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Structural Priming Persists for (at Least) One Month in Young Adults, but Not in Healthy Older Adults

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Implicit learning theories suggest that we update syntactic knowledge based on prior experience (e.g., Chang et al., 2006). To determine the limits of the extent to which implicit learning can influence syntactic processing, we investigated whether structural priming effects persist up to 1 month postexposure, and whether they persist less long in healthy older (compared to younger) adults. We conducted a longitudinal experiment with three sessions: Session A, Session B (1 week after A), and Session C (4 weeks after B). For young adults, we found passive priming effects to persist and accumulate across sessions (1 week and 4 weeks). However, for older adults the effects persisted for 1 week but not 4. This suggests that for young adults, who unlike older adults experience no age-related decline in implicit memory, the limit to the duration of structural priming persistence is longer than 4 weeks. In a second longitudinal experiment with two sessions 1 week apart we found that priming in Session A affected syntactic processing in a different, independent task in Session B, both for young and older adults. Experiment 2 suggests that implicit persistence of the learned syntax is not limited to a specific context or task. Together, our findings give insight into how structural priming can contribute to language change throughout the life span, showing that implicit learning is a pervasive and robust mechanism that contributes to syntactic processing.

Keywords: long-term structural priming, cumulative structural priming, implicit learning, healthy ageing, cognitive decline

Supplemental materials: https://doi.org/10.1037/xlm0001123.supp

Structural priming refers to the tendency of language users to repeat syntactic structures across utterances. This phenomenon has been observed for different syntactic structures (Bernolet et al., 2016; Bock, 1986; Bock & Griffin, 2000), in different languages (Bock, 1986; Hartsuiker & Kolk, 1998; Sung, 2015), and using different priming modalities (Branigan et al., 1999, 2000; Hartsuiker et al., 2008). The continued investigation into structural priming is fueled by two main theoretical concerns: First, the presence (or absence) of priming can be revealing with respect to the nature of the representations that underlie language use (Pickering & Ferreira, 2008). Structural priming behavior has therefore been a major contributor to suggestions that language comprehension and production may trade on the same (or similar) processing mechanisms (Bock et al., 2007; Segaert et al., 2012). Second, it has been proposed that structural priming may play a role in language acquisition and language change (Chang, 2008). The repetition of recently heard or produced syntactic structures may serve to strengthen representations of a given structure, aiding in the language acquisition process (Tomasello, 2006), and may also alter the long-term probability of using a given syntactic structure, thereby contributing to language change (e.g., Chang, 2008; Dell & Chang, 2013). Understanding the extent to which structural priming can explain observations from language acquisition and language change depends on how priming effects persist over time and over different contexts.

In the present study we investigate: (a) Whether structural priming effects persist for 1 week and/or 4 weeks, (b) if the persistence effect is similar for young and older, healthy adults. Recent studies have shown a disconnect in the structural priming effects between these two age groups (Heyselaar et al., 2017, 2021), which we will further elaborate on below. Additionally, we will investigate whether (c) the effects found in Aims 1 and 2 are task-specific, or whether structural priming affects syntactic processing in a different, independent context and task, and (d) if priming effects transfer across contexts similarly for young and older, healthy adults.

Our language use is adaptive and driven by past experience. As language users, we develop processing preferences, which are continuously adapting. This phenomenon can be observed in our

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language use in multiple ways. First, the probability of producing primed structures increases throughout the length of an experimental session, which we will refer to as the *cumulative priming effect*. The cumulative priming effect shows development of the structure preferences on a trial-by-trial basis within a single experimental session, providing information about the rate of learning over time (Hartsuiker & Westenberg, 2000; Jaeger & Snider, 2013). This is in contrast to the consecutive, *short-term priming effect*, which is traditionally calculated by looking at the probability of producing the primed structure in the immediately following target sentence. Second, changes in the probability of producing primed structures can be observed between experimental sessions separated by a time interval, which is referred to in this article as the *long-term priming effect*. Further investigations into the cumulative priming effect and into long-term priming effects are of interest for the following reason: If studies of structural priming are going to be informative with respect to language acquisition and language change, it is necessary to observe how structural priming persists over a broader temporal timeframe and broader scope of language use than the relationship between the individual prime and target sentences (i.e., short-term priming).

Cumulative and long-term priming effects are demonstrated to rely on implicit learning mechanisms (Chang et al., 2006; Hartsuiker et al., 2008; Jaeger & Snider, 2013; Kutta et al., 2017), as 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 of structural priming differ in the mechanisms they propose to explain this implicit learning; however, they all propose some type of learning account where participants update their structural preferences based on both prior and recent experience (Chang et al., 2006; Jaeger & Snider, 2013; Reitter et al., 2011). These "updates" are never completely lost, even with intervening time or stimuli (e.g., Bock & Griffin, 2000; Branigan et al., 1999, 2000; Hartsuiker et al., 2008; Kaschak, 2007; Kaschak, Kutta, & Jones, 2011; Reitter, 2008), allowing a build-up over time with repeated exposures. The time course of the structural priming effect for long-term priming could therefore be hypothesized to behave in two different ways. First, if a single 30-minute experimental session is influential enough to show changes in structural preferences, then these changes due to learning may not be very robust and therefore could be overwritten as soon as the participant steps out of the lab. In contrast, if structural priming is indeed an important component of the language acquisition process (Tomasello, 2006), then any changes in structural preferences should survive beyond the experimental session.

The majority of work, thus far, looking into the time course of the long-term priming effect has been conducted by Kaschak and colleagues. In their studies, they conducted structural priming experiments by first introducing a bias toward one structure over another in a Bias phase, and then testing the participants' tendencies in a following priming phase. The results indicated that participants increased their use of the biased structure, even with a week intervening the bias and priming phases (Kaschak, 2007). Further experiments observed that this effect was not modality dependent: Whether the participants read sentences and described pictures aloud, or typed their answer into a computer, or conducted the priming phase in a different room compared to the Bias phase, they always showed a significant effect of the change in bias, even with a week between the phases (Kaschak, 2007; Kaschak et al., 2014; Kaschak, Kutta, & Jones, 2011; Kutta & Kaschak, 2012). The only experiment challenging the robustness of these effects was when their Bias phase and Prime phase used different tasks (Kaschak et al., 2014): In the Bias phase, the participants had to type sentence completions, whereas in the priming phase they had to type picture descriptions (Experiments 3 and 4), or vice versa (Experiments 5 and 6). For all four experiments, they saw a significant transfer across tasks if the Bias and Prime phase were completely immediately after each other. However, if there was a week in between, the effect disappeared. The authors explain this result as highlighting the importance of the encoding–retrieval match for optimal memory performance. For accurate memory retrieval, the circumstances surrounding the retrieval process must match (to some extent) to the circumstances in which the memory was initially encoded. The need for this is heightened when a delay intervenes between encoding (i.e., Bias phase) and retrieval (i.e., priming phase). The authors explain that, as the tasks were different, the participants didn't retrieve the bias they had learned in the Bias phase when conducting the priming phase. In the same study, participants also showed a weaker priming effect if the Bias phase was read aloud but the priming phase was typed, again suggesting a strong memory link underlying this priming behavior. Kaschak, Kutta, and Schatschneider (2011) draw parallels to having a conversation with a person—you will remember the conversational context, preferences, and so forth of your interlocutor so that when you have another conversation with them, those preferences come forward. However, these conversational preferences will not necessarily influence how you communicate with everyone, and hence these preferences may not carry over when conversing with a novel interlocutor. Speaking somewhat against this are the findings of Hwang and Shin (2019): They showed that cumulative priming is a processing mechanism that is not specific to one language, and therefore likely would transcend specific conversation partners. Chinese speakers integrated cumulative learning within Chinese into future syntactic choices made in Chinese as well as English.

