complexity during syntax selection and planning

We found no age group differences in the priming of active and passive sentences containing plural and coordinate noun phrases (**Chapter 2**) or in the planning scope of sentences containing initial simple and coordinate noun phrases (**Chapter 3-4**). This demonstrates an age-related preservation of the syntactic processes involved in the selection and planning of sentences containing multiple phrases and at least three entities. However, within everyday conversation, sentences may be more complex in structure (e.g., contain embedded clauses and a greater number of entities). Further work is therefore needed to fully understand the nature of older adults' syntax selection and planning mechanisms during the production of more syntactically complex sentences. As we demonstrated in **Chapter 5**, certain syntactic features are more sensitive to age-related declines in comprehension than others, and this may also be the case for sentence production.

Future studies could address this question in multiple ways. Firstly, the planning scope paradigm we used in **Chapter 3 (Experiment 2)** could be adapted to include a more complex initial phrase structure by increasing the number of moving lexical items on screen (e.g., *"[the A, the B, the C and the … Nth noun] move above the X]"*). The more nouns within the initial phrase, the greater the amount of lexical information that must be encoded and held within the working memory buffer prior to speech onset (Slevc, 2011; Wheeldon et al., 2013). It is therefore inevitable that, as the number of nouns within the initial phrase increases, speakers will at some point begin to have problems with buffering and maintaining a linearized output; this may, in turn, lead to more error-prone speech and/or the adoption of a different planning strategy (i.e., only planning a subset of the initial phrase prior to articulation). The interesting question though is whether there is an age-related change in this limit of manageable lexical items, and crucially whether young and older adults differ in the strategies that they adopt when this limit is surpassed. Wheeldon et al. (2013) demonstrated that young adults continue to engage in a phrasal planning scope when the initial phrase contained three lexical items, but that a preview benefit was not reliably maintained for the third lexical item, suggesting that differences are already starting to emerge in the scope of lexical planning as the size of the initial phrase increases. Future studies investigating how older adults' planning scope changes as the complexity of the initial phrase increases will provide further insight into the effect of healthy ageing on the incremental planning mechanisms involved in fluent sentence production.

Turning to the effect of increased syntactic complexity on structural priming in older adults, one way this could be investigated in future studies is by including an embedded clause component within transitive verb primes and targets (e.g., *"The teacher saw that [the boy is being chased by the girl]"*; Branigan et al., 2006). Alternatively, more complex sentences could be used that contain low or high relative clause attachments (e.g., *"The tourist guide mentioned that the bells of the church that …was very old* [low attachment] " / *…were very old* [high attachment]"; Scheepers et al., 2011). If choice structural priming effects continue to persist in older adults for more complex structures, this would further demonstrate that the nature of syntactic representations does not change with old age. Moreover, given that structural priming may have long-lasting effects on the biases of different structures (Chang et al., 2006), the priming of more complex structures could potentially serve as a tool for increasing the variety of syntax that older adults use. This is important because a decline in the use of complex syntactic structures with age is often associated with negative appraisal by others, which may lead to patronising behaviour towards older adults (Ryan, Boich, & Hummert, 1995). One way to test whether structural priming facilitates older adults' long-term use of more complex structures would be to use an arithmetic-to-production paradigm. Scheepers et al. (2011) demonstrated that speakers could be biased to produce sentences with high or low clause attachments if, beforehand, they had solved mathematical equations of a similar structure (see also Scheepers, Galkina, Shtyrov, & Myachykov, 2019; Scheepers & Sturt, 2014). If similar priming effects are observed in older adults, this suggests that regular completion of specific equations (designed to mimic the structure of complex syntax) could be a practical tool for increasing the production of more syntactically complex sentences in old age.

