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PAPER

Speed isn't everything: complex processing speed measures mask individual differences and developmental changes in executive control

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Abstract

The rate at which people process information appears to influence many aspects of cognition across the lifespan. However, many commonly accepted measures of 'processing speed' may require goal maintenance, manipulation of information in working memory, and decision-making, blurring the distinction between processing speed and executive control and resulting in overestimation of processing speed contributions to cognition. This concern may apply particularly to studies of developmental change, as even seemingly simple processing speed measures may require executive processes to keep children and older adults on task. We report two new studies and a re-analysis of a published study, testing predictions about how different processing speed measures influence conclusions about executive control across the lifespan. We find that the choice of processing speed measure affects the relationship observed between processing speed and executive control, in a manner that changes with age, and that choice of processing speed measure affects conclusions about development and the relationship among executive control measures. Implications for understanding processing speed, executive control, and their development are discussed.

Research highlights

- Many measures of processing speed tap executive control.
- This concern applies particularly to developmental populations.
- Thus developmental change and individual differences in executive control have been underestimated.

Introduction

People process information at different rates, and these differences appear to matter. Individual differences in processing speed are believed to reflect variation in neural speed, efficiency, and capacity (Birren & Fisher, 1995; Mendelson & Ricketts, 2001), as well as age-related changes in neural processing, including the development and decline of axonal myelination across the lifespan (Charlton, Barrick, McIntyre, Shen, O'Sullivan, Howe, Clark, Morris & Markus, 2006; Charlton, Landau, Schiavone, Barrick, Clark, Markus & Morris, 2008). Processing speed predicts automaticity, fluency, and variability of cognitive performance across a wide variety of tasks (Bryan & Luszcz, 2001; Finkel, Reynolds, McArdle & Pederson, 2005; Kail & Salthouse, 1994; Salthouse, 2005). Moreover, age-related changes in processing speed appear to account for a substantial portion of age-related change across a wide variety of abilities (Bryan & Luszcz, 1996; Cepeda, Kramer & Gonzalez de Sather, 2001; Earles & Coon, 1994; Kail & Hall, 1994; Madden, 1992; Mendelson & Ricketts, 2001; Salthouse, 1991; Salthouse & Meinz, 1995). Based on these forms of evidence, many researchers attempt to remove the influence of general processing speed from their dependent measures in order to focus on contributions from other cognitive processes of interest.

In theory, factoring out processing speed allows researchers to remove general age and individual differences, in order to focus on specific, higher-level abilities,

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such as executive control. These include 'goal selection, planning, monitoring, sequencing, and other supervisory processes' (Foster, Black, Buck & Bronskill, 1997, p. 117) that 'enable a person to engage successfully in independent, purposive, self-serving behavior' (Lezak, 2004, p. 35). Thus, a primary goal in developing processing speed measures is to 'minimize the contribution of higher cognitive function' (Fry & Hale, 2000, p. 2) in order to measure 'the speed with which many cognitive operations can be executed' (Salthouse, 1996, p. 403; see also Myerson, Hale, Wagstaff, Poon & Smith, 1990).

However, these goals are difficult to meet, because the term 'processing speed' has been used to refer to a variety of measures that get used in different ways and that may tap underlying components to varying degrees. Consider four commonly used processing speed measures: box completion, digit copying, digit-symbol substitution, and letter comparison. In box completion, participants are asked to draw the fourth side on an array of three-sided boxes; in digit copying, to copy a random series of digits into empty boxes below those digits; in digit-symbol substitution, to write a visual symbol associated with the numbers 0 to 9, using a lookup table, across a series of random numbers; and in letter comparison, to indicate whether two strings of three to nine letters are identical (Earles & Salthouse, 1995; Wechsler, 1991). We believe that these tasks and other measures of processing speed involve varying amounts of executive control (Table 1), and that the extent of executive control demands may change as a function of age. Even the simplest task, box completion, requires some maintenance of a task goal (e.g. 'draw the fourth side of the box'), as well as filtering background information (Lustig, Hasher & Tonev, 2006) and visuospatial processing (Miyake, Friedman, Rettinger, Shah & Hegarty, 2001). The more complex tasks also require maintaining and manipulating task-related stimuli in working memory (i.e. 'controlled attention'; Eastwood, 2001; Luciana & Nelson, 1998; Salthouse & Babcock, 1991) and cognitive decision-making (Bunce & Macready, 2005). Thus, processing speed tasks may predict executive control (and other aspects of cognition) because processing speed tasks require executive control (Diamond, 2002).

Differences among processing speed tasks are recognized to some extent by the field, namely the division of processing speed into a simpler, motor-weighted factor known as 'psychomotor speed' or 'sensorimotor speed' or 'sensory-motor processes' (essentially, time to complete repetitive motor tasks), and a more-complex, executive-weighted factor known as 'perceptual speed' or 'cognitive speed' or 'higher-order processes' (essentially, time to complete comparison- and substitution-based tasks on which errors will not be made).[1] This distinction has some empirical support (Cerella, 1985; Earles & Salthouse, 1995; Hale & Jansen, 1994, reported in Myerson, Hale, Zheng, Jenkins & Widaman, 2003; Hale & Myerson, 1993, reported in Myerson *et al.*, 2003; Salthouse, 1993, 1994), although it is not consistently followed.[2]

These concerns about the different skills necessary to perform well on different processing speed measures highlight the need to systematically address issues of construct validity. While processing speed tasks appear to measure something that is stable within individuals (Hogarty, Flesher, Ulrich, Carter, Greenwald, Pogue-Geile, Kechavan, Cooley, DiBarry, Garrett, Parepally & Zoretich, 2004; Salthouse, 1996), across tasks (Dougherty & Haith, 1997; see also Kail, 2000), and across time (Schaie, 1989), there is little explicit mention in the literature about construct validity, which requires that measures actually assess the theoretical construct (i.e. have convergent validity) and do not assess unrelated constructs (i.e. have discriminant validity). The work that has tested construct validity of processing speed (Salthouse, 1993, 1994) has not been extended to the full range of processing speed measures used by researchers or across populations of different ages, and has not tested discriminant validity. The result is a lack of clarity in the literature about *what* is being measured by existing processing speed measures, which may explain the use of potentially very different tasks under the single umbrella term processing speed.

Our concerns about the varying degree of executive control demands in processing speed measures may be especially critical for researchers who study developmental change at either end of the lifespan. The specific abilities that support performance on each processing speed task are likely to develop and decline at different rates, in a complex manner (Geary & Wiley, 1991), thereby leading to patterns of development and decline that will depend on the chosen processing speed measure. For example, young children are likely to need more executive control for writing-intensive tasks (e.g. box

[1] Other speed factors, such as 'decision speed' (time to complete tasks on which errors are likely to be made; Salthouse, 2000) and 'neural speed' (time to convert a sensory input signal and transmit this signal to the brain; Welford, 1988) have been proposed, but because these additional factors are not commonly included in the term 'processing speed', we do not consider them here.

[2] Our task analysis suggests that Myerson *et al.*'s (2003) 'sensorimotor speed' tasks (i.e. choice RT, line-length discrimination, and letter classification) map onto Salthouse's (2000) description of 'perceptual speed', while their 'cognitive speed' tasks (i.e. abstract matching, mental paper folding, and visual search) map onto Salthouse's description of 'decision speed'.

