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Cognitive correlates of memory integration across development: Explaining variability in an educationally relevant phenomenon

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Abstract

The current research was an investigation of the cognitive correlates of individual differences in participants' capacity to derive new factual knowledge through integration of information acquired across separate yet related learning episodes. In a sample of 117 adults (Experiment 1) and 57 children aged 8 to 10 years (Experiment 2), we investigated the respective roles of verbal comprehension, working memory span, and relational reasoning in self-derivation of new knowledge through memory integration. The findings revealed patterns of consistency and inconsistency in the cognitive profiles underlying this form of learning in adults and children. In both adults and children, verbal knowledge and skills accounted for variability in self-derivation. Variance in adults, but not in children, was further explained by working memory. Given that individual differences in self-derivation have implications for real-world academic outcome, we also investigated the association between self-derivation and academic performance. We found that performance on the experimentally-based self-derivation paradigm was related to concurrent and longitudinal academic success in both samples. The present research thus builds on the growing body of behavioral and neuroscientific research to advance our understanding of the cognitive factors associated with behaviors that depend on memory integration in both childhood and adulthood, and also provides suggestive evidence of critical ways in which the process may differ in children and adults. Together, the findings provide a theoretically plausible and practically significant framework from which to guide future research aimed at enhancing this educationally relevant learning phenomenon.

Keywords

memory integration; knowledge representation; episodic memory; semantic memory; cognitive abilities

1. Introduction

The question of how knowledge is represented and expanded is of central significance to cognitive science (Gentner, 2010). Research has made clear that representational structures that are highly interconnected are maximally useful for reasoning, problem solving, and other productive processes (Chi, Hutchinson, & Robin, 1989; Chi & Koeske, 1983; Mandler,

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Bauer, & McDonough, 1991; McKenzie et al., 2014). Accumulating evidence indicates that formation of such interconnected knowledge structures depends on *memory integration*—representation of the overlap between discrete yet related elements (Schlichting, Mumford, & Preston 2015; Varga & Bauer, 2017a; 2017b). Newly learned content that exhibits greater overlap with existing knowledge has been shown to be preferentially integrated in memory in adults (Van Kesteren, Rijpkema, Ruiter, Morris, & Fernandez, 2014) and children (Bauer, King, Larkina, Varga, & White, 2012; Gobbo & Chi, 1986). Yet despite the importance of memory integration for the formation and accumulation of knowledge across the lifespan, the cognitive correlates of individual differences in this learning process have received little attention. In the present research, we advanced our understanding of the specific cognitive abilities associated with the derivation of new knowledge through memory integration in adulthood (Experiment 1). Guided by evidence that cognitive abilities become increasingly differentiated during childhood, we also examined the extent to which the adult-like profile was similar or different to that evidenced in children (Experiment 2). In light of the implications individual differences in the capacity to extend knowledge through self-derivation based on memory integration have for real-world outcome, we also examined the relation between self-derivation and longitudinal academic success in both samples.

1.1 The role of memory integration in the derivation and long-term accumulation of knowledge

The capacity to acquire knowledge across experiences, to integrate this information in memory, and to productively extend beyond it forms the cornerstone of knowledge development. An extensive body of research has examined the productive extension of knowledge through various logical processes, including induction, deduction, and analogy (see Goswami, 2011 for review). The work suggests that successful knowledge extension depends on whether higher-order relations among *existing* knowledge are accessible at the time of test (e.g., Gentner & Toupin, 1986). Complementary research has also examined how productive processes are engaged “in the moment” to facilitate reading comprehension, for example (e.g., Yule, 2010). Findings from this literature suggest that individual differences in the capacity to draw inferences from text are linked to working memory capacity (e.g., Mason & Miller, 1983). The inferences are likely preserved in working memory only long enough to serve immediate comprehension, however. Thus, despite evidence that individuals regularly invoke productive processes to extend their existing knowledge and to comprehend new information, relatively little is known about how these processes contribute to the retention of self-derived understandings and thus accumulation of new, real-world factual knowledge.

In the laboratory, knowledge extension paradigms capable of assessing the means by which long-lasting, integrated semantic networks are formed have been introduced (e.g., Bauer & Varga, 2016, 2017). In one exemplar paradigm (Varga & Bauer, 2017a), adults are taught novel, related “stem” facts (*Romanticism is represented in all of the work by Byron; Darkness is a famous poem by Byron*) and are later tested for self-derivation of new factual knowledge through integration of the target information (*Darkness is a poem that exemplifies________ ?*).

This experimental approach operates over real-world, factual information and is thus directly relevant to how memory integration mediates the formation of the type of interconnected knowledge structures thought to constitute the semantic knowledge base. Indeed, research using this paradigm indicates that newly self-derived factual knowledge is rapidly incorporated into the knowledge base (Bauer & Jackson, 2015). Moreover, tests for retention of the facts newly derived through integration indicate high levels of retention over 1 week (50% self-derivation and 42% recalled at Session 1 and Session 2, respectively; Varga & Bauer, 2017a). Together, these findings validate the paradigm as a test of the processes involved in the formation of integrated, enduring semantic knowledge representations.

Research on self-derivation and retention of new knowledge through memory integration has also revealed substantial individual differences. Even among high-achieving adults, the range of success in engagement of this learning process ranges from 3–93% correct across individuals (Varga & Bauer, 2017a; see also Schlichting, Zeithamova, & Preston, 2014 and Shohamy & Wagner, 2008 for findings of similar individual difference patterns in other behaviors that rely on memory integration). To date, the cognitive factors that enable integration and subsequent self-derivation of content that exhibits relational overlap have not been identified.

1.2 Cognitive constructs implicated by neuroscientific models

Investigations of the neural correlates associated with successful knowledge extension through memory integration have revealed that it is supported by a series of temporally extended subprocesses that support learning and extension of related information at encoding and test, respectively (Bauer & Jackson, 2015; Bridge & Voss, 2014; Varga & Bauer, 2017b; Zeithamova & Preston, 2010). For instance, event-related potential (ERP) results suggest that successful self-derivation depends on both reactivation of a previously learned fact (e.g., *Romanticism is represented in all of the work by Byron*) upon learning a second, related fact (e.g., *Darkness is a famous poem by Byron)*, and on detection that the newly learned information is novel (e.g., *Byron* is now associated with *Darkness*, rather than *Romanticism*) (Varga & Bauer, 2017b). Consistent with this finding, inferential reasoning based on memory integration is predicted by greater reactivation of prior events during new event encoding (Zeithamova, Dominick, & Preston, 2012) as well as by increased activation in hippocampal subfield CA_1, a region thought to play a crucial role in signaling novelty between associated memory traces (Schlichting et al., 2014). Based on these findings, it is logical to assume that cognitive factors that map onto the capacity to retrieve prior knowledge and interpret relations between novel yet discrete traces should relate to variability in this behavior.

According to prevailing theoretical models, successful memory integration depends not only on retrieval of prior knowledge, but also on subsequent processes that resolve the mismatch between the disparate yet related facts (see Bauer & Varga, 2017; Preston & Eichenbaum, 2013; Shohamy & Wagner, 2008; van Kesteren, Ruiter, Fernández, & Henson, 2012). Consistent with this suggestion, in Varga and Bauer (2017b), successful memory integration was indexed by ERPs linked to post-retrieval meaning revision and monitoring of the novel, abstracted relation, both of which unfold after initial novelty detection. As well, fMRI research has revealed a shift from hippocampal to ventral medial prefrontal cortex (VMPFC) activity when participants were exposed to the same paired associates repeatedly at encoding (Zeithamova et al., 2012). The pattern is speculated to reflect VMPFC-mediated abstraction of relational commonalities and/or updating of long-term memory to represent the resolved, integrated traces (see Schlichting & Preston, 2015 for discussion). Together, these neural correlates point to the potential contribution of several cognitive factors in the representation of complex relational understandings in memory, including memory retrieval, and processing and transformation of the individual event elements to establish an overlapping representation.

1.3 Continuity and change in behavior and cognition across development

If memory integration serves as a key mechanism through which complex knowledge structures are formed and extended across the lifespan, then this learning behavior should be evidenced early in development. A number of studies examining knowledge extension through integration of separate yet related episodes has been conducted with children 4 to 10 years of age (Bauer, Blue, Xu, & Esposito, 2016; Bauer, King, Larkina, Varga, & White, 2012; Bauer & Larkina, 2017; Bauer & San Souci, 2010; Bauer Varga, King, Nolen, & White, 2015; Esposito & Bauer, 2017). For younger children (4 to 8 years), rather than through individual sentences, novel facts are presented in the context of story passages, each with a main character, context, and story line. As for adults, memory integration is assessed via a test for self-derivation of the novel integration fact. Across childhood, there are substantial increases in self-derivation performance, from 13% in 4-year-olds, to 67% in 6-year-olds, and reaching 87% in 8-year-olds (Bauer & Larkina, 2017). Critically, like adults, children retain the newly self-derived knowledge over time, with virtually no loss of access after 1 week in either 4- (Varga, Stewart, & Bauer, 2016) or 6-year-old children (Varga & Bauer, 2013).

As is the case for adults, the cognitive factors that contribute to variability (both age-related and individual) in this fundamental learning behavior across development are largely unknown. Although it is logical to invoke the same cognitive processes across development, there is also reason to expect developmental differences, owing to the fact that the structure of cognition changes across development, related to both neural development and formal educational experience (see Mungas et al., 2013 for discussion). As one consequence, specific component cognitive abilities become increasingly differentiated with age. For instance, Mungas and colleagues (2013) examined the dimensional structure of six abilities deemed critical to cognitive function in younger children (3–6 years), older children (8–15 years) and adults (20–85 years). The so-called crystallized abilities of reading and vocabulary that underlie the capacity to accumulate “verbal knowledge and skills,” and depend heavily on knowledge acquired through formal education (Akshoomoff et al., 2013, p. 120), were distinct from each other by as early as 3–6 years. Conversely, so-called fluid abilities that support the capacity to “solve problems, think and act quickly, and encode new episodic memories” (Akshoomoff et al., 2013, p. 120) and rely heavily on domain-general information-processing skills only emerged as distinct from each other in middle childhood (8–15 years). Whereas the fluid abilities of episodic memory, working memory, and executive function/processing speed exhibited differentiation in middle childhood, they were nevertheless highly correlated with each other and with crystallized abilities (ranging from .72 to .94, which was substantially larger than that evidenced in adulthood). The sustained cognitive differentiation observed from middle childhood through adulthood, particularly with respect to fluid abilities, suggests that the cognitive correlates of self-derivation performance may differ between children and adults.

1.4 The present research

In two experiments, we assessed the relation between self-derivation of new factual knowledge through memory integration and several standardized measures of cognition. In adults, we selected fluid measures of long-term memory retrieval, relational concept formation, and working memory due to their proposed importance for the cognitive processes implicated in self-derivation through memory integration (i.e., retrieval of prior knowledge from long-term memory [long-term retrieval], identification of the novel relation between discrete traces [concept formation], and flexible transformation of directly learned traces to represent the resolved, integrated relation [working memory]). In addition to domain-general cognitive abilities that operate over mental representations, we reasoned that this learning behavior should also depend on verbal abilities. We thus also used two measures of crystallized verbal cognition which assessed comprehension of verbal information (i.e., reading comprehension) and the extent of one's existing semantic knowledge and how well individuals reason based on that knowledge (i.e., verbal comprehension). We also included a measure of short-term memory to assess a cognitive ability that serves relatively transient processing needs, and thus should be less associated with self-derivation. We employed comparable, age-appropriate assessments of fluid and verbal abilities with children.

Finally, because self-derivation of new factual knowledge through memory integration is a model for accumulation of knowledge, it is logical to expect that successful engagement of the processes would relate to academic achievement. Empirical support for the educational relevance of the self-derivation task employed in the present research comes from a recent study documenting a concurrent association between self-derivation through memory integration and school-based achievement in 5- to 10-year-old children, a subset of whom contributed to the present research (Esposito & Bauer, 2017). Whether self-derivation through memory integration predicts longitudinal educational success is unknown. Thus, in both experiments, we further explored the relation between self-derivation of the integration facts and academic success, as assessed by scholastic achievement (Experiment 1; adults) as well as school-based achievement at the time of initial participation and several years later (Experiments 1 and 2).

2. Experiment 1

2.1 Method

2.1.1 Participants—Participants were 117 adults between 18–24 years (*M* = 19.76 years, *SD* = 1.15; 63 females). The sample consisted of individuals whose self-derivation data was collected as part of two prior investigations (Varga & Bauer, 2017a; 2017b). Here we feature analyses of the cognitive and academic assessments, and their relation with performance on the factual knowledge extension task, the results of which were not reported in any prior published reports.

All participants were recruited from a pool consisting of undergraduate students enrolled in psychology courses at a competitive, private institution. The sample was 9% African American, 25% Asian, 59% Caucasian, and 4% mixed racial descent. Eight percent of the participants were of Hispanic descent. Three participants did not report racial or ethnic information. An additional 3 participants took part in the study but were excluded due to failure to comply with task instructions ($N = 1$) and self-reported diagnosis of Dyslexia which may have negatively impacted task performance ($N = 2$). Cognitive assessments were missing for two participants due to failure to return for the second session in which the measures were collected ($N = 1$) and failure to return within the specified delay interval ($N = 1$).

