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Neuroscience and Biobehavioral Reviews 26 (2002) 849–857

NEUROSCIENCE AND
BIOBEHAVIORAL
REVIEWS

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Aging, executive control, and attention: a review of meta-analyses

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Abstract

We review the results of a series of meta-analyses by the first author and colleagues, examining age-related differences in selective attention (Stroop-task survey and negative-priming task survey) and in divided attention (dual-task survey and task-switching survey). The four task families all lent themselves to state trace analysis, in which performance in baseline conditions was contrasted with performance in experimental conditions separately for college-aged subjects and for elderly subjects. These analyses found no age-related deficits specific to selective attention or local task-switching. Age deficits were found for dual-task performance and global task-switching. Unlike selective attention and local task-switching costs, dual-task and global task-switching costs were found to be additive in both young and old subjects, unmodulated by task difficulty. These forms of executive intervention then did not alter computational processes already present in the simple tasks, but rather added one or more additional processing steps or stages to the processing stream. The cost was greater in older adults, but was limited to those experimental conditions that activated multiple task sets.

Keywords: Aging; Attention; Executive control; Meta-analysis

It is by now a truism that as people grow older, performance on a plethora of tasks declines. Such age-sensitive tasks include (among many others): simple and choice reaction times, working memory, episodic memory, tests of spatial and reasoning abilities, mental rotation, and visual search (for exhaustive reviews, see Refs. [1–3]; note that performance on other tasks, such as vocabulary measures, remains relatively stable [2,3]). The challenge for cognitive aging is to identify the basic changes responsible for these declines. Given that the deficits are so widespread across the cognitive system, it is reasonable to assume that a limited number of mechanisms may explain a large number of the deficits.

Currently, two families of theories dominate the field. The first family posits age-related changes in crucial processing resources. The most dominant member of this family is probably the processing-speed hypothesis [3,4]. This hypothesis views cognition as being driven by a processing rate, and supposes that the rate in older adults is less than in younger adults. Evidence for this theory is mostly derived from mediational analyses, that is, findings that statistical control of speed measures greatly reduces the age-cognition correlation.

The second family of theories focuses on process-specific accounts of aging. The currently dominant type of theory in this family distinguishes between tasks that involve executive control processes, such as selecting information to be attended to or switching between different sources, and tasks in which these demands are negligible. These theories postulate an age-related deficit specific to particular executive processes, such as inhibitory control [5], coordination ability [6,7]), or task-switching [8]. Such deficits may be related to age-specific changes in the prefrontal cortex [9,10]. Claims for process-specific deficits are based on experimental evidence: Performance on conditions with a high demand for control processes is contrasted with performance on baseline conditions with a low demand for control. The analytic tool is analysis of variance. Age by condition interactions are taken as evidence for deficits specific to the manipulated process.

This paper evaluates the claims for control-specific deficits, by surveying the experimental literature on age and selective and divided attention. These paradigms have been identified as involving control processes that seemingly show important age-related declines (for a recent review, see Ref. [11]). The method we used was meta-analysis, pooling data from all relevant published literature. The first author has completed four such analyses [12–15], allowing us to evaluate evidence from a variety of tasks, experimental paradigms, and imputed processes.

Before proceeding to the data, we have to set up an

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PII: S0149-7634(02)00071-4

analytic framework. First, we formalize the processing-speed hypothesis, and show how a failure to take the effects of general slowing into account may lead to erroneous conclusions concerning age by condition interactions. Second, we introduce the notions of additive and multiplicative complexity effects, and the scatter plots utilized to identify them. These tools provide principled interpretations of the results of the meta-analyses.

