The Mismeasurement Of Mind: Lifespan Changes in Paired Associate Test Scores Reflect The 'Cost' Of Learning, Not Cognitive Decline

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Abstract

The age-related declines observed in scores on Paired Associate Learning tests are widely taken as evidence that supports the idea that human cognitive capacities decline across the lifespan. In a computational simulation, we show that the patterns of change in PAL scores are actually predicted by the models that formalize the associative learning process in other areas of behavioral and neuroscientific research. These models also predict that manipulating language exposure can reproduce the experience-related performance differences erroneously attributed to age-related decline in age-matched adults. Consistent with this, old bilinguals outperformed native speakers in a German PAL test, an advantage that increased with age. These analyses and results show that age-related PAL performance changes reflect the predictable effects of learning on the associability of test items, and indicate that failing to control for these effects is distorting our understanding of cognitive and brain development in adulthood.

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The ability to learn and recall arbitrary word pairs – e.g., *jury–eagle* – during Paired Associate Learning (PAL) tests declines systematically as adult age increases. Along with similar patterns of change on other neuropsychological tests, this is thought to show that cognitive capacities decline across adulthood, functionally characterizing the structural changes that occur as healthy brains age (Deary et al, 2009; Salthouse, 2011; Singh-Manoux et al., 2012; Lindenberger, 2014).

PAL tests are particularly sensitive to the effects of age on cognition (Rabbitt & Lowe, 2000), which are evident surprisingly early in adulthood. Average performance on the PAL subtest of Wechsler's Memory Scale (desRosiers & Ivison, 1988) of 78% in 20-29 year-olds, falls to 70% by 30-39, the largest by-decade decline on this test across the lifespan (desRosiers & Ivison, 1988; see Figure 1; Wilcoxon signed-rank test on average item scores (range: 1.13-2.97): $z = 3.71$, $p < 0.001$, 95% confidence interval: 0.14-0.33; Ramscar & Port, 2016).

However, considered alone, these changes <u>cannot</u> be considered to offer evidence of significant cognitive decline between ages 20 and 40. This is because raw PAL scores cannot be used to compare performance between groups whose experience varies unless one also assumes that PAL performance is unaffected by differences in people's prior experience of PAL items, an assumption that research into associative learning has repeatedly shown to be false. Learning to associate a cue – *jury* – with an outcome – *eagle* – <u>cannot</u> be predicted from **association rates** alone (for a review, see see Ramscar, Dye & McCauley, 2013a), and two other factors have been shown to be critical to associative learning: cue **background rates** (Rescorla, 1968; Ramscar, Dye & Klein, 2013b; in PAL tests, the frequencies at which cue words are encountered absent response words), and **blocking** (Kamin, 1969; Arnon & Ramscar, 2012; the prior predictability of a response in context).