Official records of scholastic aptitude (SAT scores) and academic achievement (college GPA at the time of participation and longitudinally) were obtained from the university registrar for participants who had these measures and authorized release of the information (a small number of students took the ACT or graduated during the semester of participation precluding analysis of longitudinal GPA). In total, SAT, concurrent GPA, and longitudinal GPA are reported from 85, 107, and 98 individuals, respectively. The protocol and procedures were approved by the university Institutional Review Board. Written informed consent was obtained prior to the start of the study, which also included permission to obtain academic measures. Participants were compensated with course credit for their participation.

2.1.2 Stimuli—The stimuli were 30 pairs of stem facts (e.g., *Hematopoiesis is the cellular formation of blood; The skeleton is the site of the production of blood)* which could be integrated to derive 30 novel integration facts (e.g., *Hematopoiesis occurs in the skeleton*). Facts ranged from 4–10 words. The facts conveyed true information that was intended to be educationally meaningful and to be unknown to participants prior to the study. Prior research employing these stimuli has demonstrated that the facts are novel to young adults and that both facts from a given pair are necessary for derivation of the target integration facts (see Varga & Bauer, 2017a; Experiment 1). Specifically, when participants were exposed to only one of the two stem facts from a pair, they produced the novel integration facts only 11% of the time (which significantly differed from the 44% demonstrated when both stem facts were provided). Thus, exposure to the information presented in both stem facts is necessary to reliably derive the corresponding integration fact.

2.1.3 Cognitive measures—The *Woodcock Johnson Test of Cognitive Abilities, Third Edition* (*WJ-III COG*) (Woodcock, McGrew, & Mather, 2001), the *Test of Memory and Learning, Second Edition* (*TOMAL-2*) (Reynolds & Voress, 2004), and the *Woodcock Language Proficiency Battery—Revised* (*WLPB-R*) (Woodcock, 1991) were used to assess six standardized cognitive factors (see Table 1, Panel A for detailed descriptions).

2.1.3.1 Verbal Comprehension.: The Verbal Comprehension subtest of the *WJ-III (Test 1)* served as a measure of the extent of one's verbal, semantic knowledge (*Median* reliability

= 0.90 from 5–19 years; 0.95 from 20–90 years); Woodcock et al., 2001). This task consisted of four subtests: Picture Vocabulary, Synonyms, Antonyms, and Analogies, which assessed comprehension of individual words, the relations among words, and reasoning based on verbal knowledge. Participants received one point for each correctly answered item and the test was discontinued when three items on a page were answered incorrectly. A total score was derived by summing scores across the four individual subtests.

2.1.3.2 Passage Comprehension.: The Passage Comprehension subtest of the *WLPB-R* (Test 7) was used to assess reading comprehension (*Median* reliability = 0.89 in young adults; Woodcock, 1991). In this task participants must use syntactic and semantic clues to identify a missing word within a short passage. Using a modified cloze procedure, this task assesses how well an individual comprehends written discourse as it is being read, requiring basic reading skills and inferential abilities. Participants received one point for each correctly answered item and the test was discontinued when incorrect answers were provided for six consecutive items. A total score was derived by summing the number of correct items.

2.1.3.3 Concept Formation.: The Concept Formation subtest of the *WJ-III COG* (Test 5) was used as a measure of relational reasoning based on inductive logic (*Median* reliability = 0.94 from 5–19 years and 0.96 from 20–90 years; Woodcock et al., 2001). In this task individuals are shown a stimulus set (i.e., a series of shape and color patterns) and are required to derive the rule that governs each sequence in the absence of prior knowledge. Participants received one point for each correctly answered item and were provided with corrective feedback throughout task administration. A total score was derived by summing the number of correct items.

2.1.3.4 Visual-Auditory Learning.: The Visual-Auditory Learning subtest of the *WJ-III COG* (Test 2) served as a measure of associative, long-term memory retrieval (*Median* reliability = 0.86 from 5–19 years; 0.91 from 20–90 years; Woodcock et al., 2001). In this task participants are shown a series of rebuses (pictographic symbols of words) and later asked to recall the visual-auditory associations from long-term memory. Participants received one point for each incorrectly answered item, defined as a failure to identify the correct word or to do so within 5 seconds of viewing a rebus. The correct word was provided if participants failed to state it within the 5-second time limit. Because scoring was conducted on-line, an independent coder listened to all audio recordings to ensure that the 5-second pause was reliably scored. If participants were allotted more than 5 seconds, the item was subsequently scored as incorrect. If participants were corrected too soon, the item was counted as a missing trial (0.59% of trials). A proportion score was then derived by dividing the total number of errors by the number of valid trials and should thus negatively correlate with other variables.

2.1.3.5 Digits Forward.: The Digits Forward subtest of the *TOMAL-2* was used as a measure of short-term memory span (*Median* reliability > 0.88 from 5–59 years; Reynolds & Voress, 2004). This task requires the individual to hold a sequence of numbers in immediate awareness before repeating them back to the experimenter, with the sequence length increasing throughout task administration. One point was awarded for the correct recall of each digit within the serial position in which it was presented. The task was discontinued when participants recalled three or fewer digits on two consecutive sequences. A total score was derived by summing the number of correctly recalled digits.

2.1.3.6 Digits Backward.: The Digits Backward subtest of the *TOMAL-2* was used as a measure of working memory span (*Median* reliability > 0.88 from 5–59 years; Reynolds & Voress, 2004). In this task the individual must hold a sequence of numbers in immediate awareness while performing a mental operation on it (i.e., reversing the sequence). Task administration and scoring were conducted in the same manner as in the Digits Forward subtest with the exception that the digits must be correctly placed in the reverse order.

2.1.4 Academic Measures

2.1.4.1 SAT.: The Scholastic Aptitude Test (SAT) is a standardized college admissions test which assesses academic readiness for college. The test primarily measures knowledge and skills learned in school, however, some items also assess aspects of fluid intelligence. The test has two parts, verbal and math, each with a maximum score of 800. In the event that participants took the exam multiple times, the highest scores on each section were used in analyses.

2.1.4.2 GPA.: Grade Point Average (GPA; average of all college course grades) was used as a measure of academic achievement. Because grades are assumed to be based on some criterion level of performance, college GPA reflects the degree to which participants mastered specific course content. GPAs were calculated at the end of the semester of participation (i.e., concurrent GPA) as well as approximately two years later (i.e., longitudinal GPA; *Mean* lag = 5.66 semesters; *SD* = 1.75; *Range* = 1–7).

2.1.5 Procedure—Participants completed two sessions spaced 1 week apart (*M* delay = 6.91, *SD* = 0.54, *Range* = 6–8 days). Participants were tested individually by one of two experimenters (including the first author), each of whom tested an approximately equal number of participants from each gender. With the exception of six individuals, participants were tested by the same experimenter at both sessions. The experimenters followed the same detailed written protocol and regularly reviewed audio-recorded sessions to ensure protocol fidelity.

2.1.5.1 Session 1: Initial learning and extension of knowledge.: Participants were instructed that we were interested in whether memory for newly learned factual information differs as a function of its subject domain. Participants read a total of 60 sentences (i.e., individual stem facts). To equate total reading time across participants, sentences were presented one word at a time (see Figure 1, Panel A). At the end of each sentence, participants were shown a decision screen and asked to indicate, via a button-press response, whether the information conveyed was novel or known. The incidental task was designed to ensure that participants were attending to the facts while also corroborating the pretext of the study purpose (i.e., learning of *novel* information). At no time were participants informed that any of the sentences were related. Stem facts from a pair were separated by a lag of 2 to

4 intervening sentences thereby creating temporal distance between to-be-integrated information. Moreover, each stem fact from a pair was presented in the first or second serial position an approximately equal number of times.

After a filled break lasting 5–10 minutes in which participants completed demographic surveys, participants were tested for self-derivation of the 30 possible integration facts. Each integration fact ended in a "?", and participants were instructed to think of the word to complete each fact (e.g., *Hematopoiesis occurs in the ?*). Participants made a button-press response once an answer was generated which was followed by an "Answer" screen cueing them to speak the answer aloud.

2.1.5.2 Session 2: Standardized cognitive assessments.: Participants returned to the laboratory approximately one week after their initial visit. Participants were instructed that we were interested in whether performance on a number of cognitive tasks related to performance at the initial session. Standardized cognitive assessments were then administered in the following fixed order: (1) short-term memory (Digits Forward), (2) relational reasoning (Concept Formation), (3) working memory (Digits Backward), (4) long-term memory retrieval (Visual-Auditory Learning), (5) reading comprehension (Passage Comprehension), and (6) verbal knowledge (Verbal Comprehension). To avoid the potential for unique order effects across the sample, we did not counterbalance the sequence of cognitive assessments. Following completion of these tasks which lasted approximately 40 minutes, memory for the integration facts was assessed via the same questions asked at Session 1.

2.1.6 Scoring on self-derivation task.—Participants received a score of 1 for each integration fact successfully derived in open-ended testing, and a score of 1 for each integration fact recalled after the delay. A proportion score was derived by dividing the total number of successfully self-derived facts by the number of possible trials (see Varga & Bauer 2017a for additional detail regarding unequal trials across participants).

2.2 Results

We explored associations between initial derivation of the integration facts, retention of the self-derived knowledge, and standardized cognitive abilities. We also examined relations between self-derivation and retention performance and academic success. As a first step in the process, we described variability in self-derivation through integration and in long-term retention. Second, we assessed whether standardized cognitive abilities differentially related to self-derivation and subsequent retention by conducting multiple regression analyses with participants who had valid data on all cognitive assessments ($n = 107$). Third, we tested the relative contributions of self-derivation and cognitive factors on academic success by conducting a series of linear regression analyses. We included participant age and gender in the first level of each multiple regression model to control for possible effects of these demographic variables on predictions of knowledge extension and academic success. In all models, these demographic variables failed to explain significant variance in the dependent measures. Moreover, we ensured that the assumptions of linear regression were met and conducted a number of diagnostic statistics for all models (i.e., examination of DFBeta statistics, Cook's distance, leverage statistics, and Mahalanobis distance). We also verified that the residuals were independent (i.e., Durban-Watson), homoscedastic, and normally distributed. In cases in which the assumptions were not met, steps taken to correct for these issues are described. All analyses were conducted using SPSS Statistics package (Version 24). All statistical tests were two-tailed.

2.2.1 Description of self-derivation and retention of the integration facts—

Descriptive statistics, including measures of central tendency and variability for self-derivation through integration (Session 1) and delayed recall of the facts (Session 2), and for all cognitive and academic variables are reported in Table 2. Substantial variability was observed with performance ranging from 3% to 93% correct. Moreover, as reported in Varga and Bauer (2017a), significant loss was observed between sessions, $t(114) = 10.04$, $p < .001$, $d = 0.53$.

2.2.2 Association of self-derivation and retention with cognitive factors—

The primary aim of the present experiment was to determine the cognitive abilities that are associated with self-derivation and retention of new factual knowledge through memory integration. As is depicted in Table 3, examination of zero-order Pearson correlation coefficients revealed that initial self-derivation was associated with all six cognitive factors (see Figure 2 for scatter plots). A similar pattern of results was observed when we examined relations between recall of the self-derived facts at Session 2 and the cognitive measures, with the expected exception that Digits Forward (which assessed transient processing) was not correlated with long-term knowledge retention (see Figure 3 for scatter plots).

To directly test whether the standardized cognitive abilities predicted unique statistical variance in derivation and retention of knowledge based on memory integration, we conducted multiple regression analyses. Based on the high intercorrelation among the cognitive measures (see Table 3), we examined collinearity statistics (i.e., VIF and tolerance) and the eigenvalues of the scaled, uncentred cross-product matrix to ensure that the variance of each predictor loaded to a different dimension (i.e., a different eigenvalue). We found VIFs to be within the acceptable range, where average model VIF around 1 (Bowerman & O'Connell, 1990) and individual predictor VIF less than 10 (Bowerman & O'Connell, 1990; Myers, 1990) is typically deemed acceptable. As reflected in Table 4 (Model 1), when all six cognitive factors were entered into the model via the forced entry method (after accounting for variance in demographic factors which were nonsignificant in Step 1, see above), the full model explained 32% of the variance in self-derivation at Session 1. Yet only verbal comprehension and working memory explained significant, unique variance in initial self-derivation performance. A similar pattern of results was obtained when we examined retention of self-derived knowledge at Session 2, such that the full model explained 35% of the variance (see Table 4, Model 2). Again, verbal comprehension was a statistically significant predictor. However, working memory failed to reach the conventional level of significance ($p = .06$). Importantly, the relations with verbal comprehension and working memory were replicated when we accounted for the proportion of stem facts participants reported knowing prior to participation in the study (see Supplemental Table 1) as well as for standardized long-term memory storage and retrieval abilities which may have supported learning and memory of the individual stem facts (see Supplemental Table 2). Thus, in our final set of analyses we explored the relative contribution of these cognitive factors and self-derivation in predicting statistical variability in academic success.