In the current research article, we aim to take our search for the possible limits on implicit learning of syntax a step further. Kaschak, Kutta, and Schatschneider (2011) investigated whether structural preferences were affected by a change in bias occurring 1 week. In contrast, we investigate whether a change in bias between alternative structures can persist and affect syntactic production for longer than 1 week. When participants leave the experiment, their ongoing language experience will continue to shape their bias toward syntactic structures, potentially overwriting the bias established within the experiment (Chang et al., 2006). The longer the time interval, the more the participant's syntactic preferences will return to the bias as present in daily language use (and thus as measured in our baseline bias measurement at the start of the experiment). In Experiment 1, we include three sessions. In Session A, we measure the baseline bias of two alternative structures (actives [e.g., *The man hugs the woman*] vs. passives [e.g., *The woman is hugged by the man*]) and then change this bias in a priming phase. In Session B and Session C, we investigate, with a 1-week and a 4-week interval, whether the change in bias survives the time interval and affects syntactic production. By comparing the same-day, 1-week, and 4-week intervals, we can determine how robust these syntactic biases are, even after extended exposure to real-world biases. Furthermore, we will examine the rate of learning within each session as measured by the cumulative priming effect.

In addition to investigating whether a change in structural bias can persist for 1 week and 4 weeks in young adults (18–30 years), in Experiment 1 we also investigate how long a change in bias would persist in healthy older adults (60–85 years). There is a growing consensus that components of implicit memory declines in healthy aging (Bäckman et al., 2006; Maki et al., 1999; Neger et al., 2014; Raz et al., 2003; *inter alia*). Implicit memory has different subcomponents, that is, conceptual memory (also referred to as skill learning) and perceptual memory (also referred to as repetition priming) and evidence suggests that these systems could 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 et al., 2000; Squire et al., 1992), 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 ((Bäckman et al., 2006; Raz et al., 2003), which would affect conceptual but not perceptual memory. While the imaging literature thus strongly suggested that conceptual and perceptual memory are differentially affected by ageing, a review of behavioral studies looking draws equivocal conclusions. This is mainly due to different experimental designs: Most aging studies take a younger age group (on average 25 years) and compare it directly to an older age group, which can vary from early 60s (Howard et al., 1986; Neger et al., 2014; Schugens et al., 1997) to late 80s (Davidson et al., 2003; Davis et al., 1990; Karlsson et al., 2003; Light et al., 1992, 2002). Additionally, many studies do not take into account other cognitive aspects of ageing, such as reduced reaction time (RT), that influence the performance in implicit memory tasks. If these are accounted for, different results emerge (e.g., Light et al., 2002). A recent study compared standardized implicit memory tasks across the 20–85 age range and indeed saw significant age-related decline for conceptual, but not perceptual, memory tasks (Heyselaar et al., 2021). The conceptual memory component is the one that underlies implicit learning, and hence would be predicted to underly long-term and cumulative structural priming.

As such, if components of structural priming are indeed supported by conceptual implicit memory, one would expect a decrease in structural priming ability with increasing age. A recent study indeed showed a significant decrease in cumulative priming in healthy, older adults (>60 years), which correlated with their performance in standardized implicit learning tasks (Heyselaar et al., 2021). In this study, the older adult participants seemed less able to update their preferences, as illustrated in their performance in a Serial Reaction Time Task, which measured conceptual (that is, procedural) implicit memory. This was correlated to the performance in the cumulative priming ability, where adults over 60 years also seemed less able to let past passive prime exposure influence their probability of producing passives on the current trial. However, this study only looked at the cumulation of structural preferences within a single session (i.e., cumulative priming), and hence to what extent older participants will show a decline in the retention of these structural preferences across sessions (that is, long-term priming) is still unknown. Investigating this issue further is of high interest for the field of healthy cognitive ageing, but for the purpose of the present article we want to highlight that it is also highly informative about the implicit learning mechanisms driving syntactic processing and language change. If implicit learning ability (procedural memory) does indeed decrease with age and we are able to demonstrate a significant decrease in the ability for older adults (>60 years) to retain this implicit knowledge over increasingly longer periods of time between priming sessions, it follows that implicit learning could indeed be a major mechanism supporting syntactic production and language change (Chang, 2008; Dell & Chang, 2013; Tomasello, 2006). This, in turn, may partly explain observations that with increasing age, language users produce less syntactically complex sentences (Kemper, 1986).

In addition to establishing the possible limits of the implicit learning of syntax over time across the life span (Experiment 1), it is also important to examine whether implicit learning of syntax is robust across different contexts and tasks. Evidence to the contrary (Kaschak et al., 2014) is problematic for broad claims on implicit learning mechanisms driving these effects. In Experiment 2, we will use a different, independent task between the bias and priming phase. The tasks are furthermore completed in a different context: They are presented as different experiments, with different experimenters, and completed in different rooms. It is again an open question whether the effects will be comparable between age groups, and as such we will additionally include older, healthy adults in this second experiment.

Experiment 1

Method

All data and models are available on the Open Science Framework (osf.io/zdw76)

Participants

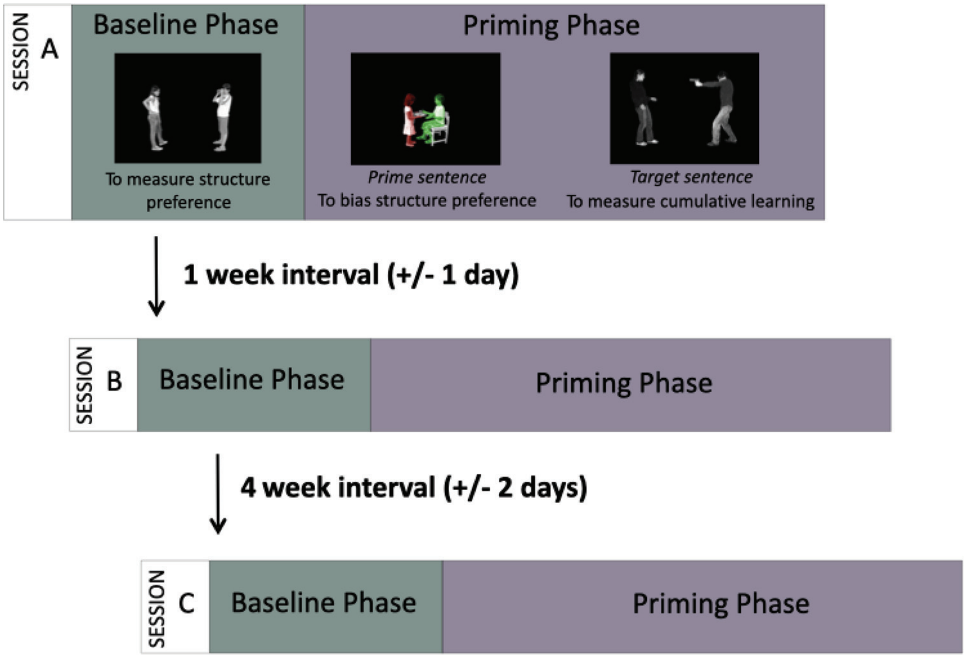
Twenty-nine young (M_{Age}: 19.4 years, SD_{Age}: .82; 2 Male) and 29 older adults (M_{Age}: 72.8 years, SD_{Age}: 5.37; 9 Male) were recruited from the Research Participation Scheme and the Patient and Life Span Cognition participant database of the School of Psychology at the University of Birmingham, U.K. Young adults received university credits for their participation; older adults were paid. All participants were required to have British English as their mother tongue. No participants reported having any neurological deficits, psychiatric disorders, dyslexia, or any other language disorders. Older adult participants completed the Montreal Cognitive Assessment (MoCA) test either prior to signing up, or before the experiment started. All older adult participants scored above 26 out of 30 (scores < 26 indicate risk of mild cognitive impairment or dementia; Smith et al., 2007). The study was approved by the research ethics board of the University of Birmingham (ERN_15-0866).

Study Design and Task

Figure 1 depicts an overview of the design of Experiment 1. All participants completed three test sessions, each consisting of a baseline phase followed by a priming phase. Session A and B were separated by 1 week (±1 day) and session B and C were separated by 4 weeks (±2 days).

