Rapid phonotactic constraint learning in ageing: Evidence from speech errors

Merel Muylle[1], Eleonore H. M. Smalle[1], Robert J. Hartsuiker[1]

[1]Department of Experimental Psychology, Ghent University, Ghent, Belgium

Author contributions

M.M. contributed to the conception, and operationalization of the study, as well as the acquisition, the analysis and interpretation of the data, preparation of the figures, and the writing of the manuscript. E.S. contributed to the analysis and interpretation of the data, and the writing of the manuscript. R.H. contributed to the conception of the study, the interpretation of the data, and the content/editing of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Correspondence Address

Merel Muylle
Ghent University, Department of Experimental Psychology
Henri Dunantlaan 2
B-9000 Gent
E-mail : merel_muylle@hotmail.com

Abstract

Older adults are able to implicitly pick up structural regularities in the environment despite declining cognitive abilities. Here, we investigated elderly's abilities to implicitly pick up novel linguistic constraints in speech production. Across four training days, young and healthy older Dutch-speaking adults were asked to rapidly recite Dutch phonotactic syllables. Two unrestricted consonants were experimentally constrained to onset or coda positions depending on the medial vowel. Analysis of speech errors revealed rapid adherence to the novel second-order constraints in both the younger and the older group. However, in the older group, there was weaker trial-specific learning compared to the younger group, potentially due to explicit memory deficits. Strikingly, the error pattern of the elderly mirrors earlier developmental work with children using the same paradigm. The findings are discussed in light of possible age-dependent differences in implicit and explicit cognitive subsystems underlying human skill learning.

Key words: ageing, implicit learning, phonotactic constraints, speech errors

Implicit learning refers to the unintended and unconscious process to pick up hidden regularities in the environment, and of which the resulting knowledge cannot easily be brought into words (Cleeremans & Jiménez, 2002). Such learning underlies the acquisition of, for instance, motor and language skills. It is often assumed that implicit learning skills – in contrast to other cognitive abilities such as working memory, attention, and cognitive control (e.g., Craik & Bialystok, 2006; Hedden & Gabrieli, 2004) – are relatively preserved in ageing (e.g., Reber, 1992; Verneau et al., 2014; see Howard & Howard, 2013, for a review) and may serve as a shield against age-related cognitive decline (Juhasz et al., 2019; Palmer et al., 2018). The current study aims to investigate whether preserved learning across age also extends to more complex skills that involve learning arbitrary dependencies implicitly, such as language.

Implicit learning across ageing has been widely investigated with the Alternating Serial Reaction Time task (ASRT; Howard & Howard, 1997), a well-known implicit sequence learning task underlying motor skill acquisition. In this task, participants respond to spatial cues on a screen with corresponding buttons. Unbeknownst to the participant, there is a repeating sequence of locations that is hidden in between alternating random (R) locations (e.g., 1R2R3R4R1R2R3R4 etc.). Learning of these repeating sequences is reflected in faster reaction times for the repeating locations than the random locations. In order to accomplish such learning, one has to detect the hidden probabilistic, second-order dependencies in the sequences. Most of the studies found that older adults were still able to pick up the hidden regularities, albeit to a weaker extent than younger adults (e.g., Bennett et al., 2007; Janacsek et al., 2012; Stillman et al., 2016). In addition, older adults benefited less from additional training and intervening sleep than younger ones, which indicates that the consolidation process in particular seems to be affected by ageing (Howard & Howard, 2013; Nemeth & Janacsek, 2011).

In contrast, some other studies found that older adults performed as well or even better than young adults on ASRT tasks (e.g., Brown et al., 2009; Juhasz et al., 2019; Verneau et al., 2014; see Campbell et al., 2012 for a similar finding in the domain of visual perception). For instance, Verneau and colleagues (2014) found that older adults performed as well as younger adults on the ASRT when no explicit information about underlying rules was given; and in contrast to the younger group, their performance did not benefit from such information. They concluded that everyday ageing-related difficulties regarding skills, if any, are due to weaker higher cognitive abilities that support explicit learning, and less to an impairment of pure implicit skill learning (see also Midford & Kirsner, 2005). This idea is in line with the developmental invariance model, which assumes that, whereas explicit learning is subject to age-related changes, implicit learning skills remain stable throughout life (Reber, 1993). In contrast, two other theories propose that specific components of implicit learning may be affected by ageing, particularly those involved in the learning of second-order regularities (such as in the ASRT task). This would be due to deficits in associative binding (i.e., the associative deficit hypothesis) or general slowing (i.e., the simultaneity theory). According to the associative deficit hypothesis (Harrison et al., 2006; Naveh-Benjamin, 2000), older adults are able to store specific items in their memory to a similar extent as younger adults (i.e., they have no problems with first order learning), but they show a deficit in creating associations between individual items and their context (i.e., they have problems with second-order learning). More specifically, they experience issues with recollecting context-specific representations (e.g., item A is followed by item B, but only in a certain context), which are important for learning higher-order dependencies across items. In contrast, the simultaneity theory (Salthouse, 1996) poses that due to general slowing in ageing, older adults have less information simultaneously activated because information from early processing stages is not available at later stages. This simultaneous activation of items may be important in implicit learning processes and especially for learning higher-order regularities (e.g., Frensch & Miner, 1994). Similar to the associative deficit hypothesis, this theory argues that the more information is needed to learn the regularities, the larger the impact of ageing. As a consequence, the theory predicts problems with learning second-order relations between items.

Finally, Howard and Howard (2013) formulated the striatal ageing hypothesis, which states that early learning of second-order regularities is unaffected by ageing, whereas consolidation is impoverished. This hypothesis is based on the finding that implicit learning involves at least two important brain regions: a) the medial temporal lobe (MTL, including the hippocampus), which is responsible for the fast acquisition of regularities in early phases of training, and b) the striatum, that guides slower learning processes and becomes more important in later phases of training. Howard and Howard (2013) postulated that the MTL is relatively spared in ageing, whereas deficits in the striatum are responsible for the weaker training and consolidation effects in older adults (see Nemeth & Janacsek, 2011). Because of this striatal deficit, older adults tend to rely more on the MTL system for implicit learning, resulting in fast learning of the regularities at the onset of learning, but no benefit from further training or consolidation (Dennis & Cabeza, 2011; Rieckmann et al., 2010). In line with this hypothesis, there is evidence for impaired implicit learning in neuro-degenerative disorders that involve the MTL and the striatum, such as Parkinson's disease (Siegert et al., 2006) and frontotemporal dementia (Weickert et al., 2013).

In sum, there is no consensus yet to what extent implicit learning abilities are affected by ageing. The current study aims to elucidate this matter by turning to the domain of language acquisition, which relies heavily on implicit learning processes (e.g., Frost et al., 2013; Hedenius et al., 2011; Morgan-Short et al., 2012).

