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VI. NIH TOOLBOX COGNITION BATTERY (CB): MEASURING PROCESSING SPEED

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Abstract

This chapter focuses on the Toolbox Pattern Comparison Processing Speed Test, which was developed to assess processing speed within the NIH Toolbox Cognition Battery (CB). We describe the development of the test, highlighting its utility in children. In addition, we examine descriptive data, test–retest reliability, validity, and preliminary work creating a composite index of processing speed. Results indicated that most children were able to understand the basic concepts of the Toolbox Pattern Comparison Processing Speed Test. Further, test–retest reliability was excellent. Analyses examining convergent and discriminant validity provided support for the utility of the test as a measure of processing speed. Finally, analyses comparing and combining scores on the Toolbox Pattern Comparison Processing Speed Test with other measures of simple reaction time from the NIH Toolbox CB indicated that a Processing Speed Composite score performed better than any test examined in isolation. Taken together, the Toolbox Pattern Comparison Processing Speed Test appears to exhibit a number of strengths: it is child-friendly and engaging, short and easy to administer, and has good construct validity, especially when used as part of a composite score.

In this chapter, we discuss the Toolbox Pattern Comparison Processing Speed Test, the measure designed to assess processing speed.

Subdomain Definition

Processing speed is an extremely important developmental construct. Age differences in speeded responses are robust and reliable across the lifespan. On simple tasks, reaction time (RT) generally decreases systematically from infancy through childhood and adolescence, reaching a minimum in young adulthood; thereafter, RT increases modestly during middle age, and more substantially in old age. The developmental profile of increasing RT speed between birth and young adulthood can be exemplified by three different types of studies. First, on a simple RT task in which children respond to an auditory or visual stimulus by pressing a key, RTs are much greater for children than for adolescents, whose RTs are somewhat larger than those for adults (Kail, 1991). Second, judging whether pairs of pictures are identical in name takes longer than judging whether they are identical in appearance (Kail, 1991); discrepancies in RT between these two types of tasks times are smallest for young adults, somewhat larger for adolescents, and much larger for children

(Kail, 1991). Finally, saccadic eye movements to targets in peripheral vision become faster with age, substantially so in the first year of life and more gradually thereafter (Canfield, Smith, Brezsnyak, & Snow, 1997; Luna, Garver, Urban, Lazar, & Sweeney, 2004).

Importance During Childhood

The developmental profile of RT is not restricted to motor processing. Instead, reductions in RT are evident in a broad range of cognitive processes, including executive function (see Zelazo et al., Chapter 2, this volume) and episodic memory (see Bauer et al., Chapter 3, this volume). Consequently, changes in RT are often described as developmental changes in information processing speed (Kail, 2008; Kail & Salthouse, 1994). Evidence shows that increases in processing speed are associated with age-related improvements in performance on a variety of cognitive tasks, including reading, memory, arithmetic problem solving, way-finding, and reasoning (Kail, 2004, 2008). In some cases, processing speed accounts statistically for all of the variance in age-related cognitive changes (i.e., significant associations between age and cognitive skill disappear when processing speed is partialled out). In addition, longitudinal research shows that measures of processing speed administered during infancy predict mental development in the preschool years (Rose, Feldman, Jankowski, & Van Rossem, 2008).

Cognitive Processing, and Biological Substrates

When measuring processing speed across the lifespan, it is important to consider the cognitive processes that drive increases in processing speed, as well as their biological substrates. First, the fact that speeds of a number of different processes increase with age does not necessarily implicate a common mechanism. One possibility—building on the well-established link between repeated practice and RT (Newell & Rosenbloom, 1981) and the view of young children as universal novices (Brown & DeLoache, 1978)—is that speeds of individual processes develop at distinct rates, each reflecting task-relevant experience. Following this logic, the usual correlation between age and processing speed is seen as a byproduct of correlations between age/experience and experience/speed. Another possibility is that developmental increases in processing speed reflect some underlying systemic change (i.e., change in a fundamental property of the developing cognitive architecture). In fact, processing speeds in different domains increase at a common rate (Kail, 1986, 1988, 1991), supporting the notion of a global mechanism. In addition, factor-analytic studies provide evidence that processing speed measures are significantly intercorrelated and can be distinguished from other related cognitive constructs such as response inhibition, working memory, and cognitive control throughout childhood and adolescence (Demetriou, Mouyi, & Spanoudis, 2008; McAuley & White, 2011).

