

Assessing the Age-Related Effects of Proactive Interference on Working Memory Tasks Using the Rasch Model

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Inhibition–reduction theory (L. Hasher & R. Zacks, 1988) hypothesizes that the age-related decline in working memory (WM) span is a result of a decrease in the ability to inhibit irrelevant information in WM. Using the Rasch psychometric model, this study found that later trials on 2 WM span tasks were more difficult for older adults than for younger adults, consistent with inhibition–reduction theory’s hypothesis that older adults are more susceptible to the effects of proactive interference (PI). Furthermore, after accounting for differential susceptibility to the effects of PI, age-related variance in WM span was reduced by about half. These results suggest that differential susceptibility to PI may account for a substantial portion, although not all, of the age-related decline in WM span.

Working memory (WM) is a system for temporary storage and processing of information during the performance of cognitive tasks (Baddeley, 1986). WM plays an important role in a wide variety of higher level cognitive functions, such as spatial visualization (Salthouse, Babcock, Mitchell, Palmon, & Skovronek, 1990) and reasoning (e.g., Kyllonen & Christal, 1990), and therefore, understanding the sources of variation in WM span is essential for a complete understanding of cognitive functioning. One important source of variation in WM span in adults is age, with a correlation of around $-.27$ (Verhaeghen & Salthouse, 1997; see also Salthouse, 1994b). A meta-analysis of WM span measures indicates that the average older adult (age, $M = 70.2$ years) lies at approximately the 21st percentile of the distribution of WM span scores among all adults (Verhaeghen, Marcoen, & Goossens, 1993). Other research suggests that the age-related reduction in WM span may be directly responsible for much of the age-related declines found in many measures of fluid cognitive functioning (Salthouse, 1994a; Verhaeghen & Salthouse, 1997).

Inhibition–reduction theory (Hasher & Zacks, 1988) is one of several theories proposed to account for the age-related decline in WM span (Light, 1991; Salthouse, 1996; see Zacks, Hasher, & Li, 2000). Hasher and Zacks (1988) proposed that “central to the efficient operation of working memory . . . are inhibitory mechanisms which, when normally functioning, serve to limit entrance into working memory to information that is along the ‘goal path’ of comprehension” (p. 212). Less efficient inhibitory mechanisms allow more irrelevant information into WM, using up storage capacity and processing resources and leading to lower measured WM span. Hasher and Zacks hypothesized that the age-related

decline in WM span is at least partially attributable to an age-related reduction in the efficiency of the inhibitory mechanisms.

According to Hasher and Zacks (1988), inhibitory mechanisms serve three functions within WM. Inhibitory mechanisms serve to restrict access to information that is relevant, delete information that is no longer relevant, and restrain production of strong but potentially incorrect retrieval of information from WM (Hasher, Zacks, & May, 1999). The reduction in the efficiency of these functions of inhibitory mechanisms leads to several unique predictions (Stoltzfus, Hasher, & Zacks, 1996). First, because inhibitory mechanisms are less efficient at blocking irrelevant information from entering WM, older adults should show evidence of more information becoming active in WM. Second, because older adults have more difficulty eliminating no longer relevant information, older adults should retain activation of information even when inconsistent with current goals. Finally, older adults should be relatively more susceptible to interference from irrelevant or previously relevant information.

This last prediction implies that older adults should be more susceptible to proactive interference (PI) and that older adults’ greater susceptibility to PI should account for some of the age-related declines in WM span (May, Hasher, & Kane, 1999). PI is a reduction in the ability to perform a cognitive task because of prior performance of the same or a related task, perhaps because information stored during previous trials interferes with the storage and processing of current information. PI is usually negligible for the first trial, providing there is no PI from previous tasks (Wickens, Born, & Allen, 1963). The second trial suffers PI from the first trial, and the third trial suffers PI from the first and second trials and so forth (Keppel & Underwood, 1962). The increase in PI with additional trials can continue across the length of a task (Keppel, Postman, & Zavortink, 1968), although evidence indicates that the effect of PI decelerates (Underwood, 1957).