In general, (second) language learning abilities seem to decrease linearly with age (Hakuta et al., 2003), also referred to as the sensitive age hypothesis, but the actual implicit learning processes involved in language acquisition have received only limited attention in ageing research. As far as we know, only very few studies directly investigated the relation between ageing and implicit language learning. Recent work using the structural priming paradigm (which is often assumed to measure the implicit acquisition of syntax, see Chang et al., 2006) reported comparable priming effects in young and older adults (Hardy et al., 2017, 2020). This finding suggests that the implicit acquisition of syntax is unaffected by ageing. In another study, Palmer and colleagues (2018) exposed young, middle-aged, and older adults to a typical statistical learning paradigm in which novel words can be segmented from a continuous stream of speech on the basis of transitional probabilities. Overall, they found that older adults performed equally well, and middle-aged adults even slightly better, than younger adults on the implicit learning task. However, the older adults performed worse under more cognitively challenging conditions, namely when the task was performed under cognitive load or when words had to be distinguished from part-words (that are harder to distinguish) rather than non-words. Palmer et al. suggested that age-related declines in language acquisition, if any, are likely due to a selective decline in higher cognitive abilities (particularly working memory updating; Palmer et al., 2018) rather than to a pure implicit learning impairment.

Another way to study implicit learning of linguistic constraints is by looking at speech errors in the context of the phonotactic constraint paradigm (Dell et al., 2000). The idea behind this experimental method is that speech slips reveal a speaker’s implicit knowledge about acceptable constraints in their acquired phonological system. Indeed, speech typically conforms to allowable sound sequences (i.e., phonotactic constraints) of the native spoken language (Fromkin, 1971). For instance, a native English speaker will seldom spontaneously slip the sound /ŋ/ to an onset position (as in *ngik*) when intending to say *king* because /ŋ/ never occurs at this position in English. Interestingly, the native phonological system can rapidly adapt to new constraints with repeated exposure, similar to second-language learning (Dell et al., 2000), and this is reflected in the speaker's unintended speech slips.

In the phonotactic constraint paradigm, participants rapidly recite spoken and/or written sequences of consonant-vowel-consonant (CVC) syllables (e.g., *hes fen meg keng*). A subset of the consonants is constrained to a syllable's onset or coda position. While some of these constraints are conform the participant's native language, also referred to as language-wide constraints (LWC, e.g., for English: /ŋ/ always occurs at coda position), other constraints only occur within the setting of the experiment, so-called experiment-wide constraints (EWC, e.g., in the experiment, /f/ is always onset, but never coda; while in English this consonant occurs at both positions). These constraints can be of first order (e.g., /f/ is always onset), or of second order (e.g., /f/ is onset when the vowel is /a/, but coda when the vowel is /i/). Other consonants remain unrestricted during the experiment (UR, e.g., in English /m/ can occur at both onset and coda). Due to the rapid recital (typically in time with a metronome), participants unintendedly slip consonants to other onset or coda positions within the sequence. If learning occurs, these slips should adhere to the underlying constraint.

Dell and colleagues (see Anderson & Dell, 2018, for a meta-analysis) widely observed that speech slips concerning LWC consonants (e.g., /ŋ/) never violated the underlying constraint (i.e., these consonants never moved to an opposite syllable-position). In contrast, UR consonants moved to the opposite position in about 32% of the slips. Note that same-position slips are between 25%-40% more frequent than would be predicted by chance. Thus, even though a consonant such as /f/ can be both onset and coda across the experiment, /f/ is more likely to slip to the same syllable position rather than to another position within the sequence. This is referred to as the syllable-position effect (Dell et al., 2000; Fromkin, 1971; Warker et al., 2008). Anderson and Dell (2018) argued that this effect might reflect a short-term version of trial-specific first-order learning (e.g., /f/ is an onset *right now*, also referred to as *local-positional* constraints in the literature, see Anderson & Dell, 2018) and provides a baseline against which long-term, incremental learning of the second-order EWC consonants can be assessed. In other words, if EWC consonants slip more often to the same position than UR consonants, this indicates long-term learning of the EWC above what can be explained by a syllable-position effect. Importantly, whereas EWC consonants may initially slip to the same position as much as the UR consonants, Dell and colleagues observed that this probability changed and exceeded that of the UR condition with only limited exposure (i.e., from a first day of training for first-order EWC, from a second day of training for second-order EWC: Anderson & Dell, 2018; Warker & Dell, 2006). This indicates that the participants rapidly adapt to novel sound-combination rules within their native phonological system. Informing participants about the constraints does not have a substantial impact on learning (Dell et al., 2000; Warker & Dell, 2006), indicating that implicit rather than explicit-memory processes are driving the effect.

Phonotactic learning has been widely demonstrated with young adults and children (see Anderson & Dell, 2018; Smalle, Muylle, et al., 2017), but, as far as we know, not with older adults. Yet, with advancing age, such skills remain essential to foreign language learning and educational training or rehabilitation programs (e.g., after stroke or in neuro-degenerative disorders). For instance, rehabilitation programs for people with Alzheimer's dementia or agrammatic aphasia often use explicit learning methods to train new skills, whereas some studies suggest that implicit rather than explicit learning is spared in these patients (Grafman et al., 1990; Hartsuiker & Kolk, 1998; Kuzis et al., 1999; Schuchard & Thompson, 2014, 2017; Van Halteren-Van Tilborg et al., 2007).

The aim of the present study is to investigate whether healthy ageing affects the ability to rapidly adapt to novel linguistic regularities within the native phonological system. We investigated younger and older adults' speech error output on the phonotactic constraint paradigm and analysed their speech slips as a measure of implicit language learning abilities. Across four days, participants rapidly produced sequences of CVC-syllables in time with a metronome to induce speech slips. Two key consonants within the syllables were constrained to onset or coda positions depending on the medial vowel (i.e., second-order EWC), whereas other consonants were language-wide constrained (i.e., LWC) or unrestricted (i.e., UR). Slips involving UR consonants served as baseline for evaluating long-term learning of the novel EWC. If pure implicit learning is relatively unaffected by ageing (i.e., the developmental invariance theory), older adults' speech production system should rapidly adapt to the novel constraints, similar to younger adults. Alternatively, older adults may show weaker learning than younger adults (i.e., the associative deficit or simultaneity hypothesis) with, particularly, no benefit from extra training or consolidation (i.e., no increase in learning across training days, as predicted by the striatal aging hypothesis).

Methods

Participants

Fifteen young (18-25 years old, M= 21.6, SD= 2.47; 10 females) and fifteen elderly adults (72-82 years old, M= 78.9, SD= 2.84; 10 females) took part in four testing sessions each. Based on the effect sizes in Smalle, Muylle, et al. (2017) and given a power (1-β) of .80, we estimated a sample size of at least n = 4 to detect reliable learning on Day 1 and a sample size of n = 12 to detect reliable differences between groups. We thus decided to test 15 participants in each group, similar to previous work (Anderson & Dell, 2018). Power calculations were done using G*Power software (Faul et al., 2007). The participants were respectively recruited from Ghent University and local senior service centres. All of them were native Dutch speakers. They had normal-to-corrected vision, did not suffer from hearing loss, and had no reported neurological, psychiatric, or language disorders. Percentile scores on the Raven's Progressive Matrices (Raven et al., 2003) were comparable between groups (younger: M= 65.7, SD= 28.5; older: M= 57.7, SD= 29.7; $t(28) = .75$, $p > .1$), ensuring similar intellectual abilities. Older adults had lower digit spans (forward: M= 4.6, SD= 0.84, backward: M= 3.6, SD= 0.84) than younger adults (forward: M= 6.3, SD= 0.98, $t(27)$= 4.98, $p < .001$; backward: M= 5.0, SD= 0.76, $t(27)$= 4.57, $p < .001$). The experimental procedure was exempted from approval by the research ethics committee of Ghent University. The participants signed the written informed consent before participation, and received financial compensation afterwards.

