# **Title:** Structural priming is supported by different components of non-declarative memory: Evidence from priming across the lifespan.

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## Abstract

This study investigates how non-declarative memory supports both the transient, short-term and the persistent, long-term structural priming effects commonly seen in the literature. Specifically, we propose that these characteristics are supported by different subcomponents of non-declarative memory: perceptual and conceptual non-declarative memory respectively. To test this proposal, we investigated how the magnitude of short- and long-term structural priming effects change throughout the lifespan. Previous studies have suggested that perceptual and conceptual memory age differently, with only conceptual memory showing age-related decline. Therefore, by investigating how decreased performance in perceptual and conceptual non-declarative memory tasks relate to decreased structural priming magnitude across the lifespan, we aim to elucidate how non-declarative memory supports two seemingly different components of structural priming. We find no change in short-term priming magnitude and performance on perceptual tasks, whereas both long-term priming and conceptual memory declined with age. We conclude that the two seemingly different components of structural priming are supported by different components of non-declarative memory. These findings have important implications for theoretical accounts of structural priming.

Keywords: structural priming; aging; non-declarative memory; syntactic priming

## Introduction

Structural priming refers to the facilitation of syntactic processing that occurs when a syntactic structure is repeated across consecutive sentences. Structural priming presents behaviourally as an increased tendency to repeat syntactic structures that have been produced either by the speaker or an interlocutor. Such structural persistence has been demonstrated experimentally for different syntactic structures (Bock, 1986; Bock and Griffin, 2000; Bernolet et al., 2016), in different languages (Bock, 1986; Hartsuiker and Kolk, 1998; Sung, 2015), and using different modalities (Branigan et al., 1999a, 2000; Hartsuiker et al., 2008). However, although structural priming is a well-established phenomenon, the mechanism underlying this effect is still under much debate (Pickering and Ferreira, 2009).

The debate is largely fuelled by the need for models having to explain not only a single structural priming mechanism, but two: a short-term, transient priming effect and a long-term, persistent priming effect (Bock and Griffin, 2000; Chang et al., 2006; Ferreira and Bock, 2006). The short-term priming effect refers to the priming effect seen for the target sentence immediately following the prime sentence. This is how priming magnitude is most commonly calculated in experimental studies.[1] Earlier studies also report a "lexical boost" effect, which refers to the increased priming magnitude as occurring due to an overlap of lexical information between prime and target sentences (Pickering and Branigan, 1998). However, a recent study by Bernolet and colleagues (2016) demonstrated that short-term priming effects are observable in experiments with minimal lexical overlap (in this case, the verb was not repeated between prime and target sentences), and occurs for all structures commonly used when studying structural priming (i.e., transitives, datives, and word order for relative clauses). The second structural priming component, the long-term priming effect, refers to the tendency for participants to increase their use of the primed structure throughout the length of the experimental session, irrespective of the previously presented prime structure (Kaschak, 2007; Jaeger and Snider, 2008, 2013). This suggests that their structural choice is not only influenced by the immediately preceding prime sentence, but also the number of exposures to the primed structure.

The long-term priming effect is commonly explained in terms of a non-declarative, or implicit, learning account. This is motivated by studies showing that participants seem to be unaware both of the priming manipulation and of the fact that they have indeed changed their structural preferences (Bock, 1986; Bock & Griffin, 2000). The current models differ in the mechanisms they propose to explain this non-declarative learning. For example, Chang and colleagues (2006) have proposed an error-based learning account where participants constantly update their predictions based on both prior and recent experience. Jaeger and Snider's (2013) expectation-adaptation model is similar to this account, except that it does not commit to a specific error-based learning mechanism (although see Jaeger & Snider (2013) for more in-depth comparisons that are beyond the scope of the current paper). However, both accounts find the short-term priming effects more difficult to explain. Jaeger and Snider (2013) suggest that non-declarative memory underlies both the long- and short-term priming effects, but they provide no details about short-term priming even though they do observe a robust effect (i.e., increased probability of re-using the prime structure in the immediately following target

[1] There are studies that calculate priming magnitude with linguistic or non-linguistic (i.e., time) fillers between prime and target trials, although the aim of these experiments is usually to assess the decay rate of priming (e.g., Branigan et al., 1999b, 2000; Bock and Griffin, 2000; Kaschak, 2007; Hartsuiker et al., 2008; Reitter, 2008; Kaschak et al., 2011).

response) in experiments 2 and 3. Chang and colleagues (2006) acknowledge that there is "a deep unresolved issue" (pg. 256) and argue that a separate process is required to account for the short-term priming effect. Recently, they have suggested a complementary systems account where short-term priming is due to fast hippocampal learning that interfaces with slow non-declarative learning mechanisms for long-term priming (Chang et al., 2012). A recent study by Bernolet and colleagues (2016) tested this theory by measuring both the decay rate of the structural priming effect as well as the decay rate of participants' explicit recognition of past sentences with the hypothesis that a correlation between the two would support similar underlying mechanisms. Although both showed decay with intervening filler sentences, the strongest priming effect was correlated with the lowest memory scores, providing evidence against this theory. Additionally, an explicit memory theory cannot explain how patients with a deficit in explicit memory still show robust short-term priming effects (Ferreira et al., 2008; Heyselaar et al., 2017).

The short-term priming effect has also been explained as residual activation (Pickering and Branigan, 1998; Malhotra, 2009; Reitter et al., 2011): Recently processed structures remain partially active, increasing the chances of re-use in an upcoming utterance. Although this very neatly explains the short-term priming effect, it does not automatically also explain the long-term priming effect. Malhotra (2009) and Reitter and colleagues (2011) propose an explicit memory basis for this residual activation, which we have argued against above. However, Reitter and colleagues do propose a way in which the short-term residual activation could support long-term non-declarative learning: The spreading residual activation has a power-law decay rate which would predict that this residual activation is never completely lost, allowing a build-up over time with repeated exposures. Hence there is a short-term priming effect due to the previously processed structures still being partially active, which increases the chances of selection when planning the next utterance, and a long-term priming effect due to the frequency of the structure being "logged" such that repeated retrieval increases the base activation of a structure, so that more frequent structures have a higher base activation, and hence a higher chance of selection in an upcoming utterance.

In this study, we propose a merge between different aspects of the above models: We propose a residual activation account, based in non-declarative memory, for short-term priming and a non-declarative learning account for long-term priming. The information transfer between these components is therefore as described above from the Reitter model. The key difference with our proposal is that we base everything in non-declarative memory. This proposal is not new, and has been explained in depth in MacDonald (2013) for general language processing. In the article, the author refers to it as Easy First (short-term) and Plan Reuse (long-term) and provide examples of this ability not only for general language production but also for other cognitive behaviours, such as motor planning. Indeed, it seems logical to apply this mechanism to structural priming, given its characteristics, and yet no study, to our knowledge, has tested this empirically. We will next explain why we believe structural priming is based solely in non-declarative memory.

Implicit, non-declarative memory has been defined as the unconscious memory of events that participants may not consciously recollect (Graf and Schacter, 1985; Schacter and Tulving, 1994). This is tested indirectly by having participants perform a task in which no apparent reference is made to any prior episode. For example, the word-stem completion task consists of three letter word-stems that the participant is asked to complete with the first word that comes to mind. However, unbeknownst to the participant, these stems can all be completed using words the participant has been exposed to earlier, via a questionnaire or other seemingly unrelated task within the same study session. Tasks can also test more complex relationships. For example, in serial reaction time tasks participants think they are completing a reaction time task (responding to a stimulus on the screen as fast as possible) but in fact the stimuli presented have an underlying pattern that the participant unconsciously learns. This learning results in decreased reaction times over the length of the session as they are able to unconsciously predict the upcoming stimuli. Non-declarative memory performance is therefore measured as an increased efficiency (i.e., increased accuracy or decreased latency) in processing information that participants have been exposed to at an earlier stage, and is attributed to slow-decaying residual activation. This type of memory has also been referred to as procedural memory (Cohen & Eichenbaum, 1993).

Studies in the memory literature have suggested that non-declarative memory is made up of (at least) two components (Gabrieli, 1998; Gupta and Cohen, 2002; Squire, 2004). *Conceptual memory* (also referred to as skill learning) supports the learning of statistical covariations and dependencies between stimuli (e.g. serial reaction time tasks), whereas *perceptual memory* (also referred to as repetition priming) maintains residual activation of a recently processed stimulus. Tasks designed to investigate perceptual memory measure how previous exposure to a specific stimulus (e.g., a word) facilitates later processing of that word or a related item (e.g. word-stem completion and fragmented identification tasks). Based on the definitions of these components, we propose that long-term priming is most likely supported by conceptual memory, whereas short-term priming most likely supported perceptual memory. We propose that non-declarative memory supports both temporal characteristics of structural priming, yet different components of this memory system underlie the different components of structural priming. To provide evidence to support our proposal, we turn to how the memory system changes as we age.