Inhibition–reduction theory predicts that the effect of PI builds up faster for older adults than for younger adults so that although the difficulty of early trials is the same for both older and younger adults, later trials are relatively more difficult for older adults than for younger adults. Testing this hypothesis requires disentangling

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the effects of PI on a WM span task from the effects of age-related differences on a measure of WM span that is free of any effects of PI. In the analyses reported here, the disentangling was achieved by using a psychometric model to decompose performance on two WM span tasks into person ability and item difficulty. Item difficulty was further decomposed into two components, *order-free trial difficulty*, assumed to be constant across age groups, and *order effects*, which are age-group dependent. Person ability can then be interpreted as WM capacity free of the effects of order and trial difficulty, and order effects can be interpreted as the effect of PI. That is, person ability is defined as a characteristic of the individual, which is partially responsible for performance on the WM span tasks and is distinct from the influences of order and difficulty. Similarly, PI is assumed to be responsible for order effects, distinct from influences of person ability and difficulty.

The psychometric decomposition yields answers to two issues important for inhibition–reduction theory:

1. By comparing the size and rate of increase of order effects across age groups, the prediction of inhibition–reduction theory that older adults are more susceptible to the effects of PI than younger adults was tested. Inhibition–reduction theory predicts that order effects should be greater and increase more rapidly for older adults than for younger adults.
2. By examining differences in estimates of WM span before and after accounting for differences in PI effects across age groups, the relevance of inhibition–reduction theory in accounting for age-related differences in performance on WM span tasks was assessed. An implication of inhibition–reduction theory is that the magnitude of the relationship between age and WM performance should be reduced after accounting for age-related differences in the effects of PI.

Method

Participants

The data were obtained from 698 persons who participated in one of four previously published studies (Salthouse, 1995; Salthouse & Coon, 1994;

Salthouse, Hancock, Meinz, & Hambrick, 1996; Salthouse & Meinz, 1995). Participants ranged in age from 17 to 92. Demographic characteristics of the participants are presented in Table 1. For ease of analysis, participants were divided into three age groups, a younger group (age < 40; $n = 280$; $M = 26.1$, $SD = 7.1$), a middle-aged group (age between 40 and 59 inclusive; $n = 187$; $M = 49.1$, $SD = 5.8$), and an older group (age ≥ 60 ; $n = 231$; $M = 69.5$, $SD = 6.1$).

Tasks

Participants completed two computer-administered WM span tasks, along with several other cognitive tasks not examined here (see original studies for details). The computation WM span task involved a series of arithmetic problems that participants were asked to solve (processing) while remembering the last digit from each problem (storage). Each problem was presented with three answer options from which participants selected the correct answer. After completion of a selected number of problems, the word *RECALL* was presented, after which participants typed in the series of digits they were to remember. For example, if presented with $4 + 2$ followed by $3 + 5$ and then *RECALL*, the correct response would be “2 5”. Participants began with a series of Length 1 (i.e., one arithmetic problem), with three trials presented at each length. If at least two of the trials at a series length were recalled correctly and in correct order, with the arithmetic problems also answered correctly, then the series length was increased by one until participants either successfully responded to fewer than two of the three trials at that series length or reached a maximum series length of nine. Before starting the task, series of Lengths 1 and 2 were presented until participants fully understood the procedure. Older adults tended to require more of these practice trials than younger adults and so may have built up more PI before the official start of the task. Unfortunately, no record was kept of the exact number of practice trials completed by each participant.

The reading span task was similar to the computation span task, except that a short sentence with a comprehension question was used instead of an arithmetic problem, with the final word of the sentence being the information to be remembered. For example, the stimulus may be *Doug rode his bike to the store. Who rode the bike?* with three options to choose from. Participants answered the question, while simultaneously remembering the word *store*. The maximum series length for the reading span tasks was eight, rather than nine as in the computation span task, because of the greater difficulty of this task.

If an entire trial was recalled in the correct order and the responses to all the arithmetic or reading problems given during the trial were correct, participants received a score of 1 on that trial. Otherwise, they were

Table 1
Demographic Characteristics of Participants

Variable	Salthouse (1995)			Salthouse & Coon (1994)		Salthouse et al. (1996)			Salthouse & Meinz (1995)		
	Younger	Middle	Older	Younger	Older	Younger	Middle	Older	Younger	Middle	Older
<i>n</i>	34	41	42	99	42	70	68	63	77	78	84
Education											
<i>M</i>	15.1	16.1	15.3	13.6	15.8	14.8	15.1	14.8	15.1	15.9	14.9
<i>SD</i>	1.5	2.4	2.7	1.3	2.5	2.3	2.3	3.2	2.2	1.8	2.3
Health											
<i>M</i>	1.7	2.3	2.1	1.6	1.6	2.0	2.1	2.0	1.8	1.9	2.0
<i>SD</i>	0.7	1.2	1.0	0.7	0.7	0.9	0.9	0.9	0.8	1.0	0.9