2.2.3 Association of self-derivation and retention with academic performance measures—

Average SAT scores and GPAs were high, though importantly, variability was still observed (Table 2). Pearson correlations assessing the association of academic performance with initial self-derivation and retention of self-derived integration facts are reported in Table 3 (see Figures 4 and 5 for scatter plots). Examination of scholastic aptitude revealed that, whereas self-derivation at Session 1 and retention at Session 2 exhibited moderate to strong associations with the verbal SAT, no associations to the quantitative SAT were observed. Investigation of the association between self-derivation and GPA indicated that initial self-derivation and subsequent recall of knowledge self-derived through integration exhibited small to moderate correlations with concurrent and longitudinal GPA. Because the standardized residuals were non-normally distributed in the case of concurrent and longitudinal GPAs, we also examined the associations after applying a reflect and inverse transformation to the raw GPA measures (i.e., a transformation designed to reduce severe negative skew). To reflect the raw values, we subtracted each GPA value from 1 plus the maximum GPA value and then took the inverse of that value (Transformed GPA = 1/[1+4.00– original GPA value]). This transformation addressed the violations of the assumption of residual normality and did not change the pattern of results reported.

We next conducted a series of multiple regression analyses to determine whether self-derivation at Session 1 and recall at Session 2 accounted for unique variance in academic performance when the significant cognitive correlates were accounted for (i.e., verbal comprehension, working memory). As reflected in Table 5, initial self-derivation performance did not account for academic outcome when verbal comprehension was included in the model. Yet when retention of the knowledge self-derived through integration was examined (Table 6), both verbal comprehension and Session 2 recall accounted for unique variance in SAT verbal and concurrent GPA (Models 1 and 2, respectively). Only retention of the self-derived facts predicted unique variance in longitudinal GPA (Model 3). The same pattern of results was observed when we examined relations to the transformed GPA variables.

2.3 Discussion

In the present experiment, we investigated the cognitive factors associated with substantial individual differences in self-derivation and retention of new factual knowledge in young adults. We found that superior performance on standardized tests of verbal comprehension (i.e., the extent of existing verbal knowledge) and verbal working memory span (i.e., Digits Backward) accounted for a significant portion of the variance in self-derivation performance at Session 1 (Full Model adj. R^2 = 32%). Although working memory was a marginally significant predictor of retention of self-derived knowledge at Session 2, only verbal comprehension reached the conventional level of significance (Full Model adj. R^2 = 35%). In addition to identifying the specific cognitive factors that contribute to individual differences in self-derivation through memory integration, we also found that this learning behavior is associated with real-world academic metrics, including SAT, concurrent college GPA, and longitudinal college GPA (assessed approximately two years later). Correlational analyses revealed a large association between initial self-derivation performance and verbal SAT scores (but not quantitative SAT), as well as small to moderate associations with concurrent and longitudinal GPA measures. When retention of the self-derived knowledge was examined, a nominal increase in the strength of the associations was observed such that the correlations with concurrent and longitudinal GPA became moderate to large.

We also investigated the relative contributions of initial self-derivation (Session 1) and retention of knowledge self-derived through integration (Session 2), and the aforementioned cognitive correlates (verbal comprehension and working memory) in predictions of academic performance through a series of multiple regression analyses. Whereas only verbal comprehension was significantly associated with SAT Verbal scores and the GPA measures when Session 1 performance was examined, both verbal comprehension and Session 2 performance (i.e., retention) emerged as unique predictors of SAT Verbal and concurrent GPA. Notably, only Session 2 recall of self-derived knowledge (not verbal comprehension or working memory) was a unique, significant predictor of longitudinal academic success (i.e., GPA two years later). Thus, this is the first demonstration of the consequences that individuals differences in self-derivation through memory integration have for longitudinal academic success.

One may speculate that the large associations between self-derivation (Session 1) and retention (Session 2) of knowledge self-derived through integration with verbal comprehension (i.e., the extent of existing knowledge) could be explained by some participants' prior knowledge of the target stem facts or general ability to store and retrieve the individual stem facts. Critically, verbal comprehension and working memory remained significant predictors even when self-reported prior knowledge and long-term memory storage and retrieval were accounted for (see Supplemental Tables 1 and 2, Models 1–4), thereby suggesting that the correlates observed were specific to the skills assessed by the standardized cognitive constructs. In the case of verbal comprehension, knowledge of individual words (vocabulary), relational knowledge (synonyms; antonyms) and reasoning based on existing knowledge (analogies) were tapped in particular. It is therefore not surprising that the extent to which individuals formed relations between *prior, accumulated* knowledge and deployed that information in response to a demand (i.e., Verbal Comprehension) predicted unique variance in the extent to which they formed and flexibly extended self-derived knowledge in the context of *new* learning (i.e., experimental task). Along a similar vein, working memory tapped the specific skills required to maintain and transform a representation held in immediate awareness (i.e., reverse a sequence of digits to form a novel representation). One possible explanation of the role of working memory is that it facilitates the amount of stem fact information that one can simultaneously activate and process in the service of forming an integrated, overlapping representation.

Given that substantial variability in self-derivation of new factual knowledge through integration has also been documented in children (e.g., Bauer & Larkina, 2017), in Experiment 2 we sought to identify the cognitive correlates that contribute to individual differences in memory integration in 8- to 10-year-old children. To do so, we took advantage of the opportunity to examine whether the pattern of results reported here was also evidenced in children who were tested simultaneously as part of a separate longitudinal study examining development. Whereas the data reported in Experiment 1 were collected from individual participants in the laboratory to examine the neural correlates of self-derivation through integration (Varga & Bauer, 2017a; 2017b), the data reported on children in Experiment 2 were collected in classrooms, as part of a longitudinal investigation of educational success under two different educational models (Esposito & Bauer, 2017). Yet although the experiments necessarily employed different study materials and procedures (to ensure developmental appropriateness as well as accommodate the classroom setting in Experiment 2) and thus could not be perfectly matched, comparable measures of standardized assessments of verbal comprehension, working memory, and relational reasoning were collected in both samples, thus providing an opportune, valuable window into the cognitive correlates of self-derivation through integration in childhood as they compare to those in early adulthood.

3 Experiment 2

3.1 Method

3.1.1 Participants—Participants were 57 typically developing students in third grade (*M* = 9.13 years; *Range* = 8.58–10.33; 31 females). The sample consisted of monolingual English speaking individuals whose self-derivation data and academic achievement data was collected as part of a separate investigation (Esposito & Bauer, 2017). The data from all monolingual English speaking 3rd grade children in the traditional education model (as opposed to a bilingual model) for whom we had parental consent to participate were included in the analyses, thus constituting a population sample. Although the sample size was constrained, the “pwr” package in R (v. 1.2.1; Champley, 2017) revealed that we had sufficient power (power > .80) to detect correlation coefficients equal to or greater than 0.36. Importantly, the correlation coefficients of self-derivation with verbal ability and working memory performance in Experiment 1 were at or exceeded 0.37, indicating that we had sufficient power to assess whether these cognitive correlates exhibited a similar pattern of relations in childhood and adulthood. One month following testing for self-derivation, we obtained individual cognitive assessments on the children. Additionally, guidance counselors provided academic achievement data (a) at the end of the school year in which self-derivation through integration was tested and (b) two years after initial testing, allowing for a longitudinal investigation of the relation between self-derivation through integration and academic achievement. The results of the self-derivation task, stem fact performance, and concurrent academic performance were reported in Esposito and Bauer (2017). The results of the cognitive assessments and the longitudinal academic achievement data were not included in the prior published report and are presented here for the first time.

The children all attended a school in a rural public school system in the southeastern United States. Consent forms were sent home through parent communication folders (the typical means of communication between the school system and students’ parents/guardians). Official academic records of reading comprehension and math performance were provided by guidance counselors both at the time of participation and two years later. The school also provided demographic information on each participating child whose parents provided consent. Reflecting the diversity of the community, based on parental report, the sample was 45% African-American, 40% Caucasian non-Hispanic, 11% Caucasian Hispanic children; the racial/ethnic background of the remaining 4% was unknown. Approximately 87% of children in the community qualified for federally funded school lunch assistance. Of the 32 participants whose families reported caregiver education, 25% had a high school education or less, 31% had some training beyond high school, 16% had a technical or associates degree, 19% had a college bachelor degree, and 9% has some training beyond bachelors degree. Participating parents and teachers were thanked with a $10 gift card to a local merchant and participating children were thanked with a small school supply item. The institutional review board and participating school system school board reviewed and approved all study protocols and procedures.

3.1.2 Stimuli—The stimuli were two novel stem facts from each of four domains: dolphins, palm trees, volcanos, and kangaroos. Within each domain, the pair of stem facts (e.g., *dolphins live in groups called pods*; *dolphins talk by clicking and squeaking*) could be combined to derive a novel integration fact (*pods talk by clicking and squeaking*). Prior research employing these stimuli in the laboratory has demonstrated that they are novel to children and that both stem facts are necessary to derive the target integration fact (e.g., Bauer & Larkina, 2017; Bauer & San Souci, 2010). Moreover, in children, the experimental measure of self-derivation through integration shows test-retest reliability over 1 week (Esposito & Bauer, 2018).

The stem facts were featured in the context of rich story passages and presented via PowerPoint®. The passages were 81 to 89 words in length, distributed over 4 pages. As depicted in Figure 1 (Panel B), each page consisted of a hand-drawn illustration depicting the main actions of the text which was projected on a 4’ by 6’ screen. The text was not depicted. Instead, audio was played aloud through a voice recording conducted by a native English speaker. The passages were similar in structure: in each passage a character (e.g., a ladybug) learned a true but novel fact in the course of a short plot. Characters differed between related stories (e.g., a ladybug in one text passage about dolphins and a lamb in the other text passage about dolphins) to ensure an optimal level of challenge and avoid ceiling effects (Bauer et al., 2012; Bauer & Larkina, 2017). Only the stem facts were included in the passages; the integration facts were not presented.

3.1.3 Cognitive measures—The *Woodcock-Muñoz Language Survey® -Revised Normative Update* (*WMLS® -R NU*) (Schrank & Woodcock, 2009), The *Test of Non-verbal Intelligence, 4th edition*, (TONI4) (Brown, Sherbenou, & Johnsen, 2010), and Backward Corsi Blocks (Berch, Krikorian, and Huha, 1998; Kessels, van den Berg, Ruis, & Brands, 2008) were used to assess three standardized cognitive domains (see Table 1, Panel B for descriptions and comparisons to comparable measures assessed in adults in Experiment 1).

3.1.3.1 Verbal comprehension.: The Verbal Comprehension test of the *WMLS® -R NU* (Test 1) served as a measure of verbal ability (*Median* Reliability = .92 from 2–80 years; Schrank & Woodcock, 2009). Two subtests were administered: Vocabulary (Test 1) and

Analogies (Test 2). Participants received one point for each correctly answered item and the test was discontinued when six items were answered incorrectly. Scores were recorded for both Test 1 and Test 2, then summed for a total score.

3.1.3.2 Test of Non-verbal Intelligence.: The $TONI_4$ was utilized to assess intelligence, aptitude, abstract reasoning, and problem solving (*Median* Test-Retest Reliability = .90 from 6–18 years). The test is designed to be language-free. In this task, individuals are shown a series of patterns and choose an image that completes each puzzle. Corrective feedback is only provided for the first 6 sample items. The total number of correctly completed puzzles was summed as the outcome variable.

3.1.3.3 Backward Corsi Blocks.: The Backward Corsi Blocks was used to assess working memory (Milner, 1971). The Corsi block task and its backwards counterpart have been used to assess spatial working memory from early childhood to late adulthood with the same standardized paradigm (Berch et al., 1998; Kessels et al., 2008; McLean & Hitch, 1999; Orsini, Schiappa, & Grossi, 1981). Task performance of 9-year-old children across unrelated studies shows similar performance: *Mean range* = 3.92–4.92, *SD*s = 0.56–0.77, and *Mean range* = 4.00–4.60, *SD*s = 0.60–0.70, from McLean and Hitch (1999) and Orsini and colleagues (1981), respectively, thus indicating task reliability for this age group. The transition from physical blocks to a digital touchscreen format shows equivalent performance between the two modalities with greater consistency in administration (Robinson & Brewer, 2016). The computerized measure was administered using touchscreen laptops (15.6-inch Asus Transformer Book Flip TP500L), which ran the Psychology Experiment Building Language (PEBL; Mueller, 2010, 2011). In this task, 9 blue squares appear on the computer screen and “light up” in a sequence. Participants must hold the sequence in mind while performing a mental operation on the sequence (reversing the sequence). Participants respond by touching the squares. The sequence begins with 2 blocks in each trial and increases by 1 block after 2 correctly completed trials. If neither trial at a given level is completed correctly, the task terminates. We recorded the Total Score, resulting in one dependent variable that reflects the correct number of touches made during the task.

3.1.4 Academic Measures

3.1.4.1 Reading Inventory.: The Reading Inventory (RI) is a computer adaptive test of text reading and comprehension (Salvia & Ysseldyke, 1998). The test adapts to the level of the child regardless of grade, providing a sensitive measure of their overall reading comprehension achievement. It has been normed and validated for use across kindergarten through high school. It is highly correlated to the SAT, the Comprehensive Test of Basic Skills, and the North Carolina End-of-Grade Test of Reading Comprehension (Salvia & Ysseldyke, 1998). We recorded the score as the dependent variable for the year of participation (i.e., concurrent Reading Inventory) as well as two years later (i.e., longitudinal Reading Inventory).