Materials

The same materials were used as in Smalle, Muylle, et al. (2017). Participants received a set of 96 sequences of four CVC-syllables (e.g., *siet mieng kief hien*) per day. The sequences consisted of, in total, eight consonants (i.e., /h/, /η/, /s/, /f/, /m/, /n/, /t/, /k/), each appearing once per sequence trial, and two Dutch vowels (i.e., /i/ or “ie” and /øː/ or “eu”) that alternated across trials. The consonants /h/ and /ŋ/ were LWC consonants and appeared at, respectively, onset or coda position conform the spoken Dutch language. The position of the EWC consonants /t/ and /k/ (typically unrestricted in Dutch) were restricted within the experiment, and appeared at onset or coda position depending on the medial vowel. For half of the participants, the consonant /t/ appeared at onset position when the vowel was /i/ and at coda position when the vowel was /øː/, whereas the consonant /k/ appeared at onset position when the vowel was /øː/ and at coda position when the vowel was /i/ (i.e., tiek-keut condition). For the other half, these rules were reversed (i.e., kiet-teuk condition). The remaining UR consonants (/m/, /n/, /s/, /f/) could equally appear at onset or coda positions across trials. A computer program from Warker and Dell (2006) generated 32 lists of 96 sequences. Any CVC-combinations that resulted in existing words were excluded. The lists were randomly assigned to the participants, and differed per day to avoid repetition. The individual word-forms were spoken by a male talker and recorded and converted to WAV-files using Audacity® recording and editing software (Audacity, 2018). In order to ensure that the syllables containing these experiment-wide constraints were similar across the two types of rules (i.e., tiek-keut vs. kiet-teuk), we performed independent samples t-tests (two-tailed) on their bigram frequency (i.e., /ti/, /ik/, /køː/,/øːt/ vs. /ki/, /it/, /tøː/, /øːk/) and neighbourhood density (i.e., for all possible syllables containing EWC consonants; see https://osf.io/mzn9j for the data and analyses). These analyses showed no differences in bigram frequency ($t(6) = -0.02$, $p = .98$) or neighbourhood density ($t(35) = -0.56$, $p = .58$).

Procedure

Participants took part in four sessions on consecutive days. During each session, they were asked to recite 96 sequences of four syllables. The syllables appeared on a standard computer screen and were simultaneously played through headphones. After presentation, the beat of a metronome started at a rate of 1 beat per second. The participants read the sequence in time with the beat (i.e., one syllable/beat). The metronome then speeded up to 2.54 beats per second and participants read the sequence three times in a row in time with the metronome. The fast pace is used to experimentally evoke speech slips involving consonant movements. After each trial, a new sequence appeared, and the same procedure was repeated. Responses were recorded on the computer for offline transcription. Additionally, the participants completed the Raven's Standard Progressive Matrices (Raven et al., 2003), a shortened version of the ASRT task, and the forward and backward digit span (WAIS-IV subtests; Wechsler, 2008) on respectively the first, second, third, and fourth day. The data from the ASRT are not reported here, because the task was too short to reveal any learning in either group and was therefore disregarded from further analyses.

Coding of responses

A first coder transcribed each individual speech error for each session separately. A second coder, who was blind to the goal of the experiment, transcribed 14% (i.e., 18 sessions) of all sessions to test for inter-rater reliability. Because of good inter-rater reliability (98.2%), the original coding of the first coder was not changed. Cut-off errors (for instance, "s...keut") were scored as onset errors (i.e., "seut" instead of "keut"). Speech errors were coded for both the slow (i.e., first attempt at 1 bps) and the fast speech rate (i.e., the three following attempts at 2.54 bps), but only the data for the fast speech rate was included in the statistical analyses (see also Dell et al., 2000; Warker & Dell, 2006). Consonants that slipped from onset to onset or from coda to coda were coded as *same-position* errors. Consonants that slipped from onset to coda or vice versa were coded as *different-position* errors. This was done separately for each type of constraint (i.e., LWC, EWC, or UR). For example, when the stimulus sequence is *kieng nief siet hiem* and the participant says “**h**ieng **t**ief **n**ie**s** **k**iem”, there is one *same-position* LWC error, (i.e., /h/ switched from onset to another onset), one *same-position* EWC error (i.e., /k/ switched from onset to another onset), one *different-position* EWC error (i.e., /t/ switched from coda to onset), one *same-position* UR error (i.e., /n/ switched from onset to another onset), and one *different-position* UR error (i.e., /s/ switched from onset to coda). All data, transcription files, and scripts for analyses are made available on Open Science Framework (link: osf.io/mzn9j).

Results

Overall, the older participants committed significantly more speech slips (total: 4864; *M*= 377.3, *SD*= 364.7) than the younger participants (total: 2095; *M*= 146.5, *SD*= 95.6; Welch’s *t*(15): -2.30, *p* < .05). Even at the slow rate, the older group produced more slips than the younger group (796 vs. 103 slips respectively, collapsed over days). As such, there is no reason to believe that the larger number of slips in the older vs. younger adults results from more problems with speaking in time with the metronome. The raw number of same- and different-position errors for each day and group for EWC and UR consonants can be found in Table 1. Speech slips adhered to the LWC in 100% of the cases (younger adults: SE = 0, based on a total of 606 errors; older adults: SE = 0, based on a total of 702 errors).

Our primary question is whether the proportion of same-position errors involving EWC consonants exceeds that of the UR consonants, indicating phonotactic *learning*. Most importantly, we wanted to find out a) whether this *learning effect* is observed in each age group b) whether it improves with further consolidation (i.e. across days) and c) whether it is comparable across groups. We therefore built generalized linear mixed effects models for the errors using the afex package (Singmann et al., 2016) in R (R Core Team, 2016). The outcome variable was *position* (binomial: same =1, different = 0) and all factors in the models were effect coded. For all analyses, we started from the maximal random effect structure, as proposed by Barr et al. (2013). However, in case of singularity or other convergence issues, the random model was reduced using the guidelines by Bates et al. (2015). To test our hypotheses, we first fitted a logistic regression model separately for each age group, with *day* (ordered factor) and *error type* (EWC vs. UR) as fixed effects. A similar model was then fitted across age groups (i.e., with *age group* as additional factor).[1] Pairwise contrasts were calculated using the phia package (De Rosario-Martinez, 2013) with Holm correction for multiple comparisons.

