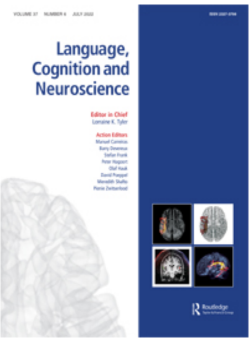

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Syntactic comprehension priming and lexical boost effects in older adults

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ABSTRACT

The extent to which syntactic priming in comprehension is affected by ageing has not yet been extensively explored. It is further unclear whether syntactic comprehension priming persists across fillers in older adults. This study used a self-paced reading task and controlled for syntactic and lexical overlap, to (1) discover whether syntactic comprehension priming exists in older adults, across fillers, (2) to uncover potential differences between older and younger adults on priming measures, and (3) identify whether Working Memory or Processing Speed affect priming in older adults. Both older ($n = 30$, $M_{age} = 68.6$, $SD = 3.68$) and Younger adults ($n = 30$, $M_{age} = 21.6$, $SD = 2.44$) showed effects of syntactic priming and lexical boost. This suggests syntactic processing does not decline with age, and that abstract priming and the lexical boost are not dependent on residual activation or explicit retention in memory.

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KEYWORDS
Syntactic priming; aging; sentence processing; lexical boost; processing speed

1. Introduction

Although increases in word retrieval difficulties (Goral et al., 2007; MacKay et al., 2002; Wulff et al., 2019), and changes in the use of semantic information during processing (Joyal et al., 2020; Vonk et al., 2020; Zhu et al., 2019) are widely observed in older populations, deficits in syntax processing have appeared harder to specify and may depend on sentential context, memory constraints, or task demands. While past research has investigated older populations' performance on *explicit* sentence comprehension tasks, such as tasks requiring conscious recall of information through comprehension questions (DeCaro et al., 2016; Kim et al., 2016; Norman et al., 1992; Poulisse et al., 2019), *implicit* tasks such as syntactic priming have recently been applied to older and memory-impaired populations as a way of uncovering more subtle age-related changes (e.g. Hardy, Segaert, et al., 2020; Heyselaar et al., 2017). In syntactic priming paradigms, processing of a grammatical structure is facilitated by experiencing the same structure previously (e.g. J. K. Bock, 1986; Tooley & Traxler, 2010). Priming is additionally amplified by lexical overlap between Prime and Target, known as the *lexical boost* (for a review, see Tooley, 2020).

There still remain significant questions around older adults' sensitivity to syntactic priming. As far as we are aware, all previous priming studies with older adults have focussed on priming in production, and none have included intervening fillers between Prime and Target. Common accounts of syntactic priming and lexical boost mechanisms contrast the longevity of abstract syntactic priming (without lexical overlap) with the short-lived nature of the lexical boost (e.g. Hartsuiker et al., 2008; Traxler et al., 2014). It is unknown whether this holds for older adults. We also sought to investigate whether declining Working Memory (hereafter WM) and Processing Speed functions with older age affect priming patterns, and in what way.

1.1. Syntactic priming

In syntactic (or *structural*) priming, the processing of a grammatical structure is facilitated by participants having read or heard the same grammatical structure earlier in the task (J. K. Bock, 1986; Pickering & Branigan, 1998; Tooley et al., 2019). Syntactic priming has been widely demonstrated to affect language production, where speakers prefer to use previously-heard grammatical structures (Jacobs et al., 2019; Raissi et al., 2020), but appears more elusive in comprehension. Syntactic priming in comprehension may depend on lexical overlap between prime and target, such that *abstract* priming, in the absence of lexical effects, is non-existent (e.g. Arai et al., 2007). Past studies have generally struggled to discover abstract comprehension priming, although Tooley and Traxler (2010) summarise that

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comprehension priming experiments have generally been conducted using online methods, and it may simply be too difficult to detect abstract syntactic priming in these paradigms. In production, syntactic priming is often investigated using picture-naming or scripted dialogue tasks (e.g. Bock, 1986; Hartsuiker et al., 2008), and the few available studies using online methods in production generally find much smaller priming effects (see Tooley & Traxler, 2010).

Nevertheless, more recent evidence from comprehension suggests that abstract priming may be more evident than previously believed (e.g. Giavazzi et al., 2018; Thothathiri & Snedeker, 2008; Ziegler & Snedeker, 2019), even when online methods are used. As Tooley and Traxler (2010) predicted, this discrepancy may be dependent on the sensitivity of the method used: Ziegler and Snedeker (2019) recorded eye movements and found abstract syntactic priming, while both Giavazzi et al. (2018) and Thothathiri and Snedeker (2008), who found abstract priming in comprehension, required active responses from participants, suggesting that abstract priming might require a more sensitive method of measurement than priming in production. More generally, syntactic priming effects can be recorded through behavioural, neuroimaging, and eye-tracking measures. Priming effects on event-related potentials (ERPs) have been demonstrated as reduced P600 amplitudes in primed compared to unprimed sentences (Ledoux et al., 2007; Tooley et al., 2009), while syntactic priming has also been shown to reduce regressions and reading times in eye-tracking paradigms (Tooley et al., 2019). Behaviourally, syntactic priming in production is often measured as the proportion of participants' responses that use the primed syntactic structure (e.g. Bock, 1986), or, in comprehension, as recordings of reading times (Tooley & Traxler, 2010).

Several competing accounts of the mechanisms underlying syntactic priming have been proposed over the years. Pickering and Branigan (1998) suggested that priming is the result of lingering activation of syntactic structures and their associated lemmas, facilitating processing of that structure and biasing speakers towards using it. However, this approach cannot account for the finding that syntactic priming persists across multiple intervening sentences (Bock & Griffin, 2000; Hartsuiker et al., 2008), and even between experimental sessions (Kaschak et al., 2011), as residual activation is short-lived and decays rapidly over time (e.g. Lewis et al., 2006). Chang et al. (2012) (see also Chang, 2008) therefore formulated the hypothesis that syntactic priming relies on an implicit learning mechanism, whereby the language processing system learns to process a grammatical structure or lexical item after exposure, thereby facilitating processing of that structure or item. These implicit learning systems are error-based, implying that the more unexpected a given structure, the greater the implicit learning effect. This principle accounts for the observation that infrequent structures are more primable than more frequent types (Fine et al., 2013; Jaeger & Snider, 2013).

Implicit learning mechanisms cannot account for lexical boost effects, however, which have been found to be far less long-lived (Hartsuiker et al., 2008). Rather than proposing a unitary model meant to explain both abstract syntactic priming and the lexical boost, Hartsuiker et al. (2008) and Tooley and Traxler (2010) suggested a dual mechanism account, whereby syntactic priming relies on implicit learning, while the lexical boost is the result of short-term lingering activation. Several distinct dual mechanism accounts exist (see Tooley, 2020), however, most accounts agree that abstract priming is caused by an implicit learning mechanism. The nature of the lexical boost is more disputed, with some models referring to Pickering & Branigan's (1998) residual activation model (e.g. Traxler et al., 2014), and others suggesting that readers explicitly remember the Prime's content words (including verbs) leading to facilitated processing (cf. Ziegler & Snedeker, 2019).