It is well established in the literature that declarative memory declines with age. This decrease in the ability to encode and retrieve explicit information has been linked to decreases in hippocampal (Golomb et al., 1993, although see Raz et al., 2003) and medial temporal lobe volume (Bailey et al., 2013) as well as impaired functioning of the right frontal regions (Stuss et al., 1996). For non-declarative memory, for quite some time there was a consensus that this system was not susceptible to age related decline. However, together with the discovery that there are subsystems within non-declarative memory, evidence has emerged that different neural networks support these systems, and that the systems could therefore be differentially susceptible to age-related decline. Neuroimaging studies of healthy older adults and patient studies have shown that conceptual and perceptual memory have distinct neural correlates. Perceptual memory is associated with activity in the posterior cortical regions (Squire et al., 1992; Bäckman et al., 2000), whereas conceptual memory is associated with a subcortical-cortical network in which the striatum is a central component (Lieberman et al., 2004). There are studies showing age-related decline in the striatum (Raz et al., 2003; Bäckman et al., 2006), which would affect conceptual but not perceptual memory. Moreover, behavioural studies investigating how non-declarative memory changes across the lifespan have produced results consistent with the proposal that conceptual learning is susceptible to age-related decline, whereas perceptual memory is spared (Maki et al., 1999; Schugens et al., 2007; Neger et al., 2014).

The aim of the current study is therefore to test our hypothesis that non-declarative memory supports both key temporal characteristics of structural persistence. In contrast to current models of structural priming (Pickering and Branigan, 1998; Chang et al., 2006; Jaeger and Snider, 2013), we propose that different subcomponents of non-declarative memory underlie long-term and short-term structural priming. Specifically, that perceptual memory underlies short-term priming, while conceptual memory underlies long-term priming. In the current study we therefore tested structural priming in 178 participants aged between 20 and 85 years. If our hypothesis about the role of conceptual and perceptual memory is accurate, we should observe that, as the age of the participant increases, their long-term priming magnitude declines whereas their short-term priming magnitude remains unaffected.

We also measured the participants' performance on well-established memory tests designed to measure conceptual and perceptual memory. The tasks included in our non-declarative memory battery have been frequently used in the literature: a word-stem completion task (Light and Singh, 1987; Light and Albertson, 1989), a fragmented identification task (Mitchell, 1989; Au et al., 1995), and a serial reaction time task (Nissen and Bullemer, 1987). The serial reaction time task measures conceptual memory. We included not one but two perceptual memory tasks: the word-stem completion task and the fragmented identification task. The former is a prominent task in the literature, however, a meta-analysis (La Voie and Light, 1994) has suggested that the word-stem completion task is prone to declarative memory contamination.

In line with previous aging studies, we predict that participants will show a decline in the conceptual task (serial reaction time task) and show no decline in the perceptual tasks (word-stem completion and fragmented identification tasks). A demonstration of a comparable effect of aging on these tasks and on the effects of long- and short-term structural priming, will provide evidence in support of our proposal that different components of non-declarative memory underlie these aspects of structural persistence.

# Materials and Methods

## Participants

178 participants (62 men) were recruited through the Patient and Lifespan Cognition participant database of the School of Psychology at the University of Birmingham and through flyers and advertisements in and around the University of Birmingham. Most participants were tested at the university and some were tested at their place of work or in their homes. We attempted to obtain an equal number of participants for each decade of life: 20 – 29 years ($n$ = 38), 30 – 39 years ($n$ = 23), 40 – 49 years ($n$ = 27), 50 – 59 years ($n$ = 23), 60 – 69 years ($n$ = 31), and 70 – 85 years ($n$ = 37). All participants were required to have British English as their mother tongue and have at least a university degree in order to minimize education-related differences in performance. At the time of testing, no participants reported any neurological deficits or psychiatric disorders. The study was approved by the research ethics board of the University of Birmingham.

Participants in the 20 – 29-year age group were given university credits as compensation, the rest of the participants were paid for their participation.

## Study Design & Apparatus

All participants completed one structural priming task, three non-declarative memory tasks (word-stem completion, fragmented identification task, and serial reaction time task), one declarative memory task, two verbal working memory tasks (backward digit span and subtract-2 span task), and one verbal IQ task (national adult reading task) in one 1.5-hour session. Figure 1 illustrates the order of events. All participants completed the tasks in the same order.

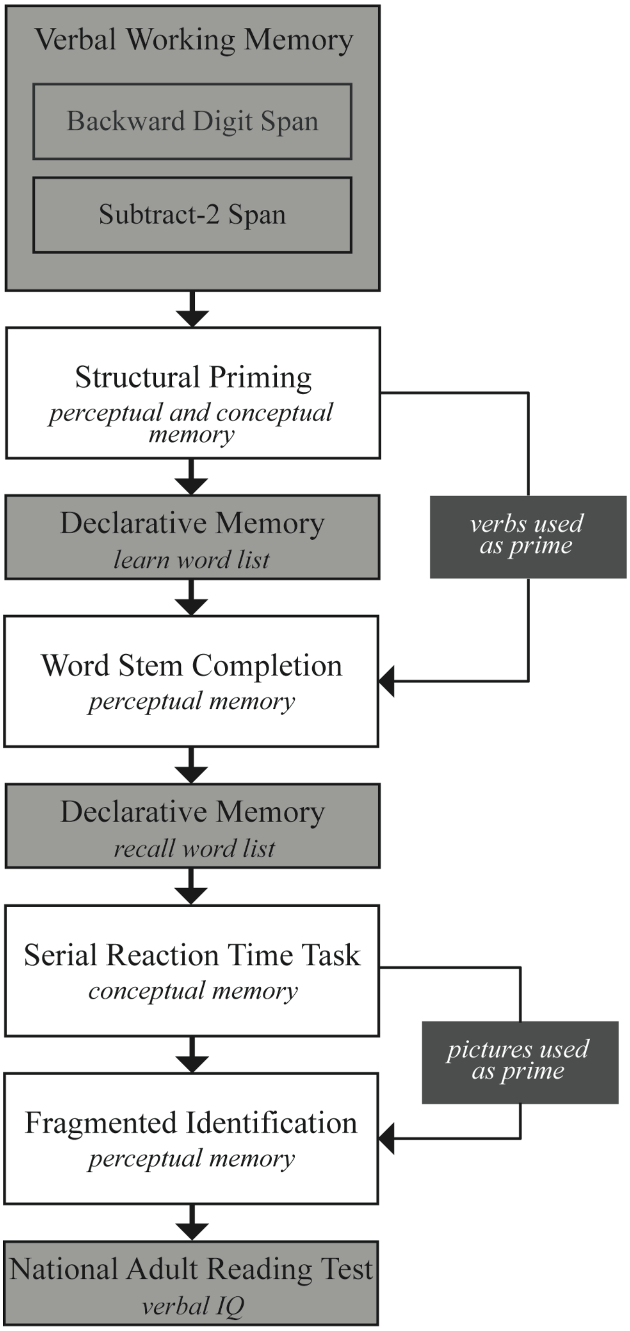



**Figure 1. Experimental Procedure.** All participants completed all tasks in the order illustrated here. Grey boxes represent control tasks, measuring working memory, explicit memory, and verbal IQ. White boxes represent the non-declarative memory tasks. Some tasks, in addition to measuring non-declarative memory, also acted as primes for future non-declarative memory tasks (black boxes).

All tasks were completed on a Dell Latitude E5470 Laptop (14" screen) using E-Prime (Schneider et al., 2002).

We included control measures of declarative memory, verbal IQ, and working memory and included each participant's score in our statistical models to partial out their contribution to performance in our non-declarative memory tasks.

**Structural Priming Task**

This task was based on a task by Menenti, Gierhan, Segaert, and Hagoort (2011).

The pictures used in this task were taken from Segaert, Menenti, Weber, and Hagoort (2011). The stimulus pictures depicted 40 transitive events such as *to chase, to interview* or *to serve* with a depiction of the agent and patient of this action. Transitive pictures were used to elicit transitive prime and target sentences. Each transitive picture had three versions: one grayscale version and two colour-coded versions with a green and a red actor. Participants were instructed to describe pictures with one sentence, naming the green actor before the red actor if the actors were depicted in colour. This allowed us to manipulate, for colour-coded primes, whether the prime sentence produced had an active (e.g., *the man kisses the woman*) or a passive (e.g., *the woman is kissed by the man*) syntactic structure.