3.1.4.2 End-of-grade, mathematics.: We recorded performance on the North Carolina End-of-Grade standardized math test (EOG math; http://www.ncpublicschools.org/

accountability/testing/generalinfo). The test is provided to all NC students in grade 3 and tests their knowledge for third grade level math content. This assessment has a range of 421–473, resulting in a single score as the dependent variable. We recorded the score as the dependent variable for the year of participation (i.e., concurrent EOG math) as well as two years later (longitudinal EOG math).

3.1.5 Procedure—

Participants completed two sessions spaced 1 month apart. Spacing was determined by the schedule of the participating school system. A one-week follow-up was not available, and thus, there is no measure of retention for Experiment 2. During Session 1, children were tested in groups in their classrooms. All testing was done by the second author, accompanied by a research assistant. In Session 2, children were tested individually by one of 12 undergraduate female research assistants in a quiet classroom in their school. Experimenters followed a detailed protocol with the second author supervising to ensure protocol fidelity.

3.1.5.1 Session 1: Initial learning and extension of knowledge.:

The 45-minute classroom sessions were divided into three phases: (1) exposure to the first set of novel stem facts; (2) exposure to the second set of paired, related stem facts; and (3) test for self-derivation of new factual knowledge through integration of pairs of related stem facts. Each phase was separated from the others by a 10-minute filler task (a class number guessing game and a class seriation game, respectively).

In Phase 1, students heard the first text passage from each of four, paired domain passages. The illustrations conveying the main actions of the passages were projected onto the classroom screen while the pre-recorded audio tracks were played through speakers (see Figure 1, Panel B, for example story). Each story was repeated immediately after initial presentation to encourage robust encoding.

Phase 2 commenced after the 10-minute filler activity. The children heard the second member of each stem fact story pair, one from each of the 4 domains and, again, each story was repeated. For both Phase 1 and Phase 2, the slides and audio were advanced automatically, ensuring consistent timing across classrooms. The text passages within domains were counterbalanced, with domain order consistent across Phase 1 and Phase 2 within a session (i.e., if A1, B1, C1, D1 then A2, B2, C2, D2). Domains were also presented in one of 4 predetermined orders, such that each domain was presented in each serial position approximately equally often across classrooms.

In Phase 3, after the second 10-minute buffer task, children were tested for self-derivation of new factual knowledge and recall of the individual stem facts. All children were provided with a test packet containing all four integration questions first in open-ended format followed by all questions again in forced-choice format. The forced-choice questions had three answer options. Each question was read aloud. The integration questions were presented in one of 4 predetermined orders such that each question was asked in each serial position equally often across classrooms and text passage orders.

3.1.5.2 Session 2: Standardized cognitive assessments.: One month after the classroom presentation, the researchers returned to the school for individual assessments. Children were escorted in small groups to an alternative classroom provided by the school to meet with a research assistant. Standardized cognitive assessments were then administered in the following fixed order: 1) working memory (Backward Corsi Blocks), 2) relational reasoning ($TONI_4$), and 3) verbal comprehension (*WMLS*® *-R NU*).

3.1.6 Scoring on self-derivation task—

Children received 1 point for each correct response. Thus they could score up to 4 on integration fact questions in both open-ended and forced-choice format. The dependent measures were total correct for each measure, resulting in 2 dependent variables. To increase comparability between experiments, we report cognitive and academic correlations as they pertain to open-ended performance.

3.2 Results

The results are reported in three parts. First, we describe variability in self-derivation through integration performance. Second, we examine relations between self-derivation and cognitive measures by conducting a multiple regression analysis with all participants who provided data on all cognitive assessments ($n = 57$). Third, we test whether self-derivation is associated with academic performance concurrently and, finally, longitudinally. We also assessed the relative contributions of self-derivation and cognitive factors through multiple linear regression analyses. As in Experiment 1, the effects of age and gender were accounted for in all models. In all cases, they made nonsignificant contributions. The same diagnostics were assessed as in Experiment 1 to test whether the assumptions of linear regression were met. Assumptions were met and no corrections were made. All analyses were conducted using SPSS Statistics package (Version 24). All statistical tests were two-tailed.

3.2.1 Description of self-derivation of the integration facts—

As depicted in Table 7, self-derivation scores encompassed the full range of the measure in open-ended assessment (0–4) and exhibited a similar range in forced-choice assessment (1–4). On average, children self-derived 38% of the novel integration facts in open-ended format and selected 77% of the facts correctly in forced-choice format. Given open-ended performance showed sufficient variability for analyses (see Table 7), subsequent models and analyses included open-ended self-derivation through integration performance and omitted forced-choice.

3.2.2 Association between self-derivation and cognitive factors—

The primary aim of the present experiment was to determine if the cognitive abilities that are associated with self-derivation of new factual knowledge through memory integration in children replicate or differ from those in adults. Performance on the cognitive factors assessed are reported in Table 7 and zero-order Pearson correlation coefficients are reported in Table 8 (see Figure 6 for scatter plots). Open-ended self-derivation through integration performance was significantly correlated with verbal comprehension and relational reasoning (i.e., $TONI_4$). Working memory (i.e., Backward Corsi) did not correlate to self-derivation performance. Critically, this null result was replicated with a verbal working memory measure tested in a separate sample of 91 children in which we had sufficient power (power

> 0.80) to detect correlation coefficients equal to or greater than 0.28 (see Supplemental Experiment 1, Supplemental Tables 3–5, and Supplemental Figure 1).

We next conducted a regression analysis to ascertain whether the cognitive measures predicted unique statistical variance in self-derivation through integration performance. The results of the regression are reported in Table 9. The full model significantly predicted 46% of the variance in self-derivation through integration performance. Only performance on the verbal comprehension test was a significant predictor; neither relational reasoning or working memory performance predicted unique variance.

3.2.3 Association of self-derivation with academic performance measures—

As depicted in Table 7, the academic performance variables were normally distributed and did not have significant skew or kurtosis. Zero-order Pearson correlations between self-derivation and the academic performance measures are reported in Table 8 (see Figure 7 for scatter plots). Self-derivation through integration performance exhibited moderate to strong associations to concurrent Reading Inventory and concurrent end-of-grade math. Self-derivation through integration also exhibited moderate to strong associations to longitudinal Reading Inventory and longitudinal end-of-grade math performance. We next conducted a series of regression analyses to determine whether self-derivation accounted for unique variance in academic performance when accounting for its significant cognitive correlate (i.e., verbal comprehension). As reported in Table 10 (Model 1), verbal comprehension accounted for significant variance in concurrent Reading Inventory and self-derivation was a marginally significant predictor. In contrast, only verbal comprehension (not self-derivation) accounted for longitudinal Reading Inventory as well as concurrent and longitudinal end-of-grade math (Models 2–4).

3.3 Discussion

The present experiment extended Experiment 1 to characterize the cognitive correlates of self-derivation through memory integration in children. Like adults, children showed substantial variability in their capacity to add to their knowledge base through memory integration and self-derivation, which was significantly correlated with superior performance on tests of verbal comprehension (i.e., the extent of verbal knowledge), and abstract relational reasoning. However, unlike the pattern of results reported for adults, neither non-verbal nor verbal measures of working memory (Supplemental Experiment 1) were associated with self-derivation of the novel integration facts.

Furthermore, as was observed in Experiment 1, verbal comprehension predicted a significant portion of the variance in self-derivation performance (Full Model adj. R^2 = 46%). Supporting the relevance of individual differences in self-derivation to educational outcomes, children's performance on the experimental self-derivation task was associated with concurrent and longitudinal academic achievement on both reading and math measures used to track academic progress in the classroom.

Whereas self-derivation of the integration facts and verbal comprehension explained significant variance in concurrent assessments of reading achievement (though the self-derivation relation was marginal), only verbal comprehension accounted for variability in performance on the concurrent math assessment and on both longitudinal academic assessments. This pattern of results closely parallels that observed for adults, such that standardized measures of crystallized knowledge (i.e., verbal comprehension) were a stronger relative predictor of academic success. It will be left to future research to determine if long-term retention of self-derived knowledge contributes unique variance to predictions of academic outcome in middle childhood.

4. General Discussion

The goals of the current research were three-fold. First, we identified the cognitive factors that contribute to individual differences in the initial self-derivation and subsequent retention of knowledge derived through memory integration in adults. Second, we tested whether a similar profile of cognitive correlates was observed in 8- to 10-year-old children, a period of development in which fluid cognitive abilities have been shown to substantially differentiate from one another (Mungas et al., 2013). Third, we sought to examine whether self-derivation through memory integration is associated with concurrent academic success in adults as it is in children (Esposito & Bauer, 2017), and extended beyond concurrent academic measures to test whether performance on the experimental self-derivation task predicts longitudinal academic outcomes, a relation which has previously been assumed but not directly examined.

4.1 Cognitive correlates of the derivation and retention of factual knowledge through integration

The findings of the research were clear. Although individual differences in self-derivation and retention of knowledge through memory integration in adults were correlated with all the cognitive abilities assessed, only the measures of verbal comprehension and working memory were uniquely associated with initial self-derivation performance and retention of the information (the full model with all cognitive constructs included accounted for 32% and 35% of the variance in Session 1 and Session 2 performance, respectively). Guided by this pattern of specific factors and previous demonstrations of relations between self-derivation and relational reasoning in preschool-aged children (Varga & Bauer, 2014), we tested the association of self-derivation of new knowledge through integration with verbal comprehension, working memory, and relational reasoning in children. Consistent with the adult profile, verbal comprehension and relational reasoning were significantly correlated with the experimental task but only verbal comprehension was uniquely associated with performance in children (the full model with all cognitive constructs included accounted for 46% of the variance in self-derivation). Moreover, in a supplemental sample of children in which we used the same verbal comprehension and relational reasoning measures but incorporated a verbal (rather than a spatial) working memory measure (Supplemental Experiment 1), we again found that both verbal comprehension and relational reasoning played a significant role in prediction of individual differences in self-derivation of knowledge through memory integration. However, unlike adults, neither spatial working memory (Experiment 2) nor verbal working memory (Supplemental Experiment 1) were correlated with successful self-derivation. Thus both similarities and differences in the patterns of cognitive correlates were observed between the child and adult groups.

4.1.1 Experimental measure of self-derivation through memory integration— Further explication of the relation between cognitive factors and self-derivation through memory integration requires consideration of the specific measures employed. We assessed self-derivation of new factual knowledge based on integration of explicitly learned stem facts (Experiments 1 and 2) and retention of the previously self-derived integration facts (Experiment 1, adults only). Of note, the cognitive factors identified remained significant even when accounting for self-reported prior knowledge of the stem facts (see Varga & Bauer, 2017a) and for standardized long-term memory storage and retrieval abilities in adults. In future research, it would be desirable to measure the strength of memory for the stem facts themselves. Although this opportunity was not available in the present research (because it would have invalidated the test for retention of self-derived knowledge), we argue that the pattern of relations is unlikely to be accounted for by comprehension of or memory for the stem facts alone. First, prior research with children has demonstrated that children do not have knowledge of the stem facts or of the integration facts prior to their participation. Second, memory for the stem facts is necessary—but not sufficient—for self-derivation (Bauer & Larkina, 2017; Bauer & San Souci, 2010). Thus, the relation is with self-derivation and is not accounted for by comprehension of or memory for the stem facts themselves. It is therefore reasonable to suggest that self-derivation relies on a culmination of specific skills, presumably related to the temporally-staged subprocesses previously implicated by results from behavioral and ERP research—(1) retrieval of previously encoded, related stem facts upon exposure to a related fact; (2) abstraction of the relation between the related stem facts; (3) formation and updating memory to represent the overlapping, integrated knowledge; and (4) verbal communication of the self-derived integrative understanding (Bauer & Varga, 2017; Varga & Bauer, 2017b). Although we focus on the individual measures of verbal comprehension, working memory, and concept formation, in drawing conclusions about the significant predictors of self-derivation, it is important to keep in mind that the different measures had some level of correlation with one another. Because multicollinearity is always a potential limitation in detecting individual predictors via multiple regression, nonsignificant predictors in the regression models should be interpreted with caution. The theoretical implications of the role of verbal comprehension, working memory, and concept formation for our understanding of memory integration are discussed below.

4.1.2 Verbal comprehension—To clarify how verbal comprehension directly contributes to successful self-derivation and retention of the integration facts in both adults and children, it is necessary to unpack the specific abilities assessed by this cognitive measure. In these tasks, adult and child participants were asked to provide verbal labels for pictures (e.g., *anvil*) and to demonstrate relational knowledge through completion of analogies (e.g., finger is to hand, as toe is to *foot*). Adults also additionally completed synonyms (e.g., empty: *void*) and antonyms (e.g., antiquated: *contemporary*) to ensure sufficient range in relational knowledge performance. Therefore, this task assessed both the extent of semantic knowledge (including both individual words and relations between words) as well as the ability to reason based on acquired knowledge. Although participants were required to learn and extend *novel* semantic material in the present research, it is logical that well-developed verbal skills would facilitate processing of the newly learned factual information, particularly with respect to comprehending the novel, overlapping relation between to-be-integrated stem facts. That is to say, a larger relational semantic network would be expected to provide a stronger context through which to comprehend and integrate new semantic information. Support for this interpretation comes from anecdotes from adults and children, such that during the initial test for self-derivation and delayed test for retention (adults only), individuals sometimes provided semantic synonyms for the target integration facts (e.g., in adults *Hematopoiesis occurs in the bones,* rather than the initially learned *skeleton*), suggesting that they interpreted the novel facts with respect to what they already knew.