1.2. Priming in older adults

Investigating priming effects in older adults may be a way to adjudicate between these competing theories, as cognitive control (Friedman et al., 2009), WM (Bopp & Verhaeghen, 2005), and – potentially – syntactic processing itself decline (van Boxtel & Lawyer, 2021), but implicit learning (Jelicic, 1996) and vocabulary size (Verhaeghen, 2003) remain largely intact. Past research has shown older adults exhibit syntactic priming effects in production (Hardy et al., 2017; Hardy, Segaert, et al., 2020; Hardy, Wheeldon, et al., 2020), but syntactic comprehension priming in older groups has, to our knowledge, not yet been investigated. In production, Hardy et al. (2017) played a dialogue with participants, taking turns to describe pictures that denoted transitive events, and could therefore be described with passives and actives. Both younger and older groups were significantly more likely to use passives after the experimenter primed them with a passive. Furthermore, lexical boost effects occurred regardless of age group, supporting the notion that underlying representations of syntax and lexical items appear intact in older adults, at least when used in language production. Note, however, that neither the Hardy et al. (2017) study nor its follow-up investigations (Hardy, Segaert, et al., 2020; Hardy, Wheeldon, et al., 2020) tested priming across several intervening fillers; whether older adults show priming across fillers therefore remains unexplored.

Including fillers in syntactic priming with older adults moreover allows for a more direct test of the accounts of syntactic priming summarised above: one of the most robust findings in the aging literature is older adults' significantly slower reading speed (Hartley et al., 1994; Kemtes & Kemper, 1997; Liu et al., 2017). The Processing Speed theory of adult cognition (Salthouse, 1996; Salthouse & Babcock, 1991, among others) suggests the slower speed at which older adults process information results in much of this information having lost the activation necessary for its retrieval or use in cognitive operations (see further Bezdicek et al., 2016; Bott et al., 2017; Caplan & Waters, 2005; Ebaid et al., 2017; Pichora-Fuller, 2003). In other words, processed information is lost or forgotten more quickly in older readers because they may fail to maintain sufficient activation of lexical items, syntactic structures, or semantic information (Salthouse, 1996, p. 406). An activation-based theory of syntactic priming (or the lexical boost) would, therefore, predict age-related differences in the degree of syntactic priming or boost effects. Conversely, since implicit memory appears relatively unaffected in older adults (cf. Ward et al., 2020), theories that consider priming the result of implicit learning mechanisms (Chang et al., 2012) should predict intact syntactic priming in older adults. Following dual mechanism accounts, which suppose the lexical boost still relies on lingering activation or on explicit memory, it could be expected that older adults exhibit a less robust lexical boost compared to younger adults. If both syntactic priming and the lexical boost are unaffected by age and persist across fillers, this would suggest both effects rely on other mechanisms.

1.3. Memory and linguistic aging

Crucially, syntactic priming effects occur independently of explicit, conscious memory or linguistic abilities – even amnesic patients (Heyselaar et al., 2017) and people with aphasia (Yan et al., 2018) have exhibited syntactic priming effects, indicating that impaired explicit memory or speech does not prevent these effects from occurring. Conversely, the study of language and aging has generally focussed on potential declines in syntactic and grammatical complexity as a result of explicit memory declines (Burke & Shafto, 2008; Kemper & Anagnopoulos, 1989; Kemper et al., 1990; King & Kutas, 1995; Kynette & Kemper, 1986, among many others). Working Memory (hereafter WM), the memory type most often investigated in relation to older adults' language, involves a system for the temporary storage, processing, and retrieval of relevant cues (Baddeley, 2010), which appears to decline as age progresses (Bopp & Verhaeghen, 2005). Connections between syntax comprehension and WM are frequent: for instance, DeDe et al. (2004) discovered that by-age differences on sentence and text comprehension measures were mostly accounted for by including WM in statistical models. Reading comprehension and WM have also been connected more recently: for example, DeCaro et al. (2016) investigated age effects on sentence comprehension accuracy using offline questions and manipulating the syntactic complexity of auditorily-presented sentences. Comparing subject-relative and object-relative structures, DeCaro et al. (2016) also included a length manipulation, expecting older adults to show less efficient processing of longer and more complex sentences. Age-related declines were discovered only on more complex object-relative sentences, and these age differences were fully accounted for by controlling for WM span and hearing acuity in statistical modelling. Similar results were obtained by Grossman et al. (2002), Caplan and Waters (2005), DeDe et al. (2004), Waters and Caplan (1996), and Sung et al. (2017).

However, increasing evidence supports the idea that WM declines in older adults' do not always impact sentence comprehension. For instance Poulisse et al. (2019) prompted older and younger participants to detect grammatical errors in short two-word phrases (such as "I work" and *"I works"), which kept memory demands to a minimum. While older readers were less accurate and slower at detecting grammatical errors than the younger group, Poulisse et al. (2019) suggest WM could not have significantly affected processing in their study due to the short stimuli used. Similarly, while DeDe et al. (2004) discovered significant impact of WM on conscious recall of sentence information in older adults, no such effect was found on online measures. Additional factors must therefore account for these age-related effects.

Poulisse et al. (2019) offer a suggestion as to what one of these additional factors might be. Older adults in their study were disproportionately slower on detecting errors on pseudoverbs (e.g. "I spuff" and *"I spuffs") compared to real verbs. This, Poulisse et al. argue, offers evidence for older readers' prioritisation of semantic information as a compensatory mechanism for syntactic processing declines. Compensation mechanisms are one of the main factors suggested to explain age-invariant performance on some linguistic tasks (e.g. Stine-Morrow, 2007; Wingfield & Grossman, 2006), and may take a variety of forms. Jackson et al. (2012) and Stine-Morrow et al. (2006, 2008) stress the importance of cognitive training, having an engaged lifestyle, and motivation to allocate resources to language processing as critical compensation mechanisms to alleviate the negative impact of age-related cognitive declines. Peelle (2019) and Wingfield and Grossman (2006) offer evidence suggesting older adults may even recruit additional brain regions not observed in younger readers. Additionally, while Poulisse et al. (2019) found evidence for semantic compensation, they also emphasise the importance of processing speed for older adults, suggesting that high processing speed may further compensate for problems processing syntax (cf. Malyutina et al., 2018).

As mentioned above, several authors have emphasised the dissociation between age-related effects on *explicit* (conscious) and *implicit* (unconscious) processing operations (e.g. DeDe et al., 2004; E. V. Ward et al., 2020; Wingfield & Tun, 2001). Language use relies heavily on implicit memory and learning: speakers are often unable to explicitly articulate the rules of their grammar, and children learn languages without explicit instruction (Fodor, 1983; Lenneberg, 1967). Nevertheless, studies investigating older adults' sentence comprehension have largely used off-line, explicit tasks (though see for instance Campbell et al., 2016), despite the great potential of implicit measures for uncovering age-related language processing changes in the absence of demands for conscious memory searches (for further reading, see Hicks et al., 2018; Rieckmann & Bäckman, 2009; E. Ward et al., 2013; E. V. Ward et al., 2020; Waters & Caplan, 2001). We therefore chose to use an implicit paradigm to contrast older and younger readers.