Each transitive event was depicted by two pairs of adults and two pairs of children. One male and one female actor were shown in each picture, and each event was depicted with each of the two actors serving as the agent. To prevent participants forming strategies, the position of the agent (left or right) was randomized. Fillers elicited intransitive sentences, depicting events such as *running, singing,* or *bowing* with one actor (in greyscale or green).

Each experimental trial consisted of a prime (a coloured picture) followed by a target (a greyscale picture). There were 20 passive prime trials (a passive picture followed by a transitive greyscale target), 20 active prime trials (an active picture followed by a transitive greyscale target), and 20 baseline trials (an intransitive picture followed by a transitive greyscale target), all randomized in one experimental session. The baseline trials allowed us to measure the frequency of producing active and passive transitives on subsequent targets without any immediate prior influence. We also included 20 filler trials (an intransitive picture followed by an intransitive greyscale target). In total, therefore, we had 80 trials consisting of 100 transitive pictures and 60 intransitive pictures.

The timing of each prime, target or filler trial was as follows: Participants were initially presented with a neutral verb (to be used in an upcoming utterance; e.g. “to run”, “to chase”, etc.) for 500ms. After 500ms of black screen a coloured picture would appear. Participants were instructed to describe the picture following the rules described above. The picture was presented until the participant responded (with a time-out after 12 seconds). There was an intertrial interval of 1500 - 2000ms (jittered) before the next verb was presented. Coloured and greyscale pictures were alternated until all pictures were described. The task took a total of 15 minutes to complete.

Responses were manually coded by the experimenter as either active or passive. Trials in which the descriptions did not match one of the coded structures were discarded (6.96% of the data). Target responses were included in the analysis only if 1) both actors and the verb were named (a sentence containing only one of the actors does not qualify as a transitive sentence) and 2) the structures used were active or passive.

The proportion of passives produced after a passive prime compared to baseline (measurement of short-term priming), as well as the number of passives produced throughout the length of the task regardless of prime type (measurement of long-term priming) were taken as variables of interest.

## Non-declarative Memory Tasks

We will describe the tasks in the order they were presented in the experiment. We included two perceptual memory tasks: The word-stem completion task (verbal memory) and the fragmented identification task (visual memory), and one conceptual memory task: The serial reaction time task.

**Word-Stem Completion (WSC) Task** This task was developed to test the non-declarative memory for words. This task is based on those described in Davis et al. (1990) and Fleischman, Wilson, Gabrieli, Bienias, & Bennett (2004) but adapted for use on a computer.

Participants were presented with 20 three-letter word-stems on the computer screen and instructed to complete the words by typing in their answer using the keyboard. Participants were encouraged to use the first word that came to mind.

10 of the word-stems could be completed using the verbs used in the syntactic priming task (randomly selected from the list of verbs each specific participant used) and 10 using novel words (randomly picked from a list of 33 stems). The 33 word-stems to be completed by novel words were selected from a word-stem database by Migo, Roper, Montaldi, & Mayes (2010). The novel word-stems could not be completed with any of the words the participants had been exposed to until this point in the session. The word frequency of the most common completions for the test stems and novel stems did not significantly differ (Independent samples *t*-test, $t(42) = -.874$, $p = .300$).

The 20 three-letter word-stems were presented one at a time, in a random order, and were only replaced with a new stem once the participant entered their completed word. The task took 5 minutes to complete.

The number of word-stems completed with verbs primed in the structural priming task as well as the reaction times were taken as variables of interest. Reaction times were trimmed to 2.5 standard deviations for each age group (11 out of 352 data points were removed; 3.13% of the data).

**Serial Reaction Time (SRT) Task** This task was developed to test statistical co-occurrences of temporally separated stimuli (Nissen and Bullemer, 1987) and therefore is a measure of conceptual memory. This task is based on a task described by Neger, Rietveld, & Janse (2014).

Participants were presented with a 3 x 3 grid on the computer screen that was filled with the digits 1 to 9. A picture would be presented on one of the 9 locations, and participants were instructed to press the corresponding number key as fast as possible. Participants were instructed to respond using the number pad, such that the keys on the number pad correspond to the same spatially located key on the grid. Crucially, the location of the subsequent picture could be predicted based on the location of the current picture. The pictures used were not relevant for this task, however, for each participant the same picture would appear at the same location for the duration of the task. Pictures and their locations were randomized between participants.

Similar to Neger and colleagues (2014), the task was composed of blocks and split into an exposure phase, a test phase, and a recovery phase. During the exposure phase, participants could learn the underlying pattern by picking up on the co-occurrence probabilities of the locations. In total, the exposure phase consisted of 16 predictable blocks. Within each block, all location combinations were repeated once, resulting in 128 exposure trials (8 x 16). The test phase consisted of two unpredictable blocks, resulting in 16 test trials (8 x 2). In these unpredictable trials, a new underlying pattern was used. Participants who implicitly learnt the patterns in the exposure phase should show a drop in performance as they would need to correct their predictions during the test phase, resulting in a slowed response to the second picture. This measure of learning is widely accepted in the literature on conceptual memory (Janacsek and Nemeth, 2013).

A picture would only appear on the specific location 500ms after the onset of the visual display and the task only proceeded if the participant pressed the appropriate target number. The new location would only be revealed 500ms after the previous picture disappeared, a time interval that has previously been shown to be necessary to successfully allow prediction effects in older adults (Salthouse et al., 1999). A fixation cross appeared for 2500ms between blocks for all phases. In total this task took 20 minutes to complete.

To assess skill learning, we measured latencies from the picture presentation to the subsequent correct button press. To correct for any changes in response time due to age, we calculated facilitation scores for each participant. Facilitation score was calculated by dividing the RT to a location by the RT to the subsequent location. Facilitation scores were trimmed to 2.5 standard deviations for each age group (5 out of 176 data points were removed; 2.84% of the data).

As each location primed the subsequent location, a single location acted as both a target on the current trial and as a prime for the next (contrary to previous versions of this task where a location can be only a prime or a target, not both). To measure skill learning, we focused our analysis only on locations where the prime location was unpredictable (<25%) and the targets were highly predictable (>75%). This decision was reached after data-collection to minimize the noisiness of the data.

We calculated percent change for each participant's facilitation score between phases and entered this as the dependent variable in the model.

**Fragmented Identification Task** This task was developed to test the non-declarative memory for pictures. This task is based on a task by Kessels, Remmerswaal, & Wilson (2011) but adapted for use on a computer.

Participants were shown a set of 16 line drawings, in a sequence of 8 pictures of decreasing degradation. The participant had been previously exposed to 8 of the line drawings during the SRT task while the remaining 8 were novel line drawings the participant had not seen before. The dependent measure was the level of degradation at which accurate identification was possible. The pictures were selected from the bank of standardized stimuli (BOSS) picture database (Brodeur et al., 2010, 2014). We used naming frequency from the BOSS database to pick 18 pictures that were 1) named with only one name and 2) named using the same name 100% of the time. This was to ensure we used pictures with the highest rate of identification. All pictures had comparable complexity scores (M: 2.29; SD: 0.402).

Fragmentation of the pictures was done manually following the methods described by Snodgrass (Snodgrass et al., 1987) but briefly: Pictures were placed into a 16 x 16 block grid.

The locations of blocks that contain picture information were then identified. Blocks with picture information were randomly selected to be erased to produce eight levels of fragmentation per picture. Level 8 is the complete picture and Level 1 is the most fragmented picture, containing only 8% of the original picture. Contours of the picture were fragmented separately to ensure that the outline of each picture was also fragmented to the same extent as the rest of the picture, i.e., at Level 1, only 8% of the contours were visible. This prevented the participants from being able to identify a picture at a low fragmentation purely because the entire outline of the picture was complete.

The participant was instructed to type the name of the picture. If the answer was incorrect, the participant would be shown the next picture in the fragmented sequence. If the participant was correct, they would be moved on to the next novel object to identify. Each picture in the sequence was presented for at least 3 seconds and until the participant indicated they were ready to see the next picture in the sequence (hence a response was not required for each fragment in the sequence). In total the task took 10 minutes to complete.

The dependent variable in this task was therefore the sequence number at which the participant correctly identified the picture, for each line drawing.

**Additional Measures**

**Verbal Working Memory Tasks** Waters & Caplan (2003) reported that test-retest reliability is considerably better when performance across several verbal working memory tasks are averaged to yield a composite span score. We chose to have participants complete the backward span and subtract-2 span tasks and use their composite score in further analysis. Waters & Caplan (2003) illustrated how these two tasks have the highest correlation of the seven verbal working memory span tasks tested (Pearson's $r = .71$, $p < .05$). The tasks used here are based on those described in Waters & Caplan (2003) but adapted for a computer.

***Backward Digit Span Task*** In this task, on each trial, the participants were required to repeat a series of digits in reverse order of presentation. The stimuli were digits drawn from the digits 1 to 9 and presented randomly.