Table 1 *Processing speed measures ranked from low to high in estimated executive control contributions*

	Working memory	Decision-making	Response selection	Interference control	Motor control	Pre-existing knowledge
Prosaccade Latency[E1]	minimal	minimal	minimal	minimal	minimal	minimal
Offset RT[B,E1]	low	minimal	minimal	minimal	low	minimal
Simple RT[E1]	low	minimal	minimal	minimal	moderate	minimal
Box Completion[B,E1,E2]	low	minimal	low	low	high	minimal
Horizontal Marks[E1]	low	minimal	low	low	high	minimal
Digit Copying[E1,E2]	low	minimal	high	low	high	low
Color Naming[E1]	low	moderate	high	moderate	low	low
Choice RT[B,E1,†]	moderate	low	moderate	high	moderate	low
Digit-Symbol Substitution[E2]	moderate	low	high	moderate	high	low
Addition and Subtraction[E1]	moderate	minimal	high	moderate	high	high
Letter Comparison[E2]	high	high	moderate	moderate	high	moderate

Note: Processing speed measures vary in their demands. These variations across tasks also vary by age, with simpler tasks requiring greater executive control in children and older adults than in young adults (variations by age not shown in table). These estimates are rough, some of these factors may overlap, and we have not covered every possible factor on which tasks differ; however, the overall pattern demonstrates important variation across processing speed measures. Criteria for the four levels (specified from minimal to high) for each factor are as follows: Working memory: none required; single goal can be held in working memory throughout entire task; single goal or stimulus held in working memory must be updated during task; additional complex operations on contents of working memory required. Decision-making: no judgment about stimuli required; simple forced-choice judgment; simple open-ended judgment; difficult judgment based on multiple aspects of stimuli. Response selection: no selection involved; one response location must be selected from several; two possible responses exist; more than two possible responses exist. Interference control: no interfering stimuli; surrounding stimuli are present; surrounding stimuli might induce errors; interference within target stimulus. Motor control: saccade required; hand lift or verbal response required; hand must press specific target among multiple potential targets; fine motor control required. Pre-existing knowledge: none required; knowledge about colors, shapes, or numbers required or beneficial; knowledge about letters and letter strings beneficial; knowledge of mathematics required. While motor control and pre-existing knowledge are not necessarily aspects of executive control, they are included because they may place varying demands on executive control. Dashed line separates psychomotor and perceptual speed tasks. Task was used in study: [B]Blackwell *et al*. (2009); [E1]Experiment 1; [E2]Experiment 2. [†]see also footnote 6.

completion and digit copying) because they are just learning to write and are still developing fine motor control; they may also need more executive control for tasks that seem straightforward to adults (e.g. digit-symbol substitution) simply because these tasks tap processes that are less familiar to children (e.g. using a lookup table). This claim is compatible with developmental observations of decreased prefrontal cortex activation on an inhibitory control task during adolescence (Durston, Davidson, Tottenham, Galvan, Spicer, Fossella & Casey, 2006) because less prefrontal top-down control may be needed as tasks become easier for any reason, including development or learning. The same concerns apply late in aging, as previously simple tasks become more demanding with cognitive decline. For example, single-task blocks in a task-switching paradigm theoretically should not require high levels of executive control and are commonly used as a measure of processing speed, but these blocks recruit executive control regions in older but not younger adults (DiGirolamo, Kramer, Barad, Cepeda, Weissman, Milham, Wszalek, Cohen, Banich, Webb, Belopolsky & McAuley, 2001).

Given the potential differences across processing speed measures, the choice of measure could strongly influence the kinds of conclusions that are drawn. We assess this possibility by evaluating the conclusions supported through the use of different processing speed measures, regarding: (1) the relationship between processing speed and executive control, (2) the influence of age on this relationship, and (3) the relationship between different executive control abilities, and how executive control changes with age, when controlling for processing speed. We present two new experiments and one re-analysis of an existing dataset to test three predictions regarding these issues. These data sets included multiple typical processing speed measures that differed in difficulty (Table 1), and covered a variety of ages (6 to 85 years) and executive control abilities (working memory, inhibition, and task switching).

These data sets are rich, but we are able to present a small, focused set of analyses to test our predictions, thereby minimizing the risk of type I error. (We provide supporting analyses in the Appendices for elaboration, completeness, and ease of interpretation.) The targeted analyses focus on hierarchical regressions examining the relative contributions of distinct types of processing speed measures to different outcomes. The number of analyses is reduced through the calculation of composite measures for executive control abilities, based on at least three representative executive control tasks, which the two new data sets are designed to allow. Use of composite measures

minimizes contributions from individual task demands (as long as chosen tasks vary in type of methodology, which is true for the data we present) and results in loadings more heavily weighted on the executive control ability of interest than would a single dependent variable from a single task. To the degree that tasks of interest load more heavily on a single construct, fit will improve (Landis, Beal & Tesluk, 2000), and in practice, equally weighted component scores, which we have chosen to use, are adequate (McDonald, 1996).

Prediction 1: Relationship between processing speed and executive control depends on processing speed measure.

First, we predict that more complex processing speed measures will correlate more strongly with executive control measures and will not show adequate discriminant validity from executive control measures. Previous studies have found larger correlations between more complex processing speed measures and executive control than between simpler processing speed measures and executive control (Bunce & Macready, 2005; Salthouse, Fristoe, McGuthry & Hambrick, 1998); however, the authors of these studies never explicitly tested discriminant validity, and the range of complexity was limited (with digit copying serving as Salthouse *et al.*'s sole simple task, and choice RT serving as Bunce and Macready's simplest task), such that discriminant validity could not be properly assessed. Our prediction has the potential to explain why different conclusions have been reached about the role of processing speed in executive control depending on the processing speed measures used (Ackerman & Cianciolo, 2000; Jurado & Rosselli, 2007) because processing speed will seem to have a larger role if more complex measures are used. We test this prediction in Experiment 1, which tests young adults on multiple typical processing speed measures and executive control abilities (working memory, inhibition, and task switching), and in the young adult sub-sample of Experiment 2, which tests multiple processing speed and working memory measures.

Prediction 2: Relationship between processing speed and executive control depends on age.

Second, we predict that the relationship between processing speed measures and executive control will vary across the lifespan. Specifically, in young children and older adults, less complex measures of processing speed will be correlated more strongly with executive control than in young adults, because processing speed tasks are likely to be more demanding of executive control in individuals with immature and senescent executive control systems. If correct, this prediction indicates that particular attention must be paid to the selection of processing speed measures at either end of the lifespan, and may explain why studies investigating age-related change often suggest large roles for processing speed (Salthouse, 1994, 1996; Salthouse & Meinz, 1995), because those measures may actually measure executive control. We test this prediction in the full sample of Experiment 2, which covers 7- to 85-year-olds using multiple measures of processing speed and working memory.

Prediction 3: Conclusions about executive control depend on processing speed measure.

Third, we predict that the choice of processing speed measure to use as a covariate will influence conclusions about executive control. More complex processing speed measures will factor out executive control along with processing speed, leading to an underestimation of the role of executive control – in developmental change, for example. We test this prediction using the developmental sample of Experiment 2. Following the same logic, we predict that more complex processing speed measures will suggest weaker relationships between executive factors. We test this prediction using two datasets with multiple measures of executive control: Experiment 1 with young adults, and an existing data set with 6-year-olds (Blackwell, Cepeda & Munakata, 2009).