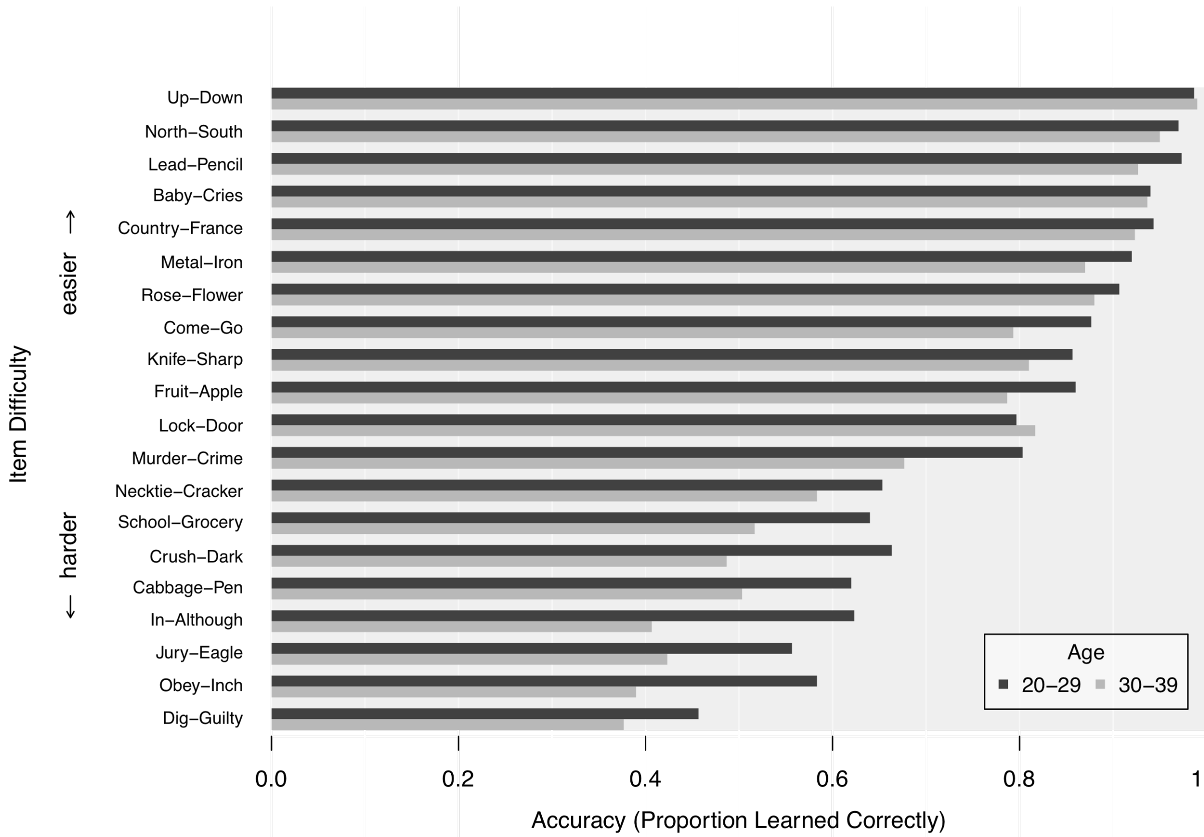

Figure 1. Average by-item performance for 400 adults aged 20-29 and 30-39 (50% females per group) on forms 1 & 2 of the WMS-PAL subtest (desRosiers & Ivison, 1988). The order of items on the y-axis is based on the mean item score across both age groups, with harder items near the bottom of the plot.

While association rates tend to promote learning, blocking and background rates inhibit it, and critically, the way these factors interact to influence the learning of a specific association is entirely a function of a learner's experience (Ramscar et al., 2013a). All three factors are also critical to explaining the pattern of PAL performance across adulthood: As Figure 1 shows, age makes "hard" PAL items proportionally harder to learn than "easy" items, a non-linear pattern that is not predicted by theoretical accounts of cognitive decline; however, as the following simulation shows, this pattern is predicted by standard models of the associative learning process.

Simulation Experiment

Methods

The development of word associations in a small lexicon comprising four “easy” (meaningful) PAL pairs (*baby-cries, baby-eagle, jury-duty* and *jury-summons*) and two “hard” (meaningless) pairs (*baby-summons* and *jury-eagle*; see Figure 1) was simulated using the Rescorla-Wagner (1972) learning rule (computationally, the rule describes a discriminative learning process; Ramscar, Yarlett, Dye, Denny & Thorpe, 2010). To reflect the distributional differences of words in natural languages, and to show how variations in word co-occurrences in a typical English-speaker’s experience will affect learning over time, the meaningless items were pre-trained with low association rates (10 times each).

The effect that experience of the more frequent meaningful pairs have on PAL learnability was then simulated by training the model on *jury-duty* 40 times, *baby-cries* and *baby-eagle* 60 times, and *jury-summons* 80 times. The order in which individual item exemplars were presented was determined randomly, subject to the probability of their occurrence in training. The simulations were run using the *ndl* package for the statistical software R, and the code for the simulation is available in the supplementary materials.

Results

The development of the word associations in the model is plotted in Figure 2. As can be seen, increased experience of a world containing *jury-duty* and *baby-eagle* serves to discriminate against the learnability of *jury-eagle*. Increased experience with the meaningful word-pairs increases the background rate of *jury* in relation to *eagle*, while simultaneously forcing *jury* into competition for associative value with the more frequent cue *baby.* This ultimately results in the model learning a negative association between *jury* and *eagle*, and negative association will have to be unlearned in order for the model to positively associate *jury* with *eagle*.