Note. Education refers to the number of years of formal education completed. Health is a self-rating on a scale ranging from 1 for *excellent* to 5 for *poor*. Middle = middle-aged.

assigned a score of 0. The three trials at each series length were scored separately. Participants in three of the four studies completed two consecutive blocks of reading span followed by two consecutive blocks of computation span. In the fourth study (Salthouse & Coon, 1994), only one block of each task was administered. Only the first block was analyzed in this study because participants differed in the number of trials completed in the first block, with a low of 3 trials and a high of 27 trials. Thus, participants differed in the amount of PI built up over the course of the first block and so would have differed in the amount of PI at the beginning of the second block. Because of this confound, data from the second block were not used in the analyses.

Model

The data were analyzed with a version of the multifaceted Rasch model (Linacre, 1989), using the Facets computer program (Linacre, 2000). The model is given in Equation 1:

$$\Pr(X_{ijn}^g = 1) = \frac{\exp(\theta_{n(g)} - \beta_{ij}^g)}{1 + \exp(\theta_{n(g)} - \beta_{ij}^g)}, \quad (1)$$

where X_{ijn}^g is the response of person n in age group g to a series of length i in series order position j , $\theta_{n(g)}$ is the ability of person n in age group g , and β_{ij}^g is the item difficulty of a series of length i in series order position j for age group g .¹ Item difficulty is then decomposed according to Equation 2:

$$\beta_{ij}^g = \gamma_i + \delta_j^g, \quad (2)$$

where γ_i is the order-free difficulty of a series of length i , and δ_j^g is the order effect for a series in order position j for age group g . Because the trials were given in order of increasing length, series length and order of presentation are perfectly confounded so that $i = j$. Because of this confound, series length difficulty cannot be estimated separately from order effects. However, series length difficulty is equal across age groups, so subtracting the item difficulty for age group k , $\beta_{ij}^k = \gamma_i + \delta_j^k$, from the item difficulty for age group m , $\beta_{ij}^m = \gamma_i + \delta_j^m$, yields an estimate of the differential effect of order of presentation, $\delta_j^m - \delta_j^k$. The order effects, δ_j^g , are assumed to be constant within an age group. Although individual differences in order effects are possible, δ_j^g can be considered a within age group average order effect.

Two assumptions about the independence of effects should be made explicit. First is the assumption that there is no interaction between person ability and series length difficulty or, equivalently, that all series have equal discrimination. Second is the assumption that, other than differences across age groups, there is no interaction between person ability and order effects. Both of these assumptions are necessary to achieve specific objectivity (Rasch, 1960/1980, 1977). Under a specifically objective psychometric model, estimates of person ability and item difficulty are statistically independent, so that comparisons between persons on their WM span can be made without being confounded by variations in order effects across age groups. Likewise, a comparison of order effects across age groups can be made independent of differences in WM span. The independence assumptions were supported by the good fit of the data to the Rasch model. In almost all cases, information weighted fit was between 0.7 and 1.2, where values between 0.6 and 1.4 are considered good fit (see Wright & Linacre, 1994), with the only exceptions being the series that almost all persons responded to correctly. Relaxation of these assumptions yielded nearly identical, but slightly stronger results, although at the expense of reducing interpretability because of the loss of specific objectivity (see Appendix).

Two zero points must be set to anchor the three measurement scales: person ability, series length difficulty, and order effects (Linacre, 2000). First, series length difficulty of Series Length 1 was arbitrarily set to 0. Second, and more important, δ_j^g was set to 0 for $j = 1$ for all age groups. This is equivalent to the assumption that there are no order effects on the

first series length. In terms of PI, this assumes that there are no effects of PI on the three trials of Series Length 1.

An implication of inhibition–reduction theory is that accounting for differential effects of PI reduces the relationship between age and WM span. To assess this prediction, we reanalyzed the data using a second version of the psychometric model with order effects, δ_j^g , set equal for all age groups. This analysis provided estimates of WM span before allowing for differential order effects. The squared correlation of this WM span estimate with age in years was then calculated, yielding the percentage of variance in WM span accounted for by age. This was compared with the squared correlation from the original analysis, that is, after accounting for differential order effects.