Figure 1

Overview of the Design of Experiment 1, With Three Sessions Each Consisting of a Baseline Phase and a Priming Phase



Note. See the online article for the color version of this figure.

Baseline Phase Task. In the baseline phase, participants were asked to describe pictures. During each trial one picture was presented. Twenty pictures eliciting intransitive sentences were alternated with 20 pictures eliciting transitive sentences (actives or passives). The baseline trials therefore allowed us to measure the baseline preference of active versus passive structures. In Session A, the baseline structure preference was measured before any influence from the priming phase. In Session B and C, the structure preference was measured again to examine whether the priming phase of the previous session (1 week or 1 month earlier) had biased the structure preference, indicating long-term priming.

Priming Phase Task. In the priming phase, participants completed a priming experiment, similar to Segaert et al. (2011). Prime pictures were colored, followed by a target picture that was greyscale. Participants were instructed to describe pictures with one sentence, naming the green actor before the red actor if the actors were depicted in color. This allowed us to manipulate, for color-coded primes, whether the prime sentence produced had an active (for example, "the man kisses the woman") or a passive (for example, "the woman is kissed by the man") syntactic structure. For grayscale target pictures we then measured which structure (active or passive) participants chose to produce.

There were 38 passive prime trials (a passive picture followed by a transitive greyscale target) and 38 active prime trials (an active picture followed by a transitive greyscale target), all randomized in one experimental session. We also included 20 filler trials (an intransitive picture followed by an intransitive greyscale target). In total, therefore, we had 96 trials consisting of 152 transitive pictures and 40 intransitive pictures. No picture was repeated within participants across the three sessions.

In the priming phase, we measured whether the proportion of passives produced increases from the start to the end of the experimental session, indicating cumulative learning (i.e., cumulative priming).

Materials Baseline Phase and Priming Phase

The pictures were created by Menenti et al. (2011). The picture set depicts 40 transitive events such as *to chase, to interview* or *to serve* with a depiction of the agent and patient of this action. Each transitive picture has three versions: one grayscale version and two color-coded versions with a green and a red actor. Each transitive event is depicted by two pairs of adults and two pairs of children. One male and one female actor are shown in each picture, and each event is depicted with each of the two actors serving as the agent. To prevent participants forming strategies, the position of the agent (left or right) is randomized. Fillers elicit intransitive sentences, depicting events such as *running, singing,* or *bowing* with one actor (in grayscale or green).

Procedure and Trial Timing

The baseline phase and priming phase were presented as one continuous task in Experiment 1. The difference from the baseline phase to the priming phase was not obvious to the participants.

The timing of each trial (baseline and priming phase) was as follows: Participants were initially presented with the infinitive form of a verb (to be used in an upcoming utterance; e.g., "to run," "to chase," and so forth) for 500 ms. After 500 ms of black screen a colored 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 1,500–2,000 ms (jittered) before the next verb was presented. Colored and grayscale pictures were alternated until all pictures were described. No verbs were repeated within a trial. Each experimental session took a total of 45 minutes to complete.

The experiment was completed on a Dell Latitude E5470 Laptop (14" screen) using E-Prime (Schneider et al., 2002).

Data Analysis

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 (4.35% of the young adult data, 6.21% of the older adult data). Target responses were included in the analysis only if (a) both actors were named and the correct verb was used and (b) the structures used were active or passive. Detailed information can be found below on how we performed the analyses for each phase of the experiment. We used a binomial response variable to code *Target* (active [0] or passive [1]). We used a custom contrast to compare Session B to Session A, and Session C to Session B.

Results

Traditional Short-Term Priming Effects in Young and Older Adults

An initial omnibus analysis was done across the phases to determine whether there was a priming effect during the priming phase, for the purpose of comparison with traditional literature on structural priming. We compared passives produced after a passive prime with passives produced after an active prime in the priming phase. The data were analyzed with a mixed effects model, using the lme4 package (Version 1.1–23; Bates et al., 2011) in R (R Core Development Team, 2011). We attempted to use a maximal random-effects structure as described by Barr et al. (2013): The repeated measures nature of the data was modeled by including a per-participant and per-item random adjustment to the fixed intercept ("random intercept"). We attempted to include as many random adjustments to the fixed effects ("random slopes") as justified by the main effects of the model. The final model included a three-way interaction between prime type (active/passive), session (A/B/C), and group (older/younger). Prime type and sessio*n* were included as random slopes for the per-participant random intercept, and session and group were included as random slopes for the per-item random intercept. Session was custom coded, such that Session B was compared to Session A, and Session C was compared to Session B; group and prime type were sum contrast coded. Table S1 in the online supplemental materials reports the model output.

Participants showed a significant increase in the number of passives produced after a passive prime compared to after an active prime ($\beta = -.20$, $p < .001$; 8.6% difference), suggesting that indeed there was a standard short-term priming effect in the priming phase. The effect was not significantly different between groups ($\beta = -.02$, $p = .629$). There was a significant overall difference in the number of passives produced after a passive prime for Session C compared to Session B ($\beta = -.67$, $p = .005$) but no significant difference in Session B compared to Session A ($\beta = -.46$, $p = .084$).

The Baseline Phase Reveals Long-Term Priming 1-Month Postexposure for Young Adults and 1-Week Postexposure for Older Adults

The baseline phase was analyzed with mixed effects models, using the same procedure as that described above. The final model included the interaction Session by Group, with session and group as a random slope for both per-participant and per-item random intercepts. Table 1 reports the model output.

Table 1 suggests a significant difference in the number of passives produced in the baseline phase for Session C compared to Session B ($\beta = -2.14$, $p = .041$), as well as a difference between the two age groups for this comparison ($\beta = -2.72$, $p = .009$). The results from Table 1 therefore suggest no significant difference in passive production in the baseline phase for the same-day versus 1-week interval, only for the 4-week versus 1-week interval. This difference is most likely driven by the difference between the age groups.

Our original analysis plan did not include looking at per-group interactions, and hence did not design the experiment to have enough power to look at these interactions. Therefore, to ensure that the significant effects reported above are indeed valid, we conducted individual analyses per age group. We used the same procedure described above. For young adults, the final model included the main effect session, with session as a random slope for both per-participant and per-item random intercepts. For the older adults, including any random slopes resulted in a singular fit and thus the final model only included random intercepts in addition to the main effect of session. Table 2 reports the model output.

The percent of passive responses in the baseline phase (as illustrated in Figure 2) are numerically quite small, which is expected. In English (the language of the experiment), passives account for approximately 12% of transitive sentences (Cornelis, 1996). As illustrated in Figure 2, and supported by the statistical output reported in Table 2, there is a significant increase in passive production in the baseline phase for both young and older adults for Session B compared to Session A ($p = .002$; 1.5% increase for young adults; 3.7% increase for older adults). This is a result of the change in bias for active versus passive preferences established in the priming phase of Session A, which survived the 1-week interval (replicating Kaschak, Kutta, & Schatschneider, 2011).

Table 1

Summary of the Binomial Mixed Effects Model to Analyze Passive Production During the Baseline Phase

Coefficient	Estimate	*SE*	*z* value	*p* value
Intercept	−5.55	0.36	−15.51	<.001***
Session B vs Session A	0.11	0.79	0.14	.890
Session C vs Session B	−2.14	1.05	−2.05	.041*
Group	−0.16	0.35	−0.47	.637
Session B/A × Group	−0.46	0.77	−0.60	.548
Session C/B × Group	−2.72	1.04	−2.62	.009**

Note. $N = 4{,}690$; log-likelihood = −529.3.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 2

Summary of the Binomial Mixed Effects Model to Analyze the Passive Production During the Baseline Phase

Coefficient	Estimate	*SE*	*z* value	*p* value
A. Young adults				
Intercept	−6.56	0.51	−12.77	<.001***
Session B vs Session A	5.43	1.73	3.14	.002**
Session C vs Session B	3.30	0.90	3.69	<.001***
B. Older adults				
Intercept	−4.19	0.39	−10.61	<.001***
Session B vs Session A	1.11	0.37	3.04	.002**
Session C vs Session B	−0.10	0.33	−0.28	.776

Note. N = 2,493; log-likelihood = −231.8; N = 2,626; log-likelihood = −312.3.
** $p < .01$. *** $p < .001$.