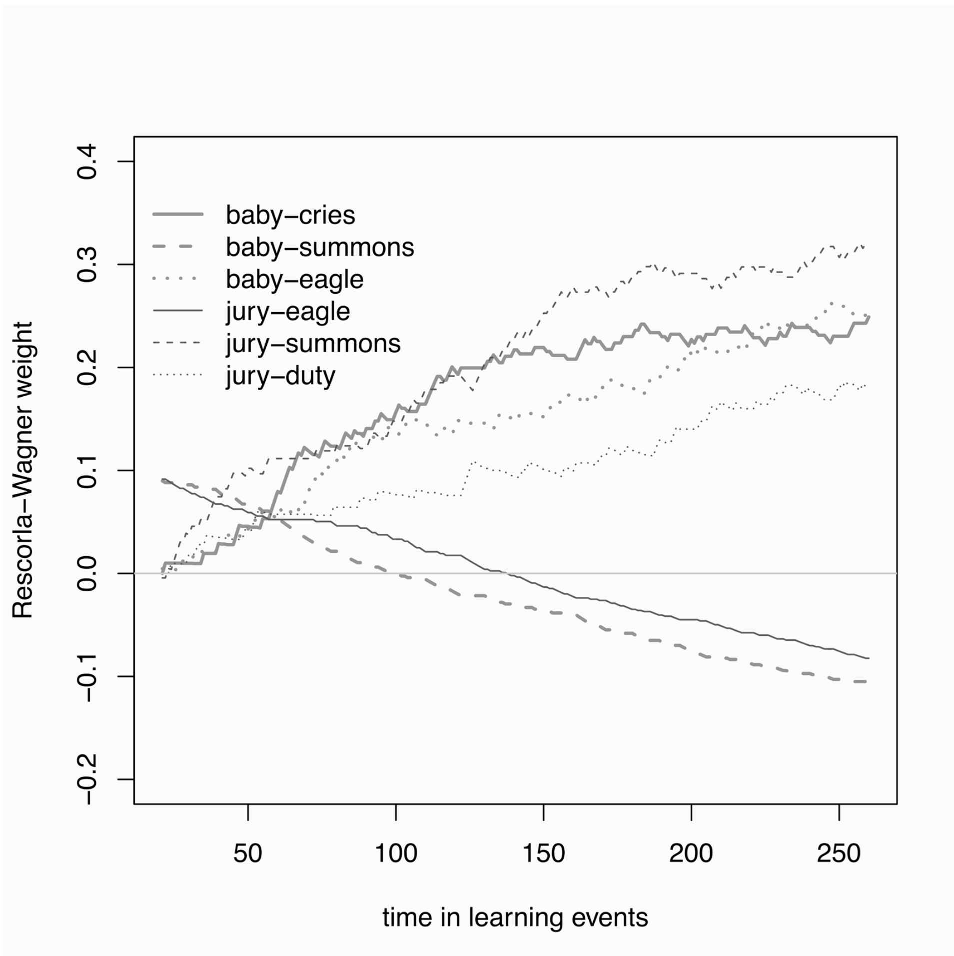

Figure 2: The development of associations between the words in the model's lexicon after each training epoch. As the model's experience of *jury* and *eagle* in other contexts increases, the strength of the *jury-eagle* association declines, such that a single new exposure will exert an ever-weaker influence of the learned strength of this pair. Eventually, the model develops a negative expectation for *eagle* given *jury*.

What do declining PAL scores tell us about cognition?

The simulation results are further supported by analyses of the WMS-PAL normative data (desRosiers & Ivison, 1988) by Ramscar & Port (2016), who found that using large text corpora to empirically derive parameters for the **background rates** (*w1* frequencies), **blocking** (frequency *w2* / frequency *w1*), and **association rates** (*w1-w2* co-occurrence rates) for the PAL pairs plotted in Figure 1 accounted for over 85% of the by-item variance in the observed performance of the 20-29 and the 30-39 year-old age groups. Consistent with the simulation results, background rates and blocking were associated with lower scores, while association-rates were associated with higher scores, with sensitivity to all of the predictors being greater in the 30-39 year-old group as compared to the 20-29 group (Ramscar & Port, 2016; see Ramscar, 2014 for a replication using different corpora). Further analyses of the full normative data set revealed that this pattern is consistent across the lifespan (Ramscar et al., 2013c), such that the oldest adults' (ages 60-69) performance showed greatest sensitivity to the factors that caused negative associations to develop in the simulation, whereas these factors did not significantly influence the youngest participants' performance at all. In terms of learning the more complex set of word associations in the English lexicon, 20-29 year-olds' performance is akin with learning at around epoch 60 in the simulation, and 60-69 year-olds' performance is more like epoch 250.