In additional to playing a role in the initial interpretation and representation of the explicitly presented information, we have reason to believe verbal comprehension was also recruited during the test for self-derivation of the integration facts. More specifically, in the study by Varga and Bauer (2017b) in which we examined ERPs from a subset of the participants included in the present research (those with 50/50 performance, rather than the full range), a single ERP differentiated processing during successful versus unsuccessful self-derivation of the integration facts at test. Moreover, this neural response was marginally correlated with performance on the verbal comprehension test. It is therefore possible that the skills tapped by verbal comprehension, particularly the ability to reason based on prior semantic knowledge, might again be engaged during the explicit test, reflective of direct retrieval and/or recombination of previously integrated memory traces.

4.1.2 Working memory—For adults, working memory was measured with the Digits Backward measure. In the self-derivation paradigm, participants may have invoked working memory skills to attend to separate yet related stem facts concurrently in order to integrate them at the time of encoding and/or to self-derive novel integration facts at the time of test. Consistent with our interpretation of the role of working memory, Cowan (2014) argues that one’s sophistication in reasoning about any real-world problem depends on working memory capacity, which is defined as the amount of relevant information that an individual can cull from long-term memory concurrently while performing, “any combination of mental strategies and processes,” that may be used to maintain and/or transform the representation (p. 207). It is reasonable to assume that greater working memory capacity facilitated the amount of stem fact information that an individual could simultaneously activate and process in the service of integrating the representations and using them to self-derive new knowledge (see Varga & Bauer, 2017b).

In contrast to adults, working memory capacity did not significantly predict variability in self-derivation in children. Like the working memory measure employed with adults, the Backward Corsi Blocks employed in Experiment 2 required children to hold a sequence in mind and reverse it. Nevertheless, despite comparable domain-general processing demands, it is possible that the tasks differentially recruited domain-specific storage components (verbal vs. visuospatial; e.g., Alloway, Pickering, & Gathercole, 2006). Yet when a verbal working memory measure was employed with a separate sample of 8- to 10-year-olds (Supplemental Experiment 1), a nonsignificant relation was observed. This finding points to the possibility of a developmental difference with respect to the recruitment of working memory skills during memory integration (discussed below).

4.1.2 Relational reasoning—In light of the proposed roles of verbal comprehension and working memory in the maintenance and manipulation of the stem facts during encoding and self-derivation, it might seem puzzling that our relational reasoning measures (Concept Formation in adults and $TONI_4$ in children) were correlated but not uniquely predictive of self-derivation behavior in adults and children (though see Supplemental Experiment 1 for alternative finding when a group-administered reasoning task and verbal working memory task were employed with a separate sample of children). Moreover, in the ERP investigation by Varga and Bauer (2017b) that examined participants in the middle of the performance distribution observed in the present research, the relational reasoning task was associated with neural correlates linked to (a) detection of relational novelty between the first and second stem facts, and (b) the single ERP associated with successful self-derivation. On the surface, these patterns may seem inconsistent with one another. Yet the ERP investigation linked the cognitive factors to temporally distinct neural subprocesses, whereas in the present investigation, the cognitive factors were examined with respect to the culminating behavioral outcome (i.e., successful or unsuccessful self-derivation of integration facts), which presumably encompassed all of the subprocesses. In the same vein, in the relational reasoning tasks, participants were presented with novel patterns for an unlimited amount of time, thereby eliminating the need to hold items in memory. In contrast, the verbal comprehension, working memory, and self-derivation measures required a combination of memory retrieval and flexible recombination operations. Thus, we speculate that the relational reasoning measure was correlated but not uniquely predictive of performance owing to the fact that the digit span measure of working memory and the analogies subtest of the verbal comprehension measure were more closely aligned to the mental operations explicitly assessed with the behavioral measure of interest and thus explained more and overlapping variance in the cumulative knowledge extension behavior assessed here.

4.2 Explaining differential cognitive correlates of memory integration in children and adults

In the present research, we found that verbal comprehension exhibited a relation to self-derivation in children and adults. However, whereas working memory was associated with individual differences in self-derivation in adults, this cognitive factor was not correlated with performance in 8- to 10-year-old children. There are a number of plausible explanations for the different pattern of relations.

First, children in Experiment 2 and the supplemental sample were tested in a school environment rather than the highly controlled laboratory setting in which adults were tested in Experiment 1. The larger variance associated with the inherent noise that accompanies school-based testing could contribute to the null effect in children. This is an unlikely explanation, however, given similar patterns of correlation of self-derivation performance with verbal comprehension and relational reasoning in the adult and child samples. Furthermore, verbal working memory exhibited consistent patterns of intercorrelation with relational reasoning and verbal comprehension, suggesting that similar underlying cognitive skills were recruited in both the child and adults samples.

Second, the samples were drawn from populations with different demographics. The children were a more diverse group racially and ethnically, and had a lower socio-economic status in comparison to the adult college students. Again, we think this explanation unlikely because the pattern of results did not differ between groups for verbal comprehension. This is especially noteworthy because verbal comprehension is more likely to be influenced by socio-demographic factors than working memory (Akshoomoff et al., 2014), and yet we observed similar patterns of relations between verbal comprehension and self-derivation between the groups.

Third, there were fewer participants in the child sample. Although power may have been lower in Experiment 2 relative to Experiment 1, in the Supplemental experiment, we had sufficient power (power > .80) to detect correlation coefficients equal to or greater than 0.28, which is below the 0.37 correlation observed between self-derivation and verbal working memory in Experiment 1. Thus, if the relation between working memory and self-derivation is developmentally continuous in magnitude between childhood and adulthood, we should have had sufficient power to detect it. It is always possible that the true effect size in children is smaller than what was observed in adults, however, this would still suggest that working memory skills are only weakly associated with the capacity to extend new knowledge through memory integration.

Finally, the self-derivation paradigm itself differed between experiments. In Experiment 1, adults were presented with facts in individual sentences, presented one word at a time. The lag between related facts was two to four intervening facts, resulting in a separation on the order of one to two minutes. In contrast, in Experiment 2 and the supplemental experiment, children were presented with related story passages or individual sentences that were separated in time by approximately 10 minutes and several intervening activities. These interleaved versus blocked procedural differences could alter the recruitment of working memory. Yet irrespective of the shorter lag in Experiment 1, adults read at least 2 sentences between related facts, and thus it is unlikely that the protocol led participants to actively maintain or rehearse previous sentences in working memory. Hence, all individuals were similarly tasked with retrieving previous information upon exposure to overlapping material in order to flexibly manipulate the representations at the time of learning.

Rather than to methodological features, we suggest that the different patterns in children and adults may point to differences in the relative roles of domain-general cognitive resources in self-derivation through memory integration in children and adults. This suggestion is consistent with the observation that working memory only begins to emerge as distinct from other fluid cognitive construct around 8 years of age (Mungas et al., 2013). As a result, the specific computations tapped by working memory in adulthood (i.e., maintaining and transforming a representation held in immediate awareness) might not be robustly or autonomously engaged to integrate separate representations in childhood. Consistent with this proposal, experiments aimed at promoting self-derivation through integration in children have shown that interventions that highlight the relevance of separate yet related episodes facilitate successful self-derivation, such as when hints are provided (Bauer et al., 2012; 2015). Importantly, hints provided at the time of test facilitate self-derivation through integration in 4- and 6-year-old children, whereas hints provided during encoding of related episodes do not. As suggested by the authors, at least in children, it appears that the processes supporting self-derivation through memory integration occur on demand rather than spontaneously upon encoding of related events (see also Varga & Bauer, 2013, for consistent evidence). This finding is consistent with the argument posed in the present research that working memory underlies the transformation of individual memory traces to represent their overlapping relation, and that at least for adults, this process begins as early as encoding (see Varga & Bauer, 2017b). Considering the entire pattern of interrelation, we propose that in both children and adults, crystallized verbal abilities are invoked during the processes of encoding (i.e., comprehension of the relation between stem facts) and the explicit test to self-derive novel integration facts (i.e., through recombination of the individual stem facts and/or retrieval of integrated traces). In adulthood, we speculate that self-derivation through memory integration is further supported by the capacity to transform the individual stem facts to form an integrated memory trace at encoding (the first opportunity to recruit working memory skills), a mechanism that children do not appear to reliably engage. Therefore, the results from the present research contribute to our understanding of the cognitive skills that relate to variability in self-derivation through memory integration. They also provide suggestive evidence of critical ways in which the process may differ in children and adults. Direct tests of these suggestions await future research.

4.3 Implications of self-derivation through memory integration for academic outcomes

Our account of the association between knowledge extension through memory integration and cognitive abilities also sheds light on our understanding of academic success. The findings indicated that our experimental assessment of memory integration was associated with concurrent and longitudinal measures of academic outcome in both children and adults. Moreover, with the exception of performance on the standardized reading achievement test in children, verbal comprehension (i.e., crystallized verbal knowledge) emerged as the only significant individual predictor of concurrent academic success relative to initial self-derivation and the other cognitive correlates of successful memory integration included in the regression models. Conversely, in adults, retention of the integrated knowledge and verbal comprehension both uniquely predicted concurrent academic measures. Indeed, retention of the integration facts was the only significant predictor of longitudinal academic success in adults (though note that the beta weight for verbal comprehension was not significantly smaller than that for retention of self-derived knowledge). Hence, these converging findings suggest that one’s more-or-less permanent store of knowledge (Session 2 self-derivation) and the ability to implement stored knowledge (as assessed via the verbal comprehension measure) are useful predictors of academic performance. Although assessment of long-term retention of the self-derived integration facts was not possible in the child sample reported here, based on evidence that knowledge newly derived through memory integration was retained in semantic memory over time in adults (Experiment 1) as well as based on parallel findings in previous research with younger children (e.g., Varga & Bauer, 2013; Varga et al., 2016), we would expect that long-term retention would be similarly predictive of academic performance earlier in development. Hence, this is a question for future research.

Finally, it should be noted that the fluid working memory constructs were not associated with unique variance in academic outcome in either experiment. Indeed, working memory exhibited few associations with academic outcome even when assessed through bivariate correlations. It has long been established that crystallized verbal intelligence is a better predictor of academic achievement than is its fluid counterpart (Kaufman, Kamphaus, & Kaufman, 1985; Kunina, Wilhelm, Formazin, Jonkmann, & Schroeders, 2007). Academic measures often reflect recent classroom learning, usually in regard to a narrower scope (e.g., exams taken over the course of a semester culminating in a GPA) or measure one's capacity to master school tasks more broadly (e.g., math, reading, etc.). Similarly, to achieve the maximum score on the SAT, participants must demonstrate knowledge acquired in school and use that knowledge in the face of new objectives on the exam (Engle, Tuholski, Laughlin, & Conway, 1999). As such, it is reasonable to suggest that the academic measures reported in the present research reflected success in building the basic knowledge targeted in formal education, rather than more abstract fluid learning skills implemented to acquire the knowledge in the first place.

4.4 Conclusions

In conclusion, the present research provides new insights into the cognitive abilities that contribute to variability in the productive formation and retention of knowledge newly self-derived through memory integration in children and adults. It makes clear that verbal comprehension relates to variability in this fundamental form of learning in both children and adults. In contrast, fluid (verbal) working memory abilities only relate to individual differences in adults. Moreover, self-derivation through integration was also associated with concurrent and longitudinal academic success, and retention of self-derived knowledge was a significant predictor of longitudinal academic success in adults. These findings are important because they suggest that interventions aimed at promoting successful self-derivation through memory integration might have implications for facilitating educational attainment. Along a similar vein, because crystallized verbal abilities that contribute to variance in self-derivation through memory integration are thought to accrue across educational experiences and are less contingent on rate-limiting biological determinants than are fluid abilities (Horn & Noll, 1997), the present research paints an optimistic picture for future attempts at promoting this crucial learning ability. Therefore, taken together, the current research provides a theoretically plausible and a practically significant framework from which to guide future research aimed at enhancing this educationally relevant phenomenon.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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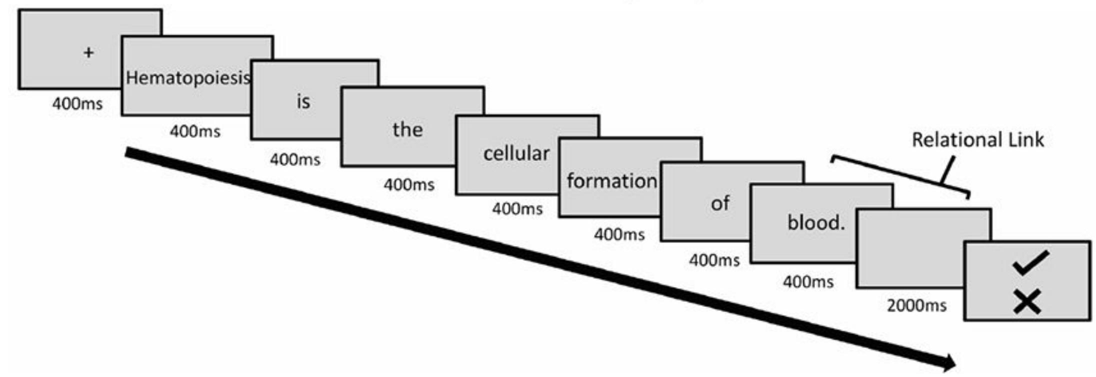
Panel A: Encoding in Experiment 1



Panel B: Encoding in Experiment 2

Passage	Page 1	Page 2	Page 3	Page 4
The Traveling Lady Bug				
	As a ladybug slept one night a strong wind came and blew her out of bed.	She woke up and found she was at sea. A friendly dolphin came up and said "hello" to her by *clicking and squeaking*.	Before the ladybug could say much more than "hello," the very strong wind blew again and she was swept back home.	The ladybug didn't get to play with the friendly dolphin. But now the ladybug knew how all *dolphins talk – by clicking and squeaking*.