6.3.3 Going beneath the surface to the neural networks

Investigating the effect of healthy ageing on behavioural measures of sentence production and comprehension is the first step towards understanding age-related changes in these domains. Within a tightly-controlled behavioural paradigm, it is possible to detect reliable age-related changes in both off-line measures, such as syntactic choices and errors, as well as on-line measures, such as speech onset latencies and eye movements (Mertins, 2016). However, in order to fully understand sentence processing in old age, it is also necessary to look beneath the surface into potential changes in the neural networks that support these critical language functions. This is important in order to identify whether atrophy in any particular brain region or neural network underlies age-related declines in behavioural performance, such as in lexical processing as we observed in **Chapters 3-4**. Moreover, minimal age group differences in behavioural performance, such as syntax selection and planning (as seen in **Chapters 2-4**), do not necessarily mean that young and older adults are engaging the exact same neural networks when performing the task. Previous studies have demonstrated that older adults recruit additional brain areas and neural networks during sentence processing (Meunier et al., 2014; Peelle et al., 2010; Tyler et al., 2010), which may be driven by general dedifferentiation in neural efficiency or by intentional recruitment designed to compensate for atrophy elsewhere (for reviews see, Peelle, 2019; Wingfield & Grossman, 2006).

Looking forward to future research, it is therefore important to understand whether the age-related effects of both decline and preservation observed in this thesis are related to any age-related changes in the neural networks that support syntactic and lexical processing. Within young adults, sentence processing has been found to predominantly rely on a left-lateralised network of brain regions (Tyler & Marslen-Wilson, 2008). In particular, activity in the left anterior temporal lobe has been found to support incremental sentence planning processes (Brennan & Pylkkänen, 2017) and activity in the left inferior frontal gyrus and left middle temporal gyrus is related to structural priming (Segaert, Kempen, Petersson, & Hagoort, 2013; Segaert et al., 2012). However, based on the existing literature, it is likely that the older adults we tested recruited additional brain areas during the structural priming and planning scope tasks in order to maintain similar behavioural performance to the young adults. Future studies using neurobiological techniques, such as EEG, MEG and fMRI, are therefore important for furthering our understanding about the effect of healthy ageing on the syntactic and lexical processing involved in fluent sentence production.

Indeed, understanding age-related changes in the neural networks involved in syntactic binding was a long-term goal of **Chapter 5 (Part B)**. Within the timeframe of this thesis, I was only able to test young adults as part of a syntactic binding MEG comprehension task; however, the completion of this experiment is one part of a much larger project that is planned. The next steps for this study are: firstly, localising the oscillatory effects observed in the young adults to specific cortical regions using beam-forming analyses; and, secondly, conducting the experiment with an older adult population in order to investigate age-related changes in syntactic binding. Behavioural evidence indicates that, compared to young adults, older adults are slower and less accurate at detecting syntactic agreement errors, indicating a possible age-related decline in syntactic binding processes (Poulisse et al., 2019). These age group differences may reflect age-related changes in the neural networks that support syntactic binding. Indeed, recent EEG work in our group suggests that the neural signature of syntactic binding is qualitatively different in older, compared to young, adults (Poulisse, Wheeldon, Mazaheri, & Segaert, *in prep*); however, it is not possible to localise these age group effects to specific brain regions without the high temporal and spatial resolution of MEG. Specifically, our findings in **Chapter 5 (Part B)** suggest that syntactic binding occurs within the left-frontal area of the brain; however, in older adults, syntactic binding may be associated with a much larger network of brain regions, either as a result of general dedifferentiation or more deliberate compensation (Wingfield & Grossman, 2006). Investigating age-related changes in sentence processing at neuroanatomical, as well as behavioural, level is therefore essential for deepening our understanding of the complex interplay between healthy ageing and language.

6.4 Concluding words

Within this thesis, I investigated the influence of healthy ageing on the syntactic and lexical processes required for fluent sentence production and comprehension. Overall, I found evidence of a complex dynamic between language and ageing; while syntactic functions (at least during production) appear relatively preserved, the ability to successfully manage the integration of lexical items into syntactic structures declines with age. These findings emphasise that there is not a straightforward linear relationship between language and ageing, and highlight how each feature of language must be carefully considered on an individual basis when investigating how it is affected by healthy ageing. Future studies should look to use more complex sentence stimuli and neuroimaging techniques to gain a more complete picture of language processing in old age.