In other words, long-established principles of learning explain why some PAL pairs are harder or easier to learn in the first place, as well as predicting that PAL performance can be expected to decline as adults age, simply because the discriminative processes that produce "associative" learning teaches English-speakers not only which words go together, but also which words do not go together. This process both increasingly differentiates meaningful and meaningless word-pairs (Figure 1) and makes meaningless pairs harder to learn (Figure 2).

Behavioral Experiment

Because of the way people are exposed to language throughout their lives, native (L1) speakers of similar ages and educational backgrounds have levels of first language experience that significantly exceed that of age-matched adult second-language (L2) speakers. Our simulation and analyses make two clear (somewhat counterintuitive) predictions about how these differences will affect PAL performance:

1. Older native speakers (OA L1) ought to perform worse on lexical PAL tests than age-matched non-native speakers of a language (OA L2).
2. The differences in native and bilingual PAL performance can be expected to increase with growing experience (see Figure 2).

By contrast, if PAL tests do in fact measure cognition simply as a function of frequency of presentation, then OA L2 speakers should not out-perform OA L1s. Indeed, given that frequent PAL pairs are easier than infrequent ones, a naïve account should predict that OA L1's greater L1 experience should lead them to outperform OA L2's.

Methods

To examine these hypotheses, we tested 20 young (18-28 year old) and 20 older (38-53 year old) monolingual speakers of German (a non-tonal language deriving most of its lexicon from the Germanic branch of the Indo-European language family) and two age-matched groups of 20 native speakers of Mandarin (a tonal member of the Sino-Tibetan language family), for whom

German is a second language. Given that PAL is a reliable measure that is particularly sensitive to the effects of aging (Rabbitt & Lowe, 2000) and that Ns < 20 are typical in neuropsychological studies that employ PAL tests, this sample was judged to be sufficient to test these hypotheses. The monolinguals completed a PAL test in German only, whereas the bilinguals completed Chinese and German PAL tests (see supplementary materials for details).

Table 1 shows the mean age for the 4 groups of participants, as well as the mean scores in vocabulary tests in German – and where applicable Chinese – which confirm native-speaker superiority when it comes to vocabulary skills.

Table 1: Mean by-group age and vocabulary scores for each of the 4 groups of participants. Medians and ranges are provided in brackets.

		Age	German Vocabulary	Chinese Vocabulary
Chinese-German Bilinguals	young	24.55 (25; 20-28)	31.75 (31.5; 25-46)	67.65 (67.50; 52-79)
	old	43.60 (43; 38-53)	40.25 (39; 29-55)	64.65 (66; 53-75)
German Monolinguals	young	23.45 (23; 18-28)	81.95 (81.5; 66-90)	- (-)
	old	44.90 (44.5; 38-52)	84.10 (84; 76-91)	- (-)

Results

An analysis of the performance of our participants using generalized additive models (GAMMs; Wood, 2006) revealed a significant age by co-occurrence frequency[1] interaction ($\chi^2 = 38.687$; $p < 0.001$). The interaction differed depending on whether the test was administered in participants' first (L1) or second language (L2; $\chi^2 = 9.122$; $p < 0.028$). For young adults (YAs), L1 and L2 performance was similar, and the interaction between age and frequency ($\chi^2 = 19.658$; $p = 0.001$)

did not differ between L1 and L2 ($\chi^2 = 1.357$; $p = 0.961$). This is consistent with previous analyses that showed that YA PAL performance is largely insensitive to background rates and blocking (Ramscar, Hendrix, Love & Baayen, 2013). By contrast, the performance of older adults (OA) was better in L2 than in L1 (revealed by an age by co-occurrence frequency interaction ($\chi^2 = 36.335$; $p < 0.001$) that differed significantly between L1 and L2 ($\chi^2 = 14.959$; $p = 0.002$), with a main effect of L1/L2 indicating that OA performance was better in L2 than L1 ($z = 2.113$, $p < 0.035$)).