To check whether the results depended on the specific set of rules (i.e., tiek-keut vs. kiet-teuk), we used a generalized linear mixed effects model with *position* as outcome variable, the *error type* * *rule* interaction as fixed effects, and a random intercept for *subject* and a random slope for *error type* over subjects as random effects. There was no interaction between *error type* and *rule* (Type II/III Anova: $\chi^2(1) = 1.54$, $p = .21$) and no main effect of *rule* (Type II Anova: $\chi^2(1) = 0.17$, $p = .68$). Hence, learning was similar for both sets of rules; *rule* was therefore not included as a separate factor in the models reported below.

(Table 1 about here)

Younger adults

The fixed effects model consisted of the *error type* (EWC vs. UR) * *day* (ordered factor) interaction and the random effects of a random intercept for *subject* and an uncorrelated random slope for *day* over subjects. The model output can be found in Table 2. Type III Anova tests revealed a significant main effect of *error type* ($\chi^2(1) = 13.79$, $p < .001$), indicating significant learning of the novel EWC consonants. This learning did not improve with consolidation (i.e., there was no interaction between *error type* and *day*: $\chi^2(3) = 0.88$, $p = .83$, and no main effect of *day*$\chi^2(3) = 1.11$, $p = .77$).

(Table 2 about here)

Older adults

Similar to the younger adults, the fixed effects model consisted of the *error type * day* interaction, but the random effects consisted of a random intercept for *subject* and an uncorrelated random slope for *day + error type* over subjects. The output of this model is presented in Table 3. Type III Anova tests showed a significant main effect of *error type* ($\chi^2(1) = 39.97$, $p < .001$) but no interaction with *day* ($\chi^2(3) = -1.10$, $p = .78$), again indicating reliable learning that remained stable across consolidation. However, there was a significant main effect of *day* ($\chi^2(3) = 10.42$, $p < .05$). Pairwise contrasts revealed that the overall proportion of same-position errors was lower on Day 1 compared to subsequent days (Day 1 vs. Day 2: $\chi^2(1) = 10.05$, $p < .01$; Day 1 vs. Day 3: $\chi^2(1) = 3.48$, $p = .06$; Day 1 vs. Day 4: $\chi^2(1) = 5.21$, $p < .05$). This indicates that older adults are less likely to slip consonants to opposite positions with practice.

(Table 3 about here)

Group comparison

Here, the fixed effects consisted of the three-way interaction between *age group* (younger vs. older), *error type* (EWC vs. UR), and *day* (ordered factor). The random effects consisted of a random intercept for *subject* and an uncorrelated random slope for *day + error type* over subjects. The model output can be found in Table 4. Type III Anova tests revealed a significant effect of error type ($\chi^2(1) = 45.64$, $p < .001$), indicating phonotactic constraint learning. This did not improve across training days (i.e., *error type * day*: $\chi^2(3) = 2.77$, $p = .43$). There was no *age group * day* interaction ($\chi^2(3) = 0.96$, $p = .81$), and the main effect of *day* did not reach the conventional threshold of significance ($\chi^2(3) = 6.39$, $p = .09$). In addition there was a significant main effect of *age group* ($\chi^2(1) = 11.01$, $p < .001$). Overall, older adults produced (in proportion) fewer same-position errors than younger adults, in support of a weaker syllable position effect in older vs. younger adults. Learning did, however, not reliably differ across groups (i.e., *error type * age group*: $\chi^2(1) = 1.62$, $p = .20$; *age group * error type * day*: $\chi^2(3) = 1.98$, $p = .58$).

(Table 4 about here)

Interim discussion

Both groups show significant learning of the novel EWC rule. In addition, there is a clear effect of age in the overall proportion of same-position errors, indicating a weaker syllable-position effect in the older adults compared to the younger ones. Interestingly, the error pattern of older adults strongly resembles that of the children in Smalle, Muylle, et al.'s (2017) study, as can be seen from Figure 1. We conducted an exploratory analysis to test whether the error pattern was indeed similar across (Dutch-speaking) children and older adults, but different from younger adults.

(Figure 1 about here)

Exploratory analysis: comparison of the current data with Smalle, Muylle, et al.’s (2017) children

To assess group differences in the error pattern, we added the errors of Smalle, Muylle et al.’s children to the data and ran generalized linear mixed effects models with *age group * error type* and *age group * day* interactions as fixed effects on this full dataset.[2] The random effects consisted of a random intercept for *subject* and an uncorrelated random slope for *error type* and *day* over subjects. The output of this model can be found in Table 5. Type III Anova revealed that there was a main effect of *error type* ($\chi^2(1) = 104.12$, $p < .001$), *day* ($\chi^2(3) = 13.63$, $p < .01$), and *age group* ($\chi^2(2) = 13.06$, $p < .01$). Pairwise comparisons showed an increase in same-position errors across days (Day 1 vs. Day 2: $\chi^2(1) = 12.56$, $p < .01$; Day 1 vs. Day 3: $\chi^2(1) = 5.02$, $p < .05$; Day 1 vs. Day 4: $\chi^2(1) = 4.18$, $p < .05$). This increase was similar in all age groups (i.e., no *age group* * *day* interaction: $\chi^2(6) = 6.65$, $p = .35$).

Importantly, both children and older adults produced fewer same-position errors than younger adults (i.e., children vs. younger adults: $\chi^2(1) = 7.59$, $p < .05$; older vs. younger adults:$\chi^2(1) = 12.62$, $p < .01$), while there was no difference between the children and older adults ($\chi^2(1) = 0.63$, $p = .43$). Again, this effect denotes a weaker syllable-position effect in the children and older adults compared to the younger adults. Learning did however not differ reliably across groups ($\chi^2(2) = 3.09$, $p = .21$).

(Table 5 about here)

Discussion

In the present study, younger and older adults were tested on an adapted version of the second-order phonotactic constraint task (Warker & Dell, 2006) in order to investigate whether learning within the mature speech production system is affected by ageing. We found that both younger and older adults showed evidence of learning, given that the proportion of same-position errors was higher for EWC than for UR consonants. This learning was present in both groups despite differences in higher cognitive abilities such as working memory as also shown with the digit span tests. The finding that older adults are able to pick up the hidden regularities in linguistic stimuli indicates that preserved implicit learning skills in ageing are not limited to the motor domain.

The finding that the magnitude of the learning effect is similar to that of younger adults is in line with the developmental invariance theory (Reber, 1993), which assumes that implicit learning capacity remains stable throughout life. Our findings do not provide support for the associative binding theory (Harrison et al., 2006; Naveh-Benjamin, 2000) and simultaneity theory (Salthouse, 1996) that predict weaker learning of second-order constraints in older versus younger adults. In addition, there is no evidence that older adults, in contrast to younger adults, show problems with consolidating the newly acquired phonotactic knowledge, as would be predicted by the striatal ageing hypothesis (Howard & Howard, 2013). In fact, the learning effects were similar for both groups across days. Taken together, the findings of the current study favour the idea of intact implicit learning in ageing.