***Subtract-2 Span Task*** In this task, on each trial, the participants were required to repeat a series of digits after subtracting 2 from each digit. The stimuli were digits drawn from the digits 2 to 11 and presented randomly.

Participants were tested on span sizes 2 to 8 in each of the two verbal working memory tasks. For both tasks, there were five trials at each span size. The participants were required to repeat all the items in the trial in the correct serial order to obtain credit for the trial. They were instructed to submit a blank answer if they could not remember what the item was. The items were presented at the rate of one per second. In total the verbal working memory tasks took 15 minutes to complete.

Span in both tasks was defined as the longest list length for which the participants correctly recalled all the items in the correct serial order on three out of the five trials. An additional 0.5 was added if the participants were correct on two out of the five trials at the next span size. The dependent variable is thus the average span of the two verbal working memory tasks.

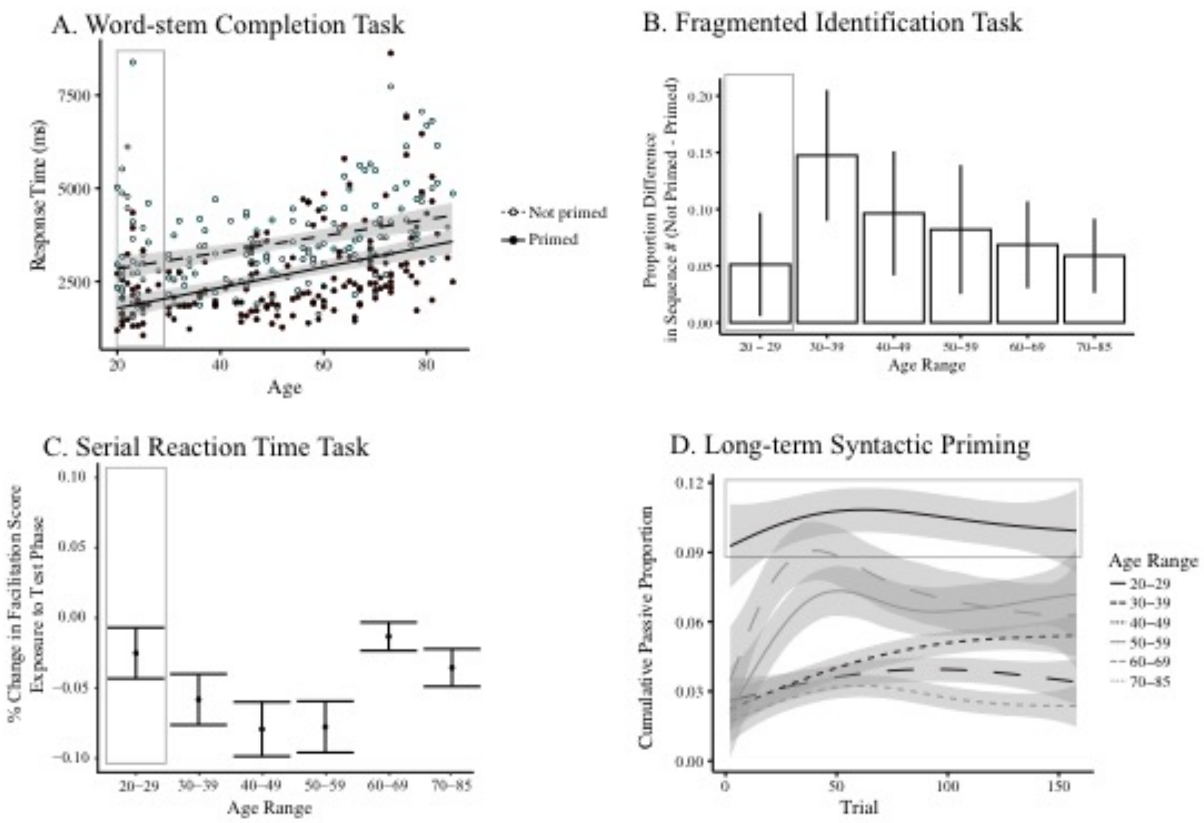
**Declarative Memory Task** The declarative memory task is based on one used in the Weschler Memory Scale (WMS-III; Wechsler, 1997), but adapted for computer use.

Before the WSC task started, participants were presented with a list of 10 words and explicitly told to remember these words. After the participants completed the WSC task, they were asked to type out as many of the to-be-remembered-words as possible. The number of correctly remembered words was used as a measure of declarative memory.

**Verbal IQ** Verbal IQ was measured using the National Adult Reading Test (NART). This task is based on Nelson and Willison (1991). The participant is given a list of 50 words and asked to read them aloud. Performance is based on whether each word was pronounced correctly. Marking for the NART was done offline by the same experimenter (E.H.) for all participants.

**Data Analysis**

Surprisingly, the youngest age group (20 – 29 years) performed worse in the 4 non-declarative memory tasks compared to the other age groups (Supplementary Figure 1). The youngest group was the only one to be compensated with university credits instead of money and therefore their performance level is most likely due to differences in motivation and attention, compared to the other groups. We therefore removed them from further analysis. This removal was done before statistical tests were run.




**Supplementary Figure 1. Performance in Non-Declarative Memory Tasks including the youngest age group.** Grey squares identify the 20 – 29-year group performance in the non-declarative memory tasks where their performance does not match the trend set by the remaining 140 participants. For more information on the sub-figures, please see figures 3 – 6.

Most of the data analysis was done coding age as a linear variable, not binned in the age groups described under *Participants*. Therefore, *Age* (factor) or age (in text) refers to age as a linear variable. *Age Range* (factor) or age group (in text) refers to age binned per decade.

**Structural priming, WSC, and Fragmented Identification** These three non-declarative memory tasks were analysed using mixed-effects models, using the lme4 package (version 1.1-10; Bates, Maechler, & Bolker, 2012) in R (R Core Development Team, 2011). We used a maximal random-effects structure as was justified by the data (Barr et al., 2013): the repeated-measures nature of the data was modelled by including a per-participant and per-item random adjustment to the fixed intercept ("random intercept"). We attempted to include as many per-participant and per-item random adjustments to the fixed effects ("random slopes") as was supported by the data. We began with a full model and then performed a step-wise "best-path" reduction procedure, removing interactions before main effects, to locate the simplest model that did not differ significantly from the full model in terms of variance explained (as described in Weatherholtz et al., 2014). For the Fragmented Identification task, we used a Poisson model to better model the count nature of the dependent variable.

**SRT Task** This task was analysed using linear models, as there were no repeated measures once percentage change was calculated, using the stats package in R. We began with a full model and then performed a step-wise "best-path" reduction procedure similar to the one described above. P values were obtained using the Anova function from the car package (version 2.1-1; Fox & Weisberg, 2011) using Wald Chi-Square tests (Type III).

# Results

## General Descriptives

Table 1 shows the average score on each of the three control measures for each age group included in the analysis. Figure 2 shows the variation of each of the three control measures with age.

**Table 1. Performance of each age group in each of the three control measures.** Value represents the mean for each age group, with the standard deviation in parenthesis.

| Age Range | N | Verbal IQ | Working Memory | Declarative Memory |
|---|---|---|---|---|
| 30 – 39 | 23 | 117.17 (5.07) | 5.56 (1.31) | 4.56 (2.33) |
| 40 – 49 | 27 | 119.47 (4.62) | 5.46 (1.15) | 4.22 (2.12) |
| 50 – 59 | 23 | 121.01 (3.13) | 5.52 (1.11) | 4.43 (1.75) |
| 60 – 69 | 31 | 122.86 (3.44) | 5.11 (0.89) | 3.32 (1.92) |
| 70 – 85 | 37 | 122.12 (4.18) | 4.27 (1.11) | 2.00 (1.72) |