Present analyses

Considerable implications for investigations of executive control follow from concerns about the relationships between executive control and processing speed measures. We first present the methods for Experiments 1 and 2. Then we step through the evidence relevant to each of our three predictions, because some predictions are tested using more than one study. Overall, results from our targeted and supporting analyses are consistent with increases in executive control demands when moving from simpler to more complex processing speed tasks, which affect estimates of age-related contributions to executive control across the lifespan and individual differences in executive control.

Experiment 1

Subjects

Subjects were 58 young adults (M = 20.2 years old; 31 female) enrolled in an introductory psychology course at

the University of Colorado, Boulder. They received course credit for participation.

Design and analysis

Each subject completed a battery of 11 processing speed tasks and an array of 11 executive control tasks that tapped task switching, working memory, and inhibition. The study used a within-subjects design. We used the multiple imputation function in SPSS v19 to impute expected values for the 7.6% missing data cells. Similar results were obtained with the same analyses based on $n = 29$ subjects with no missing data cells.

Materials and procedure

The testing battery took three hours to complete, spaced equally across two sessions administered one week apart. Processing speed tasks included prosaccade latency (move your eyes from fixation to a peripheral white circle that appears; latency measured using a Tobii x50 eye tracker; 25 trials total), offset RT (stop pressing the touch screen when a circle appears; 25 trials total; Gignac & Vernon, 2004; Náñez & Padilla, 1995), simple RT (tap a circle that appears by pressing the touch screen; 25 trials total), box completion (make three-sided boxes into four-sided boxes; 30 s allowed for completion; 35 boxes on a sheet of paper; Salthouse, 1993), horizontal line marking (make horizontal dash marks on vertical lines; 30 s provided for completion; 70 lines on a sheet of paper; Salthouse, 1993), digit copying (write the number seen directly above into a box below the number; 30 s provided for completion; 80 items on a sheet of paper; Wechsler, 1991), color naming (identify the color of 60 asterisk placeholders printed on a sheet of paper; non-word baseline from a Stroop task), choice RT task 1 (identify whether circles are red or blue, by pressing 'F' or 'J' keys; baseline choice RT block from a stop signal paradigm; 25 trials total), choice RT task 2 (identify color [red or blue] or shape [circle or star] by pressing 'F' or 'J' keys; baseline non-switch trial only blocks from a computerized task-switching paradigm; 25 trials total), choice RT task 3 (identify quantity [how many items: 1 or 3] or identity [what number is presented: 1 or 3] by pressing '1' or '3' keys; baseline non-switch trial only blocks from a computerized task-switching paradigm; 16 trials total), and addition and subtraction tasks (add 3 or subtract 3 from a series of 30 random two-digit numbers printed on a sheet of paper; baseline non-switch trial only blocks from a paper-and-pencil task-switching paradigm).

In addition, participants completed 11 executive control tasks. Five tasks were typical measures of working memory. Forward and backward digit span were administered using standardized instructions (Wechsler, 1991), and required subjects to remember and recall increasingly long strings of numbers (forward span: three to nine items; backward span: two to eight items). The number of correctly recalled strings was used as the dependent variable. Spatial span was modeled after the CANTAB Corsi Blocks task (Luciana, 2003). An array of nine boxes was present on the screen, and increasingly long strings of boxes were sequentially highlighted, from three to nine items. The number of correctly recalled strings was used as the dependent variable. Subjects used a mouse to indicate the order of highlighting. Reading, counting, and operation span (Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005) are widely used measures that require the subject to perform two alternating tasks. First, subjects must remember a series of letters, object counts, or words. Second, subjects must judge semantic correctness of sentences, and correctness of mathematical equations. The number of to-be-remembered items differed across trials, and varied pseudorandomly from two to five items per trial. The total number of items recalled correctly and in the correct order placement was used as the dependent variable.

Three tasks were typical measures of inhibition and/or interference control. For the stop signal task, subjects identified circles as red or blue using 'F' or 'J' keys, except when the word 'stop!' was spoken on 25% of trials. (The word 'go!' was presented on 25% of trials to control for semantic processing.) Seven blocks were included: a baseline choice RT block, a practice stop signal block, and five stop signal blocks that each contained 48 trials. The stop signal delay between the appearance of the circle and the onset of the stop or go signal was adjusted 50 ms faster or slower each trial, so that a successfully stopped response occurred on about 50% of trials. Stop signal reaction time (Logan & Cowan, 1984) was measured. The Stroop task included three sets of items: non-color words printed in red, orange, yellow, green, blue, or purple; these same color words printed in a differing color; asterisks ('*****') printed in these ink colors. Subjects read the ink color of each of 60 items printed on a sheet of paper. Interference score was computed as time to read the color words minus time to read the non-color words. The antisaccade task directed subjects to move their eyes from fixation in the opposite direction from a peripheral white circle that appeared. Twenty-five trials were given. Accuracy was measured using a Tobii x50 eye tracker.

Three tasks measured task switching. Task 1 used fully unpredictable shape (circle or star) and color (red or blue) switching, and three switch blocks each included exactly 25 switch trials and approximately 25 non-switch

trials. Two single-task blocks preceded the switch blocks. All stimuli were response incompatible, error feedback was provided, and the task cue appeared 100 ms prior to the target. Responses were made using a touch screen, and RT and accuracy were recorded. Task 2 used predictable switching every two trials between quantity and identity tasks (Cepeda, Cepeda & Kramer, 2000, Experiment 1). Half the trials were response compatible, and half were response incompatible. The task cue ('What Number?' and 'How Many?') and target ('1', '1 1 1', '3', and '3 3 3') appeared simultaneously, and error feedback was provided. Responses were made by pressing '1' and '3' keys on a numeric keypad, and RT and accuracy were recorded. Task 3 involved alternating between adding 3 and subtracting 3 from 30 random two-digit numbers printed on a sheet of paper. Two single-task sheets were completed prior to the switch sheet. For both computerized tasks, global switch cost was calculated using response incompatible trials, based on RTs for non-switch trials in switch blocks minus non-switch only block trials; for the paper-and-pencil task, switch sheet minus average non-switch sheet completion time was computed.

All tasks were administered in a constant order, with different types and modalities of tasks intermixed throughout the two sessions. Asterisks indicate tasks not analyzed in the present paper because they were not relevant to the questions of interest. For session 1, task order was: consent form and demographics questionnaire, task switching (color and shape), reading span, prosaccade latency, antisaccade, digit span, box completion, counting span, Stroop, simple RT, Peabody Picture Vocabulary Test-III*, and K-BIT-2 Matrices*. For session 2, task order was: stop signal, spatial span, horizontal line marking, operation span, AX-CPT*, task switching (quantity and identity), digit copying, offset RT, task switching (addition and subtraction), Raven's Advanced Progressive Matrices*, and visual binding*.

Experiment 2

Subjects

Subjects were 143 children, young adults, and older adults (children: $M = 12.8$ years old, range = 8–16, $n = 71$; young adults: $M = 23.9$ years old, range = 19–30, $n = 24$; older adults: $M = 71.5$ years old, range = 60–85, $n = 48$). Children were recruited from public schools in Urbana, IL. Young adults were recruited from the University of Illinois at Urbana-Champaign student population and the Urbana-Champaign community. Older adults were recruited from the Urbana-Champaign community, using newspaper ads. All subjects were paid $30 for participation in three experimental sessions. All subjects had a complete data set, without missing cells.

Design

Each subject completed a battery of four processing speed tasks, five working memory tasks, one interference task, and one measure of task switching. The study used a within-subjects design.

