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# Structural Priming Is Supported by Different Components of Nondeclarative Memory: Evidence From Priming Across the Lifespan

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Structural priming is the tendency to repeat syntactic structure across sentences and can be divided into short-term (prime to immediately following target) and long-term (across an experimental session) components. This study investigates how nondeclarative memory could support both the transient, short-term and the persistent, long-term structural priming effects commonly seen in the literature. We propose that these characteristics are supported by different subcomponents of nondeclarative memory: Perceptual and conceptual nondeclarative memory respectively. Previous studies have suggested that these subcomponents age differently, with only conceptual memory showing age-related decline. By investigating how different components of structural priming vary across the life span, we aim to elucidate how nondeclarative memory supports 2 seemingly different components of structural priming. In 167 participants ranging between 20 and 85 years old, we find no change in short-term priming magnitude and performance on perceptual tasks, whereas both long-term priming and conceptual memory vary with age. We suggest therefore that the 2 seemingly different components of structural priming are supported by different components of nondeclarative memory. These findings have important implications for theoretical accounts of structural priming.

*Keywords:* structural priming, aging, nondeclarative memory, syntactic persistence



Structural priming refers to the facilitation of syntactic processing that occurs when a syntactic structure is repeated across consecutive sentences. This can occur for both language comprehension and production; the current article will focus solely on the latter. Structural priming in language production presents behaviorally as an increased tendency to reuse syntactic structures that have been produced either by the speaker or an interlocutor. Such structural persistence has been demonstrated experimentally for different syntactic structures (Bernolet, Collina, & Hartsuiker, 2016; Bock, 1986; Bock & Griffin, 2000), in different languages (Bock, 1986; Hartsuiker & Kolk, 1998; Sung, 2015), and using different priming modalities (Branigan, Pickering, & Cleland, 1999; Branigan, Pickering, Stewart, & McLean, 2000; Hartsuiker, Bernolet, Schoonbaert, Speybroeck, & Vanderelst, 2008). However, although structural priming is a well-established phenomenon, the mechanism underlying this effect is still under much debate (Pickering & Ferreira, 2008).

The debate is largely fueled by the need for models having to explain not only a single structural priming component, but two: A short-term priming effect and a long-term priming effect (Bock & Griffin, 2000; Chang, Dell, & Bock, 2006; Ferreira & 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 (although see below for exceptions). Earlier studies also reported 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 & Branigan, 1998). However, a recent study by Bernolet, Collina, and Hartsuiker (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). This short-term priming effect, without lexical overlap, is also commonly referred to as abstract priming. In this article, we will focus only on abstract priming

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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 nondeclarative memory is made up of (at least) two components (Gabrieli, 1998; Gupta & 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 RT tasks), whereas *perceptual memory* (also referred to as repetition priming) maintains residual activation of a recently processed stimulus. Short-term structural priming is proposed to work in a similar way: The residual activation of a previously processed syntactic structure that persists, represented as an increased chance in reusing that structure in the following utterance. 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 by perceptual memory. We propose that nondeclarative memory supports both temporal characteristics of structural priming, yet different components of this memory system underlie the different components of structural priming. To further 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, Craik, Sayer, Franchi, & Alexander, 1996). For nondeclarative 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 nondeclarative 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 (Bäckman, Almkvist, Nyberg, & Andersson, 2000; Squire et al., 1992), whereas conceptual memory is associated with a subcortical-cortical network in which the striatum is a central component (Lieberman, Chang, Chiao, Bookheimer, & Knowlton, 2004). There are studies showing age-related decline in the striatum (Bäckman, Nyberg, Lindenberger, Li, & Farde, 2006; Raz et al., 2003), which would affect conceptual but not perceptual memory. However, a review of behavioral studies looking at the aging effect of conceptual and/or perceptual studies draws equivocal conclusions. This is mainly due to different experimental designs: Most aging studies take a younger age group (on average 25 years) and compares it directly with an older age group, which can vary from early 60's (Howard, Heisey, & Shaw, 1986; Neger, Rietveld, & Janse, 2014; Schugens, Daum, Spindler, & Birbaumer, 2007) to late 80's (Davidson, Zacks, & Ferreira, 2003; Davis et al., 1990; Karlsson, Adolfsson, Börjesson, & Nilsson, 2003; Light, Kennison, & Healy, 2002; Light, LaVoie, Valencia-Laver, Owens, & Mead, 1992). Especially at the older age group, it is unclear at what point nondeclarative memory may start to decline, which may explain why some find a significant difference with the younger age group and others do not. To our knowledge, only one study (Maki, Zonderman, & Weingartner, 1999) tested participants from each decade from 20's until 80's in a perceptual memory task (fragmented object identification) and a conceptual memory task (category exemplar), and conclude that perceptual memory declines with age, whereas conceptual memory stays intact. This is in stark contrast to our hypothesis and the neuroimaging data described above, however, as it is one study in a field of methodologically inconsistent studies we propose to measure the perceptual and conceptual memory of our participants, in order to make a more direct link to their structural priming ability.