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APPENDIX

Chapter 3 Supplementary Measurements

Here we provide information about the method and analyses relating to the eight additional measurements that participants completed alongside the main sentence production tasks of Experiment 1 (syntactic priming) and Experiment 2 (planning scope). Our aim with these measurements was to investigate what kind of inter-individual variability accounted for age-related effects and individual differences in performance within the sentence production tasks. We report information on these additional measurements because, even though we found minimal significant effects involving the measurements, it is important to continue to integrate measures of individual variability into experimental methods in order to fully understand the cognitive factors that underlie different language mechanisms (Kidd, Donnelly, & Christiansen, 2018) and what explains inter-individual variability within a given language task (Bates, Dale, & Thal, 1995; Peelle, 2019). This is particularly important when investigating language processing in older adults given the widespread variation in the type and extent of cognitive and neuroanatomical changes that occur with healthy ageing (Salthouse, 2012; Ziegler, Dahnke, & Gaser, 2012).

Method

Each participant (50 young and 56 older adults) completed eight additional measures designed to provide an indicator of current ability across cognitive, physical and physiological domains. The selection of these measures was based on the different factors identified by Lara et al. (2013) that contribute to the 'heathy ageing phenotype' (the ability to function independently, both physically and cognitively) and have been related to individual differences in the magnitude of age-related language decline or age-related changes more generally. More information on each factor and the measurements and procedures used are outlined below. We used measurements that have been found to show robust age group differences in previous studies. We choose to only operationalise a single measurement per factor because the aim of the test battery was to investigate a broad range of individual differences. Such an approach was also necessary due to time constraints and the risk of potential task fatigue (particularly in older adults) from a more extended test battery (i.e., multiple measures per factor); however, this did come at the expense of a more in-depth and reliable measurement of each factor. Testing of the eight measurements was spread across the two test sessions.

Processing speed. According to the general slowing model of ageing (Salthouse, 1996), declines in processing speed may impact upon processing efficiency across all cognitive functions, including language. In line with this, processing speed has been found to be a mediating predictor of older adults' performance in a language processing task (Huettig & Janse, 2016). We measured processing speed using the standardised WAIS-IV Coding task (Wechsler, 2008), in which participants must match as many numbers as possible to arbitrary symbols (following a key) in a two-minute time period.

Vocabulary. Knowledge of the lexical features of words and their corresponding phonological form is essential for fluent word and sentence production. Indeed, older adults with a larger vocabulary size experience fewer tip-of-the-tongue states (Segaert, Lucas, et al., 2018). We measured participants' vocabulary using the Mill Hill Vocabulary Test (Raven, Raven, & Court, 1988), a multi-choice task in which the participant must select the correct definition of a word.

Short-term and long-term memory. Normal ageing is associated with declines in both short-term memory (STM) and long-term memory (LTM) (Maylor, 2005). Memory skills are important for successful communication as speakers often need to retrieve information that has already been processed in order to be able to fully integrate new information into an evolving sentence (van Dyke, 2012). We assessed memory via the recall of 12 unrelated words taken from the Wechsler Memory Scale (Wechsler, 1997), both immediately (STM measure) and after a five minute delay (LTM measure).

Working memory. The ability to efficiently store and manage information in working memory (WM) is critical for successful sentence processing (Just & Carpenter, 1992; MacDonald & Christiansen, 2002). Overall declines in WM with age are therefore likely to contribute toward age-related declines in syntax production, as evident in studies that have found individual differences in WM to be associated with performance on syntax production measures (Hoskyn & Swanson, 2003; Kemper & Sumner, 2001). We measured WM using a backward digit span task (Waters & Caplan, 2003), in which participants had to recall a number sequence in reverse order: overall WM score was defined at the span length at which the participant could correctly recall the digits in reverse order on three out of five trials.