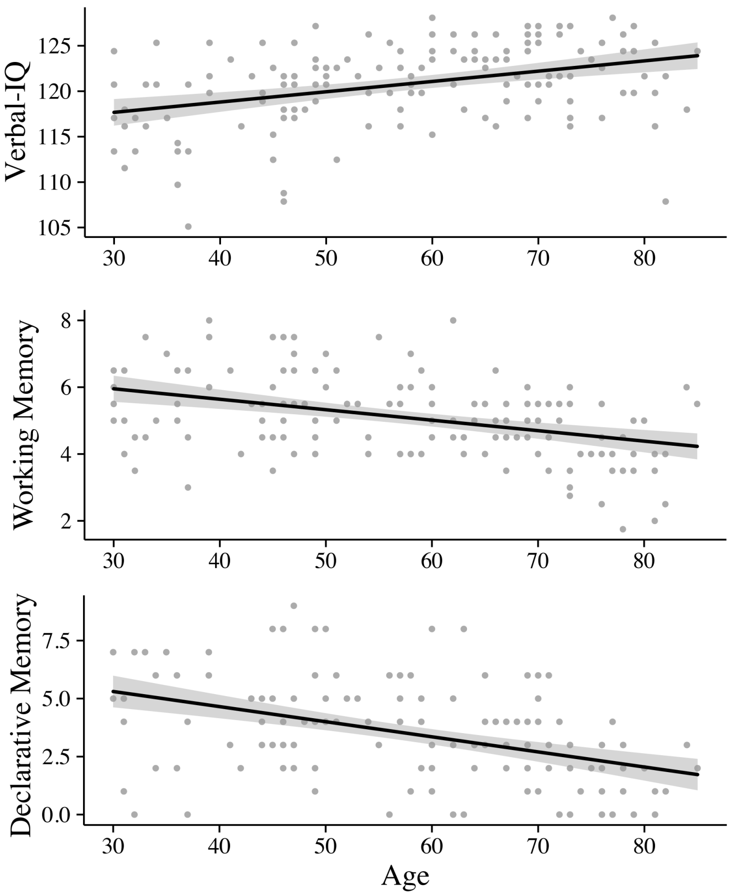



**Figure 2. Results of the three control measures.** The measure of verbal IQ (NART) showed a significant increase with age whereas the working memory and declarative memory tasks showed significant decreases with age. Error clouds represent standard error.

We observe a significant decrease in verbal working memory (Pearson's r = -0.39, $p < .001$) and declarative memory (Pearson's r = -0.44, $p < .001$) with age, which is consistent with the literature (Fleischman and Gabrieli, 1998; Fleischman et al., 2004). We observe a significant increase in verbal IQ (Pearson's r = 0.38, $p < .001$) with age.

We will describe the results in the non-declarative memory tasks by component. We will focus on the perceptual memory tasks first, then the task that measures conceptual memory, and finally the structural priming task to determine whether the long-term and short-term priming magnitudes match the age-related patterns seen in the non-declarative memory tasks.

**Perceptual Memory - Word-stem Completion (WSC)**

There was no effect of age on the number of word-stems participants completed with words primed in the structural priming task (Pearson's r = 0.04, $p = .620$). Table 2 provides the summaries for each age group, although the analysis itself was done on age as a linear variable.

**Table 2. Number of word stems completed by each age group.** The table lists the average number of word-stems completed with the primed word for each age group. Highest obtainable score is 10.

| Age Range | Average | Standard Deviation |
|---|---|---|
| 30 – 39 | 3.61 | 1.62 |
| 40 – 49 | 4.19 | 1.81 |
| 50 – 59 | 3.98 | 1.70 |
| 60 – 69 | 3.66 | 1.68 |
| 70 – 85 | 3.39 | 1.36 |

We used a linear mixed effects model to analyse the response time data. The full model contained two-way interaction of *Primed* (primed vs. not primed word-stems; sum-contrast coded) with *Age* and each of the three control measures as well as two-way interactions of *Age* with each of the three control measures. Interaction effects between *Primed* and *Age* crucially capture the age-related effects on perceptual memory for words. We included no random slopes as then the model would not converge. Table 3 shows the results of the best model, which included main effects of *Primed, Age, Working Memory* (composite score), and *Declarative Memory* (# of words correctly recalled), and a two-way interaction of *Age* and *Working Memory.* We also included the interaction of *Primed* and *Age* for illustrative purposes.

**Table 3. Summary of the best linear mixed effects model for the Word-Stem Completion Task, modelling the response time to word-stem completion.**

| | coefficient | *SE* | df | *t* value | *p* value | |
|---|---|---|---|---|---|---|
| Intercept | 1302.23 | 388.38 | 141.94 | 3.90 | < .001 | *** |
| Primed | 608.81 | 364.96 | 138.48 | 3.34 | .001 | ** |
| Age | 24.19 | 6.57 | 140.76 | 4.25 | < .001 | *** |
| Working Memory | 507.18 | 233.64 | 137.95 | 2.17 | .032 | * |
| Declarative Memory | -64.61 | 38.73 | 139.46 | -1.67 | .097 | |
| Primed * Age | 2.95 | 6.11 | 138.06 | 0.96 | .337 | |
| Age * Working Memory | -12.04 | 3.93 | 139.01 | -3.07 | .002 | ** |

N = 277 *** < .001 ** < .01 * < .05

There is a significant effect of *Primed* on response time such that participants were faster to complete the word-stem with a primed word than with a novel word (Figure 3). The main effect of *Age* was due to a slower response time as the participants increased in age, regardless of whether they completed the word-stem with a primed or not primed word. This could be due to decreased processing speed, as is established for older participants (Salthouse, 1996a), or due the decreased familiarity of typing on a keyboard for older participants, which would affect participants equally in all conditions. The interaction with *Working Memory* illustrates a similar concept: Participants with a higher working memory composite score were faster at completing the stems (regardless if primed or not), and this interacted with *Age* as working memory capacity decreases with age (as shown in Figure 2).

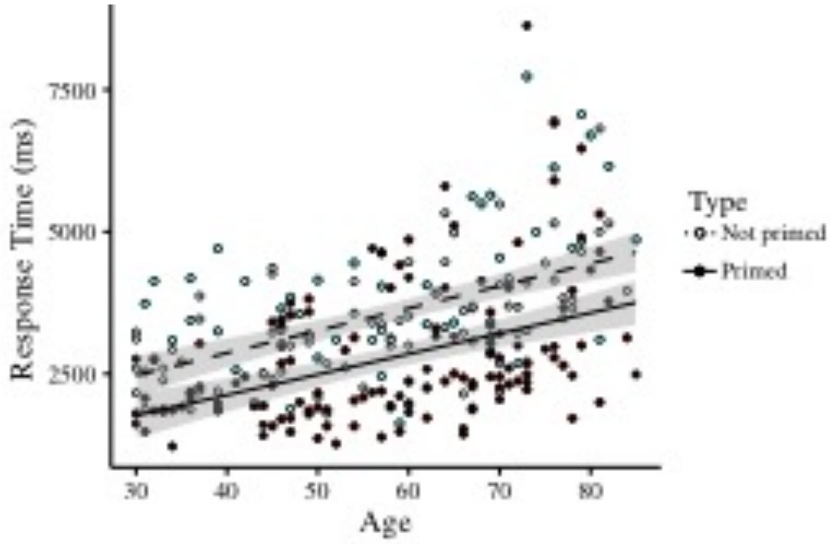



**Figure 3. Response Time for the Word-stem Completion Task.** Participants were increasingly slower with increasing age ($p < .001$), however, they were consistently faster at completing primed words compared to not primed words ($p < .001$). There was therefore no effect of age on perceptual memory performance in this task ($p = .337$). Error clouds represent standard error.

Overall, we do not see an effect of age on perceptual memory performance in this task ($p = .337$) and we do not see declarative memory contamination for the prime effects ($p = .097$).

**Perceptual Memory - Fragmented Identification**

We used a Poisson linear mixed effects model to analyse the data. The dependent variable was the number of pictures the participant needed to see before they correctly identified it. The full model contained a two-way interaction of *Primed* (not primed vs. primed pictures; sum-contrast coded) and *Age.* We also included two-way interactions between *Age* and each of the three control measures. We included no random slopes as they made no difference in how well the model captured the data. Table 4 shows the results of the full model, which was also the best model in terms of variance explained.

**Table 4. Summary of the best linear mixed effects model for the Fragmented Identification Task.** The number of pictures the participant needed to see before they were able to correctly identify the picture is the dependent variable in this model.

| | coefficient | *SE* | *z* value | *p* value | |
|---|---|---|---|---|---|
| Intercept | 1.42 | 0.06 | 22.58 | < .001 | *** |
| Primed | 0.03 | 0.01 | 3.12 | .002 | ** |
| Age | 0.01 | 0.00 | 6.63 | < .001 | *** |
| Working Memory | -0.01 | 0.01 | -1.04 | .300 | |
| Verbal IQ | -0.00 | 0.00 | -1.04 | .298 | |
| Declarative Memory | -0.00 | 0.01 | -0.47 | .640 | |
| Primed * Age | -0.00 | 0.00 | -0.36 | .721 | |
| Age * Working Memory | -0.00 | 0.00 | -0.12 | .905 | |
| Age * Verbal IQ | 0.00 | 0.00 | 2.18 | .029 | * |
| Age * Declarative Memory | -0.00 | 0.00 | -1.65 | .098 | |

N = 2255   * < .05   *** < .001

The model shows a main effect of *Primed* such that more of the not primed than the primed pictures need to be seen before the picture was correctly identified (Figure 4). There is also a main effect of age: More of the picture needed to be seen as the participants increased in age, regardless of whether the picture was primed or not. The interaction with *Verbal IQ* illustrates that participants with a higher verbal IQ needed to see more of the picture in order to identify it (regardless if primed or not), and this interacted with *Age* as verbal IQ increases with age (as shown in Figure 2).