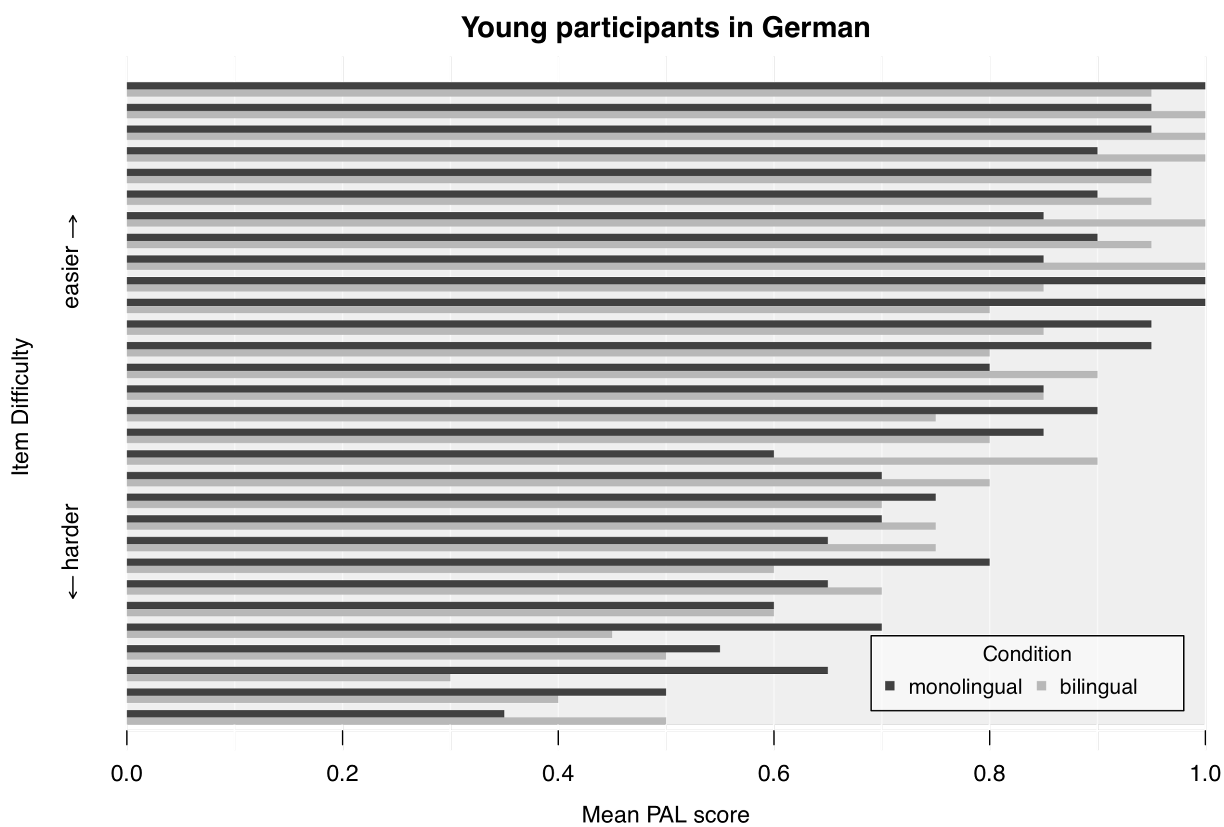

Figure 3. By-item performance for young native German speakers (YAL1) and young Chinese-German bilinguals (YAL2) in German. The order of items on the y-axis is based on the mean item score across both age groups, with harder items near the bottom of the plot.

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[1] Co-occurrence frequency, which provides a simple, objective estimate of the <u>easiness</u> of PAL pairs, was measured as the

Figure 3 shows a by-item bar plot for the performance of young monolinguals and bilinguals in German. Consistent with the GAM analysis, Figure 3 reveals that the performance of monolinguals and bilinguals in German is comparable for YAs. Bilingual YAs outperformed monolingual YAs on 14 items, whereas monolingual YAs performed bilingual YAs on 13 items (with performance being identical for the remaining three items).