The aim of the current study is thus to test our hypothesis that nondeclarative memory supports both key temporal characteristics of structural persistence. In contrast to current models of structural priming (Chang et al., 2006; Jaeger & Snider, 2013; Pickering & Branigan, 1998), we propose that different subcomponents of nondeclarative memory underlie both short-term and long-term structural priming. Specifically, we propose that perceptual memory underlies short-term priming, while conceptual memory underlies long-term priming. In the current study we therefore tested structural priming in 167 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. Reviewing the structural priming literature does not lead to any clear conclusions on how priming ability changes with age: The studies that show intact priming in older adults (Ferreira et al., 2008; Hardy, Messenger, & Maylor, 2017; Hardy, Wheeldon, & Segaert, 2018; Hartsuiker et al., 2008) are in contrast with studies showing a decline in priming ability in older adults (Heyselaar, Segaert, et al., 2017). Additionally, these studies have focused on short-term priming, with little to no results indicating how long-term priming may change with age.

We also measured the participants' performance on well-established memory tests designed to measure conceptual and perceptual memory. The tasks included in our nondeclarative memory battery have been frequently used in the literature: A word-stem completion task (Light & Albertson, 1989; Light & Singh, 1987), a fragmented identification task (Au et al., 1995; Mitchell, 1989), and a serial RT task (Nissen & Bullemer, 1987). The serial RT 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 & Light, 1994) has suggested that the word-stem completion task is prone to declarative memory contamination.

In line with neuroimaging data, we predict that participants will show a decline in the conceptual task (serial RT 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

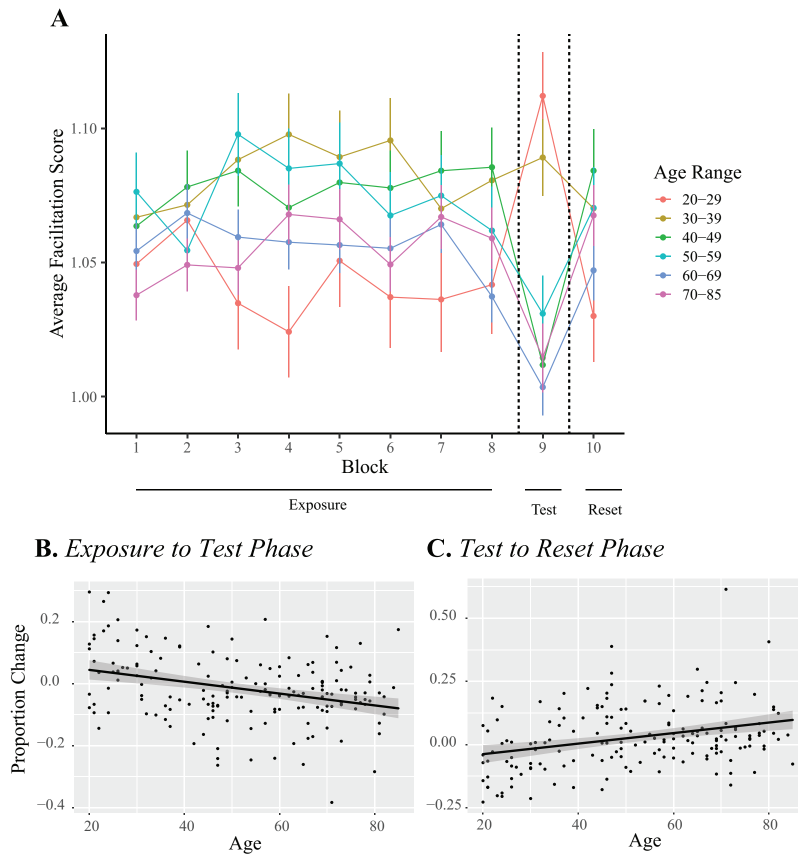


*Figure 5.* A. Average facilitation score for each block, averaged per decade for illustrative purposes. B. Percentage change in facilitation score for the exposure to test phase (when the underlying pattern was changed) and C. for the test to reset phase (when the underlying pattern was reestablished). Both plots illustrate how percent change diverges from zero as age increases, suggesting differences in conceptual memory as a function of age. See the online article for the color version of this figure.