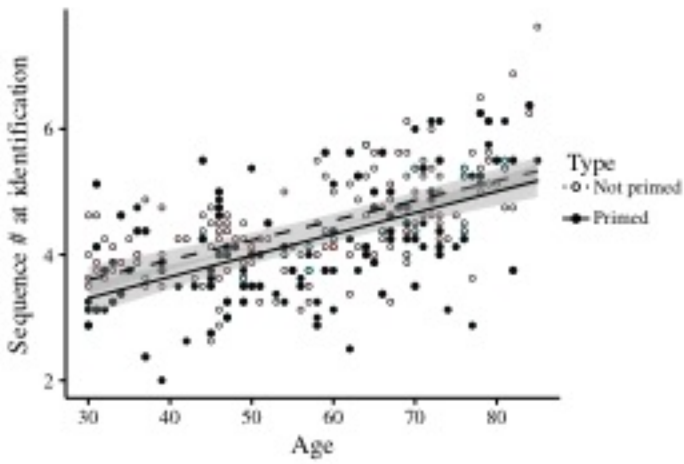



**Figure 4. Performance in the Fragmented Identification Task.** Participants needed to see more of the picture in order to correctly identify it as age increase ($p < .001$), however, they were consistently earlier at identifying a prime picture compared to a not primed picture ($p < .001$). There was therefore no effect of age on perceptual memory performance in this task ($p = .744$). Error clouds represents standard error.

However, there was no interaction between *Age* and *Type* ($p = .744$), suggesting that perceptual memory does not decline with age.

**Conceptual Memory - Serial Reaction Time (SRT)**

Our data show that participants were slower at conducting the task as age increased (Pearson's rho = 0.36, $p < .001$).

We first determined the facilitation scores for the exposure phase. Faster reaction time as the task progresses suggests participants are learning the underlying patterns, enabling them to respond faster. We therefore initially determined, using pair-wise *t* tests, the point at which participants stopped getting faster, i.e., when they had learnt the underlying patterns. There was no age-related difference in when participants stopped being significantly faster ($p < .025$, Bonferroni corrected); all participants had learnt the patterns by block 3 (i.e., after 32 trials). Therefore, to calculate the average facilitation score per participant, we averaged across blocks 3 to 16 (with 16 being the end of the exposure phase; Figure 5A).

Next we determined the percentage change in facilitation scores from the exposure phase to the first block of the test phase (when the underlying pattern was changed). We used linear models to analyse the data. We initially analysed the data with *Age* as a linear variable, as we have with the previous tasks, however, when plotting the data it was clear that there was no clear linear or polynomial effect. Hence we divided the data into age groups of 10 years in an attempt to better understand the underlying data pattern (Figure 5B). We used a Helmert contrast such that each age group was compared to the age group preceding it.

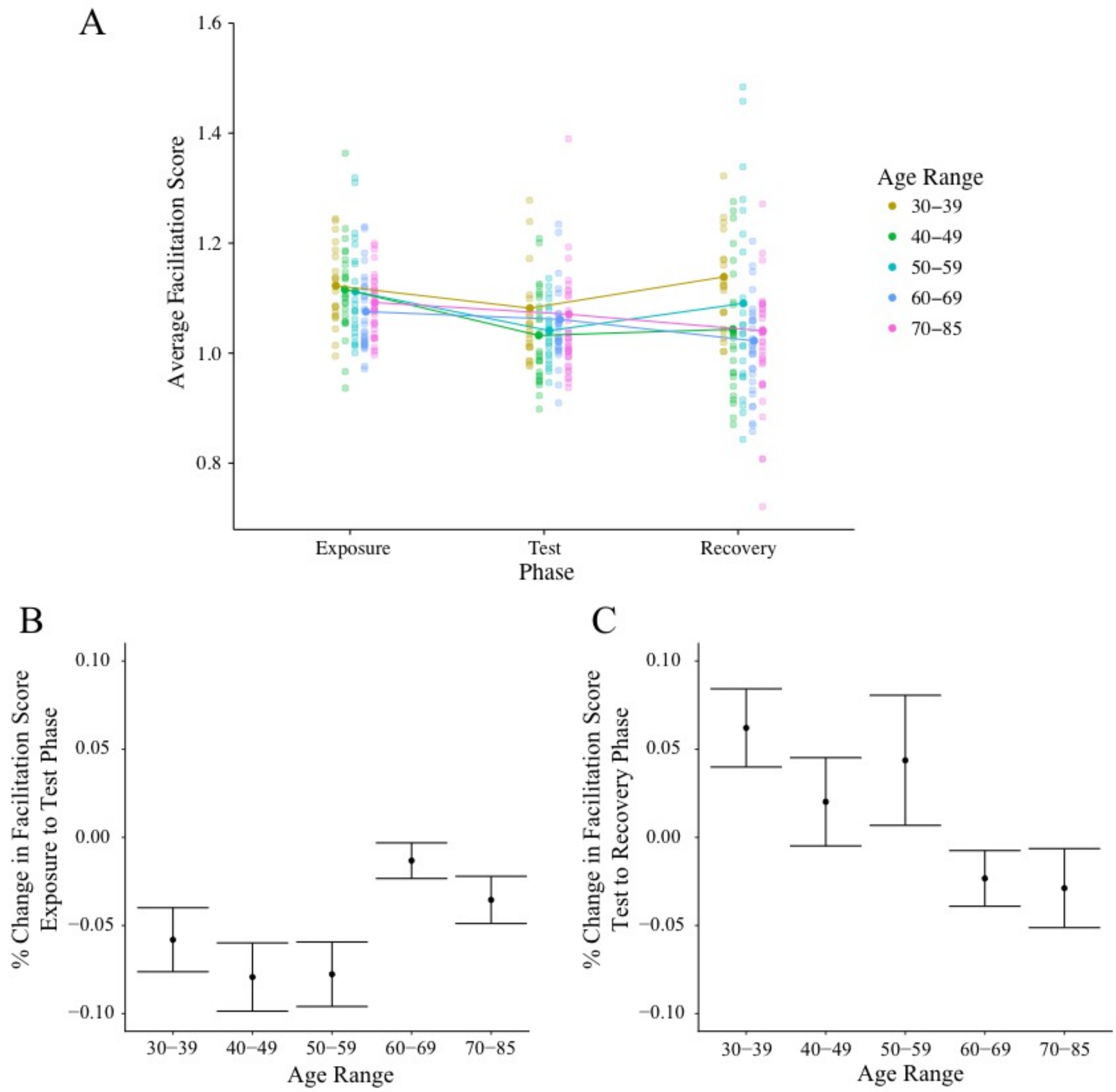



**Figure 5. Performance in the Serial Reaction Time Task. A.** Individual dots represent facilitation score in each of the three phases for each age group. The line starts at the average facilitation score in each of the three phases for each age group. Facilitation scores higher than 1 means that participants were faster on target trials compared to prime trials. A drop in facilitation score between phases therefore suggests the participants are slowing down their button press response time to the target trials relative to the prime trials – in other words, they are predicting less. **B** and **C** quantify this drop as a percentage change for the Exposure to Test (when the underlying pattern was changed) and Test to Recovery (when the underlying pattern was re-established) phase respectively. Error bars represent standard error.

The full model included main effects of *Age Range* (Helmert contrast coded) and each of the three control measures. Table 5 summarizes the results of the best model, which included *Age Range* and *Working Memory* for the percentage change in facilitation score between the exposure phase and the first block of the test phase (when the underlying pattern was changed).

**Table 5. Summary of the best linear model for the Serial Reaction Time Task** for the percentage change in facilitation score from blocks 3 - 16 of the exposure phase to the first block of the test phase (when the underlying pattern was changed).

| | coefficient | *SE* | *t* value | *p* value | |
|---|---|---|---|---|---|
| Intercept | -0.05 | 0.01 | -7.34 | < .001 | *** |
| 40 – 49 yrs | -0.01 | 0.01 | -1.09 | .277 | |
| 50 – 59 yrs | 0.00 | 0.01 | 0.02 | .983 | |
| 60 – 69 yrs | 0.01 | 0.00 | 3.26 | .001 | ** |
| 70 – 85 yrs | 0.01 | 0.00 | 1.61 | .111 | |
| Working Memory | 0.01 | 0.01 | 2.51 | .013 | * |

* < .05 ** < .01 *** < .001

A *post-hoc t*-test suggests that the main effect of *Age Range* is due to a differentiation in the percentage difference in facilitation score between the less than 60 year age groups (i.e., 30 – 59 years) and the over 60 year age groups (i.e., 60 – 85 years; Student's *t*-test, t(132.34) = -2.69, $p$ = .008). As Figure 5B and the model illustrates, participants aged 59 years and younger showed a significant drop in facilitation score between the exposure phase and the test phase, indicating they had learnt the underlying pattern. The participants aged 60 years and older did not show as steep a drop in facilitation score, suggesting conceptual memory was less pronounced in these older participants.