Interestingly, only the young adults showed a significant increase in passive production in Session C compared to Session B ($p < .001$; .6% increase), whereas the older adults did not (p = .776; 2.5% decrease). Looking at Figure 2, it appears as if the older adults have reverted back to their initial passive preference as measured in Session A. Indeed, a posthoc comparison between Sessions A and C revealed no significant differences (B = −.26, p = .106).

The Priming Phase Reveals Cumulative Learning for Young Adults and Older Adults

In the priming phase, we examined the trial-by-trial development of the syntactic preference for active versus passive structures. To accurately capture the probability of producing a passive structure on the current trial, we calculated the *Cumulative Passive Proportion.* This variable was calculated as the proportion of passives produced on the target trials that occurred before the current trial number, as suggested by Jaeger and Snider (2013).

For the analysis, we used a generalized additive mixed model (GAMM), using the mgcv package (Version 1.8–22; Wood, 2017) as previous experiments have shown that cumulative priming mirrors a growth curve more than a linear correlation over the length of the experimental session (Heyselaar et al., 2015, 2021; Segaert et al., 2016). 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 (Hastie & Tibshirani, 1990). The p-value provided therefore indicates whether or not the growth of the curve is significantly different from zero (i.e., no growth). Additionally, GAMM also allows the inclusion of random effects to capture the dependencies between repeated measures.

We, again, initially included a by-group interaction. The final model included a Session by Group interaction, trial number (modeled with a smoother), and the interaction between trial number and session (modeled with a smoother). The smoothers used were the default underlying base functions, specifically thin plate regressions. We included per-participant and per-item random smooths, with trial number as a random slope for both. Table 3 shows the model output.

The parametric coefficient portion of Table 3 illustrates the difference in intercept points between the sessions. The significant differences between the sessions suggest that each session had an overall higher proportion of passive utterances compared to the session before. that is, Session B had an overall higher proportion of passive utterances than Session A ($p < .001$), and Session C had an overall higher proportion of passive utterances than Session B ($p < .001$). This suggests that there is long-term priming from Session A to Session B 1 week later, and Session B to Session C 4 weeks later (in line with findings from the baseline phase). The model suggests that there is a difference in the overall proportion of passives produced in Session C compared to B for the two age groups ($p < .001$), this again mirrors the results from the baseline phase.

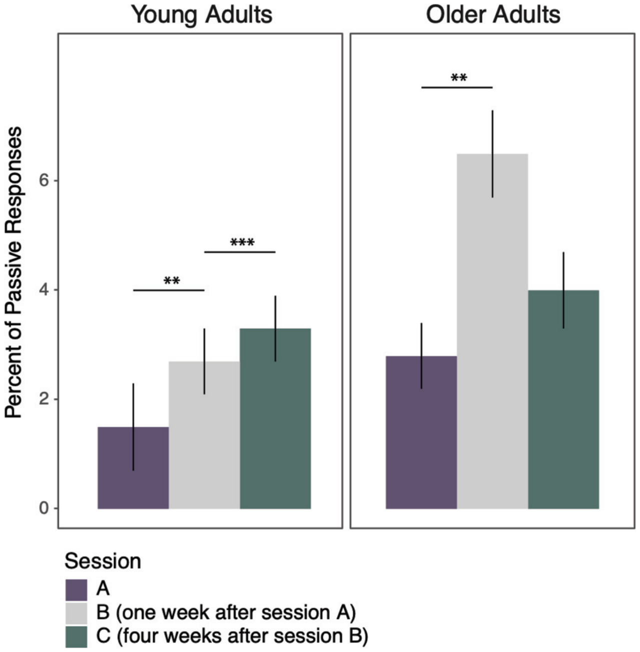
The Smooth Terms portion of Table 3 shows the change in bias for active versus passive preference on a trial-by-trial basis. The significant interaction between trial number and the difference in sessions suggests that the rate of change was significantly different between each consecutive session ($p < .001$ for Session B vs A, p = .002 for Session C vs B). Unfortunately, it is not possible to conduct three-way interactions in a GAMM model, and hence no per-group differences could be modeled. Below we will conduct these analyses per group.

Table 4 reports the model output.

Young Adults. The parametric coefficient portion of Table 4 illustrates the difference in intercept points between the sessions. As illustrated in Figure 3, this means that Session B overall had a

Figure 2

The Percent of Passive Responses in the Baseline Phase for the Older and Young Adults for All Three Sessions for Experiment 1



Note. Error bars represent standard error. ** $p < .01$. *** $p < .001$. See the online article for the color version of this figure.

Table 3

Summary of the Generalized Additive Mixed Effects Model to Analyze the Long-Term Priming Effect for the Priming Phase

Parametric coefficients	Estimate	*SE*	*t* value	*p* value
Intercept	0.05	0.01	5.43	<.001***
Session B vs Session A	0.02	0.00	12.40	<.001***
Session C vs Session B	0.01	0.00	5.45	<.001***
Group	0.01	0.01	1.23	.216
Group × Session B/A	−0.00	0.00	−1.88	.060
Group × Session C/B	−0.01	0.00	−8.20	<.001***
Smooth terms	*edf*	Ref. *df*	*F* value	*p* value
Trial number	1.00	1	18.30	<.001***
Trial by (Session B vs A)	1.00	1.18	29.22	<.001***
Trial by (Session C vs B)	1.00	1	9.73	.002**
Random smooth for participants	188.6	577	28.16	<.001***
Random smooth for items	0.00	1,325	0.00	.962

Note. $N = 11{,}836$. *edf* = effective degrees of freedom; Ref. *df* = reference degrees of freedom.
$^{**}p < .01$. $^{***}p < .001$.

higher proportion of passive utterances than Session A, and Session C overall had a higher proportion of passive utterances than Session B. This again suggests that there is long-term priming from Session A to Session B 1 week later, and Session B to Session C 4 weeks later (in line with findings from the baseline phase).

The Smooth Terms portion of Table 4 shows the change in bias for active versus passive preference on a trial-by-trial basis. The lack of a significant interaction between trial number and the difference in Session A and Session B for the young adults means that the rate of change was not significantly different between these two sessions. Therefore, for the young adults, they learned exactly the same way within Session A and within Session B ($p = .688$) (again, the only difference being that for Session B their baseline preference for passives was already significantly higher [$p < .001$]). This finding extended to the growth curve 4 weeks later, with no difference in the rate of learning within Session C and within Session B ($p = .625$; again, the baseline preference for passives is higher in Session C than Session B [$p < .001$]). Overall, the data shows that within each session, there is cumulative learning that changes the bias for active versus passive

Table 4

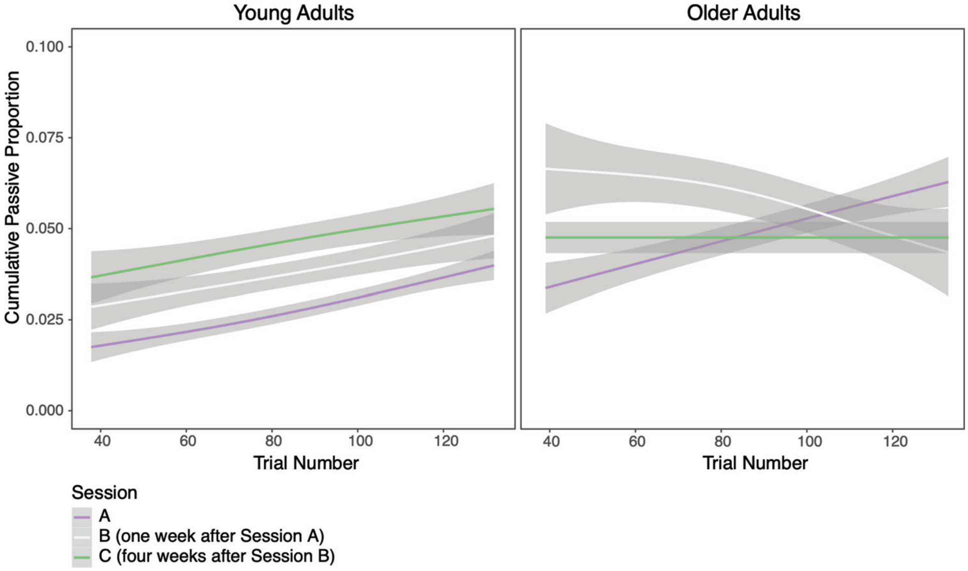
Summary of the General Additive Mixed Effects Model for the Priming Phase