To sum up, the mechanisms underlying syntactic priming could benefit from research on wider demographics, including older adults, to clarify what theoretical account of priming and the lexical boost is most in line with the data. Findings of syntactic priming in older groups could further elucidate the nature of cognitive aging, especially when connected to potential declines in Working Memory and Processing Speed. Building on previous research on syntactic priming in language production, this study is the first to examine syntactic comprehension priming in older adults and use intervening fillers between primes and targets. In short, we addressed: (1) whether abstract syntactic priming and lexical boost effects exist in older adults' comprehension across fillers; (2) whether differences between younger and older adults on these measures exist; and (3) whether WM or Processing Speed affect priming patterns.

2. Methods

2.1. Participants

74 participants took part in this study, which was fully approved by the University of Essex Social Sciences Ethics Subcommittee. Participants for this experiment were recruited through the Prolific online recruitment platform (Prolific, 2014), and were paid for their participation. All participants gave informed consent before taking part. Data from 14 participants was rejected either due to incomplete submissions or failing a predefined attentional threshold. Attention was monitored in this experiment through the inclusion of comprehension questions at random points throughout the study; if a participant's correctness score on these questions fell below 80%, their data was eliminated from the analysis. The younger participant group ($n = 30$) consisted of 18–25-year olds, while the age of participants in the older group (n = 30) ranged from 65 to 77. All participants were native speakers of English. The average number of years spent in education did not differ between groups ($t(52.4) = -.444$, $p > .05$), and neither did participants' self-reported scores on the International Standard Classification of Education (ISCED; Unesco Institute for Statistics, 2012; $t(58) = .301$, $p > .05$). A summary of other participant demographics is given in Table 1.

2.2. Reading span task

To assess WM, participants completed an online version of the Reading Span Task (RST; Daneman & Carpenter, 1980; Daneman & Hannon, 2007) before the main experiment. The RST for this study asked participants to make an acceptability judgement about sentences presented in incrementally increasing sets ranging from three to seven items, as well as to recall the final words of each sentence. The RST for this study was hosted online using Qualtrics (Provo, Utah, USA, 2021). Sentences used in the RST had an average length of 6.97 words (SD = 1.44, range = 7), all had simple grammar, no complex or compound clause structures, and included no jargon or technical phrases. Half of all sentences were designed as *appropriate* (e.g. "Yesterday I climbed a mountain.") while the other half were *inappropriate* (e.g. "The rocks in the park waved in the gale force winds. ").

Table 1. Summary of participant demographics.

	Younger group	Older group
Age	$M = 21.6$, $SD = 2.44$; [18,25]	$M = 68.8$; $SD = 3.68$; [65,78]
Gender	18 Female, 12 Male	13 Female, 12 Male
Years in education	$M = 15.37$; $SD = 2.38$	$M = 15.03$, $SD = 3.35$
Education level	*Mode* = 3 (Upper Secondary)*	*Mode* = 2 (Lower Secondary)*
RST	$M = 22.95$, $SD = 5.88$	$M = 21.98$, $SD = 6.94$
LCT	$M = 26.6$, $SD = 5.57$	$M = 16.37$, $SD = 5.27$

RST: Reading Span Task; LCT: Letter Comparison Task. Education Level was measured along the International Standard Classification of Education (UNESCO Institute for Statistics, 2012). *For full Education Level data, please refer to the online Supplementary Materials (https://osf.io/yn5dp/).

The RST was preferred over other span tasks due to the processing requirements embedded into the RST: WM differs from short-term memory in that information stored in WM is processed concurrently (Baddeley, 2010), which is effected in the RST by asking participants to answer questions about the sentences they read, while maintaining information from those sentences in memory. A full list of sentences used in the RST appears in the Supplementary Materials (https://osf.io/yn5dp/).

A participant's RST score was calculated as the total number of correctly recalled words in the correct order. Half points were further awarded for words recalled in the correct trial, but not the correct order. Performance on the RST was high in both groups, as summarised in Table 1. WM span did not differ significantly between groups ($t(56.5) = .582$, $p = .562$), and age was not significantly associated with WM span, either when considering all participants together (see the covariance matrix in Figure 1), or in the younger group ($r = .092$, $p = .503$) or the older group ($r = .064$, $p = .638$) considered separately. This lack of memory capacity difference was unexpected. Previous studies have generally shown marked declines on measures of WM with age (for reviews, see Bopp & Verhaeghen, 2005; Meguro et al., 2000). The possibility exists that the lack of a WM group difference could be a result of both groups' relatively high education levels (with means of over 15 years spent in education), since previous research has shown higher education is generally associated with higher WM spans (Boller et al., 2017; Pliatsikas et al., 2019). Alternatively, the infinite duration of the sentence presentation screens, which may have allowed for participants to rehearse the final words, may have helped older readers especially (Hering et al., 2019; Oberauer, 2019).

2.3. Letter comparison test

The Letter Comparison Test (LCT; Salthouse, 1991) was used to assess Processing Speed, and was administered after the RST. Unlike frequently used measures of Processing Speed such as the coding sub-test of the Wechsler Adult Intelligence Scale (Drozdick et al., 2018; Wechsler, 1955), the LCT involves virtually no memory demands and very little processing cost. In the LCT, participants are presented with two sets of character strings and asked to judge whether these strings are identical or different. A participant's LCT score is calculated as the number of correct answers given in a 30-second time limit.

The LCT for this study included 48 string pairs, half of which were identical. String pairs were equally subdivided into pairs of six, nine, or twelve letters. Non-matching string pairs included fully randomised letters. All strings were generated using an online letter generator and were presented in white capital letters in Arial font in the centre of a grey background, using PsychoPy 3 2020.1.3 (Peirce & MacAskill, 2018; PsychoPy/Pavlovia, 2021). Participants were instructed to indicate via a keyboard button press whether the two letter strings they saw on screen were the same or not, and to respond as quickly as possible. Five practice trials were presented before the start of the main LCT.

To ensure our models were not adversely contaminated by the strong correlation between LCT and RST scores (see Figure 1), we ran additional linear mixed models in each ROI only including either RST score (without LCT score) or only LCT score (without RST). We conducted model comparisons with these limited models and a full model including both pre-tests: in all of the defined ROIs (see Section 2.4 below), full models including both LCT and RST scores did not result in better fit than either models including only LCT or only RST (*ROI 1*: LCT-only vs. Full $\chi^2 = 4.43$, $p>.05$; RST-only vs Full $\chi^2 = 3.89$, $p>.05$. *ROI 2*: LCT-only vs. Full $\chi^2 = 3.45$, $p>.05$; RST-only vs. Full $\chi^2 = 3.30$, $p>.05$; please refer to the Supplementary Materials for the full code and model output for these additional models and comparisons). Given the correlation between LST and RST scores, and that one of our aims was to investigate whether Working Memory affects syntactic priming in comprehension, we opted to include only RST scores in our final reported models.