Results

Differential Order Effects

All comparisons between item difficulties were made with Welch's z tests for unequal variances (Glass & Hopkins, 1996, p. 295). The alpha level for the comparison between younger and older participants was set to .05. Because the remaining two comparisons, between younger and middle-aged participants and between middle-aged and older participants, were made for only one independent contrast, Bonferroni's correction was applied, yielding an alpha of $.025 = .05/2$ and a critical z value of ± 2.24 .

Figure 1 displays item difficulties for computation span. Differences between item difficulties across age groups on later presented items indicate differential order effects. There were significant differences for the younger–older comparison for order positions 4 ($z = 2.36, p < .05$), 5 ($z = 6.45, p < .01$), 6 ($z = 7.21, p < .01$), and 7 ($z = 5.26, p < .01$) and for the middle-aged–older comparison for order positions 3 ($z = 2.38, p < .01$), 4 ($z = 4.18, p < .01$), 5 ($z = 5.71, p < .01$), 6 ($z = 5.20, p < .01$), 7 ($z = 5.26, p < .01$), and 8 ($z = 3.67, p < .01$). None of the younger–middle-aged comparisons were significant. For all statistically significant comparisons, item difficulty was higher for the older age group, indicating that order effects were greater for the older group. A regression of item difficulty on order position yielded slopes of 1.47, 1.40, and 1.66 for the younger, middle-aged, and older groups, respectively. The difference in slopes between the younger and the older slope was significant ($z = 2.21, p < .05$), as was the difference between the middle-aged and the older slope ($z = 2.96, p < .01$) but not between the younger and the middle-aged slope ($z = -0.74, p = .23$). This indicates that the magnitude of order effects increased more rapidly for older adults than for younger or middle-aged adults.

For reading span, no older adults reached the series length of 7, so item difficulties for Series Length 7 and 8 were not estimable for the older age group (Wright, 1998). Figure 2 shows item difficulties for reading span. The younger age group experienced significantly smaller item difficulties than older adults on Series

¹ Item difficulty was assumed to be constant across the three trials at a given series length to reduce noise at the trial level, particularly for Series Length 1 on which the across-group anchoring was based. This has the effect of averaging order-free difficulty and order effects across the three trials. See the section on the effect of anchoring error in the Discussion for a description of the effects on the results of the assumption of constant order effects on the three trials at Series Length 1.

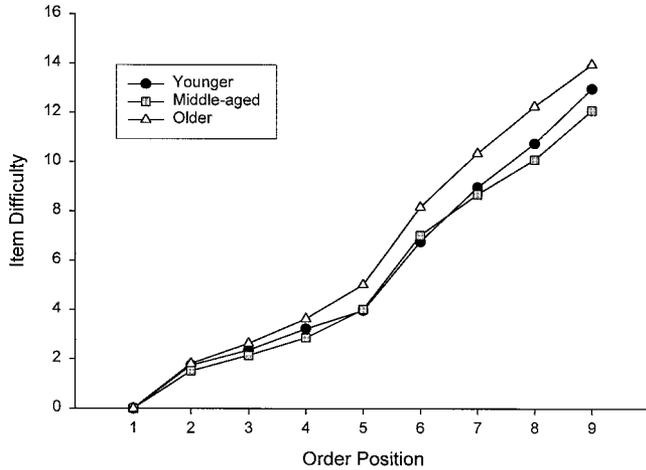


Figure 1. Item difficulty for computation span. The distance between points on the graph reflects age differences in order effects.

Lengths 2 ($z = 4.31, p < .01$), 3 ($z = 5.89, p < .01$), 4 ($z = 6.22, p < .01$), 5 ($z = 4.28, p < .01$), and 6 ($z = 2.85, p < .01$) as well as smaller item difficulties than middle-aged adults on Series Lengths 2 ($z = 4.85, p < .01$), 3 ($z = 5.55, p < .01$), 4 ($z = 5.98, p < .01$), 5 ($z = 5.15, p < .01$), 6 ($z = 2.62, p < .01$), and 7 ($z = 2.30, p < .05$). The middle-aged and older groups did not differ significantly on any series length. The slope of the regression line predicting item difficulty with order position was 2.25 for the older age group, 2.03 for the middle-aged group, and 1.81 for the younger age group. There were significant differences in slopes between the younger and the older age groups ($z = 4.67, p < .01$), between the younger and the middle-aged groups ($z = 3.07, p < .01$), and between the middle-aged and the older age groups ($z = 2.36, p < .01$), indicating that order effects grew more rapidly on reading span for older adults than for younger adults, with middle-aged adults falling in between.