1. General slowing and its consequences for conclusions regarding age sensitivity of specific processes

It has long been known that reaction times of older adults can be well described by a linear transformation of reaction times of younger adults, with a small, typically negative intercept, and a slope larger than unity [16–18]. These results show that reaction times of older adults can be expressed as a fixed ratio of reaction times of younger adults, once peripheral components (i.e. sensory and motor processes) have been subtracted out. The effect is called general slowing; the common old/young ratio, or *slowing factor*, is identifiable as the speed-of-processing deficit. The effects of this factor have implications for the interpretation of age group by task interactions. Suppose there is a baseline task that takes younger adults 500 ms to complete, and that the peripheral component is 200 ms. Assume an age-related slowing factor of 1.5 (healthy sixty–seventy year-old adults are typically 1.5 times, or 50%, slower than college-aged adults). We can then expect a reaction time of $200 + 1.5 \times 300 = 650$ ms for older adults. (Typically, peripheral processing is also slowed in older adults, but by a very small factor.) Now introduce a more complex version of the task, which increases reaction time for the young by 500 ms, leading to a total time of 1000 ms. The reaction time expected for older adults is now $200 + 1.5 \times 800 = 1400$ ms. Conventional interaction analysis tests for additive age differences, that is, whether age differences remain constant across conditions. The example shows that if general slowing is operating, then this test will yield false positives. For the case at hand, an age difference of 150 ms is recorded in the baseline condition, and of 400 ms in the more complex condition, despite the fact that no additional deficit is associated with the specific processes underlying the increased complexity. Note that when we plot the two points in a coordinate system with latency of the young on the x-axis and latency of the old on the y-axis, they describe a line with a slope equal to the age-related slowing factor in the central component (viz. 1.5), and a negative intercept (viz. -100 ms).

Several remedies for the spurious-interaction problem have been suggested (for a recent treatment, see Ref. [19]). Perhaps the clearest has been advanced by Maylor and Perfect [20]: that is to demonstrate differences across tasks in the age-related slowing factor, rather than differences in raw reaction times (for examples, see Refs. [20,21]).

An additional complication is that the effects of executive control are not well understood. The common (often implicit) assumption is that increased demand adds an extra stage, or a series of extra stages or steps, to processing (an assumption maintained by some in the task-switching literature [22,23]). In that case, the cost of executive processing is given by the reaction time in the high-demand condition minus the reaction time in the baseline condition. But it is also possible that the cost is expressed non-additively; perhaps it is multiplicative, such that each step of baseline processing is prolonged by a constant multiple in the high-demand condition.

To adequately test the hypothesis of an age-related deficit specific to executive control, both of these complications need to be dealt with: we need to take the general slowing effect into account, and also to resolve the form of the influence of executive control processes, so that the appropriate model can be applied to test for age effects. This cannot be done with data from a typical experiment, involving just a few conditions (often just two) and two age groups. One solution is to increase the number of levels in both baseline and experimental conditions. Another solution, the one pursued here, is to pool data across experiments, in the form of a meta-analysis. The meta-analysis suggests a tentative resolution of these complications. We can turn to it for some initial answers to the questions of the type of complexity involved (Section 2) and the size of the age effect. The meta-analysis may then be followed up with more targeted experimental research.

2. Two types of complexity

The methods of our meta-analyses were graphical (see Ref. [16] for an early example). Latency data were compiled from several literature surveys, and used to construct a related pair of scatter plots that exposed (a) age effects within and across conditions and (b) complexity effects within and across age groups. One plot is called a *Brinley plot* [24,16], and displays the performance of older adults across the various levels and conditions of a survey as a function of the performance of younger adults across the same levels and conditions. The resulting locus of points is the *Brinley function*. For many conditions, Brinley functions have been found to be linear or near-linear; the slope of the function gives the age-related slowing factor [17]. The other scatter plot is called the *state space* [6,25]. It displays the performance of one age group over more complex levels and conditions as a function of the performance of the same age group over corresponding baseline levels and conditions. The resulting locus of points is the *state trace*.

Many configurations of Brinley functions and state traces are possible. We construct a framework here, within which several of these configurations are open to straightforward interpretation. The framework rests on several assumptions. The first is that the reaction time can be decomposed into two independent components: peripheral processes (i.e. input/output processes), and central or computational processes [17,26]. For instance, in order to solve the arithmetic problem 73 + 91, time is needed to encode the numbers and the plus sign, to access their meaning, and once the answer is known, to key in the result or utter a verbal response—these are all treated as peripheral processes. The central process here is the computation that produces the answer. General slowing is another assumption—the duration of central processes in elderly adults will be prolonged by a fixed, multiplicative slowing factor. (Here we gloss over the smaller amount of slowing that seems to apply to peripheral processes.)

Making a task more complex will lead to some sort of latency increase. Typically, this increase is situated in the central component. (We henceforth assume that peripheral processing is unaltered.) The increase may take several forms. Verhaeghen et al. [14] offer a formal mathematical treatment of the Brinley and state-trace functions for younger and older adults under two cases: additive complexity effects and multiplicative complexity effects. We summarize the mathematical development here.