Additionally, neither pre-test correlated heavily with age, and both pre-test scores correlated heavily with our measures of Education (which were not included in any models as neither measure was predictive in any model). Our two measures of education naturally correlated very significantly.

2.4. Materials

The main priming experiment comprised 90 trial sets, with each set consisting of Prime, Filler 1, Filler 2, and Target items, totalling 360 sentences altogether. Trials were divided into three conditions: *Primed*, with syntactic but no lexical overlap; *Boosted*, with syntactic *and* lexical overlap; and *Unprimed*, with no syntactic or lexical overlap. As an additional lexical control condition (or LCC) for the lexical boost effect, we manipulated lexical overlap between Prime and Filler 2 in a subset of *Unprimed* trials: 15 Primes shared the same matrix verb as Filler 2s, and a further 15 Prime – Filler 2 pairs were designated as non-overlapping controls. No syntactic overlap existed between any Primes and Filler

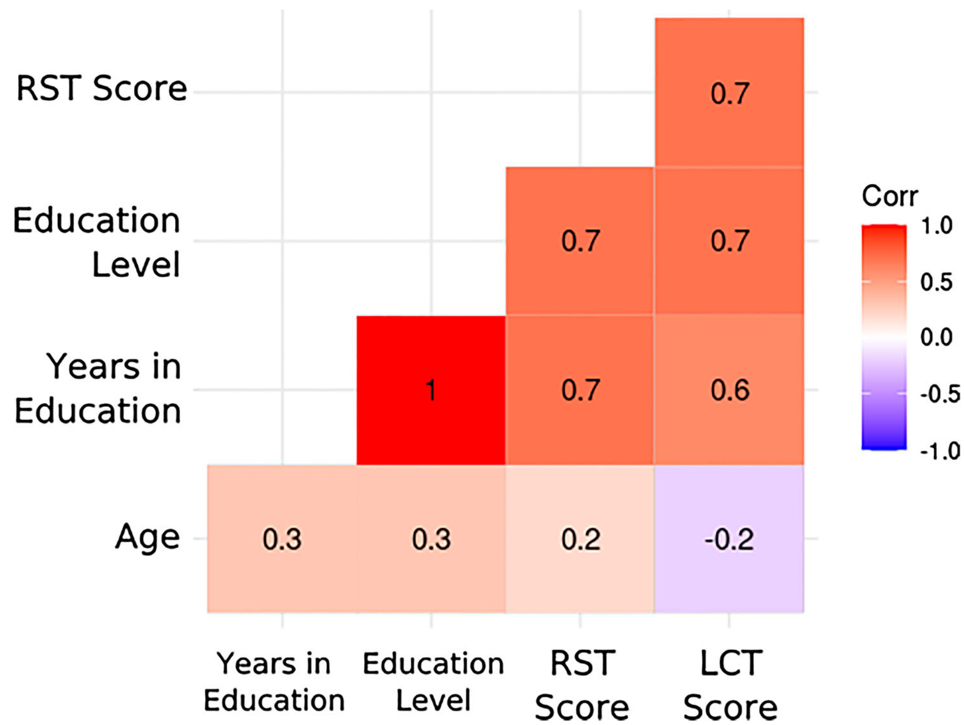

Figure 1. Covariance Matrix of predictors. Note that Years in Education and Education Level were not included in final models due to insignificant predictive power in every model.

2s. We included this manipulation in Filler 2 rather than Target sentences as we aimed to measure completely unprimed Targets, and the duration of the experiment would have exceeded 80 minutes if we had added a further 15 full Trials. By incorporating the LCC in the way we did, we could efficiently measure lexical overlap in the absence of syntactic priming in the *same* trials as our main manipulations. The LCC did not affect the number of syntactically-unrelated fillers between Prime and Target, and LCC manipulations did not affect lexical boost effects since LCC trials comprised a subset of trials in the Unprimed condition. A schematic overview and a visualisation of the experiment are provided in Figure 2.

2.4.1. Critical sentences

Targets and Primes were adapted from several different previous studies on syntactic priming (Manouilidou & Almeida, 2009; Tooley et al., 2009; Traxler, 2008). American English spellings and terminology in any sentences from previous studies were adapted to British English variants. Sentences ranged from 7 to 14 words, averaging 9.75. There was no significant difference between the lengths of Prime and Target structures ($t(169) = -.77$, $p>.05$).

All Target items were reduced relative sentences (e.g. "The child cheered by the teacher spelled the word correctly"), with the start of the reduced relative clause always set as the fourth word in the sentence to allow for reading time comparisons. Following from previous investigations of reduced relative priming (e.g. Ledoux et al., 2007; Tooley et al., 2019), the critical reading time regions in Target sentences were defined as (a) "by" and the following noun phrase (By ROI); and (b) two words following the "by" and NP, to account for spillover effects (Spillover). For example, in the Target sentence "The dealer captured by the policeman denied any wrongdoing", the By ROI comprises "by the policeman", and the spillover region consists of "denied any". Prime sentences in the *Primed* and *Boosted* conditions (which involved syntactic overlap) were also reduced relatives, while Prime items in the *Unprimed* condition comprised complex sentence types with no reduced relative clauses (e.g. "The scandalous hooligan destroyed the sculptor's valuable artwork"). A list of all critical trials appears in the Supplementary Materials. (https://osf.io/yn5dp/).

2.4.2. Filler sentences

The number of Fillers intervening between Prime and Target was set at two. This number kept task difficulty and length to a minimum while accounting for the long-lasting nature of syntactic priming (Hartsuiker et al., 2008). As this is the first investigation of syntactic comprehension priming in older adults involving fillers between Primes and Targets, we chose to maintain the

