Title

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Authors

Ramscar, Michael
Sun, Ching Chu
Hendrix, Peter
et al.

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The mismeasurement of mind: How neuropsychological testing creates a false picture of cognitive aging

Michael Ramscar (michael.ramscar@uni-tuebingen.de)

Ching Chu Sun (ching-chu.sun@uni-tuebingen.de)

Peter Hendrix (petrus.hendrix@uni-tuebingen.de)

Harald Baayen (harald.baayen@uni-tuebingen.de)

Department of Linguistics, Wilhelmstrasse 19,
72074, Tübingen, Germany

Abstract

Age-related declines in scores on neuropsychological tests are widely believed to reveal that human cognitive capacities decline across the lifespan. In a computational simulation, we show how the behavioral patterns observed in Paired Associate Learning (PAL), a particularly sensitive measure of age-related performance change (Rabbitt & Lowe, 2000), are predicted by the models used to formalize associative learning processes in other areas of behavioral and neuroscientific research. The simulation further predicts that manipulating language exposure will reproduce the experience-related performance differences erroneously attributed to age-related decline in age-matched adults. Consistent with this, older 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.

Keywords: aging, learning, cognitive modeling, bilingualism

The measurement of mind across the lifespan

When adults memorize arbitrary word pairs – e.g., *jury–eagle* – during Paired Associate Learning (PAL) tests, their ability to later recall *eagle* given *jury* declines systematically with age. Together with convergent patterns of change on other neuropsychological tests, this is taken to show that cognitive ability declines across adulthood, providing a functional characterization of the age-related structural changes that occur in healthy brains (Deary et al, 2009; Salthouse, 2011; Singh-Manoux et al., 2012; Lindenberger, 2014).

PAL tests are particularly sensitive to the detrimental effects of age on cognition (Rabbitt & Lowe, 2000), which as the data from two groups of adults completing the PAL subtest of Wechsler's Memory Scale, (desRosiers & Ivison, 1988) plotted in Figure 1 shows, are evident surprisingly early in life (Singh-Manoux et al., 2012): Mean performance of 78% in 20-29 year-olds falls to 70% in 30-39 year-olds (t(19)=5.286, p<0.01; Ramscar & Port, 2015), the largest by-decade decline observed on this test across the lifespan (desRosiers & Ivison, 1988).

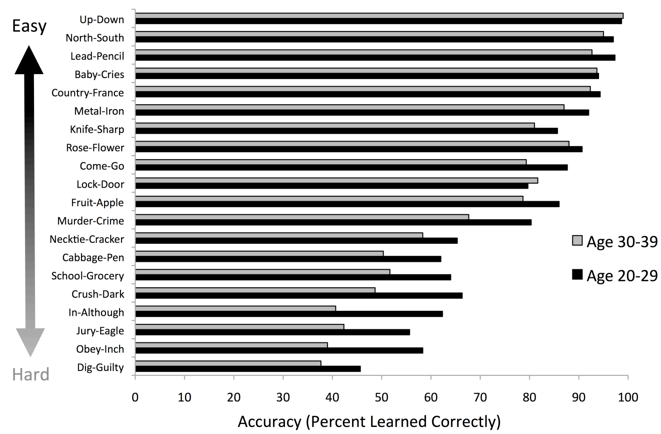

Figure 1: Average by-item performance for 400 adults aged 20-29 and 30-39 (50% females / group) on forms 1 & 2 of the WMS-PAL subtest (desRosiers & Ivison, 1988).

In what follows, we show that these changes are not evidence of cognitive decline, because raw PAL scores cannot be used to compare performance between groups whose experience varies. The reasons why begin with the fact that PAL tests present items (typically word-pairs) at a fixed rate: every word-pair is heard N times prior to testing. This means that to use raw PAL scores to compare performance in different age-groups, one must assume that learning during the test is unaffected by differences in prior experience of PAL items.

An enormous body of research has shown this assumption to be false. Psychometricians have long-known that the empirical properties of word-pairs make some easier to learn than others (desRosiers & Ivison, 1988); And research into associative learning has repeatedly shown that learning to associate a behavioral cue (the word *jury*) with a behavioral outcome (*eagle*) cannot be reliably predicted from the **association rate** of a cue and a response alone (Rescorla & Wagner, 1972; Ramscar, Dye & McCauley, 2013a).