A complexity manipulation may add an extra processing stage to a task or prolong an existing stage—perhaps by imposing a fixed overhead cost or ‘set-up charge’. We use these terms in a general, descriptive way: what the nature and source of this overhead cost is remains to be determined through experimental work; what this additional bout of processing serves likewise remains out of the scope of our meta-analysis; and we cannot even be certain that it is a single bout—it may well be a complex of processing steps distributed across processing stages.

We label this type of complexity *additive*, because the manipulation will induce additive effects between the baseline and experimental conditions: Latencies in the complex conditions will be equal to latencies in the simpler conditions plus a constant. The resulting state trace will be a line elevated above and parallel to the diagonal. The complexity cost or set-up charge is given directly by the intercept value of the state trace, that is, the distance from the diagonal. The general slowing axiom stipulates that the complexity cost for older adults will be equal to the cost for younger adults times the slowing constant (which is itself given by the slope of the Brinley function for the baseline task). This means that the state trace for older adults will be elevated above and parallel to the state trace for younger adults. The Brinley plot derived from the same axioms will show either one or two parallel lines. If two lines are present, this carries with it the implication that the overhead component of a complex task is slowed by a larger factor than the central component.

Alternately, a complexity manipulation may modulate all the central processing of a task, prolonging or ‘inflating’ each step in the chain of baseline computation. We label this type of complexity *multiplicative*, because it will induce multiplicative effects: Central-processing latencies in the complex conditions will be a fixed ratio (larger than unity) of central-processing latencies in the simpler conditions. In state space, this will lead to a line with a slope greater than unity; the inflation factor is given directly by the slope of the state trace. The state trace for older adults will either overlay the state trace for younger adults or else will diverge from it, depending on whether the complexity deficit is greater than the baseline deficit or not. The Brinley functions follow the state traces, with slopes greater than unity. Like the state traces, the high-complexity function will either overlap or diverge from the low-complexity function, depending on whether the complexity cost exceeds the age deficit in central processing in the baseline task.

To summarize, this framework provides clear signatures for two types of complexity effects. Additive complexity leads to a pair of lines in state space, one for the young and one for the old, that are parallel to the diagonal. The Brinley plot shows either a single line or a pair of parallel lines; the slope of the baseline line gives the amount of central slowing; an offset in the experimental line signals an attentional deficit greater than the baseline slowing. Multiplicative complexity leads to slopes greater than unity in both of the scatter plots. The emergence of two lines rather than one signals a specific age-related deficit in the process associated with the complexity cost.

3. Experimental evidence for two types of complexity

This framework is more than an academic exercise; both configurations have been observed in experimental data. As a prelude to the meta-analyses, we illustrate these effects with data from an experimental study in progress in our laboratory [27]. The data were collected from 27 younger adults and 27 older adults, performing a counting task (top row, Fig. 1) and an arithmetic task (bottom row, Fig. 1). The baseline counting task consisted of counting the number of Xs scattered over the screen, where n varied between 6 and 9. In the complex version of the task, 4–7 distractor Os appeared along with the Xs. We predicted that this complexity manipulation, the discarding or inhibiting of distractor stimuli, would add an attentional/perceptual step to the processing stream but would not impede the efficiency of the counting process itself. In the baseline arithmetic task, subjects worked through a chain of 4–7 arithmetic operations shown simultaneously on the screen (e.g. $5 + 2 - 3 - 2 + 6 - 3$). In the complex version, brackets were introduced, necessitating the swapping of elements in and out of storage, updating stored elements, and careful scheduling of operations (e.g. $[5 - (1 + 2)] + [(2 + 6) - 3]$). We predicted that the application of these control processes would retard the computational processes themselves, leading to multiplicative delays.

