Rapid phonotactic constraint learning in ageing: Evidence from speech errors

Merel Muylle¹, Eleonore H. M. Smalle¹, Robert J. Hartsuiker¹

¹Department 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@ugent.be

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., Hedden & Gabrieli, 2004; Craik & Bialystok, 2006) – are relatively preserved in ageing (e.g., Verneau, van der Kamp, Savelsbergh, & de Looze, 2014; see Howard & Howard, 2013, for a review) and may serve as a shield against age-related cognitive decline (Palmer, Hutson & Mattys, 2018; Juhasz, Nemeth & Janacsek, 2019). 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, Howard, & Howard, 2007; Stillman, Howard, & Howard, 2016). However, older adults benefit less from 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). Other studies found that older adults performed as well or even better than young adults (e.g., Juhasz et al., 2019). 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. This suggests 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.

A domain that relies heavily on implicit learning processes is language acquisition (Frost, Siegelman, Narkiss, & Afek, 2013; Hedenius et al., 2011; Morgan-Short, Finger, Grey, & Ullman, 2012). In general, (second) language learning abilities seem to decrease linearly with age (Hakuta, Bialystok, & Wiley, 2003), but the actual implicit learning processes involved in language acquisition have received only limited attention in aging research. As far as we know, only one study investigated the relation between aging and implicit language learning. 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 rather than non-words. They 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, Reed, Adams, & Meyer, 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 unintentionally 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, Dell, Whalen, & Gereg, 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*, in the literature also referred to as *local-positional* constraints, 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: Warker & Dell, 2006, Anderson & Dell, 2018). 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, Szmalec, & Duyck, 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). The aim of the present study is to investigate whether ageing affects the ability to rapidly adapt to novel 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. We predicted that older adults' speech production system would rapidly adapt to the novel constraints, similar to the younger adults, because pure implicit learning mechanisms are relatively unaffected by ageing.

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 ($1-\beta$) 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, Raven, & Court, 2000) 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 automatically approved 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 kiefhien*) per day. The sequences consisted of, in total, eight consonants (i.e., /h/, /ŋ/, /s/, /f/, /m/, /n/, /t/, /k/), each appearing once per sequence trial, and two Dutch vowels (i.e., /i/ or "ie" and /ø:/ 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 /ø:/, whereas the consonant /k/ appeared at onset position when the vowel was /ø:/ and at coda position when the vowel was /i/. For the other half, these rules were reversed. 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 Team, 2019).

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, a shortened version of the ASRT task (data not), 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, given that the task was too short to reveal any learning and 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”). 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 “**hi**eng tief **nie**s ki**em**”, 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

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. Our primary question is whether the proportion of same-position errors involving EWC consonants exceeds that of the UR consonants, indicating *learning*, and most importantly whether this *learning effect* is observed in each age group and when. For this, we calculated the proportion of same-position errors for each constraint type and day (depicted in Figure 1), on which we carried out non-parametric Wilcoxon signed-rank tests (cf. Anderson & Dell, 2018). To compare between groups, we used Mann-Whitney *U*-tests.

(Table 1 about here)

(Figure 1 about here)

Younger adults

Speech slips adhered to the LWC in 100% of the cases ($SE = 0$ based on a total of 606 errors). The learning effect (i.e., difference between EWC and UR in terms of the proportion of same-position errors) on the first day did not reach the conventional threshold for statistical significance ($Z = 1.726$, $p = .084$, with one tie and 10 participants in the expected direction). The effect emerged significantly on the subsequent days (Days 2-4, $Z = 3.040$, $p = .002$, $r = .555^1$; Day 2, $Z = 3.298$, $p = .001$, $r = .602$, one tie and 13 in the expected direction; Day 3, $Z = 1.12$, $p = .263$, 7 ties and 5 in the expected direction; Day 4, $Z = 2.380$, $p = .017$, $r = .435$, 7 ties and 8 in the expected direction).