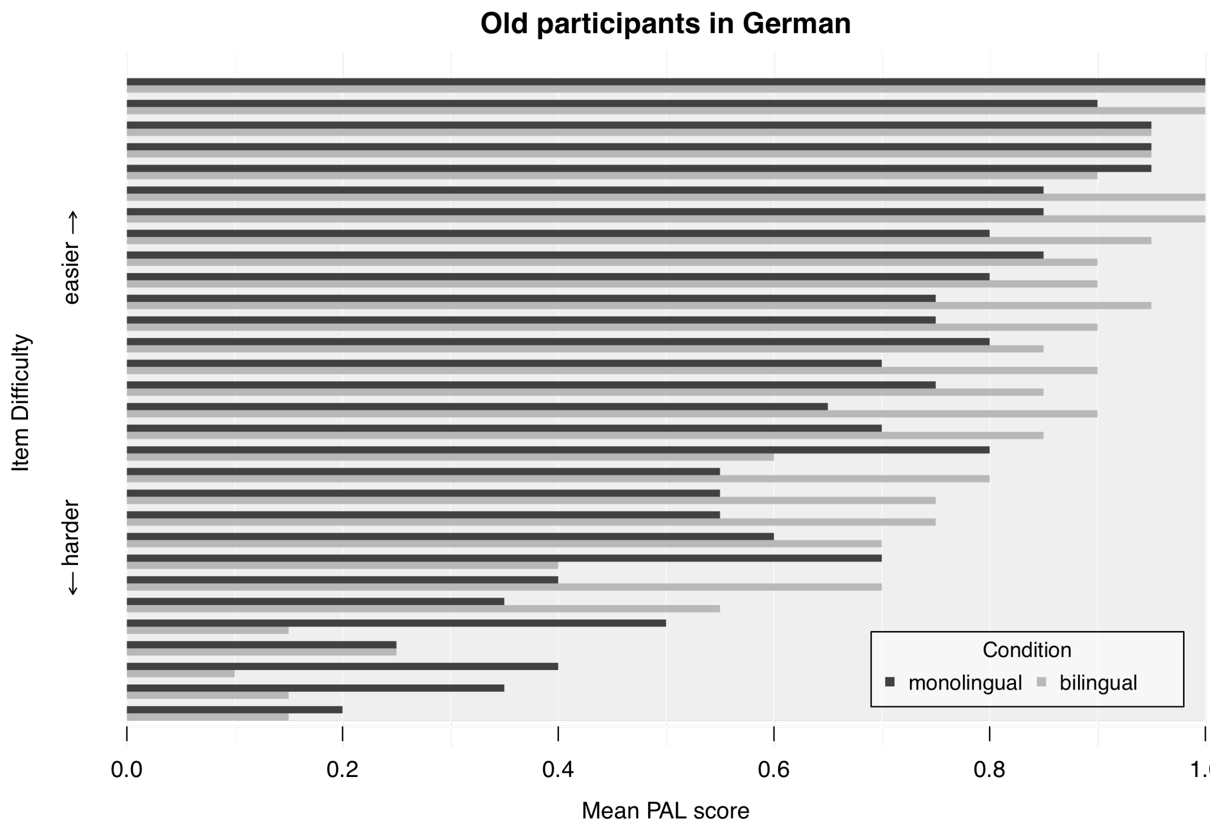

Figure 4. By-item performance for old native German speakers (OA L1) and old Chinese-German bilinguals (OA L2) in German. The order of items on the y-axis is based on the mean item score across both age groups, with harder items near the bottom of the plot.

The three-way interaction between age, association rate and first/second language is reflected in Figure 4, a by-item bar plot of the performance of old monolinguals and bilinguals in

number of times *w1-w2* appear together in *Google* documents.

German. Older participants performed better in L2 than in L1 for the majority of the co-occurrence frequency range (19/25 of the easiest PAL pairs). For the very "hardest" PAL items – i.e., those with the lowest association rates – this pattern reversed, such that the older adults performed worse in L2.[2] In addition to the improved performance of older participants in the second language, we observed an attenuation of the Age effect in the second language.