Materials and procedure

Subjects completed four processing speed tasks: box completion (make a sheet of 60 three-sided boxes into four-sided boxes; Salthouse, 1993), digit copying (write the number seen directly above into a box below the number; Wechsler, 1991), digit-symbol substitution (write the symbol associated with a number using a provided chart with digit-symbol pairings; Wechsler, 1991), and letter comparison (decided whether sheets of 20 three-item, six-item, and nine-item letter pairs are the same or different (Salthouse, 1991). Subjects completed five working memory tasks: Wechsler Memory Scale paragraph recall (immediately recall a story after auditory presentation; two stories with 67 words each; Wechsler & Stone, 1973), Rey-Auditory Verbal Learning Test (AVLT; immediately recall a list of 15 everyday words five times, followed by a novel list, followed by the original list [used in the analysis]; Rey, 1964; Lezak, 1995), card rotations (determine if a series of shapes are the same [but rotated] or different [i.e. mirror images]; two trials, 3 min each; hits − false alarms used as score; Ekstrom, French, Harmen & Dermen, 1987), backward digit span (Wechsler, 1991), and coordinative–sequential complexity (sequential: solve arithmetic problems with four single digit numbers and three operands, addition or subtraction, for 3 min; coordinative: adds to sequential task parentheses delineating priority of operations; all solutions between 1 and 9; paper-and-pencil modification of Verhaeghen, Kliegl & Mayr, 1997).

Subjects were tested in three experimental sessions. Asterisks indicate tasks not analyzed in the present paper, because they were not relevant to the questions of interest or, in the case of task switching, because only a single paradigm was run and we limited analyses to those in which an executive function composite could be computed. In the first session, demographic information, an IQ measure (Kaufman Brief Intelligence Test)*, and processing speed, working memory, and interference measures (box completion, digit copying, digit-symbol substitution, letter comparison, WAIS-R digit span, card

rotations, sequential and coordinative complexity, Rey-AVLT, WMS paragraph recall, and proactive interference*) were collected. The second and third sessions consisted of a computerized task-switching paradigm*.

Analyses

Prediction 1: Relationship between processing speed and executive control depends on processing speed measure.

Our first set of analyses tested the degree of executive control involvement in each of 11 diverse types of processing speed measure (Table 1), using young adult data from Experiment 1 and the young adult sub-sample from Experiment 2. Prediction 1 was supported by (a) hierarchical regressions indicating that more complex processing speed measures predict executive control composites better than less complex processing speed measures do, and (b) correlational analyses indicating that although both simpler and more complex processing speed measures have adequate convergent validity, only simpler processing speed measures have adequate discriminant validity from working memory.

More complex processing speed measures correlate more strongly with executive control measures

As predicted, more complex processing speed measures correlated with executive control composites above and beyond correlations involving simpler measures, as demonstrated through hierarchical regression analyses (Tables 2a and 2b). Specifically, in Experiment 1 more complex processing speed measures predicted significantly more variation in the working memory, inhibition, and task-switching composites than simpler processing speed measures did, and in Experiment 2, the prediction of working memory was only significant when letter comparison was added, not with only the simpler measures. (Full correlation tables are provided in Tables A1 and A2.)

Psychomotor speed and perceptual speed fail to show adequate discriminant validity

We expect that the observed correlations between executive control and processing speed result from a lack of sufficient construct validity of processing speed measures. Good construct validity requires both convergent and discriminant validity, meaning that tasks measure what they are supposed to measure and do not measure what they should not measure (Campbell & Fiske, 1959; Rushton, Brainerd & Pressley, 1983). Experiment 1 included a wide array of processing speed measures that allow us to examine this issue, using a standard approach of computing and comparing correlations (Carmines & Zeller, 1979; Shavelson, Hubner & Stanton, 1976; cf. Bagozzi, Yi & Phillips, 1991; Kenny, Kashy & Bolger, 1998). We first examined whether simpler (psychomotor speed) and more complex (perceptual speed) processing speed tasks each showed good convergent validity (i.e. whether processing speed measures of each type correlated with each other). We then examined whether simpler and more complex processing speed measures showed good discriminant validity from one another. Finally, we tested whether simpler and more complex processing speed tasks each showed good discriminant validity from executive control measures.

To assess convergent validity, we examined correlations between tasks that purportedly measure the same theoretical construct (e.g. psychomotor speed for simpler tasks or perceptual speed for more complex tasks), selecting tasks based on past descriptions of each theoretical construct (e.g. Salthouse, 2000). Previous studies have found reasonable convergent validity for the

Table 2a *Hierarchical regressions examining contributions of increasingly complex processing speed measures to the executive control composite scores in Experiment 1*

	Working Memory			Inhibition			Task Switching		
Processing Speed Measure	ΔR^2	F for Δ	*df*	ΔR^2	F for Δ	*df*	ΔR^2	F for Δ	*df*
Psychomotor Speed	.005	0.3	1,56	.146**	9.6	1,56	.167**	11.3	1,56
Perceptual Speed	.225**	16.0	1,55	.156**	12.3	1,55	.127**	9.9	1,55

Note: More complex processing speed measures predict additional executive control variance in young adults. $n = 58$; *$p < .05$; **$p < .01$. Task Switching composite = average of global switch cost, color and shape switching task, global switch cost, quantity and identity switching task, and switch cost, addition and subtraction switching task z-scores; Inhibition composite = average of stop signal reaction time, stop signal task, color minus non-color word completion time, Stroop task, and antisaccade percent errors, antisaccade task z-scores; Working Memory composite = average of digit span backward, spatial span backward, reading span total items correct, counting span total item correct, and operation span total items correct z-scores.

Table 2b *Hierarchical regression examining contributions of increasingly complex processing speed measures to the working memory composite score in the young adult subsample of Experiment 2*

Processing Speed Measure	ΔR^2	F for Δ	*df*
Box Completion	.006	0.1	1,22
Digit Copying	.005	0.1	1,21
Digit-Symbol Substitution	.015	0.3	1,20
Letter Comparison	.248*	6.5	1,19

Note: More complex processing speed measures predict additional working memory variance in young adults. $n = 24$; *$p < .05$; **$p < .01$. Working Memory composite = average of paragraph recall, Rey-AVLT learning, card rotations (hits-FAs), digit span backward, and coordinative–sequential complexity *z*-scores.

more general construct 'processing speed' by demonstrating moderate to strong correlations ($r = .4$ to .7) between digit copying, digit-symbol substitution, letter comparison, pattern comparison, and reading speed (Salthouse, 1993; Salthouse & Meinz, 1995), and moderate correlations between number comparison (classify multi-digit numbers as the same or different), picture identity (match a line figure to an array of five variants), and finding A's [*sic*] (find all As in a set of words; Hertzog & Bleckley, 2001; see also Ekstrom, French & Harman, 1979). However, because most of these tasks are relatively complex, one might instead interpret these previous results as evidence for convergent validity for the construct perceptual speed.