Parametric coefficients	Estimate	*SE*	*t* value	*p* value
A. Young adults				
Intercept	0.04	0.01	4.12	<.001***
Session B vs Session A	0.02	0.01	12.14	<.001***
Session C vs Session B	0.02	0.01	11.62	<.001***
Smooth terms	*edf*	Ref. *df*	*F* value	*p* value
Trial number	1.00	1	16.15	<.001***
Trial by (Session B vs A)	1.00	1	0.16	.688
Trial by (Session C vs B)	1.00	1	0.24	.625
Random smooth for participants	52.38	288	27.95	<.001***
Random smooth for items	6.37	1,118	0.01	.301
B. Older adults				
Parametric coefficients	Estimate	*SE*	*t* value	*p* value
Intercept	0.06	0.01	4.01	<.001***
Session B vs Session A	0.01	0.01	6.42	<.001***
Session C vs Session B	−0.01	0.01	−1.73	.084
Smooth terms	*edf*	Ref. *df*	*F* value	*p* value
Trial number	1.00	1.00	3.51	.061
Trial by (Session B vs A)	2.38	2.96	19.19	<.001***
Trial by (Session C vs B)	1.00	1.00	12.13	<.001***
Random smooths for participants	134.37	288	28.07	<.001***
Random smooth for items	7.74	1,322	0.01	.268

Note. $N = 6{,}325$; $N = 5{,}511$. *edf* = effective degrees of freedom; Ref. *df* = reference degrees of freedom.
$^{***}p < .001$.

Figure 3

The Cumulative Passive Proportion Per Trial for Experiment 1



Note. Analysis starts at Trial 37 as previous trials belonged to the baseline phase/practice session. Error cloud represents standard error. See the online article for the color version of this figure.

structures. The change in bias for the young adults is robust, with a 1-week interval and even with a 4-week interval. The learning that happens within a session is built upon further in the next session. These data suggest that the passive bias may survive even longer than 4 weeks, as our data show no indication of a decrease in the rate of learning.

Older Adults. For the older adults, the data reveal a different story. There is a significant difference between Session B and Session A in terms of the starting point (intercept) of the proportion of passives produced, suggesting that there is long-term priming lasting 1 week (in line with findings from the baseline phase). However, the rate of learning is significantly different ($p < .001$) between sessions. As illustrated in Figure 3, during Session A, the rate of learning is positive, as expected. However, throughout Session B, the rate of learning seems to decrease toward the end of Session B. For Session C, there seems to be no change in the proportion of passives produced throughout the session. Additionally, the intercept for Session C starts lower than the intercept for Session B, which is contrary to the results seen for the young adults. Together, this suggests that for older adults there is cumulative learning in Session A, which is robust enough to last for 1 week. However, although the intercept for Session B starts significantly higher (as shown in the results for the baseline phase above), it seems that there is little learning in Session B. The reason for this difference is hard to determine from these results.

Running a model with a Session by Group interaction as parametric coefficients reveals a significant difference between groups for both the Session B vs Session A contrast ($p = .002$) and for the Session C vs Session B contrast ($p < .001$).

Intermediate Discussion Experiment 1

Both young and older adults show cumulative learning in the first session and robust long-term priming 1-week later as a result. However, when extending these results to include a 4-week interval, a disconnect starts to emerge between the age groups. For young adults, cumulative learning takes place in all sessions and builds further from one session to the next, with long-term priming effects lasting (at least) 1 month. The lack of a significant decrease in learning in these results suggest that the change in bias can survive for even longer than 4 weeks, for the young adults. For the older adults, however, we see a difference in the rate of learning in Session B compared to Session A, namely, fewer passives are produced throughout Session B instead of more, although the changed bias survives, as indicated by the higher baseline phase (as shown in Figure 2) and the higher intercept in the priming phase for Session B compared to Session A (as shown in Figure 3). In Session C, we see no significant evidence of our bias manipulation for older adults in either the baseline phase (see Figure 2) nor in the intercept for the priming phase (see Figure 3). Overall, the results of Experiment 1 thus replicate and extend the findings of Kaschak, Kutta, and Schatschneider (2011). The results also contribute to the debate on whether implicit learning declines with age: as predicted, we see a decrease in syntactic production for the older age group from Session B (1-week interval) to Session C (4-week interval) that is not replicated in the younger age group.

An alternative explanation for the findings in Experiment 1 is that participants remember the task from the previous session. As explicit memory decreases with age, it is therefore logical that the older adults may not have remembered enough to replicate their previous performance in subsequent sessions. This explanation would suggest that our results cannot speak to the underlying implicit learning mechanisms for syntactic priming. Therefore, in Experiment 2, we attempt to replicate our results but use different independent tasks and contexts for the baseline and priming phase. Any learning taking place in the priming phase which would affect the following baseline phase, would thus be implicit and independent of the context. Since only two sessions are required to answer this specific research question, in Experiment 2 we only included Session A and Session B (1-week interval).

Experiment 2

Method

This experiment was preregistered under https://doi.org/10.17605/OSF.IO/8VRJH.

Participants

Thirty-one young (M_{Age}: 19.1 years, SD_{Age}: .91; 7 Male) and 31 older (M_{Age}: 73.3 years, SD_{Age}: 6.52; 13 Male) adults were recruited from the Research Participation Scheme and the Patient and Life Span Cognition participant database of the School of Psychology at the University of Birmingham. Participant criteria and payment was the same as in Experiment 1.

Study Design

Figure 4 depicts an overview of the design of Experiment 2. All participants completed two test sessions (Session A and B) consisting of a baseline phase “Storytelling Task” followed by a priming phase “Picture Description Task.” Session A and B were separated by 1 week (+/−1 day).

Tasks and Cover Story

To ensure that participants did not suspect that the two tasks were related to each other, they were portrayed as separate experiments. As the data collection was part of an undergraduate student project, the cover story was that two student groups were both working on a research project with a task that required a week interval, and hence if the participant had signed up for both it would help with the logistics if they did the tasks back-to-back. This way, we ensured that the baseline phase (Storytelling Task) always occurred immediately before the priming phase (Picture Description Task). The two tasks were administered by different experimenters in different rooms, to emphasize the idea that they were not related. Before each task, participants signed informed consent and received task instructions.