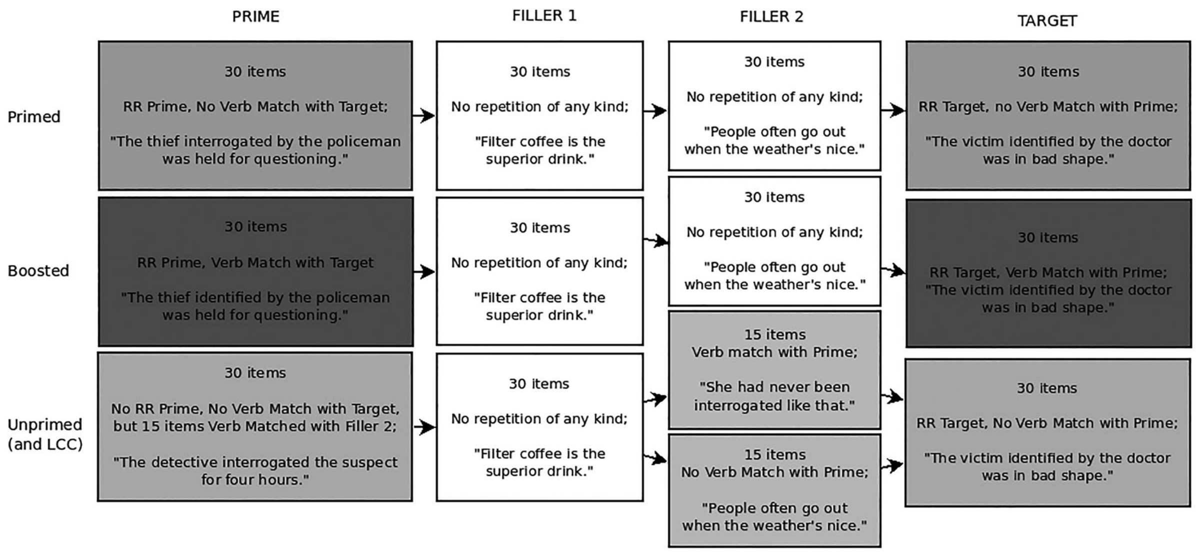

Figure 2. Schematic overview of experimental conditions. Each column denotes one sentence presented in sequence, such that all Primes and Targets were separated by two grammatically unrelated Fillers. Primed and Boosted Primes and Targets were both reduced relatives, while Prime sentences in Unprimed trials were syntactically unrelated to Targets. Verbs only matched between Primes and Targets in the Boosted condition. The LCC did not affect the verb matching of Prime and Target, but only manipulated lexical overlap between Prime and Filler 2.

number of fillers at two to create a larger likelihood of capturing syntactic priming effects (Cho-Reyes et al., 2016). Filler sentences were constructed with complex syntactic structures and excluded reduced relative clauses and lexical repetition between Prime and Filler, except for LCC items (a subset of 15 items in the *Unprimed* condition), which were specifically designed to investigate lexical overlap. A full example of trials in each condition is given in Figure 2, while a full list of all Filler sentences appears in the Supplementary Materials (https://osf.io/yn5dp/). Two ROIs were defined for LCC sentences, similar to Target ROIs: (a) the main Verb (Verb); and (b) a spillover region for the main Verb of two words (Spillover). For example, in the LCC item "The grave economist warned about a recession once again", the Verb ROI consisted of "warned" and the Spillover ROI comprised "about a".

2.5. Procedure

The experiment was presented using PsychoPy 3 2020.1.3 and hosted online using Pavlovia (Peirce & MacAskill, 2018; PsychoPy/Pavlovia, 2021). All sentences were presented on a word-by-word basis in white Arial font at the centre of a grey screen. The RST, LCT, and five practice trials preceded the main experiment. The main part of the study was presented in four blocks of 18 trial sets, consisting of 72 sentences each. Each block lasted approximately 10–15 minutes. Participants were encouraged to take a short break between blocks, and the order of blocks and trials was fully randomised across participants.

Second Filler and Target sentences were self-paced, while the presentation of Primes and Filler 1 items was externally paced. This design allowed for the recording of reading times on critical Target and LCC sentences while reducing strain on participants as much as possible. To mark self-paced trials, fixation crosses preceding Filler 2 items and Targets were surrounded by a yellow square. Participants were trained to recognise these squares in the practice trials. In externally paced sentences, the fixation cross duration was set at 1500 ms, and each word was presented for 400 ms. This is longer than some previous comprehension priming studies (e.g. Ledoux et al., 2007), however, we aimed to ensure that our older group, which was hypothesised to read more slowly, fully comprehended the sentences they read. Self-paced and externally paced sequences of the main experimental items are visualised in Figure 3.

2.6. Analysis

Data analysis was conducted in R (R Core Team, 2020) using the *lme4* package for linear mixed modelling (Bates et al., 2014), *EMAtools* for generation of Cohen's *d* effect sizes (Kleiman, 2017), *sjPlot* for model plots (Lüdecke, 2016), and *performanceAnalytics* (Peterson et al., 2018) and *ggcorrplot* (Kassambara & Kassambara, 2019) for covariance matrix generation. Linear mixed effects models were built for the two ROIs in both

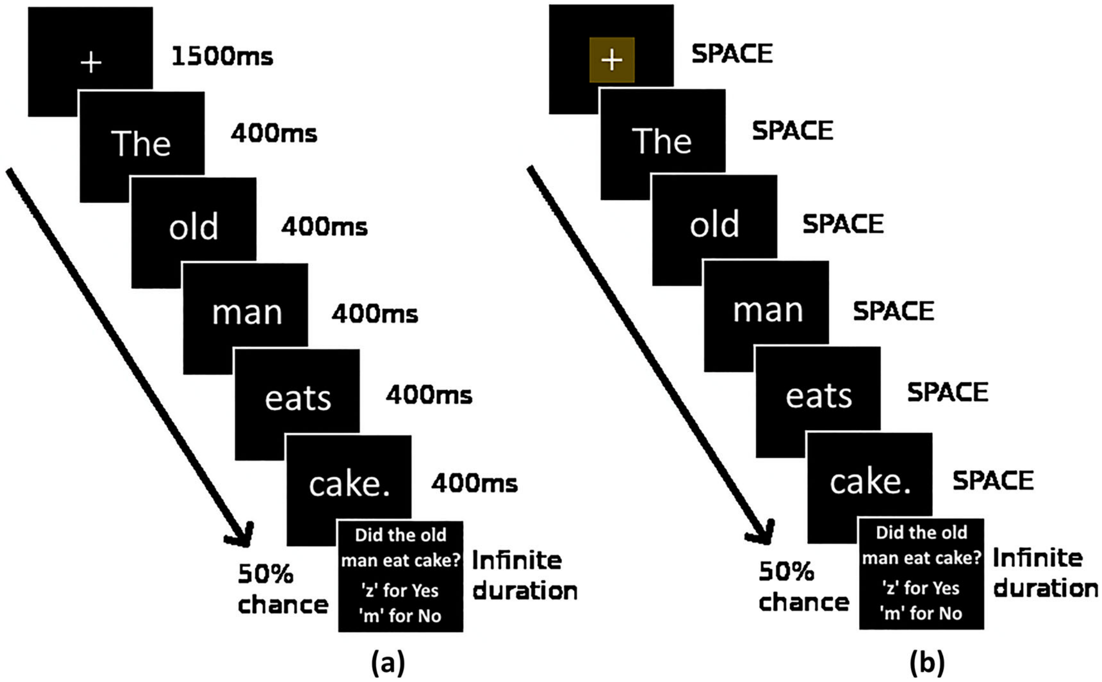

Figure 3. Figure 3(a) displays externally-paced trials while Figure 3(b) shows self-paced trials. Presentation of comprehension questions was fully randomised and did not depend on the presentation of a question in the previous sentence. Questions appeared after Primes, both Fillers, and Targets.