Noteworthy, syllable-position effects were significantly weaker in our older participants as opposed to the younger participants, which suggests that younger adults are more sensitive to local (i.e., within-sequences) constraint effects compared to older adults. Moreover, the pattern in the older group largely resembles that of the children in Smalle, Muylle, et al.'s (2017) study (i.e., 21% less position maintenance than the younger adults, see Figure 1). Our exploratory analyses comparing the three age groups confirmed this similarity between children and older adults. In fact, the proportion same-position errors was different for the children vs. younger adults, and for older vs. younger adults, but not for children vs. older adults. As Smalle, Muylle, and colleagues (2017) suggested, differences in syllable-position effects might be due to higher working memory, or explicit, hypothesis-testing capacities in the younger adult group compared to the children, which increases the tendency for trial-specific learning. We think this is also true for the comparison with older adults. The potential role of working memory in the syllable-position effect is further supported by a significant positive correlation between the proportion of same-position errors in both young and older adults and their forward and backward digit span scores (forward digit span: Spearman's *rho* = .50, *p* < .01; backward digit span: Spearman's *rho* = .50, *p* < .01). As such, explicit learning capacities seem to follow an inverse U-shaped pattern, whereas implicit learning skills remain relatively stable across age. Furthermore, some recent studies that used a non-linguistic variant of the paradigm also showed a relatively weak 'syllable-position effect' on errors involving arbitrary finger movements in young adults (Anderson & Dell, 2018; Rebei et al., 2019). Both papers discuss the possibility that these weak effects are caused by limited experience with the event schema. Similarly, the weaker syllable-position effects in children compared to younger adults might be explained by rather limited experience with syllabic structures. In young adulthood, phonological representations might become more elaborate, resulting in stronger syllable-position effects. In older adults, these representations may become weaker again due to decline in the phonological system (cf. the Transmission Deficit Hypothesis, see Burke et al., 1991; MacKay & James, 2004) and this weakening may reduce syllable-position effects. These speculations however merit more research.

We found no evidence for differences in learning across days in both groups. This finding is in contrast with previous studies testing young adults that found evidence for second-order learning only from the second day of training, that is after a night of sleep (Anderson & Dell, 2018). The absence of a significant interaction with *day*, particularly in our younger participants, may be due to the fact that they a) produce very few EWC errors in general (i.e., fewer than 100 on most days), resulting in few observations for analysis, and b) show syllable-position effects that are very close to the ceiling (i.e., around 85%), leaving only very little room for improvement.[3] As such, it may be premature to state that younger adults learned the second order constraints from the first day, particularly because Anderson and Dell's (2018) meta-analysis clearly showed that younger adults only learn these constraints from the second day, in contrast to children (see Smalle, Muylle, et al., 2017) and our older participants, who already show clear learning effects from Day 1.

Recently, Dell and colleagues (2019) proposed a connectionist account for the apparently different learning patterns in children and adults. They argued that second order representations are stored in hidden units representing the relation between vowels and consonants (e.g., /k/ in the context of /i/). These hidden units might be less commonly used in adults than children, who are still open to all possible regularities that exist in language, including those of second order. When the system further matures and complex constraints such as CVC-conjunctions appear to be less relevant in the spoken system (i.e., second-order constraints in which syllable positions depend on adjacent vowels are very rare in Germanic languages, see Dell et al., 2019), the hidden units become backgrounded within the system. As a result, more training and/or a consolidation period is needed to re-establish them within the setting of an experiment.

Why then do we observe rapid second-order constraint learning in older adults too? One additional, highly speculative possibility is that the seemingly slower learning patterns that are typically observed in younger adults (compared to children and older adults) result from a stronger reliance on explicit learning mechanisms, as discussed above. We know from the general learning literature that explicit learning systems interfere with, and slow down implicit learning processes (e.g., Borragán et al., 2017; Daw et al., 2005; Nemeth et al., 2013; Poldrack et al., 2001) and as such might slow down the adaptation of the speech production system to the (albeit backgrounded) hidden units. This competition might not occur (or at least to a much weaker extent) in children and older adults due to an underdeveloped or declined cognitive control system, respectively (e.g., Craik & Bialystok, 2006, see also Smalle, Panouilleres, et al., 2017). More research is needed to test this hypothesis, especially because the current study found no significant difference in learning between the younger and older adults.

It is not clear to which extent the learning in older adults that we observed with the phonotactic constraint paradigm is generalizable to other phonotactic learning situations. For instance, it has been found that older adults have difficulties with detecting patterns in visual sequences (e.g., Negash et al., 2003; Neger et al., 2014), but not in spoken sequences (Adank & Janse, 2010; Peelle & Wingfield, 2005). Hence, it is possible that we would not observe phonotactic learning during visual processing of syllable sequences. Further studies are needed to find out whether preserved phonotactic learning abilities in older adults is specific to the spoken modality (i.e., speech production).

To conclude, both younger and older adults are able to learn complex novel phonotactic regularities based on a relatively small amount of input. Interestingly, older adults already showed evidence for long-term learning on the first day of training despite relatively weaker trial-specific learning (i.e., smaller syllable position effect). This pattern was highly similar to what has been observed previously in children and in non-linguistic constraint learning.[4] Overall, our results indicate that language depends on implicit, domain-general learning principles that are relatively unaffected by ageing and appeal to the lifelong potential of the brain to adapt to complex, context-sensitive regularities hidden in the environment.

Notes

1. We also performed non-parametric Wilcoxon tests on these data to enable comparison with previous studies that applied this type of analyses (e.g., Warker & Dell, 2006). These analyses can be found on osf.io/mzn9j.
2. We did not investigate the interaction between *error type* and *day* (or the three-way interaction with *age group*), given that learning did not change reliably across days in both our adult groups.
3. From the current data it is not entirely clear whether younger adults show reliable learning from the first day. When we look at the EWC-UR contrast on Day 1, the effect is only marginally significant (*chi-sq*(1) = 5.66, $p = .06$) and this is confirmed by the Wilcoxon test ($Z = 1.726$, $p = .084$). In contrast, older adults clearly show learning effects on Day 1 (mixed effects model contrast: *chi-sq*(1) = 17.68, $p < .001$; Wilcoxon test: $Z = 3.12$, $p < .01$).
4. It has to be noted that the current results are based on only a limited set of Dutch consonants, which does not mean that the findings also generalize to other consonants. However, we have no strong reason not to think so (see, for instance Warker & Dell, 2006, who found similar learning effects across different sets of English consonants). In future work with this paradigm, one should consider implementing other Dutch consonants.

Declaration of interest statement

The Authors declare that there is no conflict of interest.