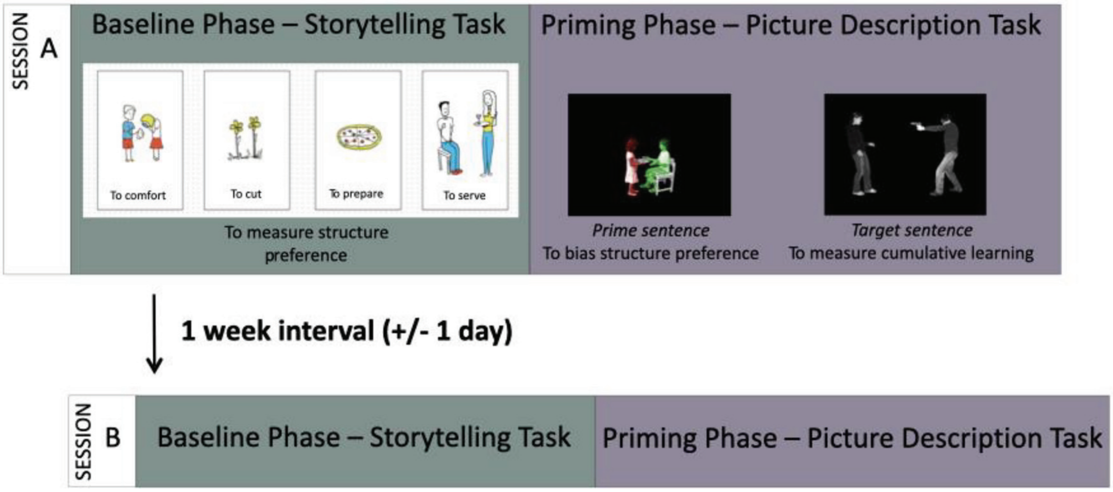
Baseline Phase–Storytelling Task. For the baseline phase, we created a storytelling task. Participants were presented with four cartoon cards on a screen with a white background (see Figure 4). Their task was to create a story linking the four cards together, using one sentence per card. The participants thus had to think of a link between the cards, generate a storyline, and decide on an order to describe the individual cards. If actors and/or objects were present, they had to name all of them. If a verb was present, they had to use this verb in their sentence. The aim of this task was to measure at least 20 transitive (active/passive) sentences (out of a total of 72 presented cards). For the example card series depicted in Figure 4, a possible story description could be: “A girl got hurt when cutting flowers; She was then comforted by a boy; A woman serves a man; She prepared a delicious surprise pizza.” From this example, we observe one passive structure and one active structure.

The storytelling task allows us to measure the baseline preference of active versus passive structures. In Session A, the baseline structure preference is measured before any influence from the priming phase. In Session B, the structure preference is measured again to examine whether the priming phase of the previous session (1 week earlier) has biased the structure preference, indicating long-term priming. Crucial in Experiment 2 is that the two tasks (baseline vs. priming phase) are unrelated.

Materials. The card deck for the storytelling task included 36 transitive pictures with actors of which 50% were adults and 50% were children. The location of the agent (left or right) and identity of the agent (man/woman/girl/boy) were counterbalanced across the deck. We also included 36 filler pictures, which consisted of an object with a verb written underneath. Some of these verbs

Figure 4

Overview of the Design of Experiment 2, With Two Sessions Each Consisting of Two Independent Tasks: 1) A Baseline Phase; i.e., Storytelling Task, and 2) A Priming Phase; i.e., Picture Description Task



Note. See the online article for the color version of this figure.

could be used to create an intransitive sentence, some could be used to make a dative sentence. Participants described 72 cards in total, divided across 18 trials.

Priming Phase–Picture Description Task. This task was identical to the task used in the priming phase of Experiment 1, using the same materials. In the priming phase, we measured whether the proportion of passives produced increases from the start to the end of the experimental session, indicating cumulative learning (i.e., cumulative priming).

Procedure and Trial Timing

The baseline phase (storytelling task) and priming phase (picture description task) were portrayed to participants as independent tasks and took place in a different environment (e.g., different testing lab, different experimenters). The experiments were presented using E-Prime (Schneider et al., 2002).

The card series with four cards in the storytelling task (baseline phase) remained on screen until the participant finished their story description and clicked to move on to the next screen. The storytelling task took between 10 and 20 minutes to complete, depending on how long the participant chose to take.

The timing of each trial in the picture description task (priming phase) was identical to Experiment 1. The picture description task took a total of 45 minutes to complete.

Data Analysis

Responses were manually coded by the experimenter as active, passive or other. For the baseline phase (i.e., storytelling task), the exclusion criterion was that participants had to produce at least 20 transitive sentences; no participants were discarded. In the baseline phase, for the young adults, 54.2% of the sentences were coded as active, .3% of the sentences were coded as passive, and 45.5% of the sentences were coded as other for Session A; this was 55.7%, 1.3%, and 43.0% respectively for Session B. For the older adults, 53.5% of the sentences were coded as active, 1.5% of the sentences were coded as passive, and 45.0% of the sentences were coded as other for Session A, this was 53.4%, 3.3%, and 43.3% respectively for Session B. Sentences coded as other were discarded. For the priming phase (picture description task), trials in which the descriptions did not match one of the coded structures were discarded (2.61% of the younger data, 2.87% of the older data). Target responses were included in the analysis if (a) both actors and the verb were named, and (b) the structures used were active or passive. Detailed information can be found below on how we performed the analyses for each phase of the experiment. We used a binomial response variable to code Target (active [0] or passive [1]).

Results

Traditional Short-Term Priming Effects in Young and Older Adults

An initial omnibus analysis was done across the phases to determine whether there was a traditional short-term priming effect during the priming phase. We compared passives produced after a passive prime with the passives produced after an active prime in the priming phase. The data were analyzed with a mixed effects model, using the same criteria as those described above. The final model included a three-way interaction between prime type (active/passive), session (A/B), and group (older/younger). Prime type and session were included as random slopes for the per-participant random intercept, and session and group were included as random slopes for the per-item random intercept. All factors were sum contrast coded. Table S2 in the online supplemental materials reports the model output.

We again see a significant priming effect in the priming phase: Participants showed a significant increase in the number of passives produced after a passive prime compared to after an active prime ($\beta = -.45$, $p < .001$; 12.1% difference), suggesting that the priming phase was successful in changing the structural preferences. Although both the young and older adults showed a significant increase, the effect was significantly more pronounced for the younger adults ($\beta = .53$, $p = .007$; 5.7% difference).

The Baseline Phase Reveals Long-Term Priming 1-Week Postexposure in an Independent Task and Context, for Young and Older Adults

The baseline phase was analyzed using mixed effects models, using the same procedure as that described above. The final model included the interaction Session by Group. As participants were given four cards at once, it was difficult afterward to determine which sentence belonged to which card, and hence we did not include a per-item random intercept. Table 5 reports the model output.

Table 5 shows a significant difference in passive production in the baseline phase for the same-day versus 1-week interval, replicating the results from experiment 1 ($\beta = -.63$, $p < .001$). The data suggest that this difference is not significantly different between the age groups ($\beta = .14$, $p = .251$).

Our original analysis plan did not include looking at per-group interactions, and hence did not design the experiment to have enough power to look at these interactions. Therefore, to ensure that the effects reported above are indeed valid, we conducted individual analyses per age group. We used the same procedure described above. Table 6 reports the model output.

As illustrated in Figure 5, and supported by the statistical output reported in Table 6, there is a significant increase in passive production in the baseline phase for Session B compared to Session A, for both young and older adults ($p < .001$; 1.7% increase for young adults; 2.9% increase for older adults). This is a result of the change in bias for active versus passive preferences established in the priming phase of Session A, which survived the 1-week interval. This replicates our results from Experiment 1, and

Table 5

Summary of the Binomial Mixed Effects Model to Analyze the Passive Production During the Baseline Phase

Coefficient	Estimate	*SE*	*z* value	*p* value
Intercept	−5.49	0.40	−13.67	<.001***
Session	−0.63	0.12	−5.03	<.001***
Group	0.68	0.33	2.09	.037*
Session × Group	0.14	0.12	1.15	.251

Note. $N = 4{,}982$; log-likelihood = −461.8.
* $p < .05$. *** $p < .001$.

Table 6

Summary of the Binomial Mixed Effects Model for the Baseline Phase

Coefficient	Estimate	*SE*	*z* value	*p* value
		A. Young adults		
Intercept	−6.14	0.68	−8.98	<.001***
Session B vs Session A	−0.77	0.22	−3.53	<.001***
		B. Older adults		
Intercept	−4.82	0.49	−9.87	<.001***
Session B vs Session A	−0.48	0.12	−4.00	<.001***

Note. $N = 2{,}488$; log-likelihood = −148.5; $N = 2{,}494$; log-likelihood = −313.2.
*** $p < .001$.

demonstrates that the long-term learning effect translates across tasks and experiment contexts.