Inhibitory control. According to the inhibitory deficit model (Hasher & Zacks, 1988), declines in inhibitory control with age result in older adults being less able to effectively control what information enters and leaves the working memory store. This creates interference during language processing which can result in poorer performance, such as older adults having greater difficulty ignoring irrelevant stimuli (Britt et al., 2016; Sommers & Danielson, 1999; Tun et al., 2002). We measured inhibitory control using a stop-signal task (Logan & Cowan, 1984). Participants had to respond to a ‘go’ stimulus as quickly as possible, but to withhold their response if a stop-signal appeared (the delay between the ‘go’ and ‘stop’ signal was varied dynamically). The stop signal reaction time (SSRT) was calculated by subtracting a participant’s average stop-signal delay from their average response time to the ‘go’ stimulus; a smaller SSRT score indicated better inhibitory control (for a more extensive explanation, see Williams, Ponesse, Schachar, Logan, & Tannock, 1999).

Grip strength. Good physical health and high levels of aerobic fitness can help protect against age-related declines in cognitive functioning (Barnes, 2015; Geda et al., 2010). This includes language processing: Segaert, Lucas et al. (2018) found levels of aerobic fitness to be a mediating factor in the number of tip-of-the-tongue states experienced by older adults. We therefore measured handgrip strength as it is an established marker of a person’s physical health (Lara et al., 2013) and has been found to be associated with the magnitude of age-related cognitive decline (Sternäng et al., 2016). Using a *Jamar* hand dynamometer, we instructed participants to squeeze with maximum effort for three seconds; the highest value across six trials (three per hand) was used for analysis.

Lung capacity. Another established marker of overall aerobic fitness, relating more to physiological health, is lung capacity (Lara et al., 2013). Lung capacity can be measured in terms of forced expiratory volume in one second (FEV1), and this has been found to associated with measures of cognitive ageing (Pathan et al., 2011). We used a *Vitalograph In2itive* spirometer and instructed participants to blow as hard as possible into the spirometer until their lungs were empty (aiming to blow for at least six seconds); the highest value across three trials was used for analysis.

Descriptive results of the measurements

Descriptive characteristics of young and older adults' performance on each measurement, as well comparisons between age groups, are reported in **Table SM.1**. As expected, young adults significantly out-performed older adults in six of the eight measurements. Surprisingly, we did not find the typical age-related declines in working memory or grip strength; we speculate that this may be related to our lack of multiple measurements per factor. Correlations between each measurement for young and older adults are reported in **Table SM.2**.

Table SM.1 *Means and standard deviations of the background characteristics and performance on the individual difference measurements for young and older adults, including the results of comparisons between the age groups (independent samples t-tests).*

		Young (N=50)		**Older (N=56)**		**Comparison**	
	Measurement used	*M*	*SD*	*M*	*SD*	*t*(104)	*p*
Processing speed	WAIS-IV coding task	80.90	14.77	67.61	14.62	4.65	< .001
Vocabulary	Mill Hill vocabulary test	16.82	2.72	23.79	3.03	-12.39	<.001
Short-term memory	Immediate word recall	7.62	1.66	5.66	1.27	6.86	< .001
Long-term memory	Delayed word recall	5.14	1.60	3.16	1.51	6.54	<.001
Working memory	Backward digit span	5.43	1.45	5.18	1.19	0.98	.331
Inhibitory control	Stop-signal reaction time (SSRT)	196.3	33.1	266.0	32.8	-10.88	< .001
Grip strength	Hand dynamometer	28.54	8.10	27.82	8.92	0.43	.667
Lung capacity	Forced expiratory volume in one second	3.46	0.75	2.26	0.66	8.82	< .001

Table SM.2 *Pearson's correlation R values between all individual difference measurements for young adults (above the diagonal line) and older adults (below the diagonal line). Results of the significance testing are denoted for significant correlations.*

	Processing Speed	Vocabulary	STM	LTM	WM	Inhibition	Handgrip	Lung Capacity
Processing speed		.19	.29*	.20	.25	-.26	-.32*	.08
Vocabulary	.40**		.13	.34	.28	-.11	-.01	.10
STM	.23	.15		.72***	.19	-.19	-.01	.18
LTM	.11	.20	.66***		.10	-.17	-.06	.02
WM	.27*	.24	.08	-.13		.05	.07	.27
Inhibition	-.01	-.11	-.28*	-.16	-.12		.20	.11
Grip strength	.06	.04	-.13	-.04	.05	.44**		.60***
Lung Capacity	.17	.38**	.00	.06	.19	.22	.52***	

Note. STM = short-term memory; LTM = long-term memory; WM = working memory. Significant *p* values were adjusted for multiple comparisons using the Benjamin-Hochberg correction. *** = $p < .001$, ** = $p < .01$, * = $p < .05$.