Targets (*By* and *Spillover*) and LCC items (*Verb* and *Spillover*). Reading times (RTs) in each ROI were residualised by character count: RTs for each word in an ROI were added together and divided by the sum of characters presented in that ROI. For instance, if a *Verb* ROI comprised the word "claimed" (7 characters) and a participant's RT to this ROI was 350ms, the residualised reading time (RRT) would come to $350/7 = 50$. RRTs were then log-transformed and trimmed such that all RRTs above or below 2.5 standard deviations from each participant's individual mean were eliminated. Any trials with incorrect comprehension responses on Target sentences were additionally rejected from the data. In total, these eliminations resulted in 7.4% of data points being rejected.

Models in each ROI included random effects for Trial and Participant and fixed effects for Condition (Priming or LCC) by Age Group, and Condition by RST score. We further examined whether random slopes of Participant by Trial were warranted, however after visual confirmation that Trial slopes were not different by Participant, we decided not to include random slopes. RST scores were centred before being added to any model. Contrasts on the Priming Condition parameter were coded such that comparisons were made between primed and unprimed trials, to examine syntax-only priming, and between primed and boosted trials, to capture the lexical boost. In LCC models, items with verb repetition were compared against unrepeated verbs.

We conducted an additional Bayesian analysis to complement the main models, in particular those models where the outcome was a null effect of our critical terms. Bayesian analyses, especially those based on Bayes Factors, may be used to more confidently express null effects as the most likely outcome of a model parameter, as opposed to traditional statistical techniques (see Kruschke & Liddell, 2018, for a discussion). We fitted Bayesian linear mixed models using the *brms* package (Bürkner, 2017) to confirm our results (see further Wagenmakers, 2007). We built sets of models including a Priming Condition * Age Group interaction, and models including only main effects of Priming Condition and Age Group as controls. All models were built with weakly informative prior ex-Gaussian distributions (Matzke & Wagenmakers, 2009), run for 3000 iterations, and resulting inverse Bayes Factors were calculated using the *bridgesampling* package (Gronau et al., 2017). Our online Supplementary Materials include the full code used for the analysis (https://osf.io/yn5dp/).

3. Results

3.1. Target sentences

3.1.1. By ROI

All readers were successfully primed in this ROI ($t(4869) = -2.419$, $p<.05$, $d = -.069$), such that primed

Table 2. Linear mixed model summary for the target (By) ROI.

Parameter	Estimate	SE	*DF*	*t*	*p*	*d*
Intercept	2.206	.0526	60.97			
Abstr. Priming	−.0180	.0074	4869	−2.419	**.0156**	−.0693
Lex. Boost	−.0009	.0073	4869	−.122	.9028	−.0035
Age Group	−.3656	.0735	57.99	−4.977	**<.001**	−1.3071
RST	.0167	.0101	3914	1.655	.0979	.0529
Abstr. Priming * Age Group	.0033	.0106	4867	.312	.7552	.0009
Lex. Boost * Age Group	.0026	.0104	4871	.250	.8025	.0072
Abstr. Priming * RST	.0063	.0052	4867	1.223	.2214	.0351
Lex. Boost * RST	.0072	.0053	4872	1.361	.1737	.0390

Notes: ($R^2_{Marginal}$ = .181; $R^2_{Conditional}$ = .641). Contrasts of priming condition included Unprimed vs. Primed (Abstract Priming) and Primed vs. Boosted (Lexical Boost). "Trial" denotes the numeric value of trial numbers in presentation order. Significant values are represented in bold.

Targets were read faster than unprimed items. However, lexical boost effects were not captured in this ROI ($t(4869) = .903$, $p = .903$, $d = -.004$), and RST score did not have a significant impact on reading times ($t(3914) = 1.655$, $p = .098$, $d = .053$). While older adults read all sentences more slowly across conditions ($t(57.99) = -4.977$, $p < .001$, $d = -1.307$), there was no interaction between age group and abstract priming ($t(4867) = .312$, $p = .755$, $d = .001$) or between age group and lexical boost ($t(4871) = -.250$, $p = .803$, $d = .007$). Additionally, RST scores did not interact with abstract priming or lexical boost parameters (both *ps*>.05). For a full overview of the model in this ROI, please refer to Table 2.

3.1.2. Spillover ROI

Both effects of abstract priming ($t(4886) = -9.494$, $p < .001$, $d = -.272$) and of the lexical boost ($t(4888) = -13.345$, $p < .001$, $d = -.382$) were evident in this ROI, indicating that primed items were read faster than unprimed items, and boosted sentences faster than primed sentences. As in the *By*-ROI, RST scores did not affect reading times in this ROI ($t(2883) = .831$, $p = .406$, $d = .031$). Additionally, RST score did not interact with abstract priming or the lexical boost (both $ps > .05$). Crucially, while priming effects were highly significant in this ROI, neither abstract priming ($t(4883) = -.737$, $p = .461$, $d = -.021$) nor the lexical boost ($t(4882) = -.074$, $p = .405$, $d = -.002$) interacted with age group, despite the finding that older adults read more slowly than younger adults across conditions ($t(57.99) = -5.529$, $p < .001$, $d = -1.452$). Table 3 displays full results for this ROI, and Figure 4 visualises condition effects.

3.2. Bayesian analysis

Bayesian LLMs were fitted with weakly informative priors along an exponential Gaussian distribution, with one model including a Priming Condition * Age Group interaction, and the other only including main effects of these parameters. 3000 iterations of each model were run using *brms*. For the *By* ROI, model comparison using *bridgesampling* returned a Bayes Factor (BF) of .0006, providing extremely strong support for the null hypothesis (that is, that effects of priming condition did *not* vary by age group). Similarly, in the Target Spillover ROI, model comparisons returned a BF of .0017, again suggesting extremely strong evidence for the null hypothesis (Lee & Wagenmakers, 2014).

3.3. LCC sentences

3.3.1. Verb ROI

The LCC manipulation had significant effects in this ROI ($t(2376) = -4.398$, $p < .001$, $d = -.180$), but not in the

Table 3. Linear mixed model summary for the target (Spillover) ROI.

Parameter	Estimate	SE	*DF*	*t*	*p*	*d*
Intercept	−2.242	.0525	60.64			
Abstr. Priming	−.0911	.0096	4886	−9.494	**<.001**	−.2717
Lex. Boost	−.1266	.0095	4888	−13.345	**<.001**	−.3818
Age Group	−.4056	.0734	57.99	−5.529	**<.001**	−1.4520
RST	.0105	.0126	2883	.831	.406	.0310
Abstr. Priming * Age Group	−.0101	.0137	4883	−.737	.461	−.0211
Lex. Boost * Age Group	−.0113	.0135	4891	−.833	.405	−.0238
Abstr. Priming * RST	−.0005	.0067	4882	−.074	.941	−.0021
Lex. Boost * RST	−.0022	.0069	4892	−.318	.751	.0091

Notes: ($R^2_{Marginal}$ = .204; $R^2_{Conditional}$ = .544.) Contrasts of priming condition included Unprimed vs. Primed (Abstract Priming) and Primed vs. Boosted (Lexical Boost). "Trial" denotes the numeric value of trial numbers in presentation order. Significant values are represented in bold.