Fig. 1 shows that these differential predictions were borne out. The perceptual manipulation induced additive

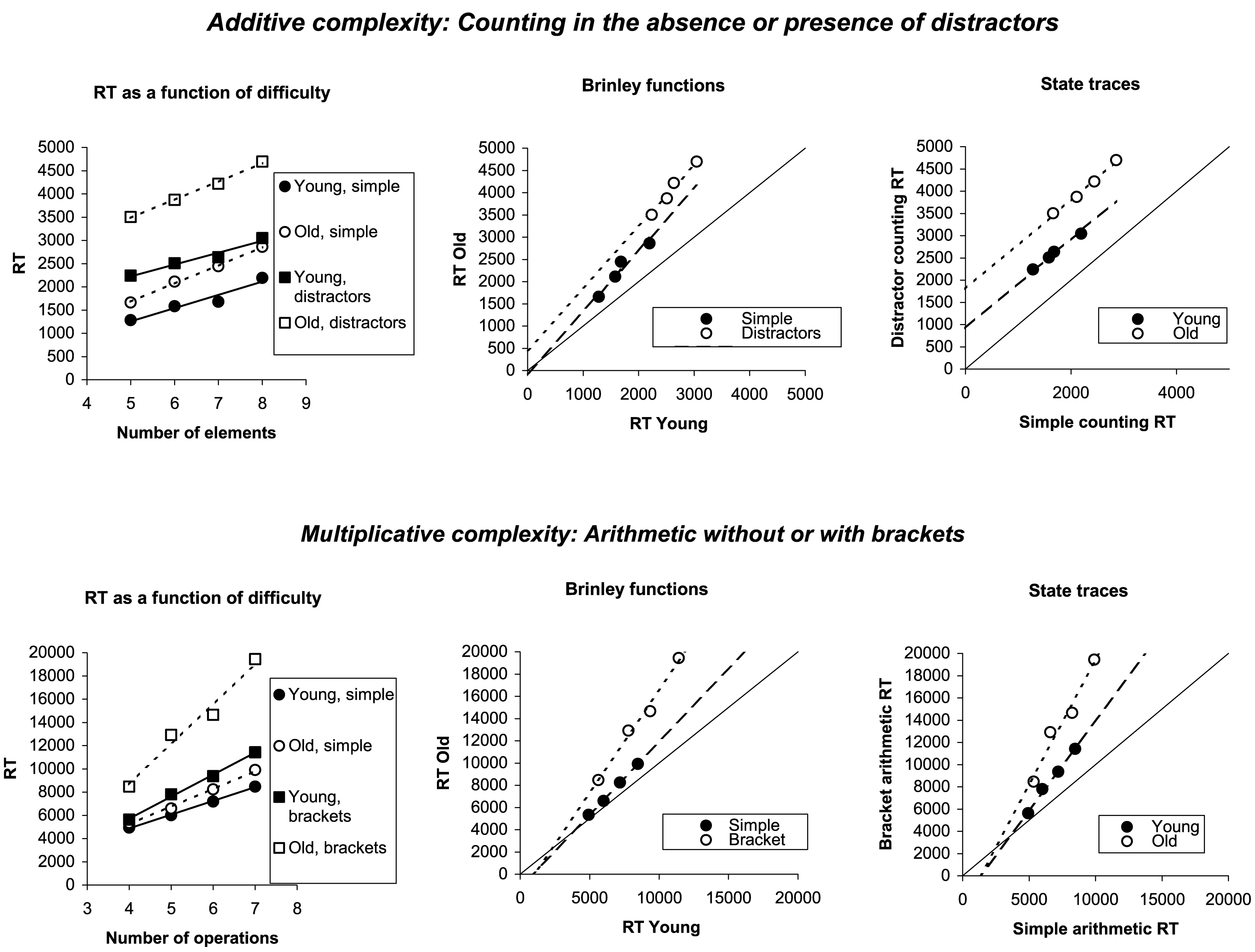

Fig. 1. Illustration of additive and multiplicative complexity effects in two experimental tasks: reaction time as a function of difficulty, Brinley plots and state traces. In the latter two graphs, the diagonal is indicated by a full line.

effects (see state plot and Brinley plot, top panels); the executive control manipulation induced multiplicative effects (bottom panels).

There have been a number of experimental demonstrations of multiplicative effects similar to those of in Fig. 1, bottom row. In the original literature, the effects have been ascribed to deficits in aspects of executive control such as coordinative processes [28] or task monitoring [29]. Experimental demonstrations of additive-stage complexity like those in Fig. 1, top row, have been rare, because, we suspect, the experiments most likely to produce them have involved only two or three conditions, which do not afford the required analyses.