Two other important factors have shown to influence associative learning: Cue **background rates** (Rescorla, 1968; Ramscar, Dye & Klein, 2013b), which, in PAL tests are the frequencies at which cue words have been encountered *absent* response words, and **blocking** (Kamin, 1969; Arnon & Ramscar, 2012), the predictability of the response given the cue (in context) prior to training. 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 given learner's experience (Ramscar et al., 2013a).

This last point is critical to understanding the patterns of PAL performance across the lifespan. As can be seen in Figure 1, aging makes "hard" PAL items proportionally harder to learn than "easy" items. This non-linear pattern of change is not predicted by simple declines in plasticity or fluid-intelligence – the changes that theories of cognitive aging posit to explain declining test scores – yet as the following simulation shows, it falls naturally out of the interaction between experience and the three factors shown to influence associative learning that we just described.

Simulation Experiment

The development of word associations in a small lexicon of PAL items was simulated using the Rescorla-Wagner (1972) learning rule (computationally, this rule describes a discrimination learning network, Ramscar et al, 2013a). The lexicon comprised four "easy," or meaningful PAL pairs (*baby-cries, baby-eagle, jury-duty* and *jury-summons*) and two meaningless, or "hard" pairs (*baby-summons* and *jury-eagle*; see Figure 1).

To reflect the fact that the distributional properties of the words that occur in natural languages differ, and to show how the 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 (each was presented 10 times). Then to simulate the effect that experience of the more frequent meaningful pairs will have on the learnability of the meaningless items, we presented the model with *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.

Results

The development of the word associations in the model's lexicon (Figure 2) illustrates how 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*; this would have to be unlearned in order for the model to positively associate *jury* with *eagle*.

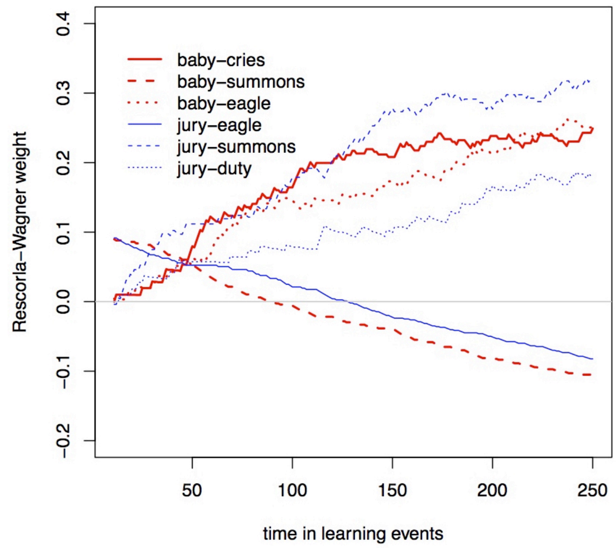

Figure 2: The development of word pair associations in the model's lexicon after each training epoch. As the model's experience of *jury* and *eagle* in other contexts increases, the strength of the *jury-eagle* association declines, such that a single new exposure will exert an ever-weaker influence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

What do declining PAL scores reveal?

Simulating PAL using a standard associative learning rule predicts that hard items will get harder over time. Since empirical studies reveal the same pattern of change (Figure 1), this raises a question: Does lifespan PAL performance reveal cognitive declines, or the predictable outcome of learning? To examine this, Ramscar & Port (2015) used 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. These parameters accounted for over 85% of the by-item variance in the observed performance of *both* the 20-29 and the 30-39 year-old age groups. As predicted by learning theory, the parameters for background rates and blocking were associated with lower scores, and the association-rate parameter was associated with higher scores, and sensitivity to each of the predictors was greater in the 30-39 than the 20-29 group (Ramscar & Port, 2015; see Ramscar, 2014 for a replication using different corpora).

An analysis of all the WMS-PAL normative data showed this pattern to be consistent across the lifespan (Ramscar et al., 2013c): oldest adults' (ages 60-69) performance showed the greatest sensitivity to the three lexical factors that learning theory predicts *should* influence the learnability of word-pairs, whereas the factors that caused negative associations to develop in the simulation did not significantly influence the youngest participants' performance (ages 20-29). In terms of learning the – obviously far more complex – ser of word associations in the English lexicon, 20-29 year-olds' performance is thus consistent with learning at around epoch 50 in the simulation, and 60-69 year-olds' performance more akin to epoch 250.