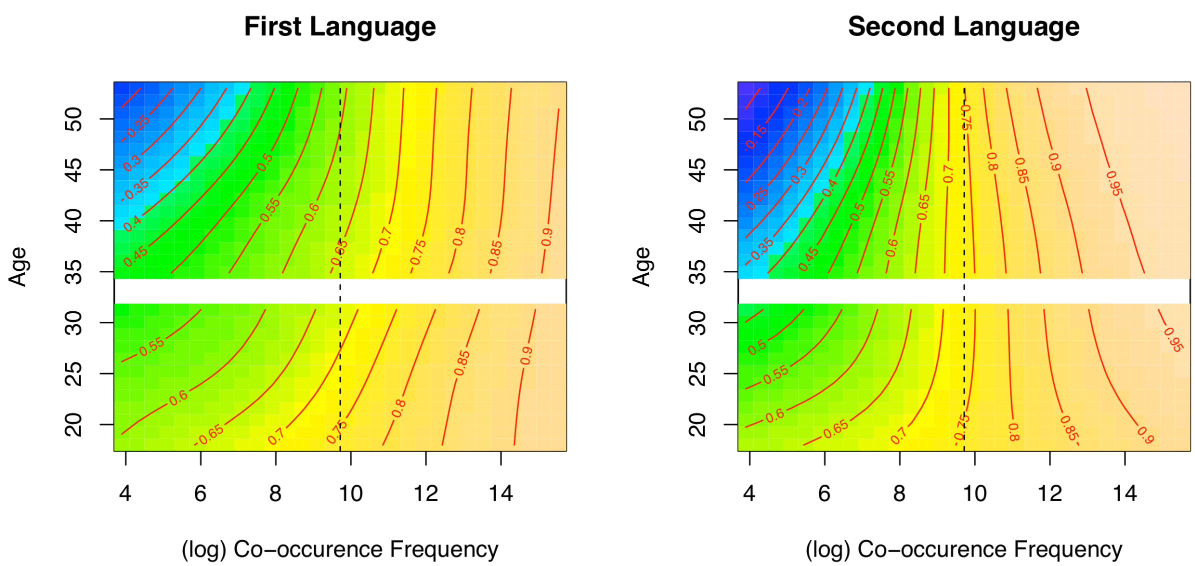

Figure 5: Effect of (log-transformed) Co-Occurrence Frequency and Age on the Paired Associate Learning performance in the first and second language. The z-axis represents proportion correct in the paired associate learning test, contour lines connect points with the same accuracy scores. Dotted lines indicate the mid-point of the (log) Co-occurrence Frequency range. Older participants, but not younger participants show improved performance in their second language. The typical age effect for monolinguals is present in L1, but reverses in L2 with increasing co-occurrence frequency.

[2] This highlights an important difference between an older bilingual and a younger monolingual: the former are not restricted to thinking about tasks in one language. There is no reason to suspect that items like *banana-lake* are more related in Chinese than they are in German, and it is likely that when faced with learning nonsensical links between the hardest items, OA L2s may have turned to their native language - where these words are at least better learned - for support.

Figure 5 shows the predicted performance (Proportion Correct) in the First Language and in the Second Language as a function of Age and Co-occurrence Frequency. As can be seen, there is a clear age effect in the first language, which is qualitatively similar to the age effects reported in monolingual paired associate learning studies. Throughout the left panel of Figure 5, the performance of the old participants is worse than that of the young participants. The difference is small for items with high association rates, but increases as co-occurrence frequency decreases. At the mid-point of the co-occurrence frequency range (as indicated by the dashed lines in Figure 5), for instance, the estimated performance of the oldest participants is 59% correct, whereas the performance of the youngest participants is 76% correct (difference: 17%). In the second language this age effect is substantially reduced. A clear age effect in the second language is present for the hardest pairs only, albeit for different reasons than in the first language (see above). At the mid-point of the co-occurrence frequency range the estimated performance is between 73% and 76% across the age range. For the easiest pairs old participants even perform somewhat better than young participants, although the performance of both groups is close to ceiling (see supplementary materials for details and further analyses).

Finally, the somewhat counterintuitive prediction tested here – that increased language experience impairs overall PAL performance – is further supported by another result of the study: OAs with doctoral degrees, the attainment of which is likely to involve a larger than usual amount of reading, performed significantly *worse* than OAs without them ($z = -2.073$; $p = 0.035$).

Discussion

Previously we have shown how age-related changes on other measures of cognitive performance are likely to reflect the effects of learning and increased knowledge rather than cognitive decline (Ramscar et al, 2013c, Ramscar, Hendrix, Shaoul, Milin & Baayen, 2014; Blanco, Love, Ramscar, Otto, Smayda, & Maddox, 2016). The present study extends this by showing how standard learning models actually predict that PAL performance will decline even where learning capacities remain constant, simply because cumulative linguistic experience will make meaningless word-pairings ever-harder to learn. This prediction is supported by the results of our study, which show that when age is controlled for, less linguistic experience predicts higher PAL scores, indicating that PAL scores measure the 'costs' that accompany the acquisition of an increasingly well-discriminated lexical knowledgebase.