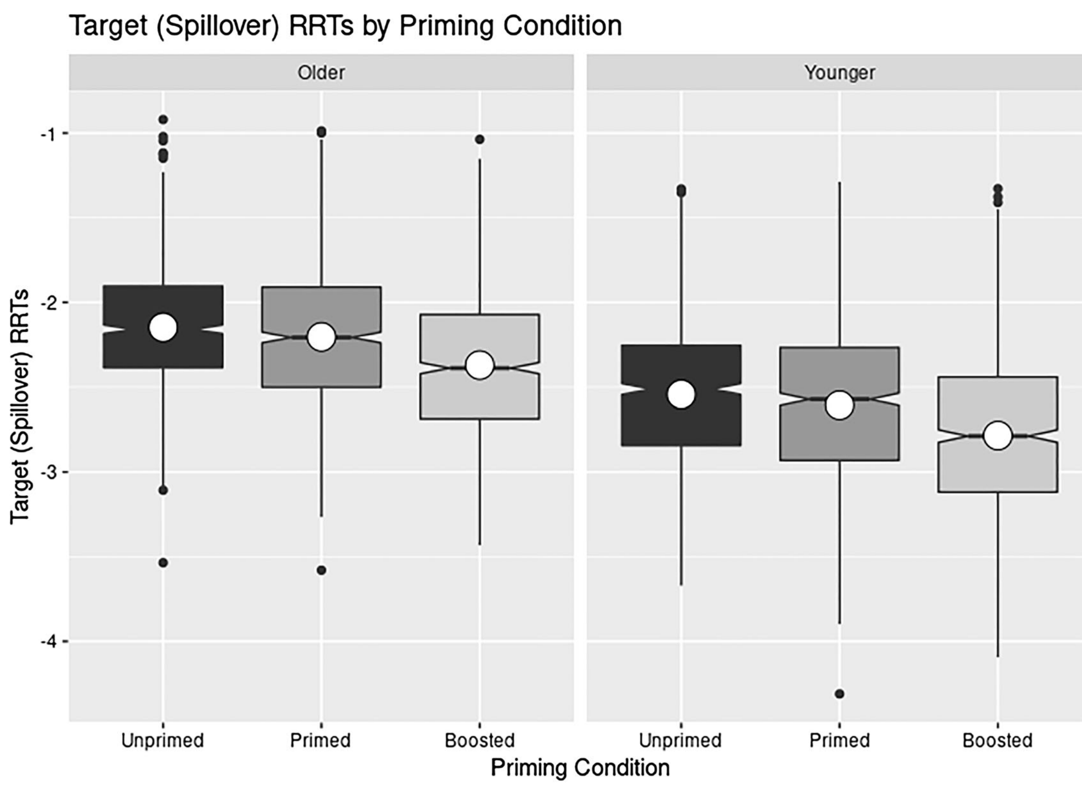

Figure 4. By-group overview of Priming Condition residualised reading times. Central dots indicate means for that condition. A clear stepwise facilitation effect can be seen in the plot, where primed trials were read faster than unprimed trials, and boosted trials faster than primed trials. Although reading times were universally slower in older compared to younger readers, age group did not affect reading times by condition.

expected direction: unrepeated verbs were read faster than repeated verbs. This effect was not modulated by age as the interaction between age group and repetition was not significant ($t(2380) = .118$, $p = .906$, $d = .005$). RST scores did not significantly affect reading times in this ROI and did not interact with repetition condition (both $ps > .05$). As in Target ROIs, older readers exhibited slower reading speeds across the board ($t(58.28) = -3.916$, $p < .001$, $d = -1.026$). Full details for the model in this ROI are given in Table 4.

3.3.2. Spillover ROI

Condition effects in the LCC Spillover ROI were reversed compared to those in the Verb ROI, and followed the expected pattern such that repeated items were read faster than unrepeated items ($t(2369) = 5.286$, $p < .001$, $d = .217$). While a main effect of age group existed ($t(58.25) = -4.724$, $p < .001$, $d = -1.238$), condition effects did not vary by age group ($t(2373) = -1.199$, $p = .231$, $d = -.049$). Reading times were marginally facilitated by RST scores ($t(927.7) = 1.784$, $p = .075$, $d = .117$), but RST scores nevertheless failed to interact with repetition condition ($t(2377) = .582$, $p = .561$, $d = .024$). Please refer to Table 5 for a full summary of effects in this ROI.

4. General discussion

The present study investigated the robustness of older and younger adults' syntactic priming in comprehension.

Table 4. Linear mixed model summary for the LCC (Verb) ROI ($R^2_{Marginal} = .098$; $R^2_{Conditional} = .447$)."Trial" denotes the numeric value of trial numbers in presentation order. Reference level for Repetition was Unrepeated. Significant values are represented in bold.

Parameter	Estimate	SE	DF	*t*	*p*	*d*
Intercept	−2.782	.0626	61.24			
Repetition	−.0569	.0129	2376	−4.398	**<.001**	−.1804
Age Group	−.3424	.0874	58.28	−3.916	**<.001**	−1.0260
RST	.0258	.0216	942.1	1.194	.2326	.0778
Repetition * Age Group	.0022	.0185	2380	.118	.9058	.0049
Repetition * RST	−.0004	.0090	2385	−.049	.9609	−.0020

Table 5. Linear mixed model summary for the LCC (Spillover) ROI ($R^2_{Marginal} = .129$; $R^2_{Conditional} = .469$). "Trial" denotes the numeric value of trial numbers in presentation order. Reference level for Repetition was Unrepeated. Significant values are represented in bold.

Parameter	Estimate	SE	*DF*	*t*	*p*	*d*
Intercept	2.279	.0546	62.09			
Repetition	.0599	.0113	2369	5.286	**<.001**	.2171
Age Group	−.3590	.0760	58.25	−4.724	**< .001**	−1.2378
RST	.0337	.0189	927.7	1.784	.0748	.1171
Repetition * Age Group	−.0194	.0162	2373	−1.199	.2305	−.0492
Repetition * RST	.0046	.0079	2377	.582	.5606	.0239

Participants' reading times to Target and Lexical Control Condition sentences (LLC; worked into Filler 2 items) were recorded to investigate the effects of syntactic and lexical overlap. Target sentences were either primed, primed and boosted, or unprimed, while verbs in LCC sentences were either repeated from the Prime or showed no overlap. A measure of Working Memory was recorded and added to linear mixed models as a covariate.

4.1. Syntactic comprehension priming

Older adults showed intact abstract syntactic comprehension priming in all defined Target ROIs, though most robustly so in the Spillover region. This study therefore does not support the notion that syntactic processing becomes impaired with age. Instead, our results suggest the measurements used in past studies of language in older adults, which have mainly relied on conscious, declarative skills, resulted in decreased performance compared to younger groups. This impaired performance may therefore have been the result of slower motor skills, reduced declarative memory, or even of more extensive searches through larger vocabularies (Ramscar et al., 2014), but given our evidence, not of impaired syntactic processing.