We found good convergent validity for psychomotor speed and for perceptual speed, with moderate to strong correlations between psychomotor speed measures, and likewise between perceptual speed measures (Table A3); with only one exception, correlations between within-construct composite scores and individual tasks ranged from $r = .34$ to .59. We also found good convergent validity for working memory and inhibition factors (Table A4); with only one exception, correlations between within-construct composite scores and individual tasks ranged from $r = .36$ to .55. Task switching failed to show adequate convergent validity, indicating that results with this composite must be interpreted cautiously; this composite is thus not reported in the remaining analyses, although task switching showed some similarity to findings from the other executive control measures.[3]

[3] Like inhibition (in Table 3), task switching did not show discriminant validity from either psychomotor or perceptual speed (in part because task switching had such a small within-construct correlation). The relationship between task switching and working memory was affected by choice of processing speed covariate in the same way as the relationship between inhibition and working memory (as shown in Table 6; significant with no processing speed covariate or a psychomotor speed covariate, but not with a perceptual speed covariate), while the relationship between task switching and inhibition failed to reach significance with or without a processing speed covariate.

Table 3 *Correlations between processing speed and executive control measures in Experiment 1*

	Perceptual Speed .384	Working Memory^ .357	Inhibition .240
Psychomotor Speed .236	.310*	−.067	.382**
Perceptual Speed .384	–	−.472**	.494**

Note: Perceptual speed does not show adequate discriminant validity from executive control constructs. Working memory but not inhibition shows discriminant validity from psychomotor speed. Psychomotor and perceptual speed show an ambiguous discriminant validity pattern. Within-construct correlations are noted in column and row headings, and between-construct correlations are noted in table cells. When the between-construct correlation is smaller than the within-construct correlations, the constructs have good discriminant validity. $n = 58$; * $p < .05$; ** $p < .01$ ^ negative because larger is better for WM. Psychomotor Speed composite = average of offset RT, simple RT, box completion, horizontal line marking, and digit copying *z*-scores; Perceptual Speed composite = average of color naming, choice RT, color task, choice RT, color and shape tasks, choice RT, quantity and identity tasks, and addition and subtraction tasks *z*-scores; Inhibition composite = average of stop signal reaction time, stop signal task, color minus non-color word completion time, Stroop task, and antisaccade percent errors, antisaccade task *z*-scores; Working Memory composite = average of digit span backward, spatial span backward, reading span total items correct, counting span total item correct, and operation span total items correct *z*-scores.

Next, we examined whether psychomotor speed and perceptual speed show discriminant validity from each other and from executive control measures.[4] Discriminant validity requires that measures do not correlate with theoretical constructs that are supposed to be unrelated to the construct of interest. To demonstrate discriminant validity, we must show that between-factor

[4] Three requirements exist (Campbell, 1960; Campbell & Fiske, 1959). First, measures must show internal consistency (e.g. via Cronbach's alpha) and inter-method reliability (e.g. analyses based on instruments that use different methods lead to the same conclusion). Second, within-construct correlations must be larger than between-construct correlations, when using the same methodology. Third, same- and different-methodology correlation patterns should match. We met criterion 1 where testable. Criterion 2 is designed to prevent differences in correlation magnitude as a result of differences in shared method variance for within- vs. between-construct correlations. Because we do not have appropriate tasks to test Campbell and Fiske's criterion 2, our analysis is based on a similar confound-free assumption. Specifically, we have assumed that method variance varies to an equal degree within- and between-constructs, which we believe is the case for our tasks. We are unable to test criterion 3.

correlations (e.g. the correlation between psychomotor speed and perceptual speed) are smaller than the corresponding within-factor correlations (e.g. the within-psychomotor speed and within-perceptual speed correlations; Campbell, 1960). Our analysis of discriminant validity between psychomotor speed and perceptual speed was ambiguous, as the within-psychomotor speed correlation was smaller than the between-factor correlation, while the within-perceptual speed correlation was larger (Table 3). Our findings are consistent with ambiguity in the literature (cf. Cerella, 1995; Hale & Myerson, 1993, reported in Myerson *et al*., 2003). More complex speed tasks also include simpler aspects of speed, which means that we expect moderate correlations between speed factors, and thus a lack of strong discriminant validity.

Critically, perceptual speed clearly did not show adequate discriminant validity from either executive control factor (Table 3). That is, perceptual speed measures do not predict one another any better than they predict inhibition or working memory, as predicted given the executive control demands of more complex processing speed measures. At a minimum, such statistical equality suggests that factoring processing speed (based on complex tasks) out of executive control performance is statistically equivalent to factoring executive control out of executive control. In contrast, psychomotor speed and working memory showed a clear pattern consistent with discriminant validity, while inhibition clearly failed to show discriminant validity from psychomotor speed (Table 3). The independence of processing speed and executive control thus depends on the specific combination of processing speed and executive control tasks chosen by the researcher.

Prediction 2: Relationship between processing speed and executive control depends on age.

Our second prediction was that simpler processing speed measures would be correlated with executive control measures in children and older adults, given the larger potential demands on executive control for simple tasks in these populations. We tested this prediction using the lifespan sample in Experiment 2. In children and older adults (as with young adults as tested in Prediction 1), more complex measures correlated with the working memory composite above and beyond simpler measures, as demonstrated through hierarchical regression analyses (Table 4). Most importantly, whereas only the most complex letter comparison task predicted significant amounts of working memory variance in young adults, simpler digit copying and/or digit-symbol substitution predicted working memory variance in children and older adults. No additional variance was accounted for by letter comparison over digit-symbol substitution in children or older adults, perhaps because both include a heavy working memory demand in this age group (compared to young adults, who might be able to quickly memorize the digit-symbol pairings). (The full correlation table is provided in Table A5.)

Prediction 3: Conclusions about executive control depend on processing speed measure.

The tests of our first two predictions demonstrate that many processing speed measures contain executive control components, particularly at either end of the lifespan. Our final prediction tests the implications of this: namely, that choice of processing speed measure to use as a covariate can influence conclusions about executive control, such as how executive control changes with development and how different components of executive control relate to one another. This prediction was supported by hierarchical regressions indicating that estimates of age-related change in working memory decreased when more complex processing speed measures were used, and by correlations between different executive control measures that were significant when simpler processing speed measures were used as covari-

Table 4 *Hierarchical regressions examining contributions of increasingly complex processing speed measures to the working memory composite score in Experiment 2, separately for children, young adults, and older adults*

	7- to 16-year-olds			19- to 30-year-olds			60- to 85-year-olds		
Processing Speed Measure	ΔR^2	F for Δ	df	ΔR^2	F for Δ	df	ΔR^2	F for Δ	df
Box Completion	.047	3.4	1,69	.006	0.1	1,22	.059	2.9	1,46
Digit Copying	.134**	11.1	1,68	.005	0.1	1,21	.040	2.0	1,45
Digit-Symbol Substitution	.182**	19.2	1,67	.015	0.3	1,20	.152**	9.0	1,44
Letter Comparison	.000	0.0	1,66	.248*	6.5	1,19	.040	2.4	1,43

Note: Simpler processing speed measures predicted more variance of working memory for children (n = 71) and older adults (n = 48), but not for young adults (n = 24). * $p < .05$; ** $p < .01$. Working Memory composite = average of paragraph recall, Rey-AVLT learning, card rotations (hits-FAs), digit span backward, and coordinative–sequential complexity z-scores.

ates but not when more complex processing speed measures were used.

Estimates of age-related change in working memory decrease when more complex processing speed measures are used

We examined how the choice of processing speed measure influences estimates of age-related change in executive control, by running a series of hierarchical regressions on the data from 7- to 30-year-olds in Experiment 2, sequentially entering decreasingly complex processing speed measures. (We were unable to conduct a similar aging analysis because we did not collect data from 31- to 59-year-olds.) A hierarchical regression analysis[5] demonstrated that more complex processing speed tasks capture more of the variance linking age and working memory performance, relative to simpler tasks (Table 5). Thus, the observed degree of age-related change in working memory depends on the choice of processing speed measure used as a covariate. (A series of hierarchical regressions also showed that a greater percentage of age-related change is attributed to executive control when using simpler processing speed measures; Table A6.)