Figure 1.

Schematic of encoding of a single stem fact in Experiment 1 (Panel A) and Experiment 2 (Panel B).

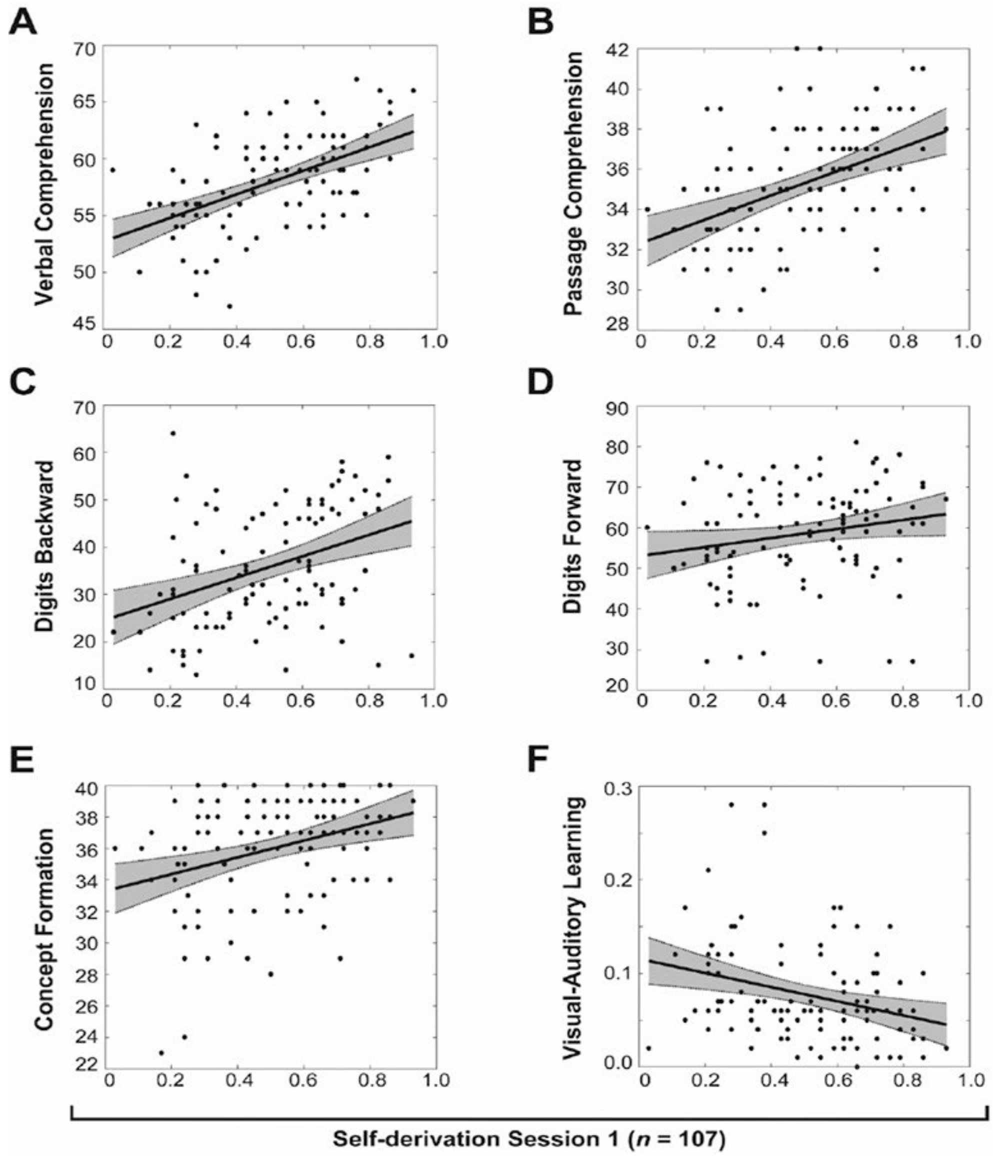


Figure 2.
Scatter plots depicting the association between self-derivation at Session 1 and verbal (A), reading (B), working memory (C), short-term memory (D), relational reasoning (E), and long-term storage and retrieval (F) abilities in adults in Experiment 1.

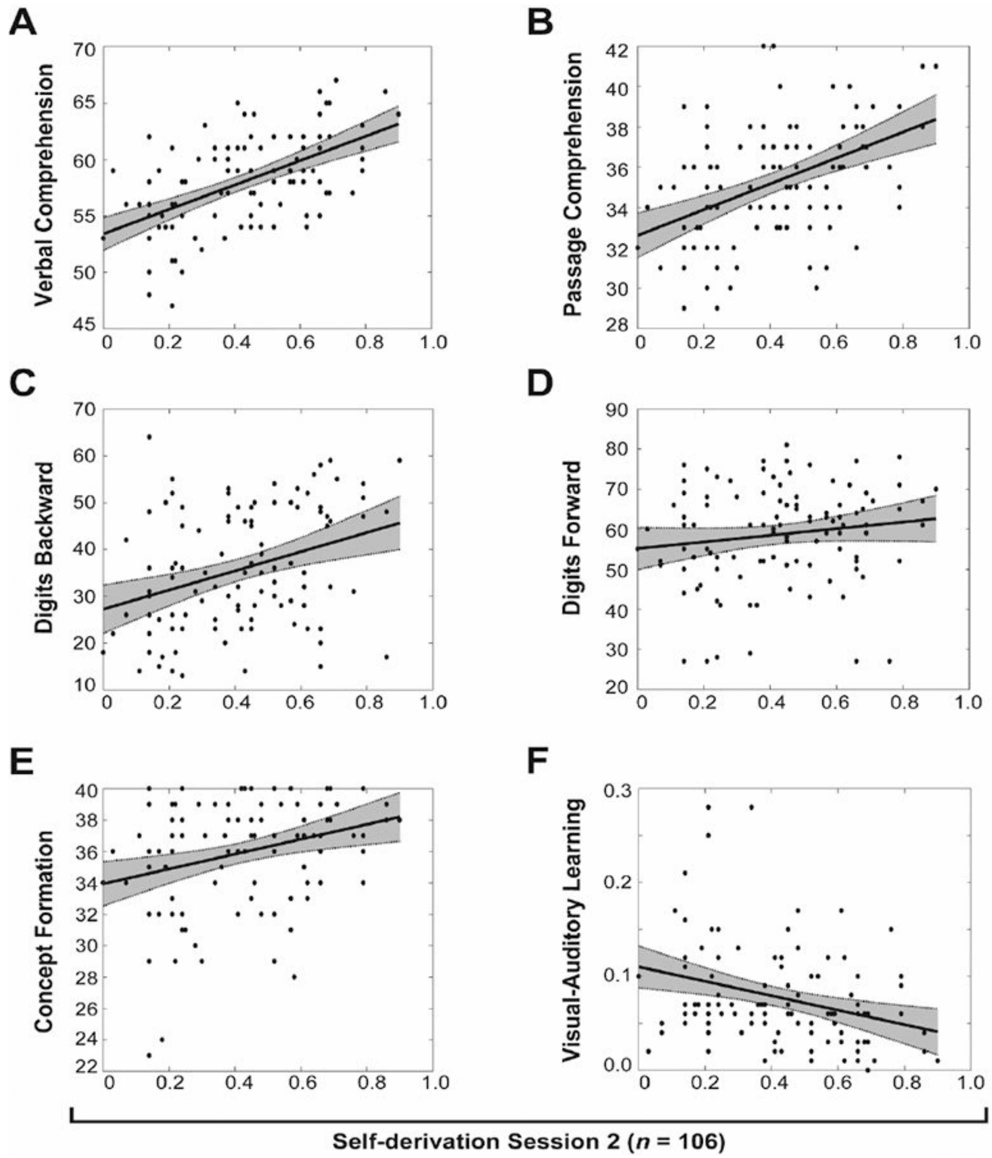


Figure 3.

Scatter plots depicting the association between self-derivation at Session 2 and verbal (A), reading (B), working memory (C), short-term memory (D), relational reasoning (E), and long-term storage and retrieval (F) abilities in adults in Experiment 1.

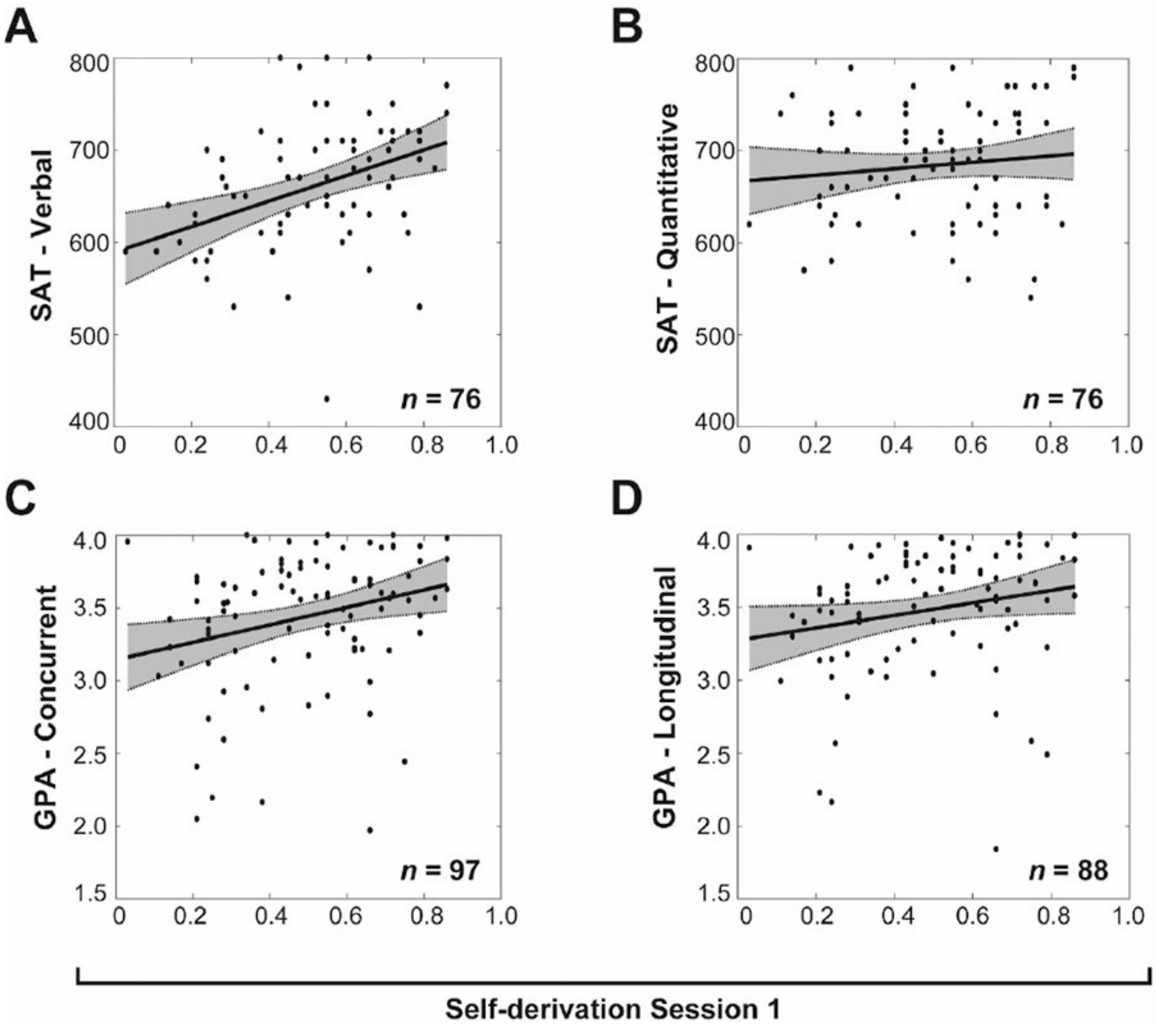


Figure 4.

Scatter plots depicting the association between self-derivation at Session 1 and scores on SAT Verbal (A), SAT Quantitative (B), concurrent GPA (C), and longitudinal GPA (D) in adults in Experiment 1.