Investigating individual variability in the experimental language tasks

Our aim was to relate participants' scores in the additional measurements to individual and age-related differences in performance in the sentence production tasks in order to better understand the influence of different kinds of inter-individual variability on sentence processing. One way to investigate this is to enter participants' scores on each additional measurement as continuous predictors into the existing mixed-effects models of Experiment 1 (syntactic priming task) and Experiment 2 (planning scope task); see Poulisse et al. (2019) for a similar approach.

Analysis procedure. We entered all the additional measurements as predictors into the mixed-effects models of the error and onset latency data of Experiments 1 and 2, except for working memory and handgrip because we did not find the excepted age-related declines in these measures (**Table SM.1**); hence, we considered that including them would not be informative about the effect of age-related declines in these domains on experimental task performance.[17]

Before entering the predictors into the models, we converted the raw scores into age-scaled scores to enable us to compare group scores from different normal distributions within the same model (Howell, 2010): we converted raw scores into standardised z-scores within age groups (and gender groups for lung capacity). When including multiple predictors in one model, it is also important to ensure that there is limited multicollinearity between the different predictors. Correlation analysis revealed only a small number of significant correlations between the different measures (**Table SM.2**) and the Variance Inflation Factor (VIF), a measure of the size of correlations between different predictors, of all models was < 1.5 indicating that there was limited multicollinearity (VIF values < 3 are acceptable; Jaeger, 2011).

In order to reach the simplest model that was best able to explain the experimental data, we began with a model that included all measurements as continuous predictors (centred and standardised prior to analysis; Gelman, 2008) and then simplified the model using a stepwise "best path" reduction procedure, removing predictor interactions and then predictor main effects to locate the simplest model that did not differ significantly from the full model in terms of variance explained (Barr et al., 2013). To do this we used the *drop1* function of the *lme4* package (Bates et al., 2014) that compares the Akaike's Information Criterion (AIC) values of the full model to a model with one interaction or main effect removed (see also Poulisse et al., 2019; Schoot, Heyselaar, Hagoort, & Segaert, 2016). This enabled us to clearly identify the variation in which addition measurements were related to performance on the experimental tasks.

Experiment 1: Syntactic priming. Following the *drop1* model simplification process, none of the additional measurements remained as continuous predictors in the model of the Experiment 1 error data. In other words, the best model of the data was one which only included the fixed effects relating to the experimental variables; therefore, indicating that no

[17] We were additionally cautious to enter working memory and grip strength as predictors because the surprising lack of age group differences suggests that the measures used may not have provided reliable indicators of participants' ability in these two domains.

individual variation in the additional measures mediated young or older adults' production of errors in the syntactic priming task. Indeed, the AIC value of the model that included all the predictors was not significantly different from the final best-fitting model (full model AIC = 2478; final model AIC = 2456; p = .595).

However, the best-fitting model of the onset latency did include the inhibition measure as a continuous predictor (**Table SM.3**), and revealed a significant interaction between age group and inhibition (p < .001). As in shown in **Figure SM.1**, young adults with better inhibitory control (i.e., a lower SSRT) were quicker to produce sentences, suggesting that, compared to young adults with poorer inhibitory control, they were better able to inhibit information that was not relevant to their target sentence production (such as the syntax of the preceding prime when it was unrelated to the target). However, this relationship was not clearly evident in the older adults (see **Figure SM.1**), indicating individual difference in older adults' inhibitory control did not substantially impact on their overall speed of sentence production.