It is thus clear that long-established principles of learning explain (1) why some PAL pairs are hard or easy (a fact psychometricians acknowledge yet fail to explain), and (2) why PAL performance ought to be expected to decline as adults age: In both cases, because of how the processes of "associative" learning have empirically been shown to work (i.e., discriminatively), experience not only teaches English-speakers which words go together, it *also* teaches them which words do not go together; and while this process increasingly differentiates meaningful and meaningless word-pairs (Figure 1), it simultaneously makes meaningless pairs ever harder to learn (Figure 2).

Behavioral Experiment

Not only do well-established models of the associative learning process predict that experience will increasingly inhibit the learning of word-pairs like *North-Dog*, they also provide a means for empirically deconfounding age and experience in PAL performance. Because of the way people are exposed to language throughout their lives, native (L1) speakers of similar ages and educational backgrounds inevitably have levels of first language experience that significantly exceed that of age-matched adult second-language (L2) speakers. Both the analysis and the simulation presented above make two clear and somewhat counterintuitive predictions about how these experiential differences will affect PAL performance:

1. Older native speakers (OAL1) ought to perform worse on lexical PAL tests than age-matched non-native speakers of a language (OAL2).
2. The difference between native and bilingual PAL performance can be expected to increase with growing experience (see Figure 2).

If, on the other hand, PAL tests actually do measure cognition independently of experience, as current practices assume, then OAL2 speakers should not out-perform OAL1s. Indeed, given that experience makes some PAL pairs easier than others, a naïve account ought to predict that OAL1's greater experience of the German items should lead them to outperform OAL2's.

Method

We tested these hypotheses on 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 (Table 1; given that PAL is a reliable measure that is particularly sensitive to the effects of aging, Rabbitt & Lowe, 2000, and 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).

Table 1: By-group age and vocabulary scores for each of the groups of participants (standard deviations in brackets).

		Age	German Vocabulary	Chinese Vocabulary
Chinese-German Bilinguals	young	24.55 (2.27)	31.75 (5.35)	67.65 (6.46)
	old	43.60 (4.66)	40.25 (7.86)	64.65 (7.09)
German Monolinguals	young	23.45 (3.06)	81.95 (6.25)	- (-)
	old	44.90 (4.36)	84.10 (4.38)	- (-)

The harder items in the PAL task contained relatively infrequent words. To ensure participants knew all the words used in the test, vocabulary tests were conducted prior to the PAL task in both languages. Performance on the vocabulary test in German was highly variable, particularly for the young Chinese-German bilinguals. Participants in this group were typically graduate students at the University of Tübingen. While some of these students were highly competent in L2, others had considerably less experience. A number of these less experienced L2 learners explicitly stated that they did not know some of the words in the German PAL test.

To minimize the risk of young Chinese-German bilingual participants not knowing words in the PAL test, the 20 participants with the best performance on the vocabulary pretest in German were selected from a larger group of 34 young Chinese-German bilinguals. Vocabulary test performance was calculated as a weighted sum of the number of correct answers, with item weights being the proportion of correct answers for the items across the young and old bilingual participants.

The items for the vocabulary and paired associate learning tests in both languages were recorded from native female speakers of Mandarin Chinese and German in a sound booth using professional recording equipment.

In the vocabulary pre-test, participants were auditorally presented with a word and the 4 possible answers and were asked to select the answer that was most similar in meaning to the test word by clicking one of four buttons labeled 1 through 4 on the screen. Participants were asked to guess if they did not know the correct answer to a question.

In the paired associate learning task each block comprised a training phase and a test phase of 10 pairs. Participants were asked to memorize the pairs of words in the training phase. For the test phase, participants were asked to produce the word that formed a pair with the auditorily presented test word. The test phase was self-paced: participants were asked to press the next button on the screen to move on to the next test word after verbally responding to a test word.

The average time required to complete the vocabulary pre-test for each language was about 30 minutes. The 3 blocks of paired associate learning took about 25 minutes per participant in each language, including a short break between each block.

Materials

The vocabulary tests for both German and Chinese consisted of 100 multiple choice questions with 4 possible answers. The 3 incorrect answers were chosen from the same parts-of-speech category as the correct answer.

The word frequency distributions for the German and Chinese vocabulary tests were matched, and items were designed to ensure that Cue Frequency, Response Frequency and Co-Occurrence Frequency (in Google documents) for the pairs in each language were approximately normal.

The PAL test in both languages consisted of three groups of 10 pairs. Pairs ranged in diffculty from easy (e.g.; “学校” - “读书” (school-study) or “Nord”-“Süd” (north-south)) to hard (e.g.; “Schiff” - “Puppe” (ship-doll) or “洋葱”-“手指” (onion-finger)). Words occurred no more than once in each of the paired associate learning tests.