References

Adank, P., & Janse, E. (2010). Comprehension of a novel accent by young and older listeners. *Psychology and Aging*. https://doi.org/10.1037/a0020054

Anderson, N. D., & Dell, G. S. (2018). The role of consolidation in learning context-dependent phonotactic patterns in speech and digital sequence production. *Proceedings of the National Academy of Sciences*, *115*(14), 3617–3622. https://doi.org/10.1073/pnas.1721107115

Audacity. (2018). *Audacity ® | Free, open source, cross-platform audio software for multi-track recording and editing.* Audacity. https://doi.org/ISSN 1980-4431

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bates, D., Kliegl, R., Vasishth, S., & Baayen, H. (2015). Parsimonious mixed models. *ArXiv E-Print, under Revision*. https://doi.org/arXiv:1506.04967

Bennett, I. J., Howard, J. H., & Howard, D. V. (2007). Age-related differences in implicit learning of subtle third-order sequential structure. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*. https://doi.org/10.1093/geronb/62.2.P98

Borragán, G., Slama, H., Bartolomei, M., & Peigneux, P. (2017). Cognitive fatigue: A Time-based Resource-sharing account. *Cortex*. https://doi.org/10.1016/j.cortex.2017.01.023

Brown, R. M., Robertson, E. M., & Press, D. Z. (2009). Sequence skill acquisition and off-line learning in normal aging. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0006683

Burke, D. M., MacKay, D. G., Worthley, J. S., & Wade, E. (1991). On the tip of the tongue: What causes word finding failures in young and older adults? *Journal of Memory and Language*, *30*(5), 542–579. https://doi.org/10.1016/0749-596X(91)90026-G

Campbell, K. L., Zimerman, S., Healey, M. K., Lee, M. M. S., & Hasher, L. (2012). Age differences in visual statistical learning. *Psychology and Aging*, *27*(3), 650–656. https://doi.org/10.1037/a0026780

Chang, F., Dell, G. S., & Bock, K. (2006). Becoming syntactic. *Psychological Review*, *113*(2), 234–272. https://doi.org/10.1037/0033-295X.113.2.234

Cleeremans, A., & Jiménez, L. (2002). Implicit learning and concsciousness: A graded, dynamic perspective. In R. M. French & A. Cleeremans (Eds.), *Implicit learning and concsciousness. An empirical, philosophical and computational consensus in the making*. Psychology Press.

Craik, F. I. M., & Bialystok, E. (2006). Cognition through the lifespan: mechanisms of change. *Trends in Cognitive Sciences*, *10*(3), 131–138. https://doi.org/10.1016/j.tics.2006.01.007

Daw, N. D., Niv, Y., & Dayan, P. (2005). Uncertainty-based competition between prefrontal and dorsolateral striatal systems for behavioral control. *Nature Neuroscience*. https://doi.org/10.1038/nn1560

De Rosario-Martinez, H. (2013). phia: Post-Hoc Interaction Analysis. In *Available: http://CRAN.R-project.org/package5phia*.

Dell, G. S., Kelley, A. C., Bian, Y., & Holmes, E. W. (2019). Tuning the blueprint: how studies of implicit learning during speaking reveal the information processing components of the production system. *Language, Cognition and Neuroscience*, *34*(9), 1246–1256. https://doi.org/10.1080/23273798.2019.1613553

Dell, G. S., Reed, K. D., Adams, D. R., & Meyer, A. S. (2000). Speech Errors, Phonotactic Constraints, and Implicit Learning: A Study of the Role of Experience in Language Production. *Journal of Experimental Psychology: Learning Memory and Cognition*. https://doi.org/10.1037/0278-7393.26.6.1355

Dennis, N. A., & Cabeza, R. (2011). Age-related dedifferentiation of learning systems: an fMRI study of implicit and explicit learning. *Neurobiology of Aging*, *32*(12), 2318.e17-2318.e30. https://doi.org/10.1016/j.neurobiolaging.2010.04.004

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*. https://doi.org/10.3758/BF03193146

Frensch, P. A., & Miner, C. S. (1994). Effects of presentation rate and individual differences in short-term memory capacity on an indirect measure of serial learning. *Memory & Cognition*. https://doi.org/10.3758/BF03202765

Fromkin, V. A. (1971). The non-anomalous nature of anomalous utterances. *Language*, *47*(1), 27. https://doi.org/10.2307/412187

Frost, R., Siegelman, N., Narkiss, A., & Afek, L. (2013). What Predicts Successful Literacy Acquisition in a Second Language? *Psychological Science*, *24*(7), 1243–1252.

https://doi.org/10.1177/0956797612472207

Grafman, J., Weingartner, H., Newhouse, P., Thompson, K., Lalonde, F., Litvan, I., Molchan, S., & Sunderland, T. (1990). Implicit Learning in Patients with Alzheimer's Disease. *Pharmacopsychiatry*, *23*(02), 94–101. https://doi.org/10.1055/s-2007-1014490

Hakuta, K., Bialystok, E., & Wiley, E. (2003). Critical Evidence: A Test of the Critical-Period Hypothesis for Second-language Acquisition. *Psychological Science*. https://doi.org/10.1111/1467-9280.01415

Hardy, S. M., Messenger, K., & Maylor, E. A. (2017). Aging and syntactic representations: Evidence of preserved syntactic priming and lexical boost. *Psychology and Aging*. https://doi.org/10.1037/pag0000180

Hardy, S. M., Segaert, K., & Wheeldon, L. R. (2020). Healthy Aging and Sentence Production: Disrupted Lexical Access in the Context of Intact Syntactic Planning. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.00257

Harrison, L. M., Duggins, A., & Friston, K. J. (2006). Encoding uncertainty in the hippocampus. *Neural Networks*, *19*(5), 535–546. https://doi.org/10.1016/j.neunet.2005.11.002

Hartsuiker, R. J., & Kolk, H. H. J. (1998). Syntactic Facilitation in Agrammatic Sentence Production. *Brain and Language*, *62*(2), 221–254. https://doi.org/10.1006/brln.1997.1905

Hedden, T., & Gabrieli, J. D. E. (2004). Insights into the ageing mind: A view from cognitive neuroscience. In *Nature Reviews Neuroscience*. https://doi.org/10.1038/nrn1323

Hedenius, M., Persson, J., Tremblay, A., Adi-Japha, E., Veríssimo, J., Dye, C. D., Alm, P., Jennische, M., Bruce Tomblin, J., & Ullman, M. T. (2011). Grammar predicts procedural learning and consolidation deficits in children with Specific Language Impairment. *Research in Developmental Disabilities*. https://doi.org/10.1016/j.ridd.2011.07.026

Howard, J. H., & Howard, D. V. (1997). Age differences in implicit learning of higher order dependencies in serial patterns. *Psychology and Aging*. https://doi.org/10.1037/0882-7974.12.4.634

Howard, J. H., & Howard, D. V. (2013). Aging mind and brain: is implicit learning spared in healthy aging? *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00817

Janacsek, K., Fiser, J., & Nemeth, D. (2012). The best time to acquire new skills: age-related differences in implicit sequence learning across the human lifespan. *Developmental Science*, *15*(4), 496–505. https://doi.org/10.1111/j.1467-7687.2012.01150.x

Juhasz, D., Nemeth, D., & Janacsek, K. (2019). Is there more room to improve? The lifespan trajectory of procedural learning and its relationship to the between? The within-group differences in average response times. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0215116

Kuzis, G., Sabe, L., Tiberti, C., Merello, M., Leiguarda, R., & Starkstein, S. E. (1999). Explicit and implicit learning in patients with Alzheimer disease and Parkinson disease with dementia. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology*, *12*(4), 265–269. http://www.ncbi.nlm.nih.gov/pubmed/10527111

MacKay, D. G., & James, L. E. (2004). Sequencing, Speech Production, and Selective Effects of Aging on Phonological and Morphological Speech Errors. *Psychology and Aging*. https://doi.org/10.1037/0882-7974.19.1.93