to account for the new change in pattern. It is logical that the younger participants were able to pick up on this change, and learn this change, faster and hence showed an overall smaller change in their facilitation scores.

Overall, we show a significant effect of age on the performance in the SRT task.

## Structural Priming Task

We define short-term priming as the influence that processing a prime has on the syntactic choice of the immediately following target, and long-term priming as the influence all past produced syntax has on the syntactic choice of the current target. Long-term

Table 5
*Summary of the Best Linear Model for the Serial Reaction Time Task for Facilitation Score of the Exposure (Blocks 7–8), Test (Blocks 9–10), and Reset Phase (Blocks 11–12)*

| Variable | Coefficient | *SE* | *df* | *t* value | *p* value | Significance |
|---|---|---|---|---|---|---|
| Intercept | 1.05 | 0.02 | 8.16 | 44.38 | <.001 | *** |
| Exposure versus test (EvT) | −0.01 | 0.01 | 5030 | −0.94 | .350 | |
| Test versus reset (TvR) | −0.01 | 0.01 | 5969 | −1.27 | .205 | |
| Age | −0.01 | 0.00 | 631.9 | −4.01 | <.001 | *** |
| Working memory | 0.01 | 0.00 | 632.5 | 2.38 | .018 | * |
| EvT × Age | 0.00 | 0.00 | 1034 | 4.39 | <.001 | *** |
| TvR × Age | 0.00 | 0.00 | 1034 | 4.28 | <.001 | *** |
| EvT × WM | −0.01 | 0.00 | 1035 | −2.08 | .038 | * |
| TvR × WM | −0.00 | 0.00 | 1034 | −1.31 | .190 | |

*Note*. $N$ = 10,622.
* < .05. *** < .001.

priming was therefore 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 *long-term priming magnitude* therefore suggests that the proportion of passives previously produced positively influences the probability of producing a passive on the current target trial. Previous studies have also referred to this as *cumulative passive proportion* (Heyselaar et al., 2017; Jaeger & Snider, 2008). We did not calculate this for active primes as very few previous priming studies have shown a significant active priming effect, and hence we did not consider this variable to model learning.

Previous studies have shown a nonlinear correlation between the syntactic choice on the current target sentence and past produced syntax (Heyselaar et al., 2017; Heyselaar, Segaert, et al., 2017; Jaeger & Snider, 2008, 2013), we therefore decided to analyze the data using generalized additive mixed models (GAMM). Unlike ANOVAs or generalized mixed-effects regression (GLMER), GAMM does not assume linearity (although it can find a linear form if supported by the data). Instead, GAMM strikes a balance between model fit and the smoothness of the curve using either error-based or likelihood-based methods in order to avoid over- or underfitting. Thus, the data guide the functional form. The $p$ value provided therefore indicates whether or not the curve is significantly different from zero. Additionally, GAMM also allows the inclusion of random effects to capture the dependencies between repeated measures.

The full model contained the two-way interaction *prime* (treatment-coded, baseline trials as reference group) by *age* 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.

The best model included main effects of *prime, age,* and two-way interactions between *age* and *long-term priming magnitude* and *age* and *prime*. *Prime* was modeled as a linear predictor as the estimated degrees of freedom were 1. The remaining predictors were modeled with smoothers, using the default underlying base functions (thin plate regression for *prime* by *age* and cubic regression for *long-term priming* by *age*). We included per-participant and per-item random smooths. The function gam.check was used to ensure adequate k was used for each predictor.

Table 6 illustrates the results from the best model but including the *prime* by *age* interaction for illustrative purposes.