Results

Analysis of our participants' PAL performance of using generalized additive models (Wood, 2006) revealed a significant age by co-occurrence frequency interaction (χ^2 = 38.687; $p < 0.01$; co-occurrence frequency, which provides a simple, objective estimate of the easiness of PAL pairs – see Figure 2 – was measured here as the number of times *w1-w2* appear together in *Google* documents). This interaction differed depending on whether the PAL test was administered in participants' first (L1) or second language (L2; χ^2 = 9.122; $p < 0.05$). For young adults (YAs), L1 and L2 performance was similar, and the interaction between age and frequency (χ^2 = 19.658; $p < 0.01$) did not differ between L1 and L2 (χ^2 = 1.357; $p > 0.9$). This is consistent with previous analyses which showed that YA PAL performance is largely determined by association rates, and insensitive to background rates and blocking (Ramscar, Hendrix, Love & Baayen, 2013). By contrast, older participants performed <u>better</u> when the PAL test was administered in L2 (revealed by an age by co-occurrence frequency interaction (χ^2 = 36.335; $p < 0.01$) that differed significantly between L1 and L2 (χ^2 = 14.959; $p < 0.01$), with a main effect of L1/L2 indicating that OA performance was better in L2 than L1 ($z = 2.113$, $p < 0.05$).

The presence of a significant three-way interaction between age, association rate and first/second language reveals that the advantage for the older participants in their second language was not uniformly distributed. For the majority of the co-occurrence frequency range (19/25 of the easiest PAL pairs), the older participants performed better in L2 (Figure 6). However, 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.

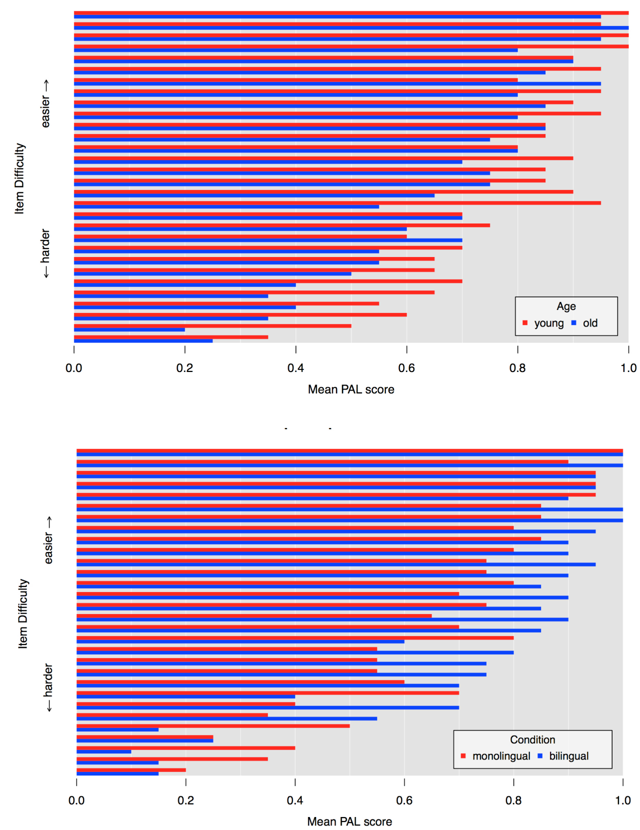

Figure 3: *Top Panel*: Average by-item German PAL performance for older and younger native German speakers (OAL1 and YAL2). *Bottom Panel*: Performance of age-matched older native German speakers (OAL1) and older Chinese-German bilinguals (OAL2) tested in German.

This highlights an important difference between older bilinguals and younger monolinguals: The former are not restricted to thinking about tasks in one language. Since there is little reason to suspect that items like *banana-lake* are any more related in Chinese than they are in German, it seems likely that when faced with learning the nonsensical links between the hardest items, OAL2s may have sought support from their native language. However, since well-learned native *dis*sociations will hinder learning on this test (and increase task complexity), this strategy will have had the opposite effect to that desired (see also Ramscar, Dye & Klein, 2013). Finally, the counterintuitive idea tested here – that increased language experience actually impairs PAL performance – gains further support from another finding from this study: OAs with doctoral degrees (the attainment of which likely involves a larger than normal amount of reading) performed significantly *worse* than OAs without them ($z = -2.073$; $p < 0.05$).