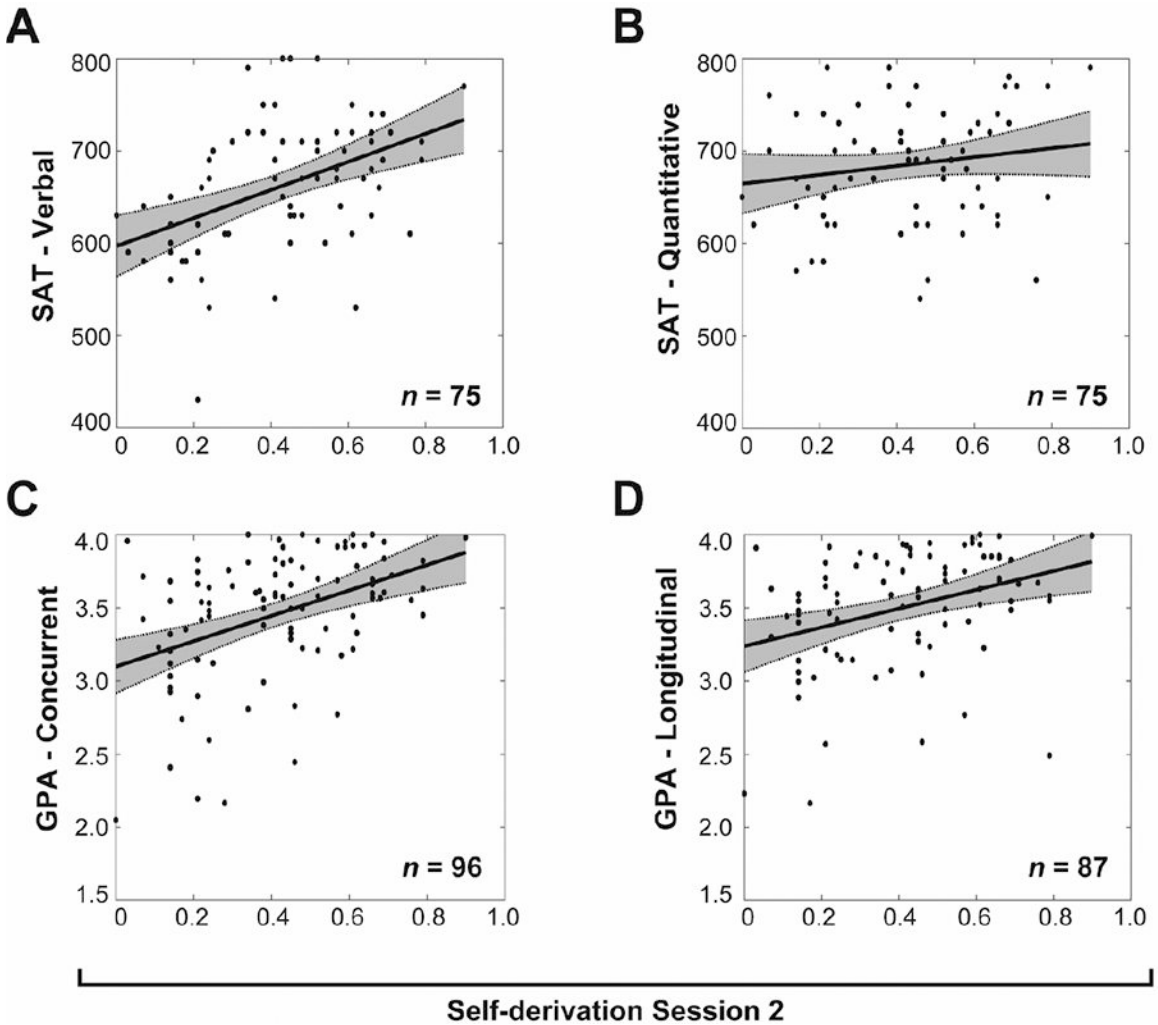


Figure 5.

Scatter plots depicting the association between self-derivation at Session 2 and scores on SAT Verbal (A), SAT Quantitative (B), concurrent GPA (C), and longitudinal GPA (D) in adults in Experiment 1.

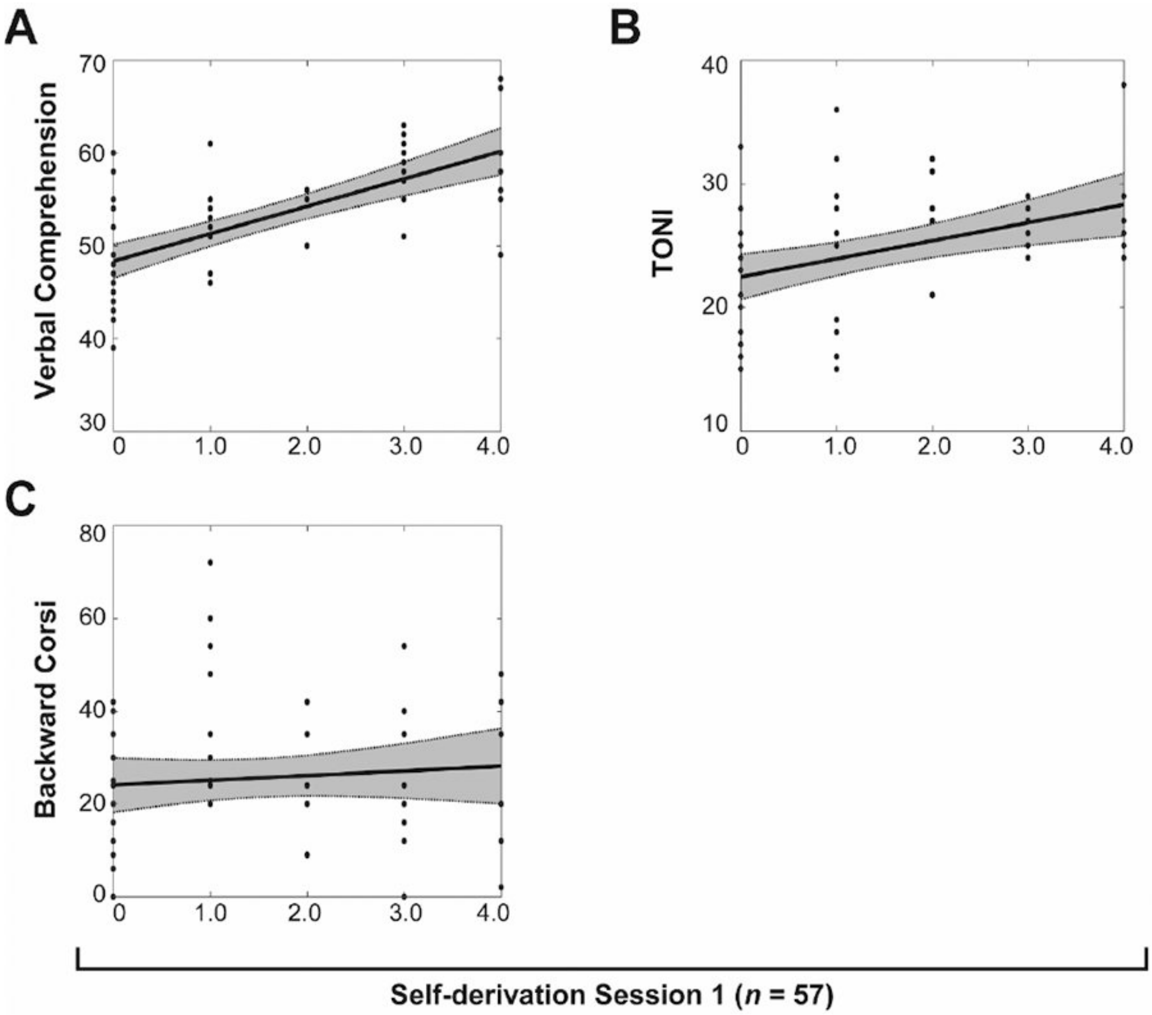


Figure 6.

Scatter plots depicting the association between self-derivation at Session 1 and verbal (A), relational reasoning (B), and working memory (C) abilities in children in Experiment 2.

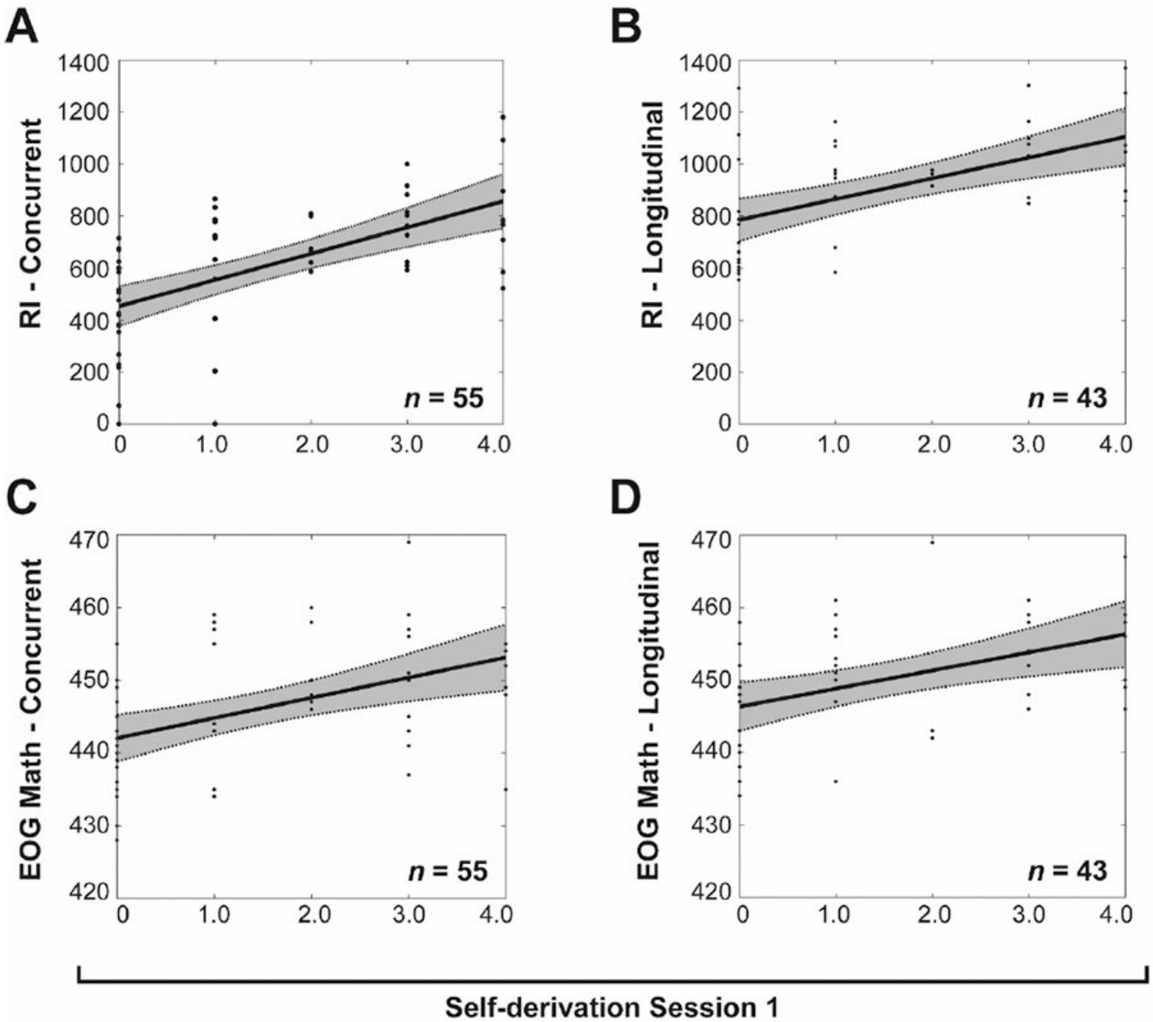


Figure 7.

Scatter plots depicting the association between self-derivation and scores on the concurrent Reading Inventory assessment (A), longitudinal Reading Inventory assessment (B), concurrent End-of-Grade math assessment (C) and longitudinal End-of-Grade math assessment (D) in children in Experiment 2.

Table 1.

Description of Cognitive Tests used to Assess the Cognitive Factors of Interest in Experiment 1 (Panel A) and Experiment 2 (Panel B).

		Panel A: Experiment 1 Cognitive Measures		Panel B: Experiment 2 Cognitive Measures	
	Construct	**Test**	**Description**	**Test**	**Description**
Cognitive Measures	Verbal Knowledge	*Woodcock Johnson-III, Test 1: Vocabulary, Synonyms, Antonyms, Analogies*	Crystallized intelligence: the extent of one's knowledge, the ability to verbally communicate knowledge, and the ability to reason based on previously learned information and experiences.	*Woodcock-Munoi Language Survey® Revised Normative Update*: Vocabulary, Analogies*	Crystallized intelligence: the extent of one's knowledge, the ability to verbally communicate knowledge, and the ability to reason based on previously learned information and experiences.
	Reading Comprehension	*Woodcock Language Proficiency Batten—Revised, Test 7, Passage Comprehension*	Reading ability, independent of verbal comprehension.	No equivalent measure.	Reading comprehension was assessed by the school as an academic outcome measure.
	Relational Reasoning	*Woodcock Johnson-III, Test 5, Concept Formation*	Fluid reasoning: general abilities to reason, generate concepts, and solve novel problems in the absence of prior knowledge.	*Test of Non-verbal Intelligence, 4th edition*	Fluid reasoning and general intelligence, specifically abstract reasoning and problem solving without the confounds of verbal abilities.
	Associative. Long-term Memory Retrieval	*Woodcock Johnson-III, Test 2, Visual-Auditory Learning (VAL)*	Storage and retrieval of information from long-term memory, not to be confused with one's long-term memory store which constitutes the *contents* of knowledge.	No equivalent measure.	
	Short-term Memory Span	*Test of Memory and Learning- 2, Digits Forward*	Holding items in memory without requiring additional mental operations on items.	No equivalent measure.	
	Working Memory Span	*Test of Memory and Learning- 2, Digits Backward*	Ability to manipulate and operate on items in shortterm memory.	*Backward Corsi Blocks*, PEBL	Ability to manipulate and operate on items in short-term memory.
Academic Measures	Aptitude	Scholastic Aptitude Test (SAT)	Standardized college admissions assessment measuring academic readiness for college.	No equivalent measure.	
		Verbal	vocabulary, text comprehension, inferential reasoning, organization of ideas, and understanding literary elements		
		Math	arithmetic operations (e.g.. fractions), algebra, geometry, statistics, problem solving, and reasoning		
	Academic Achievement	Grade Point Average (GPA)	Mastery of specific course content.	Reading Inventory (RI)	Standardized computer adaptive test of text reading comprehension.
		Concurrent	Semester of participation.	Concurrent	Year of participation.
		Longitudinal	Two-years after participation.	Longitudinal	Two-years after participation.
				NC End-of-Grade Math	Standardized test of 3rd grade level mathematics achievement.