Older adults

LWC slips were 100% same-position errors ($SE = 0$, based on a total of 702 errors). Already on the first day, there was evidence for learning (Day 1, $Z = 3.124$, $p = .002$, effect size $r = .570$, with 13 out of 15 participants in the expected direction). The effect remained significant on all subsequent days (Days 2-4, $Z = 3.067$, $p = .002$, $r = .560$; separately per day: Day 2, $Z = 2.669$, $p = .008$, $r = .478$, 11 in the expected direction; Day 3, $Z = 3.045$, $p = .002$, $r = .556$, one tie and 13 in the expected direction; Day 4, $Z = 2.271$, $p = .023$, $r = .441$, one tie and 13 in the expected direction).

Group comparison

Overall, the older participants committed significantly more errors ($M = 377.3$, $SD = 364.7$) than the younger participants ($M = 146.5$, $SD = 95.6$; $Z = 2.26$, $p = .02$). The older group showed larger *learning effects* than the younger group on all days (Day 1, $Z = -2.18$, $p = .03$, $r = .40$; Days 2-4: $Z = -3.83$, $p < .001$, $r = .41$). This was mainly due to a weaker syllable position effect in the older group, given that the same-position percentage for the UR slips was significantly lower for the older adults (Day 1: $Z = -3.30$, $p < .001$, $r = .60$; Days 2-4: $Z = -5.37$, $p < .001$, $r = .57$). No differences were observed for the EWC

condition on Day 1 ($Z = -1.18, p = .24$), but the proportion of same-position errors was higher for the younger adults on Days 2-4 ($Z = -2.90, p < .01, r = .31$).

Interim discussion

Both groups show significant learning of the EWC rule (except for younger participants on the first day). In addition, there is a clear effect of age in the overall proportion of same-position errors. The comparison between groups indicates that this effect is mainly due to a weaker syllable-position effect (i.e., the proportion of same position errors for the UR consonants) in the older adults compared to the younger ones. Interestingly, the error pattern of older adults largely 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 show that the error pattern was indeed similar across (Dutch-speaking) children and older adults, but different from younger adults.

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

To assess group differences in the error pattern, we used the Kruskal-Wallis test. In case of a significant group effect, we performed pairwise Wilcoxon tests with Benjamini-Hochberg correction in order to find out which groups were different. Overall, there was a significant group difference in learning (Day 1: $\chi^2(2) = 6.77, p = .03$; Days 2-4: $\chi^2(2) = 19.24, p < .001$). In fact, learning was stronger for children compared with younger adults (Day 1: $p = .046$; Days 2-4: $p < .001$) and for older adults compared with younger adults (Day 1: $p = .046$; Days 2-4: $p < .001$), but did not differ between children and older adults (Day 1: $p = .96$; Days 2-4: $p = .82$). In addition, the proportion of same-position errors for UR differed across groups (Day 1: $\chi^2(2) = 15.00, p < .001$; Days 2-4: $\chi^2(2) = 35.36, p < .001$). Again, this was only the case for children vs. younger adults (Day 1: $p = .002$; Days 2-4: $p < .001$) and younger vs. older adults (Day 1: $p = .002$; Days 2-4: $p < .001$), but not for children vs. older adults (Day 1: $p = .96$; Days 2-4: $p = .64$), which indicates that the syllable-position effect was weaker in children and older adults compared to younger adults.

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 for 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.

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 tested adults, see Figure 1). Our exploratory analyses comparing the three age groups confirmed this similarity between children and older adults. In fact, both the learning effects and the syllable-position effect were 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. 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, Anderson, & Dell, 2019). They 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, linguistic representations might become more elaborate and less directly related to hidden regularities in young adulthood as a function of experience. In older adults, this might shift again due to general cognitive decline. These speculations however merit more research.

Phonotactic learning in older adults was already clearly established from the first day of exposure while for young adults no reliable learning was found until the second day. However, it should be noted that there was at least a descriptive trend towards learning on the first day as well for younger adults, but this was not statistically significant according to the conventional cut-off for significance ($p < .05$). It is possible that it is harder to detect a learning effect on Day 1 for younger participants, who a) produce far fewer errors than older participants (thus resulting in fewer observations for analysis), and b) show syllable-position effects that are much closer to the ceiling, leaving less room for improvement. A more interesting possibility is that younger participants learn second-order information more slowly than the older participants. This scenario seems compatible with previous studies testing young adults that also found evidence for second-order learning only from the second day of training, i.e., after a night of sleep (Anderson & Dell, 2018). Another finding in support of the idea that young adults may be slower in learning than older adults is that children learn second order constraints more quickly than young adults (cf. Smalle, Muylle, et al., 2017).