Table 5 *Hierarchical regression predicting age in Experiment 2*

Working Memory Residual Regressing on	ΔR^2	F for Δ	*df*
Letter Comparison	.079	8.0	1,94
Digit-Symbol Substitution	.028	2.9	1,93
Digit Copying	.008	0.8	1,92
Box Completion	.390***	71.6	1,91

Note: Estimates of age-related change in working memory increase as simpler processing speed tasks are used as regressors. Independent variables in this hierarchical regression are residual scores obtained from four linear regressions, using working memory composite score as a dependent variable, and separately, each of the processing speed measures as an independent variable. Residuals, the variance that remained after regressing each processing speed measure on the working memory composite, are tested for their ability to predict age-related change in working memory. Residuals from more complex processing speed measures (first three regression steps) show minimal shared variance with age (small R^2 values), because little age-related variance remains when regressing working memory on complex processing speed measures. When the residual from the least complex processing speed measure (last regression step) was subsequently entered into the model, a significant amount of age-related variance was explained, with an R^2 value at least five times larger than the previous R^2 values. Thus, estimates of age-related changes in working memory will be smaller with more complex processing speed measures relative to less complex measures. $n = 96$; ***$p < .001$. Working Memory composite = average of paragraph recall, Rey-AVLT learning, card rotations (hits-FAs), digit span backward, and coordinative–sequential complexity z-scores.

Estimates of correlations between executive control components decrease when more complex processing speed measures are used

We examined how the choice of processing speed measure influences estimates of relationships between different executive control measures, by assessing the correlations observed when using simpler versus more complex processing speed measures as covariates. We investigated this prediction in two studies that used different executive control measures that could be compared to each other: Experiment 1, and a previously published child data set (Blackwell *et al.*, 2009). In both cases, correlations between executive control measures were significant only when using simpler processing speed measures.

In the young adult data from Experiment 1, the correlation between working memory and inhibition failed to reach significance when using perceptual speed measures (Table 6). When using psychomotor speed measures, significance was reached. The pattern of correlations between working memory and inhibition appeared quite similar when psychomotor speed was covaried and when processing speed was not entered as a covariate, suggesting that only perceptual speed measures contributed executive control variance.

We found a similar pattern in our re-analysis of a data set with 42 6-year-old children (Blackwell *et al.*, 2009; see also Cepeda & Munakata, 2007; Deák, 2003), which included three processing speed measures (offset RT, box completion, and choice RT) and two executive control measures (task switching and working memory). The original analysis of these data indicated that children who showed better task switching performed better on the working memory measure, even after controlling for processing speed, when processing speed was estimated using a composite of box completion and offset RT. For the present analysis, we extracted an additional choice RT measure, which was available as part of the task-switching measure, in which children were asked to respond to simple questions (e.g. 'Can you press the

[5] First, residual working memory composite scores were computed, using each processing speed measure (dependent variable = working memory composite score; independent variable = processing speed measure). Second, these residuals were used to predict age, in hierarchical regression analyses (dependent variable = age; step 1: enter residual remaining after predicting working memory using letter comparison; step 2: enter residual remaining after predicting working memory using digit-symbol substitution; and so on).

Table 6 *Partial correlations between inhibition and working memory composite scores in Experiment 1, controlling (or not controlling) for processing speed composite scores*

	Relationship between Inhibition and Working Memory		
	r	*p*	*df*
Not Controlling for Processing Speed	−.304*	.020	56
Controlling for Psychomotor Speed	−.302*	.022	55
Controlling for Perceptual Speed	−.093	.492	55

Note: Estimates of the relationship between inhibition and working memory decreased when controlling for more complex processing speed measures. Working memory was significantly related to inhibition when using psychomotor speed measures, but not when using perceptual speed measures. $n = 58$; *$p < .05$; **$p < .01$. Psychomotor Speed composite = average of offset RT, simple RT, box completion, horizontal line marking, and digit copying *z*-scores; Perceptual Speed composite = average of color naming, choice RT, color task, choice RT, color and shape tasks, choice RT, quantity and identity tasks, and addition and subtraction tasks *z*-scores; Inhibition composite = average of stop signal reaction time, stop signal task, color minus non-color word completion time, Stroop task, and antisaccade percent errors, antisaccade task *z*-scores; Working Memory composite = average of digit span backward, spatial span backward, reading span total items correct, counting span total item correct, and operation span total items correct *z*-scores.

cat?') by selecting between three possible responses (e.g. cat, fish, and bird).[6]

Consistent with our predictions, the qualitative significance of the relationship between working memory and task switching changed depending on which processing speed measure was used as a covariate. We conducted ANCOVAs with working memory as a dependent variable, switch status (switcher or perseverator) as an independent variable, and each processing speed measure (offset RT, box completion, and choice RT) and age as covariates. When the least-complex measure, offset RT, was used to factor out processing speed, children who successfully switched between rules performed significantly better on the measure of goal maintenance ($F(1, 36) = 4.6$, $p < .05$, $\eta^2 = .11$), but when the more-complex box completion measure was used, this advantage was only marginal ($F(1, 36) = 3.0$, $p = .09$, $\eta^2 = .08$), and when the most-complex choice RT measure was used, this advantage did not reach significance ($F(1, 36) = 2.2$, $p > .14$, $\eta^2 = .06$). These findings are consistent with our argument that even apparently simple processing speed measures can require executive control in young children.

General discussion

The richness of our data sets allowed us to investigate how different processing speed measures influence conclusions about executive control across the lifespan. These analyses were focused through the use of composite measures and the targeted testing of predictions. Results from these analyses converged to indicate that many commonly accepted processing speed measures tap executive control, such that the processing speed measure chosen can influence the conclusions drawn about executive control. Experiments 1 and 2 indicate that more complex processing speed tasks are more strongly correlated with executive control, with Experiment 1 suggesting that more complex processing speed measures are virtually interchangeable with executive control measures. Experiment 2 further indicates that seemingly simple processing speed tasks are correlated with executive control in children and older adults but not in young adults, and that more complex processing speed measures might underestimate age-related changes in executive control while overestimating age-related changes in processing speed. Finally, Experiment 1 and our re-analysis of Blackwell *et al*.'s (2009) data indicate that choosing a more complex processing speed measure will decrease the relationship observed between executive control measures.

Our findings of the strong relationship between executive control and complex processing speed (i.e. perceptual speed) tasks are consistent with other findings in the literature, but go beyond existing findings in terms of the range of ages and tasks tested, the tests of discriminant validity, and resulting conclusions. For example, Salthouse (1993) found near-perfect correlations between perceptual speed and cognition that were 'somewhat surprising' (p. 735), and noted five additional studies that showed correlations between perceptual speed and executive control that were at least $r = .75$ (i.e. Baltes, Cornelius, Spiro, Nesselroade & Willis, 1980; Cornelius, Willis, Nesselroade & Baltes, 1983; Schaie, Dutta & Willis, 1991; Schaie, Willis, Hertzog & Schulenberg, 1987; Schaie, Willis, Jay & Chipuer, 1989). Salthouse stated that perceptual speed and executive control are 'nevertheless distinguishable' (1993, p. 735), because the correlation between these factors is less than 1.0, and because the perceptual speed and executive control composite test–retest reliabilities were larger than the correlation between perceptual

[6] The choice RT tasks described in Table 1 and used in Experiment 1 have two response options and use a keyboard or button box on which the fingers may rest. By contrast, the choice RT task used in Blackwell *et al*. (2009) has three response options and requires a physical hand movement, thereby increasing response selection, interference control, and motor control demands.

speed and executive control. However, correlations can be less than 1 due to noise, and test–retest reliabilities show whether a given measure yields a stable result, not whether one measure taps a different construct from another measure.