Midford, R., & Kirsner, K. (2005). Implicit and explicit learning in aged and young adults. *Aging, Neuropsychology, and Cognition*. https://doi.org/10.1080/13825580500246894

Morgan-Short, K., Steinhauer, K., Sanz, C., & Ullman, M. T. (2012). Explicit and implicit second language training differentially affect the achievement of native-like brain activation patterns. *Journal of Cognitive Neuroscience*, *24*(4), 933–947. https://doi.org/10.1162/jocn_a_00119

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: Tests of an associative deficit hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(5), 1170–1187. https://doi.org/10.1037/0278-7393.26.5.1170

Negash, S., Howard, D. V., Japikse, K. C., & Howard, J. H. (2003). Age-Related Differences in Implicit Learning of Non-Spatial Sequential Patterns. *Aging, Neuropsychology, and Cognition*, *10*(2), 108–121. https://doi.org/10.1076/anec.10.2.108.14462

Neger, T. M., Rietveld, T., & Janse, E. (2014). Relationship between perceptual learning in speech and statistical learning in younger and older adults. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/fnhum.2014.00628

Nemeth, D., & Janacsek, K. (2011). The Dynamics of Implicit Skill Consolidation in Young and Elderly Adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *66B*(1), 15–22. https://doi.org/10.1093/geronb/gbq063

Nemeth, D., Janacsek, K., & Fiser, J. (2013). Age-dependent and coordinated shift in performance between implicit and explicit skill learning. *Frontiers in Computational*

Neuroscience. https://doi.org/10.3389/fncom.2013.00147

Palmer, S. D., Hutson, J., & Mattys, S. L. (2018). Statistical learning for speech segmentation: Age-related changes and underlying mechanisms. *Psychology and Aging*. https://doi.org/10.1037/pag0000292

Peelle, J. E., & Wingfield, A. (2005). Dissociations in perceptual learning revealed by adult age differences in adaptation to time-compressed speech. *Journal of Experimental Psychology: Human Perception and Performance*. https://doi.org/10.1037/0096-1523.31.6.1315

Poldrack, R. A., Clark, J., Paré-Blagoev, E. J., Shohamy, D., Creso Moyano, J., Myers, C., & Gluck, M. A. (2001). Interactive memory systems in the human brain. *Nature*. https://doi.org/10.1038/35107080

R Core Team. (2016). R: A language and environment for statistical computing. In *R Foundation for Statistical Computing*.

Raven, J., Raven, J. C., & Court, J. H. (2003). Section 1: General Overview. In *Manual for Raven's Progressive Matrices and Vocabulary Scales.* Harcourt Assessment.

Rebei, A., Anderson, N. D., & Dell, G. S. (2019). Learning the phonotactics of button pushing: Consolidation, retention, and syllable structure. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(11), 2072–2079. https://doi.org/10.1037/xlm0000686

Reber, A. S. (1992). The cognitive unconscious: An evolutionary perspective. *Consciousness and Cognition*. https://doi.org/10.1016/1053-8100(92)90051-B

Reber, A. S. (1993). Implicit Learning and Tacit Knowledge. In D. E. Broadbent, N. J. Mackintosh, J. L. McGaugh, A. Treisman, E. Tulving, & L. Weiskrantz (Eds.), *Implicit Learning and Tacit Knowledge: An Essay on the Cognitive Unconscious*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195106589.001.0001

Rieckmann, A., Fischer, H., & Bäckman, L. (2010). Activation in striatum and medial temporal lobe during sequence learning in younger and older adults: Relations to performance. *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2010.01.015

Salthouse, T. A. (1996). The Processing-Speed Theory of Adult Age Differences in Cognition. *Psychological Review*. https://doi.org/10.1037/0033-295X.103.3.403

Schuchard, J., & Thompson, C. K. (2014). Implicit and Explicit Learning in Individuals with Agrammatic Aphasia. *Journal of Psycholinguistic Research*. https://doi.org/10.1007/s10936-013-9248-4

Schuchard, J., & Thompson, C. K. (2017). Sequential learning in individuals with agrammatic aphasia: evidence from artificial grammar learning. *Journal of Cognitive Psychology*. https://doi.org/10.1080/20445911.2017.1293065

Siegert, R. J., Taylor, K. D., Weatherall, M., & Abernethy, D. A. (2006). Is implicit sequence learning impaired in Parkinson's disease? A meta-analysis. *Neuropsychology*. https://doi.org/10.1037/0894-4105.20.4.490

Singmann, H., Bolker, B., Westfall, J., Aust, F., Højsgaard, S., Fox, J., Lawrence, M. A., Mertens, U., & Love, J. (2016). afex: analysis of factorial experiments. R package version 0.16-1. *R Package Version 0.16-1*.

Smalle, E. H. M., Muylle, M., Szmalec, A., & Duyck, W. (2017). The different time course of phonotactic constraint learning in children and adults: Evidence from speech errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(11), 1821–1827. https://doi.org/10.1037/xlm0000405

Smalle, E. H. M., Panouilleres, M., Szmalec, A., & Möttönen, R. (2017). Language learning in the adult brain: Disrupting the dorsolateral prefrontal cortex facilitates word-form learning. *Scientific Reports*. https://doi.org/10.1038/s41598-017-14547-x

Stillman, C. M., Howard, J. H., & Howard, D. V. (2016). The effects of structural complexity on age-related deficits in implicit probabilistic sequence learning. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*. https://doi.org/10.1093/geronb/gbu135

Van Halteren-Van Tilborg, I. A. D. A., Scherder, E. J. A., & Hulstijn, W. (2007). Motor-Skill learning in Alzheimer's disease: A review with an eye to the clinical practice. *Neuropsychology Review*. https://doi.org/10.1007/s11065-007-9030-1

Verneau, M., Van Der Kamp, J., Savelsbergh, G. J. P., & De Looze, M. P. (2014). Age and time effects on implicit and explicit learning. *Experimental Aging Research*. https://doi.org/10.1080/0361073X.2014.926778

Warker, J. A., & Dell, G. S. (2006). Speech errors reflect newly learned phonotactic constraints. *Journal of Experimental Psychology: Learning Memory and Cognition*. https://doi.org/10.1037/0278-7393.32.2.387

Warker, J. A., Dell, G. S., Whalen, C. A., & Gereg, S. (2008). Limits on Learning Phonotactic Constraints From Recent Production Experience. *Journal of Experimental Psychology:*

Learning Memory and Cognition. https://doi.org/10.1037/a0013033

Wechsler, D. (2008). *Wechsler Adult Intelligence Scale - Fourth edition administration and scoring manual*. Pearson.