Recently, Dell, Kelley, Bian, and Holmes (2019) proposed a connectionist account for the apparently different learning patterns in children and adults. During the task, participants build a mini-grammar – starting from existing knowledge – in which second-order rules are stored temporarily. For this, they rely on hidden units, which might be more commonly used in children than in adults. Indeed, early in language development, children might establish hidden units representing relations between vowels and consonant positions (e.g., /k/ in the context of /i/), in order to represent all possible regularities that exist in language. However, 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 (i.e., in the mini-grammar).

Why then do we observe rapid second-order constraint learning in older adults too? One additional, alternative possibility is that the seemingly slower learning patterns in younger adults (compared to children and older adults) are also explained by the 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, Slama, Bartolomei, & Peigneux, 2017; Daw, Niv & Dayan, 2005; Nemeth, Janacsek, & Fiser, 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).

Experimental evidence for a competitive role of explicit, cognitive control systems in implicit language learning also comes from recent brain stimulation work, which showed that a temporary disruption of the left dorsolateral prefrontal cortex and related cognitive control abilities, facilitates the implicit learning of word-forms through repetition in an immediate recall task (Smalle, Panouilleres, Szmalec & Möttönen, 2017). The speech segmentation study of Palmer et al. (2018) supports the claim that age-related decline in higher cognitive mechanisms interacts with implicit language learning. Their finding that older adults perform as well as younger adults when there is no cognitive load suggests that age-related declines in language acquisition, if any, are likely due to a selective decline in explicit cognitive processes rather than to a pure implicit learning impairment.

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., lower syllable position effect). This pattern was highly similar to what has been observed previously in children and non-linguistic constraint learning.² 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. Note on r : .1 to .3: small effect; .3 to .5: intermediate effect; .5 and higher: strong effect (Cohen, 1988).
2. 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

- 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 of the United States of America*, 115, 3617-3622. <http://dx.doi.org/10.1073/pnas.1721107115>
- Audacity Team (2019). Audacity(R): Free Audio Editor and Recorder [Computer application]. Version 2.3.1 retrieved March 20th 2019 from <https://audacityteam.org>
- Bennett I. J., Howard J. H., Jr., & Howard D. V. (2007). Age-related differences in implicit learning of subtle third-order sequential structure. *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences*, 62, 98–103. <http://dx.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*, 89, 71-84. <http://dx.doi.org/10.1016/j.cortex.2017.01.023>
- Cleeremans, A. & Jiménez, L. (2002). Implicit learning and consciousness: A graded, dynamic perspective. In French, R.M. & Cleeremans, A. (Eds.), *Implicit Learning and Consciousness: An empirical, philosophical and computational consensus in the making* (pp. 1-40). Hove: Psychology Press.
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2. Auflage). Hillsdale, NJ: Erlbaum.
- Craik F. I., & Bialystok, E. (2006). Cognition through the lifespan: Mechanisms of change. *Trends in Cognitive Sciences*, 10, 131-138. <http://dx.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*, 8, 1704–1711. <http://dx.doi.org/10.1038/nn1560>
- 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, 1246-1256.
<http://dx.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*, 26, 1355–1367.
<http://dx.doi.org/10.1037/0278-7393.26.6.1355>
- 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*, 39, 175-191. <http://dx.doi.org/10.3758/BF03193146>
- Fromkin, V. A. (1971). The non-anomalous nature of anomalous utterances. *Language*, 47, 27– 52.
<http://dx.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, 1243–1252.
<http://dx.doi.org/10.1177/0956797612472207>
- Hakuta, K., Bialystok, E., & Wiley, E. (2003). Critical evidence: a test of the critical-period hypothesis for second-language acquisition. *Psychological Science*, 14, 31–38.
<http://dx/doi.org/10.1111/1467-9280.01415>
- Hedden, T., & Gabrieli, J. D. E. (2004). Insights into the ageing mind: a view from cognitive neuroscience. *Nature Reviews Neuroscience*, 5, 87–96. <http://dx.doi.org/10.1038/nrn1323>
- Hedenius, M., Persson, J., Tremblay, A., Adi-Japha, E., Veríssimo, J., Dye, C. D., et al. (2011). Grammar predicts procedural learning and consolidation deficits in children with specific language impairment. *Research in Developmental Disabilities*, 32, 2362–2375.
<http://dx.doi.org/10.1016/j.ridd.2011.07.026>
- Howard, J. H. Jr., & Howard, D. V. (1997). Age differences in implicit learning of higher order dependencies in serial patterns. *Psychology and Aging* 12, 634–656.
<http://dx.doi.org/10.1037/0882-7974.12.4.634>
- Howard, J. H. Jr., & Howard, D. V. (2013). Aging mind and brain: is implicit learning spared in healthy aging? *Frontiers in Psychology*, 4, 817. <http://dx.doi.org/10.3389/fpsyg.2013.00817>