While a number of cognitive processes influence processing speed, it is also important to consider the biological substrates of this behavior. Specifically, there is indirect evidence that increases in processing speed may be a byproduct of neural changes. For example, children with neural impairments including developmental disability (Nettelbeck & Wilson, 1997), closed head injury (Brookshire, Levin, Song, & Zhang, 2004), and phenylketonuria (Anderson et al., 2007) have slower processing speed relative to their typically developing

age-mates. In addition, long-term survivors of childhood acute lymphoblastic leukemia that have been treated with radiation (resulting in myelin damage) have slower processing speed than controls (Schatz, Kramer, Ablin, & Matthay, 2000, 2004). There also is evidence from neuroimaging studies that greater white matter (used as an index of myelination) is associated with faster processing (Soria-Pastor et al., 2008), but only for subgroups of participants (Silveri, Tzilos, & Yurgelun-Todd, 2008) or subsets of speeded tasks (Mabbott, Noseworthy, Bouffet, Laughlin, & Rockel, 2006). Taken together, results are consistent with the claim that neural development contributes to increases in processing speed, but more research is needed to identify the specific neural elements that are involved.

Measuring Processing Speed

Two approaches have been used to measure processing speed in children, adolescents, and adults. One uses tasks from experimental psychology in which a stimulus is presented and participants respond by selecting one of two alternatives, typically by pressing a button or a key on a keyboard. Tasks are constructed to include different within-participant conditions to isolate speeds of specific processes. The simplest version of this task would include two conditions. In one, participants respond whenever any stimulus appears. In the other, they make one response for certain stimuli (e.g., upper-case letters) but another response for other stimuli (e.g., lower-case letters). Responses are slower in the second condition and the difference is said to reflect the additional time for participants to make a decision, such as, whether the letter was upper or lower case. Tasks built on this logic are commonplace when investigators wish to focus on particular processes. However, these tasks are time-consuming because many trials are needed within each condition to estimate RTs accurately. Even then, the data rarely achieve accepted psychometric levels of reliability. In addition, children are often bored by the repetitive nature of these tasks, which can cause their performance to deteriorate over the duration of the task.

Consequently, many investigators rely upon psychometric measures of perceptual speed. A typical test of this sort is the Cross Out task from the Woodcock–Johnson Tests of Cognitive Ability. In this test, there are 30 rows with a target geometric figure at the left end of a row and 19 similar figures to the right. For example, one row consists of a triangle enclosing a single dot and the 19 figures to the right depict triangles with various objects (e.g., a single dot, three dots) in the interior. The participant places a line through the five figures of the 19 that are identical to the target figure at the left. The performance measure is the number of rows accurately completed in 3 min. Performance on these and similar tasks is highly reliable (e.g., test–retest reliabilities for the Cross Out tasks are .64–.73, for children and adolescents).

Toolbox Measurement: Development of the Toolbox Pattern Comparison Processing Speed Test

The Toolbox Pattern Comparison Processing Speed Test is modeled directly on Salthouse's Pattern Comparison Task (Salthouse, Babcock, & Shaw, 1991), an extensively researched assessment of choice RT in older adults but also is similar to both experimental and psychometric measures (described previously) that have been used to measure processing

speed in children. In the Toolbox Pattern Comparison Processing Speed Test, participants are asked to identify whether two visual patterns are the “same” or “not the same.” Scores reflect the number of correct responses within a finite time frame.

For an initial pilot study, eight 3-year-old children were recruited from a local nursery school to examine task feasibility. Items were administered on the computer, and examiners recorded verbal responses on a separate record form. Patterns were either identical or varied on one of three dimensions: adding/taking something away, one versus many, or changing positions. Scores reflected the number of correct items (of a possible 251) completed in 3 min.