4. Meta-analyses on attention and aging: methods

To test for an age-related deficit specific to attentional manipulations, the answer to two questions is crucial: (a) are attentional tasks associated with additive complexity effects, multiplicative complexity effects, or both? and (b) can age deficits specific to these effects be reliably observed? Our approach to these questions was meta-analytic. In these analyses, the unit of analysis was the average performance of young or older adults obtained from studies in the literature. In the plots presented below, each data point represents average performance within a single study.

Two types of attentional phenomena were investigated. First, those of *selective attention*, which relate to the ability to process one stream of information while disregarding other, concurrent streams. Two tasks that have been used extensively to examine selective attention are the Stroop color-word task [30] and the negative-priming task. In the Stroop-task, participants are presented with colored stimuli, and have to report the stimulus's color. One compares reaction time in a condition where the stimulus is neutral, for instance a patch of color or a series of Xs (the baseline condition), with a condition in which the stimulus is itself a word denoting a color (the interference condition; e.g. the word 'yellow' printed in red). In the negative-priming task, participants are shown two stimuli simultaneously, one of which is the stimulus to be reported on (the target), the other to be ignored (the distractor). For instance, the participant can be asked to name a red letter in a display that also contains a superimposed green letter. If the distractor on one trial becomes the target on the next (the negative-priming condition), reaction time is typically slower than in a neutral condition, where none of the stimuli are ever repeated (the baseline condition). Note that this effect is counterintuitive: higher levels of selective attention are associated with larger costs.

The other type of phenomena investigated were those of *divided attention*, which concern the ability to process multiple stimuli or to perform multiple tasks. One test of divided attention is to compare performance on a single task with performance on the same task when another task has to be performed concurrently (e.g. a visual reaction time task with or without concurrent auditory reaction time task); this is called dual-task performance. A more recent paradigm, called task-switching [22], requires the maintenance and scheduling of two mental task sets. The participant is shown a series of stimuli, and has to perform one of two tasks on each, the required task being indicated by the experimenter (e.g. a series of numbers is shown, if the number is printed in red, the participant must indicate whether it is odd or even; if the number is printed in blue, the participant must indicate whether it is smaller or larger than five). Two types of task-switching costs can be calculated. First, one can compare reaction times in blocks with only single tasks with reaction times in blocks when the participant has to switch between tasks. This is the 'global' task-switching cost, and is thought to indicate the set-up cost associated with maintaining and scheduling two mental task sets. Second, within a block of task-switching trials, one can compare reaction times for trials in which task-switching was actually required with trials in which the task did not switch. This 'local' task-switching cost is an indication of the executive process associated with the actual switching.

Two meta-analyses were performed on the published data on selective attention and age, one of them surveying Stroop experiments [12], and the other surveying negative-priming experiments [13]. Fig. 2 shows the Brinley plots and state spaces from these analyses; the data were modeled directly using least-squares analysis, weighting for sample size.

Two meta-analyses were performed on the published data on divided attention and age, one of them surveying dual-task experiments [14], and the other surveying task-switching experiments [15]. Fig. 3 shows the plots from those analyses; because many studies spanned more than two conditions, it was possible to apply multilevel modeling to these data, that is, to derive parameter values of the regression line by using information both within and across studies.

For each of the Brinley plots, we tested whether a single line sufficed to explain the data, or whether two lines were necessary, one for the baseline conditions and the other for the experimental conditions. If the latter, we tested whether the lines differed in intercept, slope, or both. For each of the state spaces, we tested whether a single line sufficed to explain the data, or whether two lines were necessary, one for younger adults and the other for older adults; again, we tested for intercept differences, slope differences, or both. The lines plotted in the figures show the final results of these analyses. (For more details on the studies selected, methods used, and analyses, refer to the original articles.)