Priming Phase Reveals Cumulative Learning for Young and Older Adults

We again conducted a trial-by-trial analysis of passive production using GAMMs. The final model was the same as that used in Experiment 1. We used a sum-contrast to compare Session B to Session A. Table 7 reports the model output with the group interaction, Table 8 reports the results per age group.

The parametric coefficient portion of Table 7 illustrates the difference in intercept points between the sessions. The significant difference between Session A and B ($p < .001$) suggests that Session B had an overall higher proportion of passive utterances compared to Session A. This suggests that there is long-term priming from Session A to Session B 1 week later (in line with findings from the baseline phase). The model suggests that there is a difference in the overall proportion of passives produced in Session B compared to A for the two age groups ($p < .001$), this again mirrors the results from the baseline phase.

The Smooth Terms portion of Table 7 shows the change in bias for active versus passive preference on a trial-by-trial basis. The significant interaction between trial number and the difference in sessions suggests that the rate of change was significantly different between each consecutive session ($p < .001$). Unfortunately, it is not possible to conduct three-way interactions in a GAMM model, and hence no per group differences could be modeled. Table 8 reports these analyses per group.

Although the exact trends over time are different for Experiment 2 compared to Experiment 1 (Figure 6 compared to Figure 3), we again see that the young adults have a higher intercept for Session B compared to Session A and also end higher, suggesting that they produced more passives per trial at the end of Session B compared to the end of Session A. For the older adults, in contrast to Experiment 1, there is no major difference in the rate of learning across the two sessions. The significant difference reported in Table 4 is driven by the initial 24 trials (Trial 1 to 24, analyzed via the plot_diff function), which shows a higher intercept for Session A compared to Session B. This suggests that for the older participants there was a similar rate of learning within each experimental session and that the learning persisted across sessions.

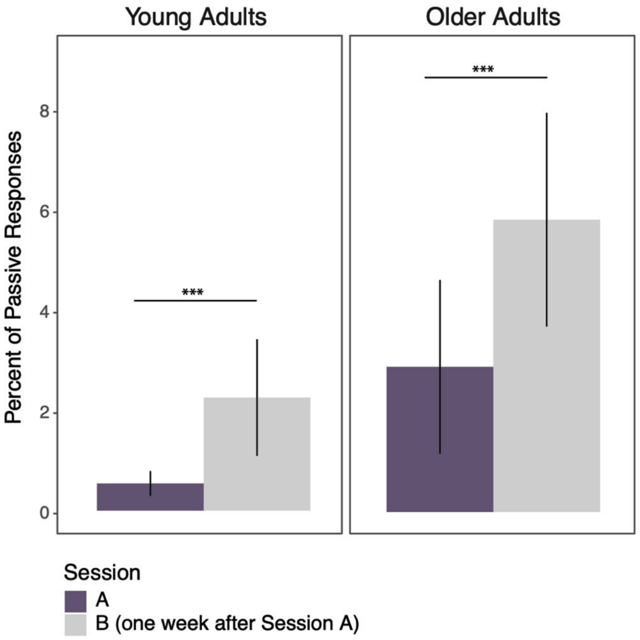
General Discussion

In two experiments we examined cumulative learning and long-term structural priming effects in young and older adults. The baseline structure preference was measured before structural preferences were biased in a priming phase. After a time interval of 1 week (Experiments 1 and 2) and 4 weeks (Experiment 1), we measured the structure preference again in a baseline phase to assess long-term priming. For Experiment 1 and 2, we also measured how the structural bias changed from the start to the end of each priming phase, to assess cumulative priming within each session. For young adults, we found that the priming phase of the previous session (both 1 week and 4 weeks earlier) had indeed changed the structural preference (as measured in the baseline phase) in a robust way, indicating long-term priming. Within the priming phase, priming was found to accumulate over time (in all sessions in Experiment 1, and in 1 out of 2 sessions in Experiment 2). For healthy older adults, priming was also found to accumulate over time (significant in 2 out of 3 sessions in Experiment 1, and in both sessions in Experiment 2). However, for the older adults, the learned changes in structure preferences were less robust over time, lasting for 1 week but not 4. Importantly, for both age groups, implicit learning was shown to not be limited to a specific context and task (Experiment 2). These findings were predicted by the implicit learning account of structural priming, and thus lend strong support to these theories.

There are numerous empirical studies showing robust structural priming is possible within a single experimental session. However, if structural priming plays a role in language acquisition and language change, as has been proposed (Chang, 2008; Dell & Chang, 2013; Tomasello, 2006), then these structural biases must be able

Figure 5

The Percent of Passive Responses in the Baseline Phase for the Old and Younger Adults in Experiment 2



Note. Error bars represent standard error. *** $p < .001$. See the online article for the color version of this figure.

Table 7

Summary of the Generalized Additive Mixed Effects Model to Analyze the Long-Term Priming Effect for the Priming Phase

Parametric coefficients	Estimate	*SE*	*t* value	*p* value
Intercept	0.06	0.01	10.44	<.001***
Session	−0.00	0.00	− 4.80	<.001***
Group	0.01	0.01	2.04	.042*
Group × Session	0.01	0.00	10.19	<.001***
Smooth terms	*edf*	Ref. *df*	*F* value	*p* value
Trial number	0.98	0.98	0.17	.68
Trial by Session	1.14	1.26	26.83	<.001***
Random smooth for participants	284.69	620	26.03	<.001***
Random smooth for items	98.80	1,118	0.15	<.001***

Note. *N* = 8,728. *edf* = effective degrees of freedom; Ref. *df* = reference degrees of freedom.
* $p < .05$. *** $p < .001$.

to survive over time, including between experimental lab sessions. When Kaschak, Kutta, and Schatschneider (2011) showed that structural preferences survived a 1-week interval, it indicated that the structural biases built up in short experiments are more robust than was previously assumed. Several other studies also showed long-term structural priming effects to be robust over time intervals up to 1 week (Kaschak et al., 2014; Kaschak, Kutta, & Jones, 2011; Kaschak, Kutta, & Schatschneider, 2011; Kutta & Kaschak, 2012). We pushed the limits of this and tested whether a learned change in structural bias could last for as long as 4 weeks. Indeed, we found (for young adults) that long-term priming is robust enough to last for (at least) 1 month.

Recent studies have suggested that healthy, older adults may show a significantly less robust structural priming effect, within single sessions (Heyselaar et al., 2017; but see Hardy et al., 2017), and have correlated this effect with a decline in implicit learning (Heyselaar et al., 2021). As the major theoretical models proposed to underlie the structural priming effect involve unconscious learning (Chang et al., 2012; Jaeger & Snider, 2013; Reitter et al., 2011), it was an open question whether healthy older adults would also show long-term priming. Indeed, we found a disconnect between the performance in long-term priming between sessions, as well as the accumulation of passive production within sessions, between the younger and older adults. As stated above, there was an increase in structural priming with a 1-week interval between sessions, but not 4. The theoretical models suggest that structural priming is based on error-based learning. That is, we make predictions about upcoming information (in this case, grammatical structure) and if the input we receive mismatches with our expectations, then the resulting error is used to adjust our expectations, with the aim of increasing the chances of a

Table 8

Summary of the General Additive Mixed Effects Model for the Priming Phase

A. Young adults

Parametric coefficients	Estimate	*SE*	*t* value	*p* value
Intercept	0.01	0.12	0.06	.949
Session B vs Session A	−0.13	0.01	−12.98	<.001***
Smooth terms	*edf*	Ref. *df*	*F* value	*p* value
Trial number	5.47	6.50	2.13	.038*
Trial by (Session B vs A)	4.93	5.96	4.00	<.001***
Random smooth for participants	127.03	308	20.02	<.001***
Random smooth for items	43.80	1,007	0.07	<.001***
N = 4,344				