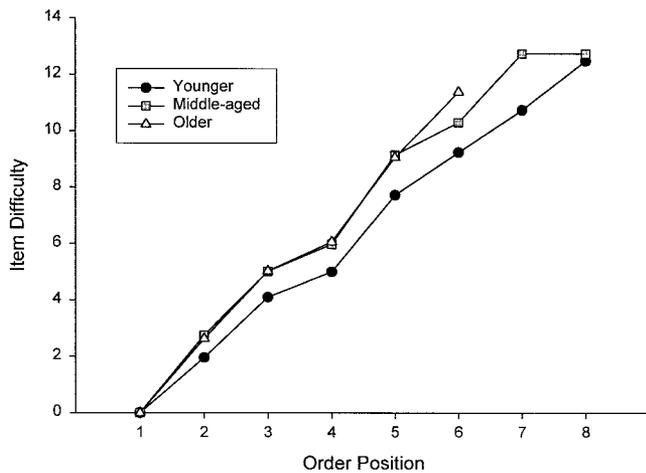


Figure 2. Item difficulty for reading span. The distance between points on the graph reflects age differences in order effects.

Age-Related Differences in Order-Free WM Span

The shared variance between WM span and age before and after accounting for differential order effects is given in Table 2. On computation span, 6.6%, $F(1, 689) = 49.0, p < .01; r = -.26$, of the variance in WM span was shared with age before allowing for age group differences in order effects. After accounting for differential order effects, 3.7%, $F(1, 689) = 26.4, p < .01; r = -.19$, of the variance in WM span was shared with age, a 44.5% reduction in variance explained by age. On reading span, the change in percentage of variance explained is larger, with 9.9%, $F(1, 694) = 76.2, p < .01; r = -.32$, of the variance explained by age before accounting for differential order effects, and 4.3%, $F(1, 694) = 31.1, p < .01; r = -.21$, after accounting for differential order effects, a 56.7% reduction in variance explained. Across both tasks, the average percentage of variance in WM span related to age before accounting for differential susceptibility to PI is 8.2% and 4.0% after accounting for differential order effects. This is a 4.2 percentage point decline in unexplained shared variance, a 50.6% reduction.

Discussion

As predicted by inhibition–reduction theory, later presented items were relatively more difficult for older adults than for younger adults. For computation span, although series presented first, second, or third did not differ significantly in difficulty, order positions 4 through 8 were harder for older adults than for younger adults. For reading span, there were no age differences in the series presented first, but order positions 2 through 7 were significantly harder for older adults. The rate of increase in item difficulty was faster for older adults than younger adults, so that, although the first-presented series did not differ, the difference in item difficulty between older and younger adults increased with later presentation. These results suggest that older adults were relatively more affected by PI at every stage of the WM span tasks. Furthermore, the 50.6% reduction in shared variance between WM span and age after accounting for differential susceptibility to PI indicates that inhibition–reduction theory may account for a substantial portion of the age-related decline in WM span. However, several potential limitations to these conclusions must be addressed.

Effect of Anchoring Error

The interpretation of the results of the current analyses depends in part on the quality of the scale anchoring. As noted earlier, the

Table 2
Percentage of Variance in Working Memory Span Accounted for by Age

Variable	Computation span	Reading span	Average
Before order effects	6.6	9.9	8.2
After order effects	3.7	4.3	4.0
Change	2.9	5.6	4.2
Percentage change	44.5	56.7	50.6

Note. Before and after order effects refer to before and after accounting for age group differences in order effects.

item difficulty scales were anchored across age groups by assuming that there were no order effects for the three trials at series of Length 1, equivalent to the assumption of no PI on the first three trials. However, PI may build up during the first three trials, so that some PI may be affecting the item difficulty estimates for Series Length 1. The item difficulty estimate for Series Length 1 would then be the sum of order-free series length difficulty and a nonzero average effect of PI across the first three trials.