Three-year-olds received average scores of 44.4 ($SD = 12.3$; range 25–59). In addition, participants made an average of 9.5 errors ($SD = 12.3$; range 3–13). When errors were tallied, there were 8 items that were potentially problematic (where four or more participants made errors). From these data, the task was revised to allow children to indicate responses via touchscreen, minimizing the bias introduced by an examiner needing to both record responses and prompt the next item once a response was provided. In addition, we decided to eliminate discriminations that involved changing positions, as there were not very many items along this dimension.

In a second (“prevalidation”) pilot study, children were asked to identify whether two visual patterns are the “same” or “not the same”: children ages 3–7 years indicated responses by pressing either a “smiley face button” or “frown face button” on the touchscreen; children ages 8–14 years indicated responses using a “yes” or “no” button on the touchscreen. Patterns were either identical or varied on one of three dimensions: color, adding/taking something away, or one versus many. We examined participants ages 3–4 years ($n = 35$), 5–7 years ($n = 26$), and 8–14 years ($n = 28$). In addition, we utilized three different time cut-offs (60, 90, or 120 sec) to determine optimal test administration time. Test–retest reliability was in the adequate range ($ICC = .56-.69$); performance was generally comparable regardless of the test administration time. We decided to move ahead using the 90 sec version of the test. In addition, items with less than 75% correct response rates were dropped, and findings provided support for deleting the one versus many discrimination for children ages 3–7 years. The 90 sec version of the test was administered in a validation study that included the full age range of the NIH Toolbox, ages 3–85 years. This monograph focuses on the results of this study for children and young adolescents ages 3–15 years. The validation data from the adult and elderly populations will be published in a separate series of papers so that each population can be addressed in greater depth.

METHOD

Participants

The participants in the validation study are described in detail in Weintraub et al. (Chapter 1, this volume; Table 3). Eighteen children did not complete the task; all were ages 3–5 years. Reasons included lack of attention or alertness or general noncompliance. One 15-year-old had an outlying score of zero and was excluded from analysis.

Toolbox Measures

Participants were tested with the Toolbox Pattern Comparison Processing Speed Test. In addition, RT scores from other NIHTB-CB measures (Toolbox Dimensional Change Card Sort [DCCS] Test and the Toolbox Flanker Inhibitory Control and Attention Test) were utilized to generate a Processing Speed Composite score.

The Toolbox Pattern Comparison Processing Speed Test—The Toolbox Pattern Comparison Processing Speed Test provides a measure of processing speed. The validation version of this measure required participants to identify whether two visual patterns are the “same” or “not the same.” Children registered their responses as described above for the second, “prevalidation” pilot study. Patterns were either identical or varied on one of three dimensions: color (all ages), adding/taking something away (all ages), or one versus many (only ages 8–15 years; see Figure 11). Scores reflected the number of correct items (of a possible 104 for ages 3–7 years and 130 for ages 8–15 years) completed in 90 sec; items were designed to minimize the number of errors that were made (i.e., items with less than 75% accuracy during pilot testing and prevalidation were not included in the final version of this task).

Processing Speed Composite—The processing speed composite was composed of the Toolbox Pattern Comparison Processing Speed Test and two other CB measures, the Toolbox Dimensional Change Card Sort (DCCS) and the Toolbox Flanker Inhibitory Control and Attention Test, both of which are described in detail in Zelazo et al. (Chapter 2, this volume). For the composite measure, we examined mean RT for all DCCS (frequent and nonfrequent) and all Flanker (congruent and incongruent) trials.

Validation Measures

In addition to the CB measures, we administered several other tasks to test convergent (Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition or Wechsler Intelligence Scale for Children, 4th Edition Processing Speed Composite, Paced Auditory Serial Addition Test) and discriminant validity (Wechsler Intelligence Scale for Children, 4th Edition Letter-Number Sequencing, Peabody Picture Vocabulary Test, 4th Edition' PPVT-IV).