Table SM.3 *Summary of the best-fitted mixed-effects models for the Experiment 1 onset latency data with the additional measurements included as continuous predictors.*

Predictor	Coefficient	SE	Wald Z	*p*
Intercept	-1085.01	25.70	-42.22	< .001
Prime type	-45.33	12.95	-3.50	< .001
Age group	136.76	28.87	4.74	< .001
Inhibition	-59.37	28.32	-2.10	.036
Prime type * Age group	5.01	18.93	0.26	.791
Prime type * Inhibition	-13.85	19.61	-0.71	.480
Age group * Inhibition	-141.66	31.88	-4.44	< .001
Prime type * Age group * Inhibition	-33.99	31.59	-1.08	.282

Note. The final model of the complete dataset did not differ significantly from the full model in terms of variance explained (full model AIC = 41919; final model AIC = 41893; p = .986).

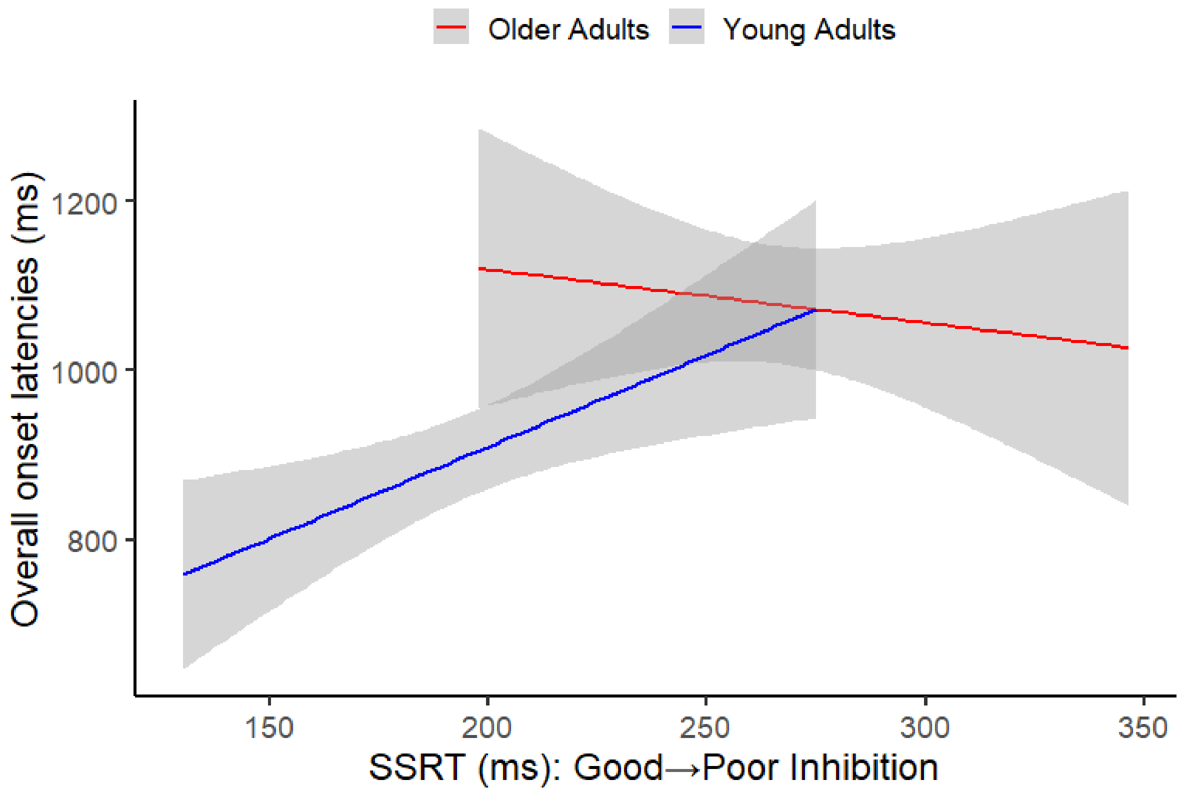

Figure SM.1 *Relationship between participants' overall stop-signal reaction time (SSRT) score (a measure of inhibitory control) and overall onset latencies when producing target sentences in the Experiment 1 syntactic priming task for young and older adults. Grey shading reflects 95% confident intervals around the mean.*