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 ($p < .001$). Following active primes, there was no increase in active responses compared with baseline ($p = .699$). This is the standard pattern of results reported in the literature (e.g., Bernolet et al., 2016; Bock, 1986; Ferreira & Bock, 2006). There was no interaction of *prime* with *age* ($p > .258$; Figure 6A) suggesting that the short-term priming effect does not vary as a function of age.

We do observe a significant interaction between *long-term priming magnitude* and *age*, suggesting that there is an effect of age on long-term priming (Figure 6B). The model and figure suggest that the interaction between *age* and *long-term priming magnitude* is not a simple quadratic correlation; however, the interaction is significant ($p < .001$) suggesting there is an effect of age on long-term priming. The figure suggests that after 40 years of age, there is an increase in the average long-term priming magnitude; which means that past use of a passive structure plays a stronger role in predicting whether the current utterance will use a passive structure. The figure suggests that after age 60, this effect disappears, although it is hard to conclude why this happens from our data.

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

## Interaction of Conceptual and Perceptual Memory on Syntactic Priming

As a final element to support our hypothesis that perceptual memory underlies short-term priming and that conceptual memory underlies long-term priming, we attempted to correlate the individual participant scores from each memory task with their short-term and long-term priming performance.

Table 6
*Summary of the Best Generalized Additive Mixed Effects Model for the Structural Priming Task*

| A. Parametric coefficients | | | | | |
|---|---|---|---|---|---|
| | Estimate | *SE* | *z* value | *p* value | Significance |
| Intercept | −4.55 | 0.18 | −25.39 | <.001 | *** |
| Active prime (AP) | −0.06 | 0.15 | −0.39 | .699 | |
| Passive prime (PP) | 0.47 | 0.14 | 3.31 | <.001 | *** |
| Age | 0.11 | 0.06 | 1.94 | .052 | |
| **B. Smooth terms** | | | | | |
| | edf | Ref. df | $\chi^2$ value | *p* value | |
| Smooth for age - baseline | 2.03 | 2.50 | 3.02 | .390 | |
| Smooth for age - AP | 0.00 | 0.00 | 0.00 | .994 | |
| Smooth for age - PP | 2.94 | 3.59 | 4.36 | .258 | |
| Smooth for age - LtPM | 10.89 | 12.4 | 452.90 | <.001 | *** |
| Random effect for participants | 31.81 | 152.00 | 50.19 | <.001 | * |
| Random effect for items | 32.62 | 56.00 | 88.70 | <.001 | *** |

*Note*. LtPM = long-term priming magnitude. $N = 8{,}587$.
* < .05. *** < .001.

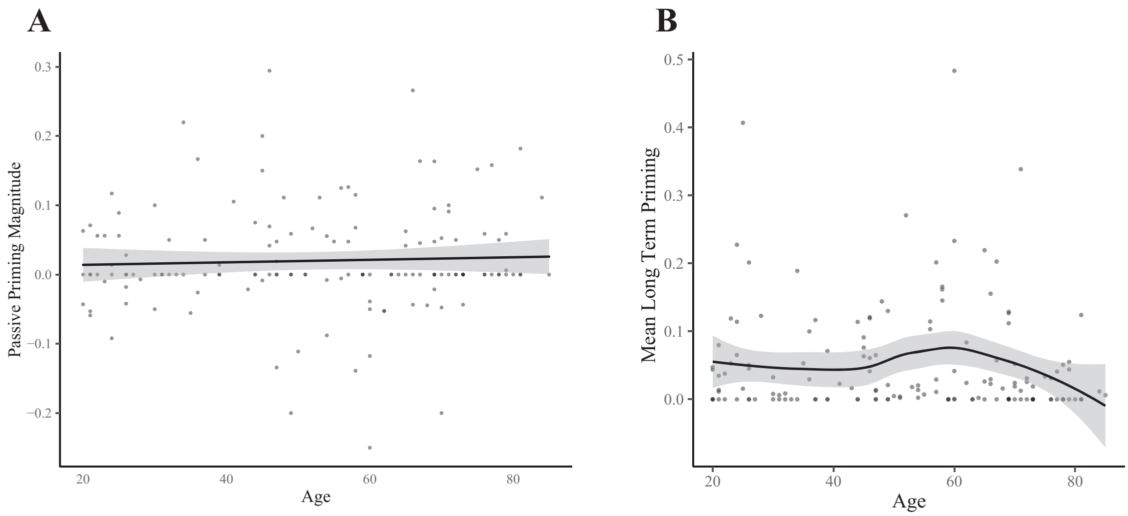


*Figure 6.* Performance in the structural priming task. A. Short-term priming. We observed no significant effect of age on short-term priming magnitude ($p > .105$). B. Long-term priming. We observe a nonlinear influence of age on long-term priming magnitude between 50 and 70 years. Error clouds/bars represent standard error.