Weickert, T. W., Leslie, F., Rushby, J. A., Hodges, J. R., & Hornberger, M. (2013). Probabilistic association learning in frontotemporal dementia and schizophrenia. *Cortex*. https://doi.org/10.1016/j.cortex.2011.09.011

Table 1. *Number of same-position and different-position errors in young and older adults.*

		Experiment-wide constraint			**Unrestricted**			
	Day	**Same**	**Different**	**% Same**	**Same**	**Different**	**% Same**	**Total**
Younger	**1**	131	8	94.2	326	54	85.8	519
	2	81	3	96.4	261	47	84.7	392
	3	62	4	93.9	173	25	87.4	264
	4	52	2	96.3	193	24	88.9	271
Older	**1**	366	71	83.8	361	199	64.5	997
	2	321	35	90.2	423	154	73.3	933
	3	320	35	90.1	417	218	65.7	990
	4	355	21	94.4	399	212	65.3	987

Table 2. *Model output for the learning effect in the younger adults across days.*

Summary of the fixed effects in the multilevel logit model (*N* = 1446; log-likelihood = -500.7)

Formula: position ~ error_type * day + (day || subject)

	coefficient	SE	Wald's Z	p-value
(Intercept)	2.57	(0.175)	14.64	< 0.001
error_type1	0.55	(0.149)	3.71	< 0.001
day1	-0.20	(0.226)	-0.90	0.37
day2	0.08	(0.284)	0.29	0.78
day3	-0.12	(0.276)	-0.43	0.67
error_type1:day1	-0.08	(0.204)	-0.41	0.69
error_type1:day2	0.20	(0.263)	0.75	0.45
error_type1:day3	-0.16	(0.248)	-0.65	0.52

Table 3. *Model output for the learning effect in the older adults across days.*

Summary of the fixed effects in the multilevel logit model (*N* = 3907; log-likelihood = -1902.2)

Formula: position ~ error_type * day + (error type * day || subject)

	coefficient	SE	Wald's Z	p-value
(Intercept)	1.88	(0.159)	11.83	< 0.001
error_type1	0.90	(0.142)	6.32	< 0.001
day1	-0.34	(0.120)	-2.85	< 0.01
day2	0.19	(0.097)	2.01	< 0.05
day3	-0.03	(0.093)	-0.37	0.71
error_type1:day1	-0.13	(0.134)	-0.99	0.32
error_type1:day2	-0.03	(0.142)	-0.18	0.86
error_type1:day3	0.00	(0.114)	-0.03	0.97

Table 4. *Model output for the learning effect in younger and older adults across days.*

Summary of the fixed effects in the multilevel logit model (*N* = 5353; log-likelihood = -2410.7)

Formula: position ~ age_group * error_type * day + (day + error_type || subject)

	coefficient	SE	Wald's Z	p-value
(Intercept)	2.25	(0.127)	17.81	< 0.001
age_group1	0.41	(0.123)	3.32	< 0.001
error_type1	0.76	(0.113)	6.76	< 0.001
day1	-0.28	(0.120)	-2.35	< 0.05
day2	0.14	(0.153)	0.91	0.36
day3	-0.08	(0.141)	-0.57	0.57
age_group1:error_type1	-0.14	(0.111)	-1.27	0.20
age_group1:day1	0.10	(0.120)	0.87	0.38
age_group1:day2	-0.02	(0.153)	-0.13	0.90
age_group1:day3	-0.08	(0.136)	-0.56	0.57
error_type1:day1	-0.16	(0.110)	-1.47	0.14
error_type1:day2	0.05	(0.139)	0.37	0.71
error_type1:day3	-0.06	(0.131)	-0.49	0.62
age_group1:error_type1:day1	0.06	(0.110)	0.58	0.56
age_group1:error_type1:day2	0.16	(0.139)	1.13	0.26
age_group1:error_type1:day3	-0.09	(0.131)	-0.65	0.52

Table 5. *Exploratory model output comparing the learning effect in the current data with Smalle, Muylle et al.'s (2017) children.*

Summary of the fixed effects in the multilevel logit model (N = 8876; log-likelihood = -4138.2)

Formula: position ~ age_group * error_type + age_group * day + (error_type + day || subject)

	coefficient	SE	Wald's Z	p-value
(Intercept)	2.12	(0.095)	22.31	< 0.001
age_group1	-0.17	(0.127)	-1.32	0.19
age_group2	0.50	(0.143)	3.49	< 0.001
error_type1	0.79	(0.078)	10.20	< 0.001
day1	-0.22	(0.067)	-3.34	< 0.001
day2	0.14	(0.067)	2.06	< 0.05
day3	0.04	(0.081)	0.47	0.64
age_group1:error_type1	0.15	(0.103)	1.46	0.15
age_group2:error_type1	-0.21	(0.122)	-1.68	0.09
age_group1:day1	-0.10	(0.087)	-1.14	0.26
age_group2:day1	0.14	(0.108)	1.27	0.20
age_group1:day2	0.15	(0.087)	1.69	0.09
age_group2:day2	-0.24	(0.111)	-2.21	< 0.05
age_group1:day3	0.04	(0.099)	0.36	0.72
age_group2:day3	-0.04	(0.130)	-0.34	0.73

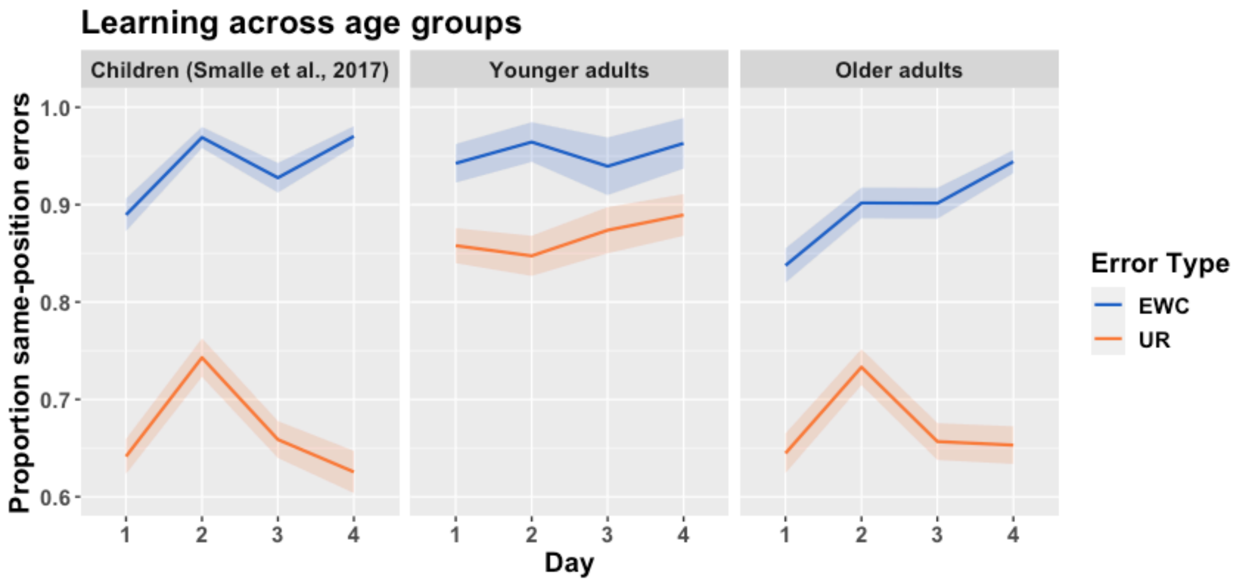

Figure 1. *Mean proportion same position errors for EWC and UR in younger and older adults from this dataset compared with children from Smalle, Muylle, et al.'s (2017) dataset.*