5. Meta-analyses on attention and aging: results

Starting first with the *selective attention* surveys in Fig. 2,

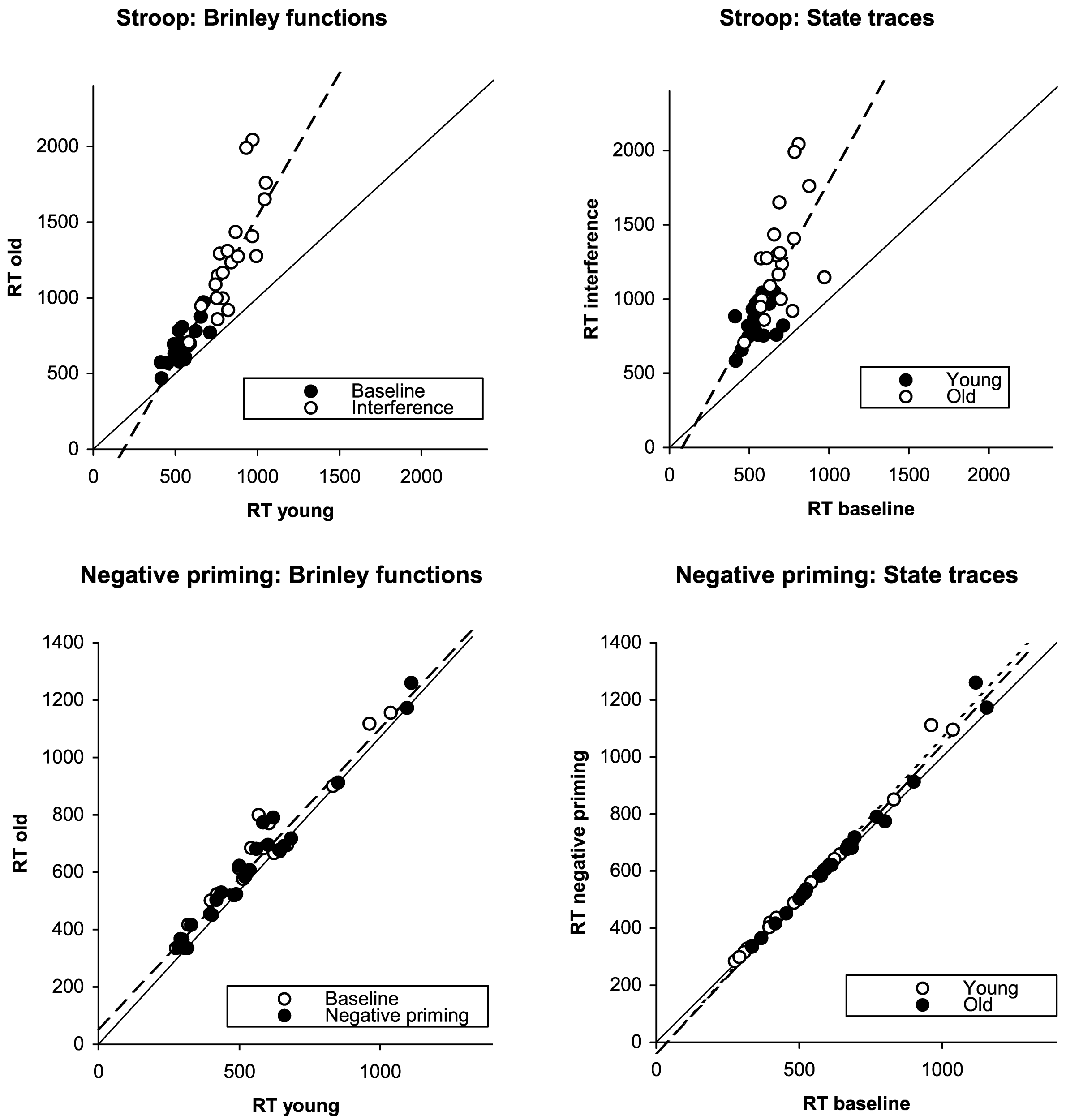

Fig. 2. Brinley plots and state traces for selective attention (Stroop and negative priming). The diagonal is indicated by a full line.

the first thing to observe is that the two state traces show the same configuration: both effects are multiplicative (although the magnitude of the effect differs). Both Stroop interference and negative-priming induced multiplicative complexity effects, signaled by greater-than-unity slopes, and indicating that the deployment of selective attention inflates central processing. The inflation factor in the Stroop-tasks (a slope of 1.9, indicating 90% inflation) was much larger than in the negative-priming tasks (a slope of 1.1, indicating 10% inflation). The difference may be due to the temporal dynamics of the two tasks. The Stroop-task involves selection of one of two information sources simultaneously present; negative-priming involves reactivating a stimulus that was deactivated on the previous trial. The time delay alone may explain the smaller effect of the latter.

The second thing to observe in Fig. 2 is the absence of age deficits specific to the interference effects. A single line was sufficient to capture the inflation of central processes in both young and old state traces; so too, a single line was sufficient to capture both baseline and experimental conditions in the Brinley plot. (Note that our data did show a very slight age difference in the state trace for negative-priming, 10% inflation in the young versus 8% inflation in the old; a recent update of this meta-analysis showed completely equivalent complexity effects in younger and older adults [31].)