In order to combine the scores, we conducted a principal components analysis (PCA) on the data sets used to model the word-stem completion (WSC), the fragmented identification, and the serial RT (SRT) tasks, respectively. For the WSC, we calculated the *difference* in RT between the primed and unprimed conditions, for the fragmented identification task, we calculated the *difference* in the number of pictures seen between the primed and unprimed conditions, and for the SRT, we calculated the *difference* in the facilitation score between the exposure and test phase, as well as the test and the reset phase. We ensured that all the data used was the same as the data entered into the model for each respective task. In total, our dataset included four variables: WSC difference, fragmented identification difference, exposure-test difference, and test-reset difference. As certain participants were removed in individual tasks due to outliers, we only included the data from 158 participants that had scores in all four variables.

A PCA was conducted on the four items with orthogonal rotation (varimax). Bartlett's test of sphericity, $\chi^2(158) = 211.36$, $p < .001$, indicated that correlations between the items were sufficiently large for PCA. Both the Kaiser rule (eigenvalues $>1.0$) and parallel analysis (a simulation procedure using randomly generated data to estimate the number of components), suggested a two-factor model. Table 7 reports the factor loadings for each of the two components, as well as the proportion of variance and Cronbach's alpha. Note that the Cronbach's alpha for the perceptual memory component is extremely low. However, extracting three components (and therefore separating WSC and the fragmented identification task) provided the same final conclusion and hence here we will report the results that match our hypothesis.

The factor scores were then added to the structural priming data set, which resulted in a dataset for 138 participants who had scores in all variables. We created a hypothesis-driven model, such that the model included a main effect for *prime,* the *conceptual* and *perceptual memory* components, as well as two-way interactions between *prime* and *perceptual memory*, and *long-term priming magnitude* and *conceptual memory. Prime* and its interaction was, again, modeled as a linear predictor, while *long-term priming* and its interaction were modeled as smooth terms. Table 8 reports the results of this model.

The model shows no significant interaction between short-term priming and perceptual memory ($p = .528$), suggesting that the participant's perceptual memory performance does not influence their likelihood of producing a passive target after having produced a passive prime. However, there is a significant interaction between long-term priming and conceptual memory ($p < .001$), suggesting that performance in the serial RT task is correlated to the participant's long-term priming magnitude.

## Discussion

In this study we aimed to test the proposal that both long-term and short-term structural priming are supported by nondeclarative memory. Specifically, we tested our hypothesis that long-term priming is supported by conceptual memory whereas short-term

Table 7
*Factor Loadings of the SRT, WSC, and Fragmented Identification Task Scores*

| Item | Varimax rotated factor loadings: Conceptual memory | Perceptual memory |
|---|---|---|
| TvR facilitation score diff. | **0.96** | |
| EvT facilitation score diff. | **0.95** | |
| WSC RT diff. | | **0.74** |
| FI pictures seen diff | | **0.69** |
| Eigenvalues | 1.88 | 1.03 |
| Proportion variance | 0.47 | 0.26 |
| α | .92 | .01 |

*Note*. No loadings were omitted ($N = 158$). EvT = exposure versus test phase (SRT task); TvR = test versus reset phase (SRT task). Values in bold represent loadings higher than |0.4| as they contribute the most to the meaning of a factor.

Table 8
*Summary of the Generalized Additive Mixed Effects Model for Relationship Between the Structural Priming Task and the Nondeclarative Memory Components*

| A. Parametric coefficients | | | | | |
|---|---|---|---|---|---|
| | Estimate | *SE* | *z* value | *p* value | Significance |
| Intercept | −4.38 | 0.18 | −24.45 | <.001 | *** |
| Active prime (AP) | −0.10 | 0.15 | −0.69 | .492 | |
| Passive prime (PP) | 0.34 | 0.14 | 2.40 | .016 | * |
| Perceptual memory (PM) | −0.03 | 0.13 | −0.21 | .833 | |
| Conceptual memory (CM) | 1.58 | 1.05 | 1.50 | .133 | |
| AP × PM | −0.03 | 0.15 | −0.22 | .825 | |
| PP × PM | 0.09 | 0.14 | 0.63 | .528 | |
| **B. Smooth terms** | | | | | |
| | edf | Ref. df | $\chi^2$ value | *p* value | |
| Smooth for CM - LtPM | 7.52 | 7.86 | 414.49 | <.001 | *** |
| Random effect for participants | 33.86 | 138 | 58.73 | <.001 | *** |
| Random effect for items | 31.42 | 56 | 81.53 | <.001 | *** |