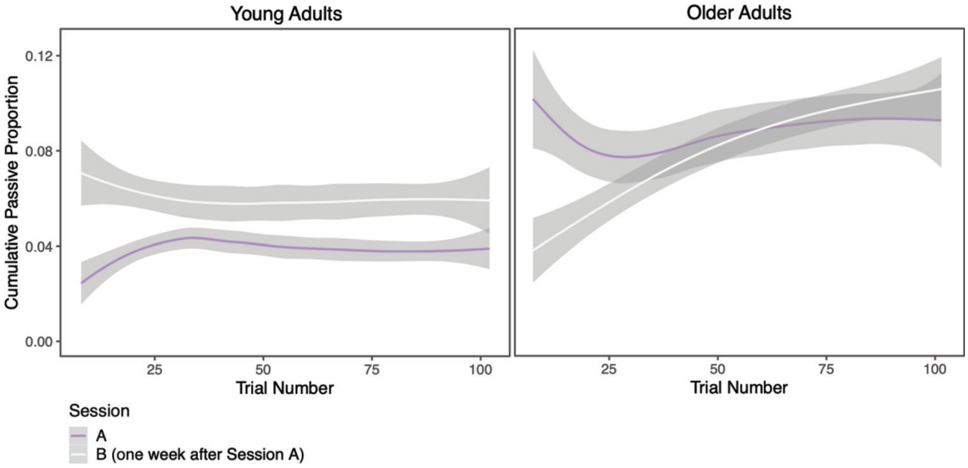
B. Older adults

Parametric coefficients	Estimate	*SE*	*t* value	*p* value
Intercept	−0.01	0.15	−0.06	.954
Session B vs Session A	0.03	0.01	3.36	<.001***
Smooth terms	*edf*	Ref. *df*	*F* value	*p* value
Trial number	8.82	8.93	3.90	<.001***
Trial by (Session B vs A)	7.14	8.16	12.17	<.001***
Random smooths for participants	143.32	308	29.56	<.001***
Random smooth for items	81.74	1,073	0.12	<.001***

Note. *N* = 4,384. *edf* = effective degrees of freedom; Ref. *df* = reference degrees of freedom.
* $p < .05$. *** $p < .001$.

Figure 6

The Cumulative Passive Proportion Per Trial for Experiment 2



Note. Error clouds represent standard error. See the online article for the color version of this figure.

successful prediction in future utterances. How is this linked to the participants producing more passive structures in our experiment? "A learner, given an entire history of linguistic input, can eventually 'join in' and start *saying* its prediction" (Dell & Chang, 2013; Hsu et al., 2013, p. 46). Linking this back to our results, one possible mechanism is that the older adults are faster at updating their preferences. This is reflected in their baseline passive preferences increasing more after a week delay (3.7% and 2.9% increase for Experiment 1 and 2, respectively), compared to young adults (1.2% and 1.7% increase respectively). Unfortunately, a statistical comparison between the two age groups revealed no significant differences. As stated in the Results section, our initial analysis plan did not include this comparison and hence we are not sure if a null effect could be due to lack of power. Future studies will have to replicate this effect before we can make strong claims.

If a statistical difference is supported, this could be due to bigger prediction errors produced, or that the prediction error itself has more impact in changing existing preferences. This also explains the faster decay rate: This sensitivity to updating your predictions carries on outside the lab, and hence the older participants are more prone to overriding their newly learned biases compared to the young adults. Indeed, there was no significant difference in the proportion of passives produced in Session A compared to Session C, suggesting that the structural preferences had returned to baseline sometime between 1 and 4 weeks after the priming phase. In contrast, no substantial decrease in passive preferences was observed for the younger age group, suggesting that participants between 18 and 30 years may maintain these new biases for much longer than 4 weeks.

There are other marked differences in task performance between the older and younger participants, namely that the older participants showed a higher passive preference in general compared to the younger adults. Additionally, the difference in the passive preference between Session A and B was higher for the older adults (3.7% increase) than the younger adults (1.2% increase). It could be that older adults are more vulnerable to being biased toward infrequent syntactic structures. A similar trend was found in the performance of older adults in a statistical learning task (serial RT task; Heyselaar et al., 2021), suggesting that this effect could be due to their declining implicit memory system and may not be language-specific. Patients with amnesia also show a more robust passive priming magnitude after a single session (Heyselaar et al., 2017). Additionally, the robust increase in the baseline phase in Experiment 2 did not completely carry over to the priming phase. This may be due to our methodological choices for Experiment 2: Between the baseline and priming phase the participants were returned to the waiting room, as they were led to believe that the two sessions were for unrelated experiments. We made this choice to control for any context-based learning (as discussed in our Interim Discussion). The drop in performance between the two phases suggests that older participants do rely on explicit learning in part when learning structural biases. This finding is not novel: It is known that when one memory system fails (such as implicit memory in the older population), other memory systems may be recruited to compensate (Poldrack & Packard, 2003; Ullman & Pullman, 2015).

We can therefore conclude that our findings are in line with our first two hypotheses: (a) We showed that structural priming effects persist for 1 week and/or 4 weeks, and that (b) this effect is longer lived for younger (4 weeks), compared to older (1 week), healthy adults. However, the question remains whether the effects found in Experiment 1 are task-specific or indeed a representation of the modality-independent implicit learning mechanism.

Previous research has indicated that there may be limits to the extent at which implicit learning drives syntactic production. In one study, Kutta and Kaschak (2012) used a different task, in a different room, for the baseline and the prime phase. Their argumentation was that if an explicit memory system is used, then the structural preferences may be retrieved once the participant returns to the same room and conducts the same task, therefore making the structural preferences task- and location-specific. Indeed, they found that if a 1-week interval separated different tasks in the baseline and prime phase, no significant structural priming was measured. In order to confidently conclude that implicit (as opposed to explicit) learning played a role in our findings, we also tested whether learning was limited by the experimental context and the task. In Experiment 2 we presented each phase as a separate experiment, conducted in a different room by different experimenters with seemingly different research goals. We additionally created new stimuli for the baseline phase and asked participants to do a different task: Participants were asked to tell a story based on the set of actions depicted on the screen. This yielded more variable and free language production than the highly prescriptive "green before red" task used in the priming phase. If the structural priming effects observed in Experiment 1 relied on implicit learning mechanisms, and priming indeed plays a role in language acquisition and change, then any learning should be abstract enough to be applied in a variety of contexts. For example, learning about verbs in a second-language class should not prevent you from applying these newly learned grammatical rules outside of the classroom, in a different task with different people. Indeed, for both age groups, in Experiment 2 we observed a significant increase in passive preference in the baseline phase in Session B (1 week later) compared to Session A. This increase in passive preference could only have occurred if the structural bias survived the 1-week interval between the priming phase of Session A and the baseline phase of Session B.

The performance between Experiment 1 and Experiment 2 are not completely identical. This could be due to using a different sample, or, possibly there are elements from our Experiment 1 that were task-specific. There was a difference in cumulative learning between the experiments (Figure 3 and Figure 6). However, the results showed that there is a significant increase in passive preference between Session A and B, and thus we can confidently conclude that the structural preferences built up in the bias phase affected participants' performance in the seemingly unrelated priming phase, and hence these structural preferences are task-independent and abstract.

Overall, our findings provide further evidence that the syntactic biases built up during structural priming experiments are robust enough to last for at least a week for young and older adults, and for at least 1 month for young adults. Furthermore, syntactic priming effects transcend across different experimental tasks and contexts, both for young and older adults. Together, our findings lend strong support to implicit learning being an important contributing mechanisms to structural priming. On a very practical level, our results highlight that structural priming researchers should take caution when recruiting their participants: Participants who have conducted a structural priming study in recent months may conduct a current experiment with altered structural bias, compared to other participants. Additionally, the differences between age groups adds another piece of information regarding the age-related differences in structural priming, an element that has yet to be worked into current models in more detail.

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