Discussion

In other work, we have shown how age-related performance changes on other neuropsychological tests are likely to reflect the effects of cumulative learning rather than cognitive decline (Ramscar et al, 2013c, Ramscar, Hendrix, Shaoul, Milin & Baayen, 2014; Blanco, Love, Ramscar, Otto, Smayda, & Maddox, 2016; Baayen, Tomaschek, Gahl, and Ramscar, *in press*). The present study extends this, showing how discriminative learning theories (Rescorla, 1988; Ramscar, Yarlett, Dye, Denny, & Thorpe, 2010; Ramscar et al., 2013a) predict that PAL performance will decline even when learning capacities are constant, simply because cumulative linguistic experience will make meaningless word-pairings ever harder to learn.

These predictions are supported by the results of our empirical study – which show that when age is controlled for, less linguistic experience predicts higher PAL scores – and by other studies of aging and associative learning, e.g.,: Naveh-Benjamin (2000) showed that older adults are worse at learning associations between unrelated "units of information" than when they are meaningfully related; Castel (2005) showed that older adults are better at associating realistic prices with grocery items than unrealistic prices; and Old & Naveh-Benjamin (2008) showed that adults encode less information about background context in memory tests as they age.

While these findings are usually taken reveal age-related "associative deficits" that are (somehow) lessened when associative information is consistent with the environment, it is notable that when the same pattern of learning the informative and neglecting the uninformative is seen as infants lose their sensitivity to non-native phonetic distinctions in the course of learning a language (Werker & Tees, 1984) it is not usually seen as decline. Our analyses have shown how all these patterns of data are consistent with what is known about the actual processes of associative learning (see also Ramscar, Suh & Dye, 2011), and that far from declining, associative processes appear to be stable and consistent across the lifespan.

It is often claimed that surprising results are more likely to be false (Lindsay, 2015), and since this last claim – and indeed, our main finding – may surprise many readers, it seems worth considering why. As we have sought to show, the widely held assumptions about learning that underpin current interpretations of lifespan PAL performance are fundamentally incompatible with the detailed understanding that has emerged out animal, behavioral and neuroscience research into associative learning processes (see Ramscar et al., 2013a, for a review). Some 30 years ago, Rescorla (1988) critically described the outdated and misleading way in which learning theory was taught in most areas of cognitive science, and what current interpretations of lifespan PAL data appear to reveal is that little has changed since. Accordingly, it is worth emphasizing that our main result is so well predicted by learning models that had we obtained opposite results, this would have suggested our entire understanding of learning (including Pavlovian conditioning) is wrong. This really would be surprising.

By contrast, despite widespread beliefs about its inevitability, the current behavioral evidence for "healthy cognitive decline" amounts to little more than a series of (mainly) negative correlations between neuropsychological test scores and increased adult age, while the biological evidence correlates the same declining test scores with predictable physical changes in neural morphology (such change in cortical grey matter, Sowell et al, 2003, Alemán-Gómez, 2013), response times (Deary & Ritchie, 2016), etc. It thus follows that determining whether biological changes in healthy adult brains are evidence of decline – or something else, such as a progressive adaptation to the metabolic cost of cognition (Attwell & Laughlin, 2001; Wen & Chklovskii, 2008) – depends on establishing that declining neuropsychological test scores actually do reflect functional declines. We have shown how PAL scores, thought to be particularly sensitive measures of age-related decline (Rabbitt & Lowe, 2000), reflect no such thing.

Accordingly, it is important to note that all current neuropsychological tests make use of learned information, while assuming that cognitive performance can be measured independently of experience (Deary et al, 2009; Salthouse, 2011; Singh-Manoux et al., 2012; Lindenberger, 2014). This assumption is incompatible with behavioral, animal, and neurobiological models of how information is actually learned (McDannald, Jones, Takahashi, & Schoenbaum, 2014; Daw, Courville, & Dayan, 2008; Schultz, 2006; Waelti, Dickinson, & Schultz, 2001; Sutton & Barto, 1981; Rescorla & Wagner, 1972). Learning theory differs from theories of cognitive decline in that its processes are clearly specified, and formalized in models. These models have proven adept at predicting behavior (such as that reported here), as well as the responses of the neural structures that appear to implement them in the brain, with surprising accuracy (Ramscar et al, 2013a; Schultz, 2006). Since learning theory contradicts many beliefs about cognitive decline, one or the other must be substantively wrong. We suggest it is the latter; and that it matters.

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