We also looked at the change in facilitation score between the last block of the test phase and the first block of the recovery phase. In the recovery phase, the same underlying pattern as what the participants learnt during the exposure phase is re-introduced, and therefore an increase in facilitation score is expected. The best model for these data also contained main effects of *Age Range* and *Working Memory* although none significantly predicted the percentage difference in facilitation score between the test phase and the recovery phase. Figure 5C illustrates that this is mainly due to the younger age group (<60 years): Although they do show a positive percentage difference, suggesting they have recognized that the underlying patterns have returned, the variability of this effect is greater than in Figure 5B, and hence is not significantly different from the older age group (>60 years). The older age group show no overall percent change between the test and recovery phase, indicating that their response times have not changed, suggesting they have not noticed a change in the underlying pattern – or rather, they had not learnt the pattern to begin with, and hence changing the pattern does not influence their behaviour.

Overall, we show a significant effect of age on the performance in the SRT task, as younger participants significantly learnt the underlying pattern, whereas the older participants (60 years and older) did not.

### Structural Priming Task

Similar to the analysis for the SRT task above, in order to reduce the noise of the data, we divided the participants into 10-year age groups. We used a logit mixed model to analyse the data, again with a Helmert contrast for *Age Group*. The full model contained the two-way interaction *Prime* (treatment-coded, baseline trials as reference group) by *Age Range* in addition to interactions of *Prime* with each of the three control measures. *Prime* represents the active, passive, or baseline structure the participant produced during the prime trials and whether this affects the structure produced on the subsequent target trials. This therefore measures the short-term priming effect.

We also included *Cumulative Passive Proportion* as an interaction with *Age Range*. *Cumulative Passive Proportion* was calculated as the proportion of passives out of the total transitive responses produced on the target trials before the current target trial. A positive and significant *Cumulative Passive Proportion* therefore suggests that the proportion of passives previously produced positively influences the probability of producing a passive on the current target trial. It therefore measures the long-term priming effect. We did not calculate a Cumulative *Active* Proportion as very little previous priming studies have shown a significant active priming effect, and hence we did not consider this variable to model learning.

The best model included main effects of *Prime, Age Range,* and a two-way interaction between *Age Range* and *Cumulative Passive Proportion.* We included *Prime* and *Cumulative Passive Proportion* as a random slope for the per-participant random intercept. Random slopes for the per-item random intercept did not significantly improve the model. Table 6 illustrates the results from the best model, but including the *Prime* by *Age Range* interaction for illustrative purposes.

**Table 6. Summary of the best logit mixed effects model for the syntactic priming task.**

| | Coefficient | *SE* | Walds *z* | *p* value | |
|---|---|---|---|---|---|
| Intercept | -4.04 | 0.24 | -17.09 | < .001 | *** |
| Active Prime | -0.13 | 0.26 | -0.50 | .620 | |
| Passive Prime | 0.55 | 0.22 | 2.51 | .012 | * |
| 40 – 49 yrs | 0.15 | 0.34 | 0.43 | .664 | |
| 50 – 59 yrs | 0.29 | 0.17 | 1.76 | .079 | |
| 60 – 69 yrs | -0.02 | 0.11 | -0.15 | .884 | |
| 70 – 85 yrs | -0.07 | 0.10 | -0.72 | .474 | |
| C. Pass. Prop. | 2.20 | 0.27 | 8.13 | < .001 | *** |
| Active Prime * 40 – 49 yrs | 0.30 | 0.39 | 0.78 | .440 | |
| Passive Prime * 40 – 49 yrs | 0.08 | 0.34 | 0.24 | .810 | |
| Active Prime * 50 – 59 yrs | -0.13 | 0.19 | -0.67 | .501 | |
| Passive Prime * 50 – 59 yrs | -0.19 | 0.17 | -1.15 | .250 | |
| Active Prime * 60 – 69 yrs | 0.07 | 0.12 | 0.62 | .535 | |
| Passive Prime * 60 – 69 yrs | -0.13 | 0.11 | -1.14 | .256 | |
| Active Prime * 70 – 85 yrs | 0.07 | 0.12 | 0.56 | .575 | |
| Passive Prime * 70 – 85 yrs | 0.02 | 0.11 | 0.19 | .852 | |
| 40 – 49 yrs * C. Pass. Prop. | -0.10 | 0.28 | -0.36 | .723 | |
| 50 – 59 yrs * C. Pass. Prop. | -0.15 | 0.15 | -0.98 | .326 | |
| 60 – 69 yrs * C. Pass. Prop. | -0.08 | 0.09 | -0.87 | .385 | |
| 70 – 85 yrs * C. Pass. Prop. | 0.23 | 0.10 | 2.32 | .020 | * |

N = 6951, log-likelihood = -964.4    *** < .001   ** < .01   * < .05

The negative estimate for the intercept indicates that in the baseline condition (intransitive prime followed by transitive target) active responses were more frequent than passive responses. Following passive primes, more passive responses were produced compared to baseline ($p$ = .012). Following active primes, there was no increase in active responses compared to baseline ($p$ = .620). This is the standard pattern of results reported in the literature (e.g., Bernolet, Collina, & Hartsuiker, 2016; Bock, 1986; Ferreira & Bock, 2006). There was no interaction of *Prime* with *Age Range* ($p > .250$; Figure 6A) suggesting that the short-term priming effect does not vary as a function of age.

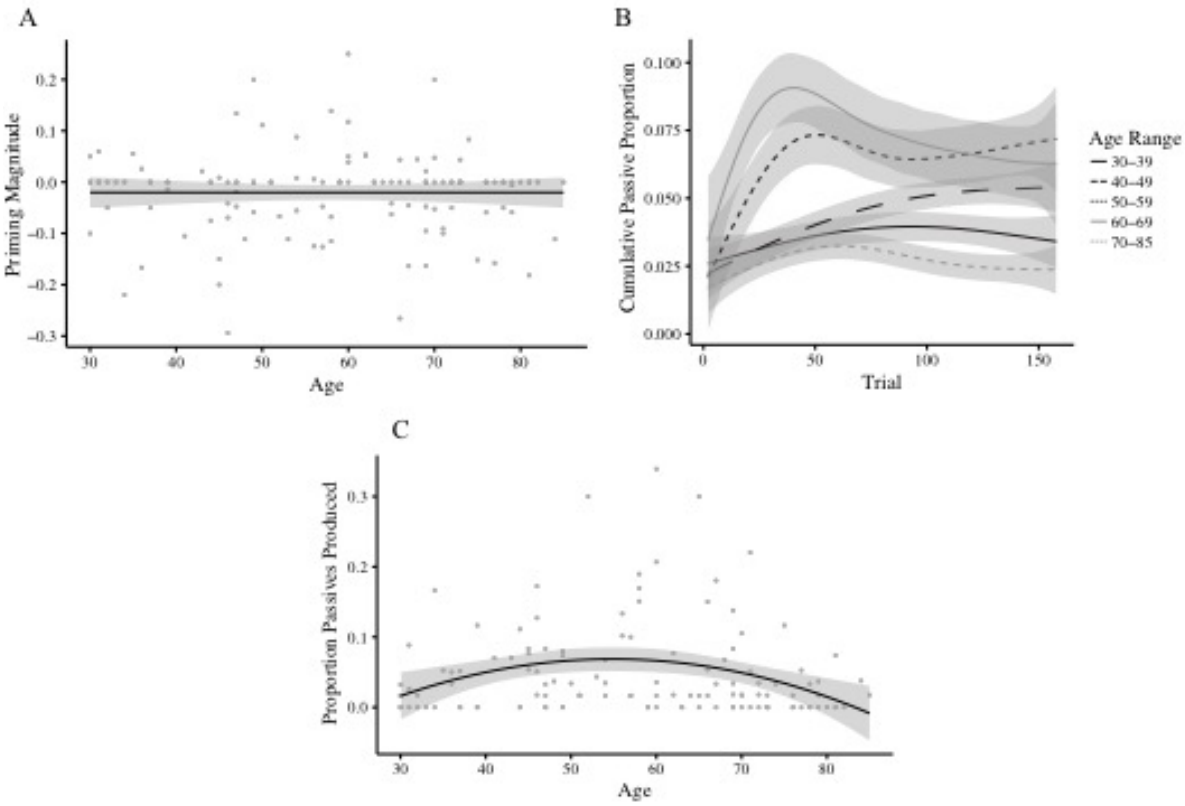



**Figure 6. Performance in the Syntactic Priming Task A. Short-term priming.** We observed no significant effect of age on short-term priming magnitude ($p > .250$). **B. Long-term priming.** We observe a clear influence of age on the long-term priming magnitude, such that older participants are more likely to produce passives sooner compared to their younger peers ($p > .006$). **C. Proportion of Passives Produced.** Although there are no significant differences in the proportion of passives produced (regardless of prime type) as a function of age, there is a trend for an inverted U-shaped curve as a function of age. This may influence (or be influenced by) the long-term priming behaviour. Error clouds represent standard error.