Convergent Validity—Participants ages 5–6 years completed the Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition (WPPSI-III) and participants ages 8–15 years completed the Wechsler Intelligence Scale for Children, 4th Edition (WISC-IV) Processing Speed Composite tasks (Wechsler, 2002, 2004). The Processing Speed Composite is a composite score that combines performance on WPPSI-III/WISC-IV Coding and WPPSI-III/WISC-IV Symbol Search. WPPSI-III/WISC-IV Coding requires the participant to associate numbers and symbols using a key. Scores reflect number of items completed correctly in 120 sec (maximum 135). WPPSI-III/WISC-IV Symbol Search requires the participant to identify whether target symbols (two symbols) are part of a group of five symbols. Scores reflect number correct minus number incorrect in 120 sec (maximum 60). This composite score averages performance on WPPSI-III/WISC-IV Coding and WPPSI-III/

WISC-IV Symbol Search; it does not adjust for age (as does the WPPSI-III/WISC-IV Processing Speed Index).

Participants ages 8–15 years completed the Paced Auditory Serial Addition Test (PASAT; Gronwall, 1977). The PASAT is a measure of cognitive function that specifically assesses auditory information processing speed, sustained attention, and calculation ability. Single digits are presented every 2 sec and the participant must add each new digit to the one immediately prior to it. The test result is the number of correct sums given (maximum 50).

Discriminant Validity—Participants ages 3–15 years completed the PPVT-IV (Dunn & Dunn, 2007). The PPVT-IV provides a measure of receptive vocabulary and word retrieval. Participants are asked to identify which of four pictures is denoted by a specific word. Scores are based on the number correct (maximum 228).

Participants ages 8–15 years completed the WISC-IV Letter-Number Sequencing test (Wechsler, 2008). In this test, participants are presented with a mixed list of numbers and letters, and their task is first to repeat the list by saying the numbers in ascending order and then to repeat the letters in alphabetical order; it provides a measure of working memory. Scores reflect the number of correct responses (maximum 30 points), with higher scores indicating better performance.

Data Analysis

For all tests, scaled scores were created by first ranking the raw scores, next applying a normative transformation to the ranks to create a standard normal distribution, and finally rescaling the distribution to have a mean of 10 and a standard deviation of 3. The WPPSI-III/WISC-IV Processing Speed Composite described above was calculated by averaging the individual scaled scores and then renormalizing.

We examined the relations between the Toolbox Pattern Comparison Processing Speed Test and age, test–retest reliability, and construct validity. Pearson correlation coefficients were used to assess the relation between age and Toolbox Pattern Comparison Processing Speed Test performance. Intraclass correlation coefficients (*ICC*) were calculated to evaluate test–retest reliability. Convergent validity was assessed via Pearson correlation coefficients between the Toolbox Pattern Comparison Processing Speed Test and established measures of the same construct (i.e., WPPSI-III/WISC-IV Composite Score and PASAT). Evidence of discriminant validity consisted of lower correlations with selected validation measures of *different* cognitive constructs: working memory (WISC-IV Letter Number Sequencing) and receptive vocabulary (PPVT-IV).

We also conducted analyses to create a composite score of processing speed using multiple measures from the CB. For these analyses, we compared different summary scores that reflected processing speed estimates using (1) the Toolbox Pattern Comparison Processing Speed Test, (2) the Toolbox DCCS (mean RT on all trials, including frequent and infrequent), (3) the Toolbox Flanker Inhibitory Control and Attention Test (mean RT on all trials, including congruent and incongruent), as well as (4) the average of these three scores. Specifically, we examined the relations of this composite score with our validation measures

(WPPSI-III/WISC-IV Processing Speed Composite and the PASAT). In addition, we examined test–retest reliability for our composite score.

RESULTS

Age Effects

Figure 12 provides a graphic presentation of performance on the Toolbox Pattern Comparison Processing Speed Test from ages 3 to 15 years. A positive association between age and the Toolbox Pattern Comparison Processing Speed Test ($r(187) = .77$; $p < .0001$) was seen in children, and a quadratic model provided the best fit of the data, with $R^2 = .66$. Pairwise comparisons between age groups are reported in Appendix.

Test–Retest Reliability

Overall *ICC* for the Toolbox Pattern Comparison Processing Speed Test (ages 3–15 years) was .84 (95% CI: .75, .90; $p < .0001$).

Effect of Repeated Testing

Practice effects were computed as the difference between test and retest normalized scaled scores, with significance of the effect being tested with *t* tests for dependent means. For the total child group (ages 3–15 years, $n = 66$), the Toolbox Pattern Comparison Processing Speed Test showed a practice effect over an average 2-week test–retest interval: *mean practice effect* = .67, *SD* = 1.60, $t(58) = 3.22$, $p = .002$.