- 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- and within-group differences in average response times. *PLoS ONE*, 14: e0215116. <https://doi.org/10.1371/journal.pone.0215116>
- Morgan-Short, K., Finger, I., Grey, S., & 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, 933–947. http://dx.doi.org/10.1162/jocn_a_00119
- Nemeth, D., & Janacsek, K. (2011). The Dynamics of implicit skill consolidation in young and elderly adults. *The Journals of Gerontology: Series B*, 66B, 15-22. <http://dx.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*, 7, 1-13. <http://dx.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*, 33(7), 1035-1044. <http://dx.doi.org/10.1037/pag0000292>
- 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*, 414, 546-550. <http://dx.doi.org/10.1038/35107080>
- Raven, J., Raven, J. C., & Court, J. H. (2000). *Manual for Raven's progressive matrices and vocabulary scales. Section 3: The standard progressive matrices*. Oxford, UK: Oxford Psychologists Press; San Antonio, TX: The Psychological Corporation.
- 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*. Advance online publication. <http://dx.doi.org/10.1037/xlm0000686>
- 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, 1821-1827. <http://dx.doi.org/10.1037/xlm0000405>

- Smalle, E., Panouilleres, M., Szmalec, A., & Möttönen, R. (2017). Language learning in the adult brain: disrupting the dorsolateral prefrontal cortex facilitates word-form learning. *Scientific Reports*, 7, 13966. <http://dx.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. *The Journals of Gerontology: Series B*, 71, 212-219. <http://dx.doi.org/10.1093/geronb/gbu135>
- Verneau, M., van der Kamp, J., Savelsbergh, G. J., & de Looze, M. P. (2014). Age and time effects on implicit and explicit learning. *Experimental Aging Research*, 40, 477–511. <http://dx.doi.org/10.1016/j.actpsy.2015.01.009>
- Warker, J. A., & Dell, G. S. (2006). Speech errors reflect newly learned phonotactic constraints. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32, 387-398. <http://dx.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*, 34, 1289–1295. <http://dx.doi.org/10.1037/a0013033>
- Wechsler, D. (2008). *Wechsler Adult Intelligence Scale—Fourth Edition*. San Antonio (TX): Pearson.

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

	Day	Experiment-wide constraint			Unrestricted			Total
		Same	Different	% Same ^a	Same	Different	% Same ^a	
Younger	1	131	8	92.9	326	54	84.2	519
	2	81	3	98.5	261	47	86.8	392
	3	62	4	95.6	173	25	92.1	264
	4	52	2	95.6	193	24	89.5	271
Older	1	366	71	89.2	361	199	65.0	997
	2	321	35	89.9	423	154	72.0	933
	3	320	35	93.8	417	218	72.6	990
	4	355	21	92.4	399	212	70.9	987

^a Proportions listed here are calculated as the mean across the participants' individual proportions.

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.