We do observe a significant interaction between *Cumulative Passive Proportion* and *Age Range*, suggesting that there is an effect of age on long-term priming. We see this in two ways. Firstly, the oldest age group (70 – 85-year olds) showed a significant difference in long-term priming from their immediately younger peers (60 – 69-year olds; $p = .020$). Secondly, Figure 6B shows that the rate of accumulation of passives increases as the participants increase in age from 30 to 69 years. However, as we used a Helmert contrast, which only compares the current age group to the immediately preceding one, the between decade changes are too small to be significantly different. Hence, to find support for our claim that *Cumulative Passive Proportion* (and therefore long-term priming) does vary with age, we reran the model but treatment contrasting *Age Group* such that each decade was compared to the 30 – 39-year olds. Indeed, we see a significant difference between this youngest age group and 50 – 59-year olds (β = -

0.81, $p$ = .006) and 60 – 69-year olds (β = -0.73, $p$ = .009) suggesting that long-term priming at these age groups have significantly changed from the youngest age group.

Overall, we see no effect of age on short-term priming, while we see a clear effect of age on long-term priming.

## Discussion

In this study we aimed to test the proposal that both long-term and short-term structural priming are supported by non-declarative memory. Specifically, we tested our hypothesis that long-term priming is supported by conceptual memory whereas short-term priming is supported by perceptual memory - both subcomponents of the non-declarative memory system. We investigated how the magnitude of these two priming effects varied with the age of the participants. Previous studies in the memory literature have suggested that the two subcomponents of non-declarative memory age differently by demonstrating age-related decline in conceptual memory but not in perceptual memory. We therefore investigated how age-related decline in these two components of non-declarative memory relates to performance in structural priming, in order to elucidate how non-declarative memory supports two seemingly different components of structural priming.

Our tasks and their key findings are summarised in Table 7. The results in this study show a clear link between performance in the perceptual memory tasks and short-term structural priming magnitude, as well as a clear link between the performance in the conceptual memory tasks and long-term priming magnitude. We elaborate on this below.

**Table 7. Summary of key results for the non-declarative memory tasks**

| Task | Non-declarative Memory Component Measured | Key Results |
|---|---|---|
| Word-stem completion | Perceptual memory | No age effect |
| Fragmented Identification | Perceptual memory | No age effect |
| Serial Reaction Time | Conceptual memory | Decrease in performance in 60+ age groups |
| Structural Priming | Short-term: Perceptual memory | No age effect |
| | Long-term: Conceptual memory | Decrease in priming magnitude with increasing age; biggest drop in 70+ age groups |

Firstly, our study shows a clear difference in the age-related effects on performance in the two subcomponents of non-declarative memory, with a decline in conceptual memory but not in perceptual memory. This difference matches trends seen in the memory literature, although our study is one of the few that compares conceptual as well as perceptual memory performance within participants (Maki et al., 1999; Schugens et al., 2007). Instead, most previous studies have investigated the effect of age on a single task (for example, Davis et al., 1990; Light et al., 2002; Karlsson et al., 2003). Therefore, our study makes important contributions to the literature on age-related decline in different components of non-declarative memory.

Second, our findings demonstrate an age-related decline in long-term structural priming but not in short-term structural priming, suggesting a link between the temporal characteristics of structural priming and the two subcomponents of non-declarative memory. We conclude that short-term priming is supported by perceptual memory: All measures show that there is no decline with age. The evidence from long-term priming performance also suggests our hypothesis is confirmed: We observed a decrease in long-term priming and a decrease in conceptual memory performance for the older age groups. For long-term priming, we observed an increase in long-term priming as age increased, suggesting that participants show more non-declarative learning as they increase in age. However, this significantly dropped for the oldest age-groups (70-85-years). This is related to the conceptual memory task, were performance significantly dropped for the older age-groups (60 – 85-years).

Our study is an important first step towards providing evidence of a connection between non-declarative memory and both temporal characteristics of structural priming. Future studies will focus on the nature of the link between structural priming and different memory components. One way of doing so, is by testing a greater number of participants in a key age range (our study reveals that this is from 60 years onwards) to allow a regression analysis directly linking short-term and long-term priming performance to the memory tasks.

Previous studies using patients with amnesia have highlighted the supporting role that the non-declarative memory system plays in structural priming. Both Ferreira and colleagues (2008) and Heyselaar and colleagues (2017) have illustrated a robust priming magnitude when testing amnesia patients on either double-object/prepositional-object or active/passive structural priming tasks. Therefore, it has been accepted that structural priming is supported by non-declarative memory. However, as structural priming itself is made up of both a short-term and a long-term component, models have been struggling to explain how one system could support both of these temporally distinct characteristics. We suggest these two different structural priming components are subserved by different non-declarative memory components, which has important implications for theoretical accounts of structural priming.

Our results suggesting that perceptual memory underlies the short-term component and conceptual memory underlies the long-term component of structural priming is most in line with the ACT-R model proposed by Reitter and colleagues (2011). They model priming as spreading activation, and assume that lexical forms persist in a working memory buffer in order to process their semantic contributions, e.g., for the duration of a sentential unit, until they are replaced by other lexical forms. Similarly, they propose that semantic information can persist even beyond the utterance. By virtue of being in a buffer, lexical forms and semantic information can then spread activation from the buffer to associated chunks in memory, such as syntactic categories. The more frequent the syntactic category is, the greater its prior probability. Non-declarative memory works in a similar fashion: Perceptual memory measures the residual activation of a previously processed item that persists, represented as the decreased reaction time when this item is processed a second time. With repeated exposures to this item, however, a link can be made to conceptual memory, if there are underlying links between the items (Poldrack et al., 1999). Therefore, repeated exposures to the same item(s) enhances this link, influencing its baseline-activation and hence the probability of it influencing an upcoming response, mostly measured as a decrease in processing latency of the item or construct (as in the serial reaction time task, for example). This type of model also supports structural priming effects seen in reaction times (Corley and Scheepers, 2002; Wheeldon and Smith, 2003; Segaert et al., 2011, 2014, 2016), an important and robust phenomenon usually not included in models of structural priming. Segaert and colleagues (2011, 2014, 2016) have proposed a two-stage competition model to explain the reaction time effects, the basis of which is very similar to Reitter and colleagues (and our) proposal of a base-level residual activation that spreads and is updated depending on repeated exposures. Of course, Reitter and colleagues propose explicit memory influences in their baseline-activation, whereas we propose the whole system be fully based in non-declarative memory.

The observed influences of age on syntactic priming can also be explained with the same non-declarative mechanisms as those we described above. There are two aging theories that speak to the tasks we used in this study, the processing-speed theory (Salthouse, 1996b) and the transmission deficit hypothesis (Mackay and Burke, 1990). The processing-speed theory (also referred to as general slowing), proposes that information from different sources may become available to a central processor so slowly that the earlier information has decayed or is no longer active by the time the later information arrives. In terms of syntactic priming, this could suggest that the residual activation of a structure is not available long enough to influence updating the statistical knowledge of that structure, and hence it's baseline-activation is never changed. Therefore, we would see the short-term priming effect, but a diminished long-term priming effect. The transmission-deficit hypothesis is very similar in this regard: The authors suggest that the encoding of new memories and retrieval of existing memories depends on the rate of transmission across the connections linking representational units in memory. They provide a priming related example in their text: "Priming is a form of sub threshold excitation that prepares a unit for activation or retrieval, and the rate of priming transmission depends on the strength of connections among units. Aging is postulated to weaken connection strength." Again, the weakening of connection strength also explains why we see robust short-term priming effects, but weak long-term priming effects for the oldest age groups.

In conclusion, our study supports our proposal that non-declarative memory underlies two distinct structural priming effects: Short-term and long-term priming. The perceptual component of the non-declarative memory system supports short-term priming effects, whereas the conceptual component supports long-term priming effects. Our study is the first to link age-related changes in structural priming. We therefore provide crucial new insights into the relationship between non-declarative memory and language production.

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