Furthermore, PI may have already built up even before the first trial, whether from interference from a previous task, from the practice trials, or from experiences occurring before the testing session. For example, in all four studies from which the data were collected, computation span was administered immediately following reading span. It is possible that information from the reading span tasks interfered with the storage and processing of information on computation span. Thus, participants may have had some effects of PI even on the first trials. This would have an analogous effect as PI built up over the first three trials in that item difficulty for Series Length 1 would then be the sum of order-free series length difficulty and a nonzero effect of PI from previous tasks. Therefore, the remaining discussion of anchoring error is given in terms of PI from previous tasks, although the results are equivalent for the effect of PI built up during the first three trials.²

If the effect of PI from previous tasks is identical across age groups, then the anchoring was successful because when taking the difference in item difficulties the effect of PI shared by all age groups was subtracted out, leaving only differential effects remaining. However, if adults differed in the effects of PI from previous tasks, then the differential effect of PI at any order position may be underestimated or overestimated.

To describe mathematically the effect of the first three trials PI, or of previous-task PI, on anchoring, suppose item difficulty is the result of order-free trial difficulty, PI from the current task, and PI from the previous task. Then,

$$\beta_{ij}^g = \gamma_i + \delta_j^g + \zeta_j^g, \quad (3)$$

where, as before, β_{ij}^g is the item difficulty, γ_i is the order-free series length difficulty, and δ_j^g is the order effect for age group g , but now ζ_j^g is the effect of PI from the previous task for age group g on order position j . When anchoring on the item difficulty for Series Length 1, the differential effect of PI from previous tasks is lost. That is, the age-specific anchoring constant c is set so that Equation 4 holds:

$$\gamma_1 + \zeta_1^m + c^m = \beta_1^m = \beta_1^k = \gamma_1 + \zeta_1^k + c^k, \quad (4)$$

where the superscript indicates age group. This simplifies to

$$c^m - c^k = \zeta_1^k - \zeta_1^m. \quad (5)$$

Thus, the anchoring, which should reflect only the equality of order-free trial difficulty across age groups, is contaminated by differential effects of PI from previous tasks. Then, when estimating the differential order effects for age group m compared with age group k by subtracting estimated item difficulties,

$$\begin{aligned} \beta_{ij}^m - \beta_{ij}^k &= \gamma_i + \zeta_j^m + \delta_j^m + c^m - (\gamma_i + \zeta_j^k + \delta_j^k + c^k) \\ &= \delta_j^m - \delta_j^k - [(\zeta_1^m - \zeta_1^m) - (\zeta_1^k - \zeta_1^k)], \end{aligned} \quad (6)$$

the estimate of the differential effects of PI is underestimated by the amount:

$$(\zeta_1^m - \zeta_j^m) - (\zeta_1^k - \zeta_j^k), \quad (7)$$

where $(\zeta_1^m - \zeta_j^m)$ is the change in the effects of previous task PI from the first item to the current item for group m . If the effect of PI from previous tasks remains constant, or if the rate of change in the effect is constant across age groups, then Equation 7 is equal to 0 and the estimated age differences in the effects of PI are unaffected. However, if the rate of change in the effects of PI from previous tasks differs across groups, then the estimated age differences in the effects of PI on the current task would be biased by the difference in the rate of change. For example, the age differences in PI in the current task would be underestimated if the effect of PI from prior tasks decreases over the course of the current task at a slower rate for older adults than for younger adults.

Problems with anchoring could also occur as a simple result of error of estimation. For example, the standard error (*SE*) of estimated item difficulty on Series Length 1 for computation span was 0.24 for the younger age group and 0.18 for the older age group. Suppose item difficulty for the younger group is overestimated by 1 *SE*, whereas for the older group, it is underestimated by 1 *SE*. Mathematically (ignoring the potential of differential effects of PI from previous tasks),

$$\beta_{ij}^g = \gamma_i + \delta_j^g + e_{ij}^g, \quad (8)$$

where e_{ij}^g is the error of estimation. When subtracting item difficulties to yield differential order effects,

$$\begin{aligned} \beta_{ij}^o - \beta_{ij}^y &= \gamma_i + \delta_j^o + e_{ij}^o - (\gamma_i + \delta_j^y + e_{ij}^y) \\ &= \delta_j^o - \delta_j^y - .24 - .18, \end{aligned} \quad (9)$$

which leads to a .42 underestimation of the differential order effects on all series.