Like the inflation factor, the age-related slowing factor was larger for color naming (with or without interference,

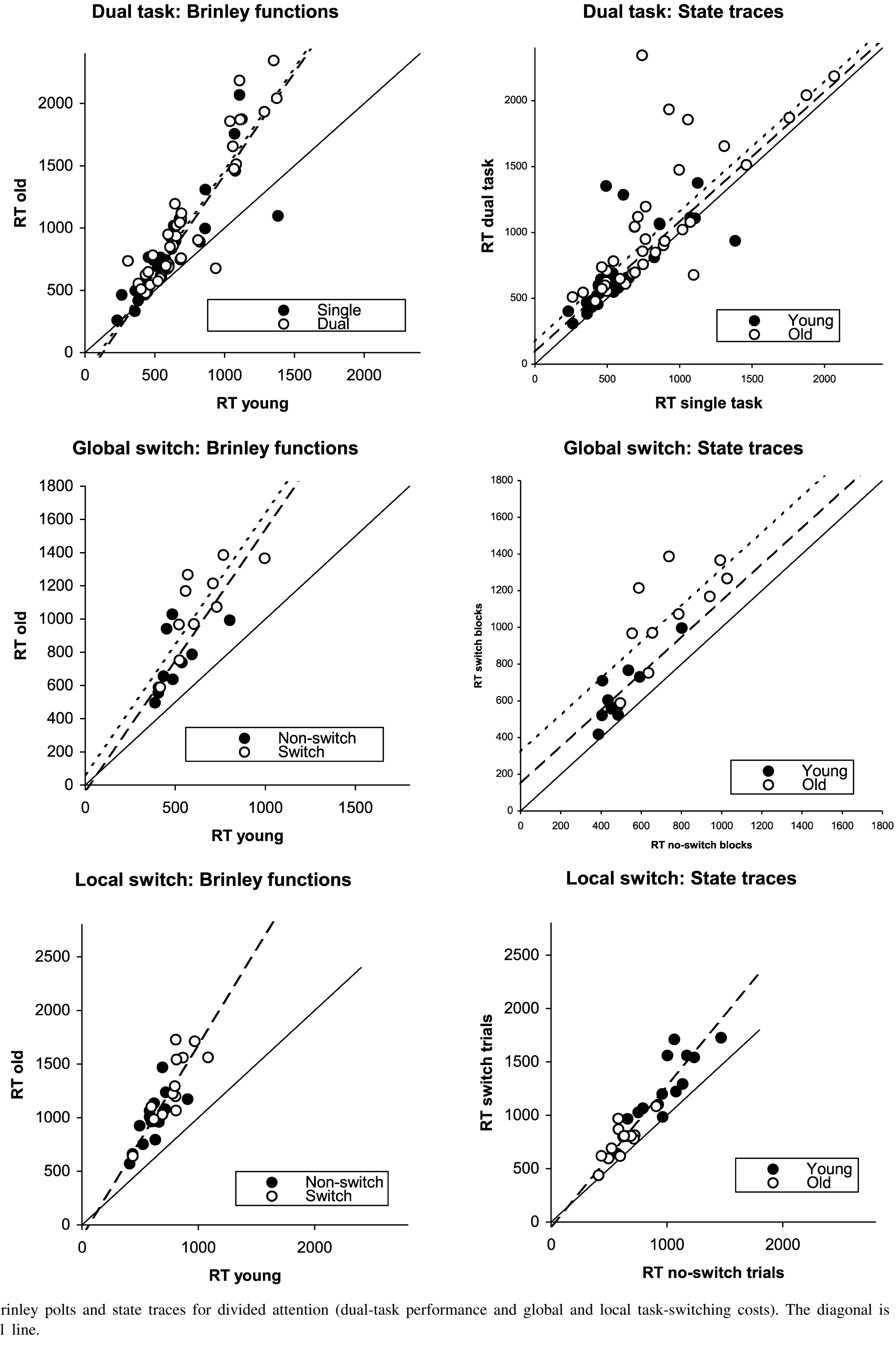

Fig. 3. Brinley polts and state traces for divided attention (dual-task performance and global and local task-switching costs). The diagonal is indicated by a full line.

the slope of the Brinley function was 1.8) than for negative-priming (with or without priming, the slope of the Brinley function was 1.04). This difference may be due to the fact that the task involved in negative-priming is typically the naming of letters or of depicted objects, while the color-naming required by the Stroop-task may be a spatial process. The different degrees of slowing probably reflects the often-replicated dissociation between lexical and non-lexical age effects [20].