*Note*. LtPM = long-term priming magnitude. $N$ = 7,899.
* < .05. *** < .001.

priming is supported by perceptual memory—both subcomponents of the nondeclarative 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 nondeclarative 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 nondeclarative memory relates to performance in structural priming, in order to elucidate how nondeclarative memory supports two seemingly different components of structural priming.

Our tasks and their key findings are summarized in Table 9. The results of this study show that there is no age-related effect in either the perceptual memory tasks or the short-term structural priming magnitude. In contrast, our results do demonstrate an age-related effect on the performance in both the conceptual memory tasks and the long-term priming magnitude. This pattern of results is consistent with our hypothesis, which locates short-term structural priming in perceptual memory and long-term structural priming in conceptual memory. We elaborate on this below.

First, our study shows a clear difference in the age-related effects on performance in the two subcomponents of nondeclarative memory, with changes in performance in conceptual memory tasks but not in perceptual memory tasks. In the SRT task, we observed more pronounced changes in the facilitation score of the older participants compared to their younger peers. This change does not necessarily indicate that older participants have a better conceptual memory than younger participants, but that they are slower to adapt to new patterns. During the SRT task, they did not adapt their predictions even when it was clear there was a new underlying pattern, and hence the percent decrease from the exposure to test phase (3.59%, *SD* = 10.48%) is close to the percent increase from test to reset phase (6.39%, *SD* = 12.55%) as the older participants did not update their predictions.

Our results contribute substantially to the broader question of age-related changes in nondeclarative memory. As discussed in the Introduction, previous literature has provided equivocal conclusions whether either nondeclarative memory decreases with age. A major factor was that previous studies would directly compare younger participant groups with older groups, with the average age of the older participants varying from early 60s (Howard, Heisey, & Shaw, 1986; Neger et al., 2014; Schugens et al., 2007) to late 80s (Davidson, Zacks, & Ferreira, 2003; Davis et al., 1990; Karlsson et al., 2003; Light et al., 2002; Light, LaVoie, Valencia-Laver, Owens, & Mead, 1992). In our study, we therefore opted for a longitudinal design, and tested participants between 20–85 years. Our results show that there is a significant age-related decline, and that this already starts around 50 years of age. Additionally, we find an opposite trend to that found in Maki and colleagues (1999), one of the only empirical studies that do look at age as a continuous variable

Table 9
*Summary of Key Results for the Nondeclarative Memory Tasks*

| Task | Nondeclarative 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 | More pronounced changes in performance with increasing age |
| Structural priming | Short-term: Perceptual memory | No age effect |
| | Long-term: Conceptual memory | Increased long-term priming magnitude between 50–70 years |

in their study design. They observed a significant decrease in age for the perceptual memory task (fragmented object identification) and no change for their conceptual memory task (category exemplar). This could be due to difference in task design and execution (see La Voie & Light, 1994 for a discussion on this for the word-stem completion task), and therefore more empirical work is necessary to further standardize nondeclarative memory tasks and report their results on age-related decline.

Second, our findings demonstrate an age-related effect on performance 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 nondeclarative memory. In our data, the older participants were more likely to produce a passive on the current trial if they had produced passives previously. This again hints that these participants are less able to adapt to changes and instead are more likely to repeat what they have done in the past, similar to the SRT task. This interpretation is purely post hoc given the data but there are already numerous studies arguing for long term priming to be supported by implicit learning (Chang et al., 2006; Chang et al., 2012; Jaeger & Snider, 2013; Reitter et al., 2011, inter alia).