Errors in anchoring, whether from ignoring PI from previous tasks or from estimation error, affect the intercept but not the slope of the regression of item difficulty on order position, so the conclusion that older adults accumulate PI more rapidly than younger adults would not be affected. However, the size of the differential order effects may be distorted. Furthermore, the results on age-related differences in order-free WM span before and after accounting for differential order effects depend strongly on the anchoring. If item difficulty on computation span was overestimated by 1 *SE* (.24) for the younger group and underestimated by 1 *SE* (.18) for the older group, then the percentage of variance in WM span associated with age would be 5.6% after accounting for differential order effects, which is higher than the original estimate

² The percentage of correct responses on the first trial was 85.0, 82.0, and 78.4 for younger, middle-aged, and older adults, respectively, on computation span and 74.9, 77.0, and 68.1 on reading span. These age differences may be caused in part by PI from previous tasks. However, it has no effect on the modeling, as the age differences in average person ability (5.87, 5.05, and 4.71 in a logit metric), that is, age differences in average WM capacity free of the effects of trial difficulty and PI, lead to model predictions of age differences in the percentage of correct responses on the first trial.

of 3.7% leading to a reduction in WM span variance shared with age after accounting for differential order effects of 15.4% instead of 44.5%. If the estimation error is in the other direction, the percentage of variance in WM span shared with age is 2.1% after accounting for differential order effects. Estimation error of this magnitude or greater is extremely unlikely, with the probability of occurrence being less than 3.0% if the errors are independent and even lower if the estimation errors are positively correlated.³ The possibility of anchoring error suggests that the estimates of age-related differences in order-free WM span should not be considered definitive. However, the magnitude (50.6% reduction on average) and consistency (44.5% and 56.7% in the two tasks) of the reduction in age-related variance in WM span imply that differential order effects have a substantial effect on the relationship between age and WM span.

Interpretation of Order Effects

Although the effects of PI should be manifested as order effects, differential order effects may not be a reflection of differential PI effects alone. Instead, differential order effects may also result from other factors that vary with age. One simple possibility is that older adults become fatigued more rapidly than younger adults. This hypothesis predicts that later items would be relatively more difficult for older adults than for younger adults, which is precisely the same hypothesis about PI made by inhibition–reduction theory. Another possibility with identical predictions about order effects is that younger adults benefit more from within-task practice, so that later items are relatively easier for younger adults than for older adults. The results of this study are therefore consistent with the inhibition–reduction theory prediction about differential order effects, but the results cannot differentiate between inhibition–reduction theory and any other theory that also predicts that age-related differences in item difficulty would increase over the course of the task. It should also be noted that the results of this study cannot differentiate between inhibition–reduction theory and any other theory that also predicts that older adults would be more susceptible to PI than younger adults (Kliegl & Lindenberger, 1993).

Item Response Modeling and Cognitive Psychology

These analyses highlight the usefulness of Rasch modeling in particular, and item response modeling in general, in cognitive psychology (Embretson & Reise, 2000). Item response models in the Rasch family share the statistical property of specific objectivity, which allows for the estimation of effects of one factor independent of other influences on the responses to individual items. Cognitive psychology has traditionally focused on the experimental approach in which estimation of the effects of one factor independent of other factors involves manipulating the factor of interest and leaving all other factors unchanged. This may prove difficult, as evidenced by attempts to experimentally manipulate the level of PI. The level of PI cannot be assigned in an experimental paradigm but instead must be inferred from manipulations that are assumed to affect the level of PI by the same amount for all participants. These assumptions may not always be valid. For example, May et al. (1999) introduced two manipula-

tions designed to reduce PI on a WM span task, each of which, on their own, affected performance for older adults but not for younger adults. However younger adults do experience PI, even if the magnitude of the effect is lower than for older adults. Therefore, if an experimental manipulation of PI is successful, then it should result in an alteration in performance on a WM span task even for younger adults. The fact that the performance of younger adults in the May et al. study was unaffected by either experimental manipulation when administered alone raises questions about what effects the manipulations actually had on PI. Item response modeling provides an alternative means of exploring questions in cognitive psychology and thus provides valuable converging evidence for studies with experimental manipulations of questionable validity.