A steadily accumulating body of evidence in the domain of linguistic cognition indicates that the skills of speakers increase with age and experience: speakers' vowel spaces expand with age, suggesting that the articulation of specific words becomes more distinct with age (Baayen, Tomaschek, Gahl, and Ramscar, *in press*); and although older speakers respond more slowly in the lexical decision task, their accuracy on less frequent words is substantially higher than that of young speakers (Ramscar, Hendrix, Love, and Baayen, 2013), indicative of both more extensive lexical knowledge (Keuleers, Stevens, Mandera, & Brysbaert, 2015) and a speed-accuracy trade-off favoring precision.   Similarly, although speakers increasingly use more pronouns as they age (which has been taken to reflect declining processing capacity, Hendriks, Englert, Wubs & Hoeks, 2008), further examination reveals that this characteristic applies not only to individual speakers, but also to *languages* as they change across generations; and since languages do not age, it seems that in both cases this trend is likely to reflect adaptation to the demands of processing an ever expanding vocabulary (Baayen, Tomaschek, Gahl, and Ramscar, *in press*).

The present results and analyses show that when age is controlled for, higher PAL scores are a "benefit" of the less well-discriminated knowledge associated with less experience. Studies of aging and associative learning outside the linguistic domain support this conclusion: Naveh-Benjamin (2000) shows that older adults are worse at learning associations if "units of information" are unrelated rather than meaningfully related; Castel (2005) shows that older adults are better at associating realistic prices with grocery items than unrealistic prices; and Old & Naveh-Benjamin (2008) show that adults encode less information about background context in memory tests as they age. These findings have previously been taken to reveal age-related "associative deficits" that are (somehow) lessened when associative information is consistent with the environment. However, it is notable that the same pattern of learning the informative and neglecting the uninformative is also seen when infants lose their sensitivity to non-native phonetic distinctions in the course of learning a language (Werker & Tees, 1984), where it is not (typically) seen as cognitive decline. Similarly the finding that, despite their highly developed spatial skills and distinctive hippocampi, London taxi drivers are worse than controls at learning novel object-location associations (but not associations in other domains) is taken to reveal a puzzle, not pathology (Woollett & Maguire, 2012). What the analyses presented here show is that all these phenomena are consistent with what is known about the actual processes of associative learning (Ramscar et al, 2010), and that far from declining, they suggest that when properly analyzed, the learning processes in healthy adults appear to function in a remarkably consistent way across the lifespan.

Our current ideas about age-related cognitive decline are irrevocably linked to the tests used to study the effects of age on cognition, such that cognitive decline is defined in terms of declining test performance. These tests comprise two broad groups that were originally developed across the course of the 20th Century for other purposes: first, a variety of relatively simple clinical tests for assessing neuropsychological injuries and pathologies, designed to allow the loss or damage to a localizable function to be identified by comparing patient performance to normal performance in a population for age, gender, etc. (Strauss, Sherman & Spreen, 2006); and second, a variety of relatively simple psychometric tests developed to assess intelligence in school children, military recruits, etc. (Gregory, 2004). All of these tests make use of learned information, however, in repurposing them for assessing aging researchers have (albeit sometimes implicitly) assumed that performance on them is independent of experience (Deary et al, 2009; Salthouse, 2011; Singh-Manoux et al., 2012; Lindenberger, 2014). Our analyses and results emphasize just how incompatible this assumption is with what we know about how learning from experience actually works (see e.g. McDannald, Jones, Takahashi, & Schoenbaum, 2014; Daw, Courville, & Dayan, 2008; Schultz, 2006; Sutton & Barto, 1981; Rescorla & Wagner, 1972).

It is clear that a proper assessment of cognitive performance in healthy ageing cannot be made unless the knowledge and skills that are inevitably accumulated as experience grows are controlled for. For tests such as PAL, which make use of linguistic stimuli, big linguistic data now make this straightforward, as we have shown. Deconfounding the effects of experience on other tests of lifespan cognitive performance is likely to be less straightforward, but it is nevertheless equally critical. In the meantime, in absence of assessments of the effects of learning on other tests, and in the light of the fact that changes in performance on other lifespan measures of cognitive performance correlate well with corresponding PAL scores (Rabbitt & Lowe, 2000), scientific prudence indicates that the way the results of these tests are interpreted should be tempered. Indeed given that our results indicate that basic learning processes do not decline across the lifespan, and given that the model we used to predict these results has proven remarkably adept at accurately predicting learning across a range of behavioral domains (as well as responses in the structures that implement learning processes in the brain, Schultz, 2006), scientific prudence further indicates that current beliefs about the supposed deterioration of our cognitive faculties across the lifespan ought to be seriously questioned: We have shown that when the interaction between learning and processing is controlled for, the development of linguistic cognition across the lifespan is hopelessly mischaracterized by simple ideas about “decline;” If, as we expect, the effects we have described generalize to other cognitive domains, the associated societal and economical consequences will be profound.

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