Finally, we used principal components analysis to support the existence of a link between the performance in the conceptual and perceptual memory tasks and short- and long-term priming magnitude. Our results showed a significant interaction between long-term priming and the conceptual memory component ($p < .001$), however, we observed no correlation between short-term priming and the perceptual memory component. One explanation is that there were problems in having the two perceptual memory components load onto the same factor (Cronbach's alpha = .01), even though both tests are commonly used to measure perceptual memory. Therefore, it could be that the factor did not capture perceptual memory as we intended, and as such the existence or lack of a correlation with the short-term memory (STM) magnitude should be interpreted with caution. However, the lack of an age-related effect in performance for the perceptual memory tasks as well as in the short-term priming magnitude does suggest that the underlying memory systems could be related. A replication is therefore necessary before any strong conclusions can be drawn about the link between perceptual memory and short-term syntactic priming.

Our study is one of the first to show a clear dissociation in how increasing age affects short-term and long-term priming, as even though the short-term priming magnitude is lower than other structural priming studies, we are still about to see a clear age effect for the long-term compared to the short-term priming magnitudes. Many developmental studies have shown that children show higher priming magnitude and a higher tendency to prime compared with adult studies (Branigan & Messenger, 2016; Kidd, 2012), and thus priming ability already declines from 3 to 4 years old to the student population. We have provided insight into how this decline continues as we age.

Our study is an important first step toward providing evidence of a connection between nondeclarative 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. In our study we focused on abstract priming in transitives; in order to establish our proposed nondeclarative memory account, the findings reported here should be replicated with other syntactic structures (i.e., datives), as well as lexical overlap reintroduced into the paradigm to determine what role it plays in supporting structural priming ability as we age. Additionally, as older adults are known to recruit additional brain areas to compensate for lost efficiency elsewhere (Reuter-Lorenz & Park, 2014; Wingfield, Peelle, & Grossman, 2003), neuroimaging studies will shed additional light on if/how the brain networks underlying structural priming differ as we get older.

Previous studies using patients with amnesia have highlighted the supporting role that the nondeclarative memory system plays in structural priming. Both Ferreira, Bock, Wilson, and Cohen (2008) and Heyselaar, Segaert, et al. (2017) have demonstrated 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 nondeclarative 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 nondeclarative memory components, which has important implications for theoretical accounts of structural priming.

Our results suggest that perceptual memory underlies the short-term component and that conceptual memory underlies the long-term component of structural priming. This is supported by a combination of different existing structural priming models: We propose a residual activation account, based in nondeclarative memory (similar to that proposed by Malhotra, 2009; Pickering & Branigan, 1998; Reitter et al., 2011), for short-term priming and a nondeclarative learning account (similar to that proposed by Chang et al., 2006; Jaeger & Snider, 2013) for long-term priming. The information transfer between these components is based on the information transfer proposed above in the Reitter model. They model priming as spreading activation, and assume that lexical forms persist in a working memory buffer in order to process their semantic contributions, for example, 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. Nondeclarative memory works in a similar fashion: Perceptual memory measures the residual activation of a previously processed item that persists, represented as the decreased RT 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, Selco, Field, & Cohen, 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 RT task, e.g.). This type of model also supports structural priming effects seen in RTs (Corley & Scheepers, 2002; Segaert, Weber, Cladder-Micus, & Hagoort, 2014; Segaert et al., 2016; Segaert et al., 2011; Wheeldon & Smith, 2003), an important and robust phenomenon usually not included in models of structural priming. Segaert et al. (2011, 2014, 2016) have proposed a two-stage competition model to explain the RT effects, the basis of which is very similar to Reitter and colleagues (2011) (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 nondeclarative memory.

The observed influences of age on structural priming can also be explained with the same nondeclarative 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, 1996) and the transmission deficit hypothesis (Mackay & 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 structural 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 its 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 (Burke & Mackay, 1997; p. 1852): "Priming is a form of subthreshold 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 nondeclarative memory underlies two distinct structural priming effects: short-term and long-term priming. The perceptual component of the nondeclarative memory system supports short-term priming effects, whereas the conceptual component supports long-term priming effects. In this study, we focused solely on abstract priming (no lexical overlap between prime and target trials); it remains to be investigated how these mechanisms may change with lexical overlap. Our study is also the first to show divergent effects of age on the two components of structural priming, an important characteristic that needs to be included in models of structural priming. It therefore provides important new insights into the relationship between nondeclarative memory and language production and, in addition, new insights into how both memory and language are affected by age.

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