Experiment 2: Planning scope. As in Experiment 1, the best-fitting model of the error data in Experiment 2 was not significantly improved by the inclusion of any of the additional measures (full model AIC = 6403, final model AIC = 6356, p = .773). However, the best-fitting mode of the onset latency data did include the short-term memory (STM) measure as a continuous predictor (**Table SM.4**) and revealed a significant 4-way interaction between phrase type, preview and age group and STM (p = .045). This indicates that STM ability may have affected the magnitude of the preview benefit differently for young and older adults dependent on whether they were producing a sentence with an initial coordinate or initial simple noun phrase. Closer inspection of the data in **Figure SM.2** suggests that young adults with better STM skills (i.e., scored higher on the immediate word recall task) displayed a greater preview benefit (i.e., quicker to initiate a sentence when the second to-be-produced lexical item had been previewed). This may relate to young adults with better STM being better able to store and retrieve lexical information relating to the previewed picture, and therefore being able to more quickly plan and produce sentences. Notably, this effect does not appear to differ between phrase types for young adults, in line with our main experimental findings that the young adults displayed significant preview benefits in both the initial coordinate and initial simple noun phrase conditions.

By contrast, while older adults with better STM skills displayed a similar pattern in the initial coordinate noun phrase condition (i.e., those who scored higher on the immediate word recall task also displayed a larger speed preview benefit), this pattern was not observed in the initial simple noun phrase condition (see **Figure SM.2**). The pattern of results draws certain parallels with the effect observed in the main experimental analyses that older adults displayed a preview benefit when the preview fell within the initial phrase (coordinate condition), but not outside of it (simple condition). As we discussed in the main manuscript (see **Chapter 3**), previewing a lexical item outside of older adults' preferred phrasal planning scope appears to have an overall disruptive effect on their sentence planning processes (causing them to become slower and more error-prone). Thus, it would seem that the magnitude of this disruptive effect when previewing a lexical item outside the initial phrase may outweigh any sentence planning benefits that older adults with better STM skills may experience, leading to a lack of an observable relationship between individual differences in STM and the preview benefit in the initial simple noun phrase condition.

Table SM.4 *Summary of the best-fitted mixed-effects model for the Experiment 2 onset latency data with the additional measurements included as continuous predictors.*

Predictor	**Coefficient**	**SE**	**Wald Z**	***p***
Intercept	1008.34	8.56	117.83	< .001
Preview	-58.08	8.60	-6.75	< .001
Initial phrase type	-43.16	6.41	-6.73	< .001
Age group	-132.38	15.26	-8.67	< .001
STM	0.92	15.34	0.06	.952
Preview * Initial phrase type	50.50	10.57	4.78	< .001
Preview * Age group	-25.44	15.61	-1.93	.086
Initial phrase type * Age group	0.43	12.71	0.03	.973
Preview * STM	-17.55	15.80	-1.11	.267
Initial phrase type * STM	1.99	12.81	0.16	.877
Age group * STM	-45.39	30.69	-1.48	.139
Preview * Initial phrase type * Age group	-21.10	20.96	-1.01	.314
Preview * Initial phrase type * STM	7.66	21.22	0.36	.718
Preview * Age group * STM	-2.97	31.78	-0.09	.925
Initial phrase type * Age group * STM	25.55	25.67	1.00	.320
Preview * Initial phrase type * Age group * STM	-85.21	42.60	-2.00	.045

Note. STM = short-term memory. The final model of the complete dataset did not differ significantly from the full model in terms of variance explained (full model AIC = 90333; final model AIC = 90284; p = .994).