Reading times across conditions were, nevertheless, slower in the older group, which likely reflects a general slowing of cognitive functions related with age (Salthouse, 1996, inter alia) – importantly, however, this slowdown did not affect Priming Condition. The finding of intact syntactic priming in comprehension corresponds with the findings of Hardy et al. (2017); Hardy, Segaert, et al. (2020); Hardy, Wheeldon, et al. (2020), who found similar effects in production, and with Heyselaar et al. (2017), who found intact priming effects in patients with amnesia whose explicit memory was severely impaired.

Our finding of intact abstract comprehension priming across two intervening fillers in our older sample contradicts the residual activation account of syntactic priming (Pickering & Branigan, 1998), especially since older adults' processing speed limitations are thought to affect the effectiveness of cue retrieval via residual activation. However, both an implicit learning account (Chang et al., 2012) and dual mechanism accounts (Tooley & Traxler, 2010) could explain these patterns, as implicit learning does not suffer from the same age-related declines as activation decay does. Our abstract syntactic priming findings therefore offer insufficient evidence to discern between implicit learning and mixed accounts. However, results from the lexical boost condition in our experiment are more informative.

4.2. Lexical boost

This study is, to our knowledge, the first to demonstrate intact lexical boost effects in comprehension across two intervening fillers. Importantly, this effect occured in both age groups with comparable significance, again suggesting unimpaired processing with older age.

The relatively long-lived nature of our lexical boost may be seen to contradict several previous investigations (notably Hartsuiker et al., 2008). Indeed, Hartsuiker and colleagues only reported lexical boost effects in immediately adjacent sentences. However, upon further inspection of Hartsuiker et al.'s data, some lexical boost effects are still observable in their "lag 2" condition, where two intervening fillers were produced between Prime and Target. There is also some indirect evidence from previous studies to suggest that the lexical boost in syntactic comprehension priming might be observable across two sentences. For instance, Ledoux et al. (2007) recorded syntactic priming and lexical repetition effects on ERP responses while "at least two" fillers intervened between Prime and Target. This study confirmed Ledoux et al.'s suggestion with evidence that speaks directly to both abstract priming and lexical boost effects across two fillers. We suggest active manipulation of the number of intervening fillers in future studies, as well as monitoring of participants' brain responses as Ledoux et al. did, could help to elucidate the persistence of the lexical boost further.

Crucially, the lexical boost in this study was completely intact in the older group, casting doubt on most dual mechanism accounts of syntactic priming, which still consider the lexical boost to be the result of residual activation or explicit memory. Given the much lower performance of older adults on the LCT, activation of lexical representations should decline faster in older compared to younger adults, resulting in decreased lexical boost effects following dual mechanism accounts. This prediction was not reflected in our data, as older adults showed equally strong lexical boost effects after two fillers compared to the younger group. There were, additionally, no group differences on LCC trials, suggesting that lexis-only priming is also intact in older readers.

Prediction error-based models of syntactic priming, such as those put forward by Jaeger and Snider (2013) and Malhotra et al. (2008), could also explain the abstract syntactic priming effects in this study. Under these accounts, priming is the result of expectation-based error, that is, of the surprisal readers experience when encountering a structure. The more exposure to a structure a reader experiences, the more facilitated processing becomes. Reduced relatives, as used in this study, are an infrequent structure that elicits high prediction error and therefore large priming effects. However, previous evidence suggests the lexical boost is not affected by prediction error (Tooley et al., 2019), and indeed, our study largely used common verbs in Targets and Primes (such as "checked", "rescued", "cleaned", etc.; for a full list of stimuli, please refer to our online Supplementary Materials at https://osf.io/yn5dp/), which would not have been associated with large prediction error. While our findings of abstract syntactic priming may therefore have been the result of prediction error effects, our lexical boost effects do not support error-based models.

Tooley (2020) formulated a mechanistic account of the lexical boost which posits that lexical effects result from a connection between syntactic structure representations and lexical lemmas (much like in the account of Pickering & Branigan, 1998). Our older adults, however, also exhibited processing facilitation when *only* the verb was repeated in our Lexical Control Condition. Verb-structure pairing, therefore, also cannot be the only explanation for the lexical boost.

Instead, our evidence suggests that the lexical boost relies on similar mechanisms as abstract priming, and is therefore in line with implicit memory or learning accounts. Specifically, a recent proposal by Heyselaar et al. (2021) is supported by our data. The Heyselaar et al. account stipulates that both abstract priming and lexical boost effects are grounded in non-declarative (i.e. implicit) memory, with *perceptual* non-declarative memory (which supports activation of recently-processed information) underpinning short-term effects such as the lexical boost, while long-term abstract priming is subserved by *conceptual memory* (the learning of relationships between stimuli). Heyselaar et al.'s (2021) account is particularly strong in its explanation of intact priming in aging, when declarative skills decline. Although our data are in line with this account, we did not specifically test subsystems of non-declarative memory, something which would be of interest for future studies. The current investigation should therefore be expanded upon with additional pre-tests of different memory types, as well as deliberate manipulation of the number of fillers intervening between Prime and Target to test the conflicting accounts of syntactic priming and examine whether the Heyselaar et al. account is indeed supported.

4.3. Working memory and processing speed

As syntactic priming is an implicit linguistic measure, and the RST used in this study tested explicit, declarative skills, the absence of predictive power of WM on priming condition was to be expected. While span tasks have been correlated to linguistic performance by past authors (e.g. Brébion, 2003), the language measures used in these studies generally tested delcarative skills. This is a crucial difference between the present study and past investigations. Alternative methods of measuring performance on the RST, potentially involving reaction times or the processing component of the test, may have the potential for more effective co-correlation with implicit linguistic tasks. This would be an additional benefit of using the RST compared to other span tasks, and would make effective use of its processing task.

The minimal impact of WM on syntactic priming is not unique to this study: Hardy et al. (2017) hypothesised that WM would be insignificant to their results to such a degree that they did not even collect a measure of WM. Nevertheless, our groups did not show significant differences on the RST despite large distinctions in processing speed, and a replication of the present study with a larger sample and more than one WM measure could be more effective in discovering and controlling for WM-related effects.

4.4. Conclusions

The present study examined syntactic comprehension priming in younger and older adults across two intervening fillers. Previous studies of priming in production suggest little to no age-related differences on priming measures, a prediction that the current results support. Older adults showed significant priming and lexical boost effects in line with the younger group. Moreover, none of our priming effects relied on measurements of Working Memory, and both abstract priming effects as well as the lexical boost persisted across intervening fillers. Taken together, these findings cast doubt on models that consider either abstract syntactic priming or the lexical boost the result of residual activation or Working Memory. We suggest future studies on syntactic priming should incorporate both younger and older adults while actively controlling the number of intervening fillers between Prime and Target. We further emphasised the potential of neuroimaging studies with older and younger groups as a way to uncover more subtle priming patterns.

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