Conclusion

Increased age was associated with larger order effects and more rapid increases in order effects with later presentation. This result is consistent with the prediction of inhibition–reduction theory that older adults are more susceptible to the effects of PI than younger adults. Differential susceptibility to PI accounts for about half of the age-related variance in WM span. Although these results might also be explained by hypotheses other than inhibition–reduction theory, such as anchoring error, differential fatigue, or age differences in within-task practice, the large size of the reduction in WM span variance explained by age suggests that differential susceptibility to PI may be an important component of age-related individual differences in WM span. However, on average, about half of the explained variance still remains, indicating that differential susceptibility to PI cannot account for all of the age-related decline in WM span. Thus, this study gives support for inhibition–reduction theory while highlighting that other theories about the aging of WM must also be considered (e.g., Salthouse, 1996) and that other potential effects of inhibition reduction on WM beyond differential susceptibility to PI must be explored.

³ Prob (true item difficulty for younger < 1 SE below estimate) = 0.17. Prob (true item difficulty for older > 1 SE above estimate) = .17. If the errors are independent, then the probability of both occurring is the product of the two probabilities: $.17 \times .17 = .029$.

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Appendix

Results From Relaxing Independence Assumptions

Method

The model with independence assumptions relaxed was identical to the model with independence assumptions, except Equation 2 for the Rasch model was converted to a 2PL model:

$$\Pr(X_{ijm}^g = 1) = \frac{\exp a_{ij}(\theta_{n(g)} - \beta_{ij}^g)}{1 + \exp a_{ij}(\theta_{n(g)} - \beta_{ij}^g)}, \quad (A1)$$

where a_{ij} is the slope parameter for series length i in order position j . This model forces the interaction between person ability and item difficulty to be constant across age groups, a typical assumption in item response theory differential item functioning studies, and a necessary assumption to make cross-group comparisons of person ability. All analyses were performed in Bilog-MG (Zimowski, Muraki, Mislevy, & Bock, 2002).

Results

Differential Order Effects

All results for differential order effects were similar to those from the Rasch model reported in the main Results section. For computation span,

younger adults had significantly lower item difficulty than older adults on Series Lengths 3 ($z = 2.33, p < .05$), 4 ($z = 3.95, p < .01$), 5 ($z = 2.37, p < .05$), 6 ($z = 6.88, p < .01$), 7 ($z = 6.71, p < .01$), and 8 ($z = 2.33, p < .05$). Younger adults had significantly lower item difficulty than middle-aged adults on Series Lengths 6 ($z = 4.58, p < .01$) and 7 ($z = 2.33, p < .05$), whereas middle-aged adults had lower difficulty than older adults on Series Lengths 4 ($z = 2.60, p < .01$), 6 ($z = 2.81, p < .01$), and 7 ($z = 4.11, p < .01$). The slope of the regression line predicting item difficulty with order position was 0.431, 0.448, and 0.479 for the younger, middle-aged, and older groups, respectively. The difference in slope between younger and older was significant ($z = 2.35, p < .01$) but neither the younger–middle-aged ($z = 0.83, p = .20$) comparison nor the middle-aged–older ($z = 1.52, p = .06$) comparison was significant.

For reading span, item difficulty was significantly lower for younger adults than older adults on Series Lengths 2 ($z = 2.17, p < .05$), 3 ($z = 3.77, p < .01$), and 4 ($z = 5.26, p < .01$) and for younger adults than middle-aged adults on Series Lengths 2 ($z = 4.28, p < .01$), 3 ($z = 5.99, p < .01$), 4 ($z = 8.28, p < .01$), 5 ($z = 2.35, p < .05$), and 6 ($z = 2.69, p < .01$). Older adults found Series Length 3 ($z = -3.54, p < .01$) easier

than middle-aged adults. The regression slope for item difficulty predicted by order position was 0.656 for younger adults, 0.739 for middle-aged adults, and 0.866 for older adults. The difference in slopes was significant for the younger–older comparison ($z = 1.97, p < .05$) but not for the younger–middle-aged comparison ($z = 1.04, p = .15$) or for the middle-aged–older comparison ($z = 1.19, p = .12$).

Age-Related Differences in Order-Free WM Span

Results were similar to those reported in the main Results section. On computation span, 7.7%, $F(1, 689) = 57.4, p < .01$, of the variance in WM

span was accounted for by age before allowing for age group differences in order effects. After accounting for differential order effects, 2.5% $F(1, 689) = 17.9, p < .01$, of the variance in WM span was shared with age, a 67.1% reduction. On reading span, the change in percentage of variance explained was 42.6%, from 9.1%, $F(1, 693) = 69.2, p < .01$, before accounting for differential order effects to 5.2%, $F(1, 693) = 37.9, p < .01$ after accounting for differential order effects.

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