Turning to the *divided-attention* surveys in Fig. 3, the picture is more complex. Two of the state traces, for dual-task performance and global task-switching, show an additive complexity effect; the third state trace, for local task-switching, shows a multiplicative effect. We can only speculate on the cause of this difference. Dual-tasking and global task-switching involve the simultaneous activation and maintenance of two mental task sets; local task-switching involves selection between two mental task sets that are already active. The former requirement may challenge the cognitive system in a way similar to the counting data we presented in Fig. 1, when distractors were added to the stimulus array: the complication is disposed of by means of a discrete bout of set-up processing; baseline processing then proceeds unimpeded. The latter requirement, on the other hand, seems close to that imposed by the selective attention tasks (selection between simultaneous sources); it is not surprising that the resulting costs are qualitatively similar in the two cases (i.e. multiplicative). This interpretation remains admittedly post hoc.

Age effects were absent in local task-switching costs, as they were in selective attention costs; this is apparent from both the state trace and the Brinley function. In contrast, age effects were seen in dual-task performance and global task-switching: In the state space, separate (and parallel) lines were required for the two age groups; in Brinley space, separate (and parallel) lines were required for the two condition levels. As noted in our analytical framework, distinct lines are to be expected in the state space if the complexity cost is additive, on the basis of general slowing alone. From the dissociation found in the Brinley plots, we can infer further that the age deficit specific to the set-up charge exceeded the general-slowing deficit. Estimates of the two deficits are provided by the framework: The general-slowing factor is given by the slope of the (baseline) Brinley functions, and the set-up deficit is given by the ratio of the intercepts of the state traces. The regression values showed an age ratio for the dual-task cost of 1.8, which was reliably greater than the 1.6 age ratio for single task performance; and an age ratio for global task-switching cost of 2.2, which was reliably greater than the 1.6 ratio for non-switch trials.

6. Conclusion

Reviewing the five meta-analyses, a pattern in the age outcomes is apparent. It can be formulated at two levels. At an abstract and mathematical level, we can state that no specific attention-related age deficits were observed whenever complexity costs were multiplicative, that is, when central processes were inflated. Whenever costs were additive, that is, when a processing stage was added or extended, age deficits did emerge, deficits larger than those extrapolated from the baseline tasks. At a more concrete level, closer to the tasks, we found that specific deficits did not emerge in tasks that involved active selection of relevant information, such as determining the ink color of words (Stroop), in actively ignoring or inhibiting a stimulus (negative-priming), or in relinquishing attention from one aspect of the stimulus to reattach it to a different aspect (local task-switching). In those cases, the selection requirement inflated central processing, but the degree of inflation was not greater in older adults than in younger adults. Age differences did emerge in tasks that involved the maintenance of two distinct mental task sets, as in dual-task performance or global task-switching. The costs of maintaining such dual states of mind were additive—a stage was added to processing, or prolonged. This processing penalty was greater for older adults than that manifested in baseline slowing.

From these meta-analyses we conclude that there is no age-related deficit specific to selective attention, but that dual-task set maintenance does involve a deficit over and beyond the effects of general slowing. If we are correct, then a simple, one-parameter slowing theory is insufficient, although the framework accounts for a large proportion of the variance in the data assembled in Figs. 2 and 3. At the same time, our findings do not support theories that have proposed specific deficits in the executive processes involved in selecting stimulus characteristics or mental task sets (see Refs. [32,33] for similar theoretical claims). Moreover, our results cast doubt on the assertion that the multiplicative age observed in tasks involving coordination in working memory [6,7,21,29] are caused by age deficits at the level of attentional processes, because the latter are characterized by additive age-related complexity deficits (for a deeper, mathematical discussion of this issue, see Appendix B in Ref. [14]).

Acknowledgements

This research was supported in part by a grant from the National Institute on Aging (AG-16201). We thank Lieve De Meersman, Martin Sliwinski, David Steitz, and Christina Wasylyshyn for their contributions to the original research.

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