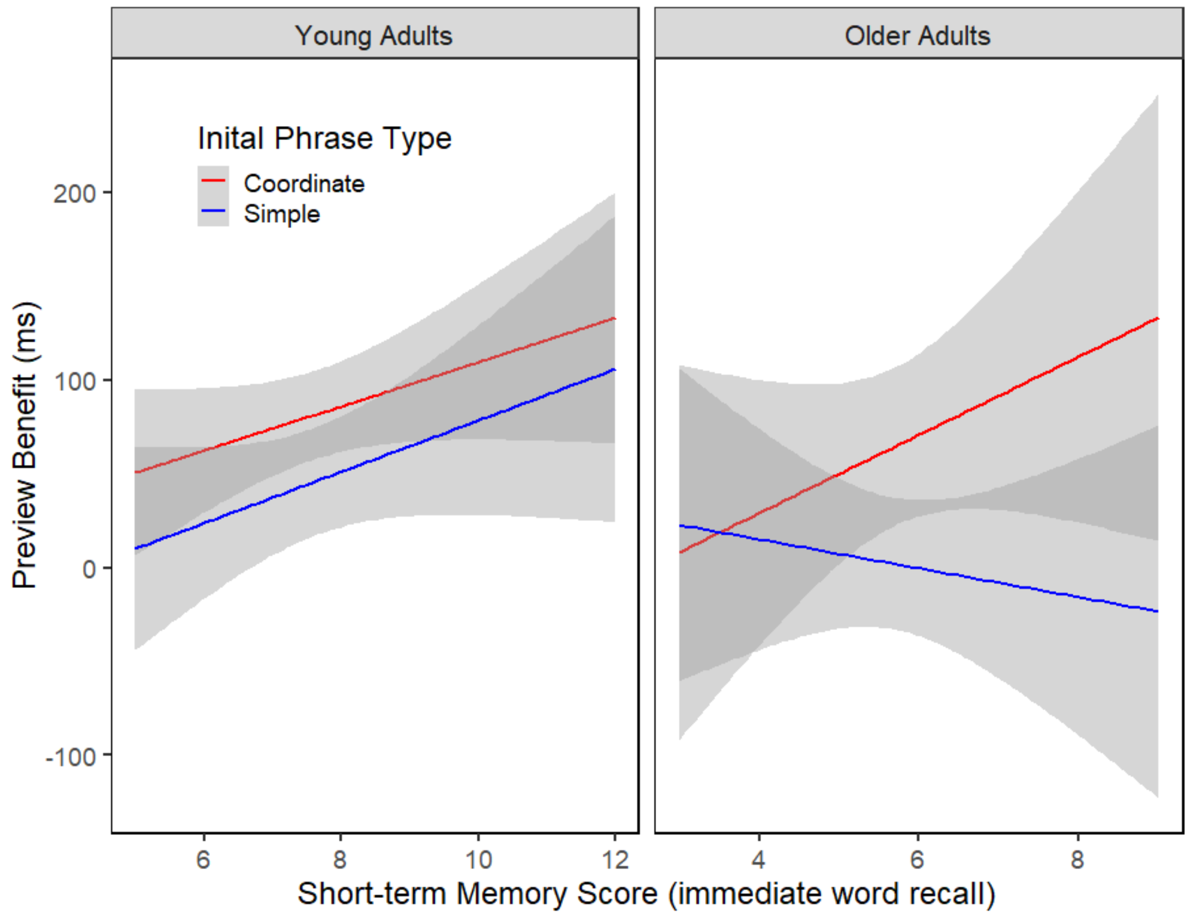

Figure SM.2 *Relationship between participants' immediate word recall score (a measure of short-term memory) and overall speed preview benefit in Experiment 2 for young and older adults when producing sentences with initial coordinate and initial simple noun phrases. Grey shading reflects 95% confident intervals around the mean.*

Brief discussion

Our aim was to investigate what kind of inter-individual variability accounted for individual differences in performance in the sentence production tasks. However, we found little evidence to suggest that participants' scores on the eight additional factors that we measured were accounting for any individual variation in performance in Experiments 1 and 2. Significant effects were limited to an influence of inhibitory control on the young adults' onset latencies in Experiment 1 and an influence of short-term memory ability on the magnitude of the speed preview benefit in Experiment 2. We speculate that our lack of significant findings may be due to the fact that we only used a single measurement per construct, which would have impacted on measurement reliability. This limitation was the result of the broad range of measures we employed, which led to time constraints in testing to avoid participant fatigue. Moreover, there are inherent difficulties involved in measuring individual difficulties within a factorial design, particularly one that involve measures of speed (Hedge et al., 2017; Miller & Ulrich, 2013). Further research using a stronger battery of measures is therefore required to gain more meaningful insight into the causes of individual differences within language processing in young and older adults.