Convergent and Discriminant Validity

Table 11 shows results for convergent and discriminant validity for ages 3–15 years; please note that we did not administer measures of processing speed for children under the age of 5. Correlations for convergent validity ranged from $r = .31$ to $r = .43$ (all $p < .01$), suggesting that the Toolbox Pattern Comparison Processing Speed Test has adequate convergent validity and is indeed tapping processing speed. Correlations with discriminant validity measures of working memory and receptive vocabulary ranged from $r = .20$ to $r = .44$. Discriminant correlations did not differ significantly from the corresponding convergent correlations.

Processing Speed Composite Score

Three measures of processing speed (Toolbox Pattern Comparison Processing Speed Test, and mean RT from all DCCS and Flanker trials) were utilized to create an NIH Toolbox Processing Speed Composite Score. The individual scores (Toolbox Pattern Comparison Processing Speed, Toolbox DCCS, and Toolbox Flanker Inhibitory Control and Attention Test mean RT) and the Processing Speed Composite Score demonstrated similar correlations with age ($r = .77$ –.83; see Table 12) and test–retest reliabilities ($r = .84$ –.87; see Table 12). The NIH Toolbox Processing Speed Composite demonstrated higher correlations with established measures than did the Toolbox Pattern Comparison Processing Speed Test (see Table 13).

DISCUSSION

In this chapter we described the development of the Toolbox Pattern Comparison Processing Speed Test from the NIH Toolbox Cognition Battery and explored its utility in children as well as its use as a measure of processing speed. Data were presented for 208 children (age 3–15 years) on three important psychometric characteristics: sensitivity to cognitive improvement during childhood, test–retest reliability, and construct validity tested against established measures in the field. In addition, data were presented that explore the optimal method of estimating processing speed within the NIH Toolbox using both the Toolbox Pattern Comparison Processing Speed Test, as well as two other cognitive measures from the NIH Toolbox that include simple RT assessment (DCCS and Flanker). As noted above, results indicated that most children were able to understand the basic concepts of the Toolbox Pattern Comparison Processing Speed Test. Further, test–retest reliability was excellent.

In addition, evidence for test validity was supported by multiple findings. Specifically, as mentioned earlier, processing speed follows a well-defined developmental trajectory: it increases systematically through childhood and adolescence, peaks in young adulthood, slows modestly during middle age, and more substantially in older age (Kail, 1991, 2008; Kail & Salthouse, 1994). Findings from this study demonstrate similar age-related performance patterns across childhood.

Analyses examining the convergent and discriminant validity of the Toolbox Pattern Comparison Processing Speed Test also provided some support for the utility of this task as a measure of processing speed. Specifically, the new test demonstrated moderate relations with other measures that examine processing speed (i.e., a composite score based on WPPSI-III/WISC-IV Coding and Symbol Search, and the PASAT), and slightly less strong associations with measures that assess other domains of cognitive function (working memory as assessed by WISC-IV Letter-Number Sequencing and language as assessed by the PPVT-IV). The moderate relations with convergent validity measures were lower than we had anticipated, which may be attributed to the fact that responses were recorded via touchscreen. The touchscreen introduced some unanticipated response variability—even though all participants were instructed to respond “as quickly as possible,” some individuals hovered over the response buttons, whereas others returned a resting position (by lowering their hand or placing it on the table in between trials). As a result of these findings we have made additional changes to this measure that will require individuals to respond using a computer keyboard. These changes will be implemented for the norming study. Assuming that results from the norming study are promising, additional validation data will be needed to better establish convergent validity.