Thus, testing whether executive control and complex processing speed measures tap different constructs requires a consideration of correlations within-construct and across-constructs, as reported here. Moreover, we believe that our analysis provides a broader test of discriminant validity, because it more fully covers the range of tasks included in theoretical descriptions of these constructs. These findings of strong correlations and lack of discriminant validity indicate that the vast majority of variance between these executive control and complex-processing speed measures is shared – so much so that in practical terms, they are essentially the same construct. The reason why processing speed has seemed so important for executive control may be that executive control has been systematically required to perform processing speed tasks (see also Diamond, 2002). Complex processing speed tasks are thus not appropriate baselines for studies of executive control, as they will factor out substantial variance of interest and lead to underestimations of executive control contributions. These concerns apply even to some simple processing speed tasks, particularly in children and older adults.

Concerns about the role of executive control in processing speed tasks also apply to a number of tasks not investigated here, which have been interpreted across many studies as providing support for the role of processing speed in executive control (e.g. Charlton *et al.*, 2008; Fisk & Warr, 1996; Hillman, Belopolsky, Snook, Kramer & McAuley, 2004; Leskelä, Hietanen, Kalska, Ylikoski, Pohjasvaara, Mäntylä & Erkinjuntti, 1999; Perrotin, Isingrini, Souchay, Clarys & Taconnat, 2006; Polderman, Posthuma, De Sonneville, Stins, Verhulst & Boomsma, 2007; Salthouse, Atkinson & Berish, 2003; Salthouse & Miles, 2002; Schretlen, Pearlson, Anthony, Aylward, Augustine, Davis & Barta, 2000; Travis, 1998). These studies used tasks and measures such as digit-symbol substitution, letter and pattern comparison, and Trail Making Test A (connecting the numbers 1 to 25, which are printed on a sheet of paper, in ascending order; see also Gaudino, Geisler & Squires, 1995). Such tasks are likely to tap executive control processes, not just general processing speed, following the same logic presented in Table 1.

Simpler processing speed measures – such as prosaccade latency, offset RT, simple RT, box completion, horizontal line marking, and digit copying – may thus be preferable. These simpler tasks are not without concerns, however. Digit copying may tap executive control in children and older adults, and some simple processing speed measures that load less heavily on executive control may not factor out all the relevant processing variance. For example, prosaccade latency (Canfield, Smith, Brezsnyak, Snow, Aslin, Haith, Wass & Adler, 1997; Kirchner & Thorpe, 2006) was minimally related to executive control, but also failed to correlate with other simple processing speed measures. This measure relies on reflexive responses that are present even at birth (Richards, 2001) and that utilize brainstem processing (Scudder, Kaneko & Fuchs, 2002; Sparks, 2002), and thus may not provide a valid measure of processing speed relevant to cognitive performance, at least in young adults. Thus, trying to select the most appropriate processing speed measures, while critical, is not simple.

We believe that a number of alternative behavioral and brain measures of processing speed warrant further study in the context of the issues we have raised. For example, inspection time measures (Burns & Nettelbeck, 2005; Nettelbeck & Rabbitt, 1992) involve the brief presentation of stimuli (< 200 ms), with subjects deciding which of two simultaneously presented lines is shorter, for example. Individuals with higher accuracy at the fastest presentation rates are assigned better scores. Some executive control demands are minimized (Vickers, Nettelbeck & Willson, 1972), as reaction time data are not used, only one pair of stimuli is presented at a time, and no complex decisions are made. Potential brain measures include structural and functional measures relevant to processing speed. Structurally, the myelination of neurons allows rapid, synchronized neural transmission; myelination can be measured using a new myelin-specific MRI technique (Deoni, Mercure, Blasi, Gasston, Thomson, Johnson, Williams & Murphy, 2011), or less directly through diffusion tensor imaging (DTI; Charlton *et al.*, 2006, 2008). Functionally, precise temporal information about neural processes can be obtained via electrophysiological measures, such as event-related potential (ERP) component latencies measured from the scalp, or electrocorticogram (ECoG) recordings taken directly from the surface of the brain in neurosurgical patients (Canolty, Soltani, Dalal, Edwards, Dronkers, Nagarajan, Kirsch, Barbaro & Knight, 2007; Edwards, Nagarajan, Dalal, Canolty, Kirsch, Barbaro & Knight, 2010). Some ERP components (e.g. the mismatch negativity, or MMN) have been associated with reaction time measures of processing speed (Jääskeläinen, Pekkonen, Alho, Sinclair, Sillanaukee & Näätänen, 1995; Sculthorpe, Stelmack & Campbell, 2009; Tervaniemi, Winkler & Näätänen, 1997; Tzambazis & Stough, 2000).

The issues we have raised concerning processing speed measures likely apply to potential brain and behavioral measures as well. For example, some early ERP components (e.g. brainstem auditory evoked components) may reflect processes that are too simple, as our measure of prosaccade latency may have been for young adults. Later ERP components (e.g. P3 and N400) may reflect processes that require executive control (Donchin, 1981; Lau, Phillips & Poeppel, 2008). Similarly, even in inspection time tasks, participants may benefit from sustained attention to detect the briefly presented stimuli and the ability to compare stimuli. Looking-time measures used to assess processing speed in infants (Rose, Feldman & Jankowski, 2002) may also benefit from executive control: Infants might habituate relatively quickly to visual displays because of a greater ability to direct their attention to a range of relevant portions of the displays, rather than because of greater raw processing speed. Consistent with this account, slow habituaters (who continue to look at old displays for a relatively long time) can be induced to behave like fast habituaters (who scan broadly and prefer novel displays) when their attention is exogenously directed to different points in the displays (Frick, Colombo & Saxon, 1999).

Given that the issues we have raised likely apply to a broad range of processing speed measures, we believe that future research should focus on both task development and analysis methods that would allow processing speed to be measured separately from executive control. One step toward accomplishing this goal is to use less complex tasks; another is to use analytic techniques such as latent variable analyses (Gefen, Straub & Boudreau, 2000) and multitrait-multimethod approaches (Campbell & Fiske, 1959). Both of these approaches minimize unwanted variance by analyzing the commonalities among multiple tasks that assess the construct of interest and require tasks that load heavily on a single trait (e.g. psychomotor speed) and vary in methodology (e.g. both paper-and-pencil and RT tasks), so the relative contributions of trait and method variance can be distinguished. These criteria must be met across all of the age groups being studied, which requires a consideration of changes in executive control demand with development.