Finally, when three indices of processing speed were combined (Toolbox Pattern Comparison Processing Speed scores, Toolbox DCCS RT, and Toolbox Flanker Inhibitory Control and Attention Test RT), relations between the NIH Toolbox Processing Speed Composite and the validation measures were higher than those between the Toolbox Pattern Comparison Processing Speed Test (alone) and the validation measures. We anticipate that the NIH Toolbox Processing Speed composite score will be refined during the norming

phase of the NIH Toolbox study. It is likely that this score will be more robust, more sensitive, and include less measurement error, than any processing speed score derived from a single test. Ultimately, this type of composite score should have utility in clinical trials and longitudinal research involving participants across a broad age range.³

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³Findings of this sort do not undermine claims that task-specific experiences contribute to age-related change in processing speed. Indeed, there is evidence that speeds of some processes develop at different rates from the global mechanism (Kail & Miller, 2006; Kiselev, Espy, & Sheffield, 2009) and that expertise can enhance children's processing speed (Roth, 1983). It is plausible that speeds of many processes develop at a common rate reflecting the same underlying mechanism but that speeds of other processes develop at different rates, reflecting distinct mechanisms.

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Figure 11.

Examples of varied dimensions for discriminations on the Toolbox Pattern Comparison Processing Speed Test.

Note. that discriminations are made for color (ages 3–15 years), adding something versus taking something away (ages 3–15 years), and one versus many (ages 8–15 years).

Figure 12. Normalized scaled scores on the Toolbox Pattern Comparison Processing Speed Test across age groups. Error bars are ± 2 standard errors. Best-fitting polynomial curve is also shown (see text).

TABLE 11

Pearson Correlations Between the Toolbox Pattern Comparison Processing Speed Test and Convergent and Discriminant Validation Measures

Toolbox Pattern Comparison Processing Speed Test						
Validation Measure	(Ages 3–6 years)			(Ages 8–15 years)		
	df	r	p-Value	df	r	p-Value
Convergent Validity Measures						
WPPSI-III/WISC-IV Processing Speed Composite ^a	55	.43	<.0001	83	.40	<.0001
PASAT	—	—	—	82	.39	<.0001
Discriminant Validity Measures						
PPVT-IV	97	.44	<.0001	84	.36	<.0001
WAIS-IV Letter-Number Sequencing	—	—	—	82	.20	.07

Note. Unadjusted scaled scores were utilized in analyses. WPPSI-III, Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition; WISC-IV, Wechsler Intelligence Scale for Children, 4th Edition; PASAT, Paced Auditory Serial Attention Test; PPVT-IV, Peabody Picture Vocabulary Test-4th Edition; WAIS-IV, Wechsler Adult Scale of Intelligence, 4th Edition.

^aWISC-IV Processing Speed Composite was calculated for children ages 5–6 years.

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TABLE 12

Pearson Age-Related Correlations and Test–Retest Correlations (Intraclass Correlations; ICC) for the NIH Toolbox Pattern Comparison Processing Speed Test and the NIH Toolbox Processing Speed Composite Score (Using Toolbox Pattern Comparison Processing Speed Test, Toolbox DCCS, and Toolbox Flanker) for Children Ages 3 to 15 Years

NIH Toolbox Cognition Domain/Instrument	<u>Age-related correlations</u>		<u>Test–retest correlations</u>	
	<i>df</i>	<i>r</i>	<i>df</i>	<i>ICC</i>
Toolbox Pattern Comparison Processing Speed Test	187	.77	57	.84
NIH Toolbox Processing Speed Composite	203	.83	64	.88

Note. © 2006–2012 National Institutes of Health and Northwestern University.

All *ps* <.0001.

TABLE 13

Pearson Correlations Between NIH Toolbox Processing Speed Composite Score (Using Toolbox Pattern Comparison Processing Speed Test, Toolbox DCCS, and Toolbox Flanker) and Validation Measures

Processing Speed Estimate	Validation Measure									
	WPPSI-III/WISC-IV Processing Speed Composite					PASAT				
	(Ages 5–6)					(Ages 8–15)				
	r	df	p-Value	r	p-Value	r	df	p-Value	r	p-Value
Toolbox Pattern Comparison Processing Speed Test	.40	55	<.002	.39	83	.39	82	<.0002	.73	183
NIH Toolbox Processing Speed Composite	.37	56	<.004	.44	84	.34	83	<.001	.82	198

Note. WPPSI-III, Wechsler Preschool and Primary Scale of Intelligence, 3rd Edition; WISC-IV, Wechsler Intelligence Scale for Children, 4th Edition; PASAT, Paced Auditory Serial Attention Test; PPVT-IV, Peabody Picture Vocabulary Test-4th Edition.