Despite previous theoretical speculations (Conway, Cowan, Bunting, Therriault & Minkoff, 2002; Geary & Wiley, 1991; Miyake *et al*., 2001) and empirical demonstrations (Bunce & Macready, 2005; Lustig *et al*., 2006) of problems from the use of complex processing speed measures, researchers continue to use these measures. By analyzing three data sets, we have demonstrated how executive control demands in commonly used processing speed measures have likely resulted in widespread overestimates of processing speed contributions to cognition and age-related cognitive change, and to underestimates of relationships between executive control factors and of developmental- and aging-related contributions to executive control. These findings highlight the need for the further development and validation of processing speed measures that can be distinguished from executive control, and further consideration of executive control demands in selecting processing speed measures and in drawing conclusions based on these measures about cognition and age-related change.

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Appendix

The patterns observed in our targeted analyses were also evident in correlation tables, which are included here for completeness and for potentially more intuitive summaries of the data.

Table A1 *Correlations between processing speed tasks and executive control composite scores in Experiment 1*

	Working Memory^	Inhibition	Task Switching
ORT	−.053	.546**	.233
SRT	−.073	.066	.246
BC	.049	.193	.217
HM	−.019	.183	.194
DC	−.114	.204	.385**
CN	−.151	.468**	.367**
CRT1	−.470**	.314*	.441**
CRT2	−.374**	.378**	.320*
CRT3	−.341**	.362**	.215
AS	−.343**	.237	.313*

Note: More complex processing speed measures (perceptual speed; CN through AS) were often correlated with executive control in young adults (12 out of 15 correlations between processing speed task and executive function construct reached $p < .05$), but simpler speed measures (psychomotor speed; PL through DC) were rarely correlated with any of the executive control composites (2 out of 15 correlations reached $p < .05$). $n = 58$; *$p < .05$; **$p < .01$; ^ negative because larger is better for working memory tasks. Dashed line separates psychomotor and perceptual speed tasks. Processing Speed Measures (from low to high in executive control contributions): ORT = offset RT; SRT = simple RT; BC = box completion; HM = horizontal line marking; DC = digit copying; CN = color naming; CRT1 = choice RT, color task; CRT2 = choice RT, color and shape tasks; CRT3 = choice RT, quantity and identity tasks; AS = addition and subtraction tasks. Task Switching composite = average of global switch cost, color and shape switching task, global switch cost, quantity and identity switching task, and switch cost, addition and subtraction switching task *z*-scores; Inhibition composite = average of stop signal reaction time, stop signal task, color minus non-color word completion time, Stroop task, and antisaccade percent errors, antisaccade task *z*-scores; Working Memory composite = average of digit span backward, spatial span backward, reading span total items correct, counting span total item correct, and operation span total items correct *z*-scores.

Table A2 *Correlations between processing speed tasks and working memory composite score in the young adult subsample of Experiment 2*

	Working Memory
Box Completion	.076
Digit Copying	.101
Digit-Symbol Substitution	.144
Letter Comparison	.483*

Note: The most complex processing speed measure (Letter Comparison), but not simpler speed measures, load on working memory in young adults. $n = 24$; *$p < .05$; **$p < .01$. Working Memory composite = average of paragraph recall, Rey-AVLT learning, card rotations (hits-FAs), digit span backward, and coordinative–sequential complexity *z*-scores.

Table A3 *Convergent validity of processing speed measures: correlations in Experiment 1*

	Psychomotor Speed	Perceptual Speed
ORT	.380**	.405**
SRT	.167	.333*
BC	.581**	−.005
HM	.342**	.014
DC	.366**	.219
CN	.397**	.547**
CRT1	.342**	.448**
CRT2	.260*	.588**
CRT3	.155	.542**
AS	−.052	.494**

Note: Psychomotor speed (ORT through DC; upper left shaded region) and perceptual speed (CN through AS; lower right shaded region) both show good convergent validity. $n = 58$; *$p < .05$; **$p < .01$. Dashed line separates psychomotor and perceptual speed tasks. ORT = offset RT; SRT = simple RT; BC = box completion; HM = horizontal line marking; DC = digit copying; CN = color naming; CRT1 = choice RT, color task; CRT2 = choice RT, color and shape tasks; CRT3 = choice RT, quantity and identity tasks; AS = addition and subtraction tasks; Psychomotor Speed composite = average of ORT, SRT, BC, HM, and DC *z*-scores; Perceptual Speed composite = average of CN, CRT1, CRT2, CRT3, and AS *z*-scores. Processing speed measures were removed from composite *z*-scores as needed so that within-task correlations were avoided.

Table A4 *Convergent validity of executive control measures: correlations in Experiment 1*

	Working Memory	Inhibition	Task Switching
DS	.553**	−.249	−.330*
SSpan	.425**	−.022	−.232
RSpan	.425**	−.186	−.198
CSpan	.531**	−.357**	−.215
OSpan	.553**	−.246	−.064
SS	−.114	.378**	.152
Stroop	−.301*	.356**	.120
Anti	−.226	.194	.165
CS	.031	.032	.024
WH	−.448**	.176	.276*
AS	−.152	.187	.143

Note: Working memory (upper left shaded region) and inhibition (middle shaded region) each show good convergent validity, while task

switching (lower right shaded region) does not. $n = 58$; *$p < .05$; **$p < .01$. Dashed lines separate working memory, inhibition, and task switching tasks. DS = backward digit span; SSpan = spatial span; RSpan = reading span; CSpan = counting span; OSpan = operation span; SS = stop signal; Stroop = Stroop; Anti = antisaccade; CS = task switching, color / shape; WH = task switching, what number / how many; AS = task switching, add / subtract. Working Memory composite = average of DS, SSpan, RSpan, CSpan, and OSpan *z*-scores; Inhibition composite = average of SS, Stroop, and Anti *z*-scores; Task Switching composite = average of CS, WH, and AS *z*-scores. Executive control measures were removed from composite *z*-scores as needed so that within-task correlations were avoided.

Table A5 *Correlations between processing speed tasks and working memory composite score in Experiment 2*

Processing Speed Measure	8- to 16-year-olds	19- to 30-year-olds	60- to 85-year-olds
Box Completion	.218	.076	.242
Digit Copying	.419**	.101	.313*
Digit-Symbol Substitution	.586**	.144	.499**
Letter Comparison	.477**	.483*	.431**

Note: Simpler processing speed measures loaded on working memory for children ($n = 71$) and older adults ($n = 48$), but not for young adults ($n = 24$). *$p < .05$; **$p < .01$. Working Memory composite = average of paragraph recall, Rey-AVLT learning, card rotations (hits-FAs), backward digit span, and coordinative–sequential complexity *z*-scores.

Table A6 *Hierarchical regressions examining contributions of age to the working memory composite score in Experiment 2, above and beyond processing speed, based on increasingly complex processing speed measures*

	7- to 30-year-olds			
Processing Speed Measure	ΔR^2	*F* for Δ	*df*	% Age Effects Not Mediated by Processing Speed
Age	.322**	44.7	1,94	
Box Completion	.087**	8.9	1,94	
+ Age	.237**	32.7	1,93	73.6
Digit Copying	.258**	32.7	1,94	
+ Age	.085**	12.1	1,93	26.4
Digit-Symbol Substitution	.343**	49.0	1,94	
+ Age	.039**	5.9	1,93	12.1
Letter Comparison	.333**	46.9	1,94	
+ Age	.080**	12.7	1,93	24.8

Note: Estimates of age related change decreased as more complex processing speed measures were used. $n = 96$; *$p < .05$; **$p < .01$. Working Memory composite = average of paragraph recall, Rey-AVLT learning, card rotations (hits-FAs), backward digit span, and coordinative–sequential complexity *z*-scores.