	Panel A: Experiment 1 Cognitive Measures		Panel B: Experiment 2 Cognitive Measures	
Construct	**Test**	**Description**	**Test**	**Description**
			Concurrent	Year of participation.
			Longitudinal	Two-years after participation.

Table 2.

Experiment 1 Descriptive Statistics for all Measures

	Measures	*n*	*M*	*SD*	*Range*	Skew	SE_{Skew}	Z_{Skew}	Kurtosis	$SE_{Kurtosis}$	$Z_{Kurtosis}$
Self-Derivation	Immediate	117	.50	.21	.03–.93	−.10	.22	−.45	−.96	.44	-2.18^{*}
	Delay	115	.43	.21	.00–.90	.14	.23	.61	−.86	.45	−1.91
Cognitive Measures	Verbal Comprehension	107	57.95	4.11	47–67	−.10	.23	−.43	−.15	.46	−.33
	Passage Comprehension	107	35.32	2.91	29–42	.02	.23	.09	−.48	.46	−1.04
	Concept Formation	107	35.99	3.47	23–40	−1.31	.23	-5.70^{***}	1.93	.46	4.2^{***}
	Visual-Auditory Learning	107	.08	.05	0–.28	1.49	.23	6.48^{***}	2.97	.46	6.46^{***}
	Digits Backward	107	35.88	12.81	13–64	.11	.23	.48	−1.07	.46	-2.33^{*}
	Digits Forward	107	58.6	12.34	27–81	−.68	.23	-2.96^{**}	.32	.46	.70
Academic Measures	SAT - Verbal	85	658.47	70.36	430–800	−.34	.26	−1.31	.43	.52	.83
	SAT - Math	85	682.35	62.1	540–800	−.15	.26	−.58	−.65	.52	−1.25
	GPA - Concurrent	107	3.46	.45	1.97–4.00	−1.32	.23	-5.74^{***}	1.72	.46	3.74^{***}
	GPA - Longitudinal	98	3.5	.43	1.84–4.00	−1.54	.24	-6.42^{***}	2.78	.48	5.79^{***}

Note:

* denotes p <.05,

** indicates p < .01,

*** indicates p< .001.

Concept Formation = relational reasoning; Visual-Auditory Learning = long-term memory retrieval; Digits Backward = working memory; Digits Forward = short-term memory

Table 3.

Experiment 1 Correlation Matrix for all Self-derivation, Cognitive, and Academic Measures

Target measure	SD-Int (Imm)	SD-Int (Delay)	Verbal Comp	Passage Comp	Concept Form	Visual-Aud	Dig Back	Dig Forw	SAT-V	SAT-Q	GPA (Con)	GPA (Long)
SD-Int Immediate	--											
SD-Int Delay	.92**	--										
Verbal Comprehension	.53**	.57**	--									
Passage Comprehension	.44**	.47**	.54**	--								
Concept Formation	.32*	.29*	.34**	.29*	--							
Visual-Auditory Learning	−.29*	−.30*	−.42**	−.26*	−.23*	--						
Digits Backward	.37**	.34**	.24*	.37**	.16	−.34**	--					
Digits Forward	.19*	.14	.17	.29*	.01	−.15	.44**	--				
SAT - Verbal	.40**	.45**	.46**	.33*	.21	−.07	.30*	.34*	--			
SAT - Quantitative	.12	.16	.22+	.06	.31*	−.19	.31*	.24*	.46**	--		
GPA - Concurrent	.27*	.41**	.39**	.20*	.29*	−.17	.12	.16	.39**	.34*	--	
GPA - Longitudinal	.21+	.34*	.35*	.14	.21*	−0.11	.06	.08	.44**	.31*	.83**	--

Note:

+ indicates $p<.06$,

* indicates $p \leq .05$,

** indicates a $p \leq .001$;

SD-Int Immediate = proportion of successfully self-derived integration facts at Session 1; SD-Int Delay = proportion of integration facts recalled at Session 2; Concept Formation = relational reasoning; Visual-Auditory Learning = long-term memory retrieval; Digits Backward = working memory; Digits Forward = short-term memory. Cognitive correlations examined for only those individuals who contributed data for all six measures (n= 107). Academic correlations similarly tested in those individuals who contributed cognitive and academic data (n= 76 SAT, n= 97 Concurrent GPA, n = 88 Longitudinal GPA).

Table 4.

Experiment 1 Summary of Multiple Regression Analyses Explaining Variability in Self-derivation and Retention

Predictor		ΔR^2	β	VIF	*p*
Model 1: Self-derivation (Session 1)					
Step 1		.04			.13
	Age		.19 *	1.00	.047
	Gender		−.02	1.00	.86
Step 2		.34 **			<.001
	Age		.06	1.17	.50
	Gender		.05	1.06	.53
	Verbal Comprehension		.37 **	1.68	.001
	Passage Comprehension		.10	1.70	.34
	Concept Formation		.12	1.23	.19
	Visual-Auditory Learning		−.02	1.36	.87
	Digits Backward		.23 *	1.49	.02
	Digits Forward		−.01	1.30	.92
Total adj R^2	.32 **				<.001
Model 2: Delayed Recall (Session 2)					
Step 1		.01			.52
	Age		.09	1.00	.35
	Gender		−.06	1.00	.52
Step 2		.39 **			<.001
	Age		−.06	1.17	.46
	Gender		−.002	1.06	.98
	Verbal Comprehension		.41 **	1.69	<.001
	Passage Comprehension		.20 +	1.70	.06
	Concept Formation		.08	1.25	.37
	Visual-Auditory Learning		−.01	1.37	.92
	Digits Backward		.18 +	1.49	.06
	Digits Forward		−.06	1.29	.52
Total adj R^2	.35 **				<.001

Note:

* indicates $p \leq .05$,

** indicates a $p \leq .001$,

+ $p \leq .06$;

Beta weights are standardized.

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Table 5.

Experiment 1 Summary of Multiple Regression Analyses Explaining Variability in Academic Outcome as a function of Initial Self-derivation and Cognitive Correlates

	Predictor		ΔR^2	β	VIF	*p*
Model 1: SAT Verbal (*N* = 76)						
Step 1			.001			.98
	Age			.003	1.00	.98
	Gender			.02	1.00	.84
Step 2			.27**			<.001
	Age			−.09	1.09	.42
	Gender			.06	1.04	.59
	Self-derivation (Session 1)			.19	1.64	.16
	Verbal Comprehension			.36*	1.39	.004
	Digits Backward			.10	1.39	.40
Total adj R^2		.22**				<.001
Model 2: Concurrent GPA (*N* = 97)						
Step 1			.02			.32
	Age			.11	1.00	.29
	Gender			−.11	1.00	.29
Step 2			.14*			.002
	Age			.004	1.09	.97
	Gender			−.09	1.05	.38
	Self-derivation (Session 1)			.12	1.56	.33
	Verbal Comprehension			.33*	1.42	.004
	Digits Backward			−.04	1.26	.71
Total adj R^2		.12*				.002
Model 3: Longitudinal GPA (*N* = 88)						
Step 1			.06			.08
	Age			.12	1.01	.25
	Gender			−.21*	1.01	.048
Step 2			.11*			.02
	Age			.02	1.10	.84
	Gender			−.19	1.07	.07
	Self-derivation (Session 1)			.11	1.61	.41
	Verbal Comprehension			.30*	1.50	.02
	Digits Backward			−.10	1.28	.40
Total adj R^2		.11*				.02

Note:

* indicates $p \leq .05$,

** indicates a $p \leq .001$;

$^{+}$indicates $p < .06$ Beta weights are standardized.

Table 6.

Experiment 1 Summary of Multiple Regression Analyses Explaining Variability in Academic Outcome as a function of Retention of Self-derived Facts and Cognitive Correlates

Predictor		ΔR^2	β	VIF	*p*
Model 1: SAT Verbal (*N* = 75)					
Step 1		.002			.93
	Age		−.02	1.00	.89
	Gender		.04	1.00	.71
Step 2		.29**			<.001
	Age		−.08	1.06	.45
	Gender		.09	1.02	.39
	Self-derivation (Session 2)		.27*	1.56	.04
	Verbal Comprehension		.31*	1.43	.01
	Digits Backward		.09	1.31	.45
Total adj R^2	.24**				<.001
Model 2: Concurrent GPA (*N* = 96)					
Step 1		.01			.56
	Age		.08	1.00	.44
	Gender		−.08	1.00	.45
Step 2		.21**			<.001
	Age		−.008	1.07	.93
	Gender		−.06	1.03	.52
	Self-derivation (Session 2)		.32*	1.48	.006
	Verbal Comprehension		.24*	1.46	.04
	Digits Backward		−.09	1.21	.40
Total adj R^2	.18**				<.001
Model 3: Longitudinal GPA (*N* = 87)					
Step 1		.04			.21
	Age		.08	1.01	.44
	Gender		−.18	1.01	.10
Step 2		.16*			.002
	Age		−.01	1.10	.91
	Gender		−.17	1.04	.09
	Self-derivation (Session 2)		.28*	1.52	.02
	Verbal Comprehension		.22	1.53	.08
	Digits Backward		−.15	1.21	.19
Total adj R^2	.14*				.002

Note:

* indicates $p \leq .05$,

** indicates a $p \leq .001$;

+ indicates $p < .06$ Beta weights are standardized.

Table 7.

Experiment 2 Descriptive Statistics for all Measures

	Measures	*n*	*M*	*SD*	*Range*	Skew	SE_{Skew}	Z_{Skew}	Kurtosis	$SE_{Kurtosis}$	$Z_{Kurtosis}$
Self-Derivation	Open-ended	57	1.49	1.50	0–4	.48	.32	1.51	−1.30	.62	−2.08 *
	Forced-choice	57	3.05	1.04	1–4	−.79	.32	−2.51 *	−.57	.62	−.92
Cognitive Measures	Verbal Comprehension	57	52.77	6.54	39–68	.08	.32	.24	−.47	.62	−.76
	$TONI_4$	57	24.67	5.31	15–38	−.04	.32	−.13	−.16	.62	−.25
	Backward Corsi	57	25.65	15.63	0–72	.63	.32	1.99 *	.34	.62	.55
Academic Measures	RI -Concurrent	56	606.68	250.24	0–1180	−.44	.32	−1.38	.35	.63	.56
	RI- Longitudinal	43	906.16	222.13	554–1369	.12	.36	.34	−.82	.71	−1.16
	EOG math - Concurrent	55	446.15	9.30	428–469	.05	.32	.17	−.70	.63	−1.11
	EOG math - Longitudinal	43	450.12	8.53	434–469	.00	.36	.00	−.54	.71	−.76

Note:

*denotes $p < .05$. $TONI_4$ = relational reasoning; Backward Corsi = working memory. Reading comprehension as measured by Reading Inventory (RI), range 0–2000 across grades K-12, expected range for Grade 3 is 415–760 and Grade 5 is 770–1080. Mathematics as measured by NC end-of-grade test (EOG), range 425–470 within grade.

Table 8.

Experiment 2 Correlation Matrix for all Task-specific, Cognitive, and Academic Measures

Target measure	Self-Derivation	Verbal Comp	$TONI_4$	Backward Corsi	RI (Con)	RI (Long)	EOG math (Con)	EOG math (Long)
Self-Derivation	--							
Verbal Comprehension	.68**	--						
$TONI_4$	.41**	.53**	--					
Backward Corsi	.10	.32*	.34**	--				
RI - Concurrent	.61**	.68**	.55**	.22	--			
RI - Longitudinal	.55**	.72**	.56**	.13	.78**	--		
EOG math - Concurrent	.44**	.56**	.35**	.32*	.62**	.44**	--	
EOG math - Longitudinal	.45**	.72**	.46**	.30	.65**	.66**	.61**	--

note:

* indicates $p \leq .05$,

** indicates a $p \leq .001$;

$TONI_4$ = relational reasoning; Backward Corsi = working memory; RI = reading inventory; EOG math = end-of-grade math. Cognitive correlations examined for only those individuals who contributed data for all three measures (n = 57). Academic correlations similarly tested in those individuals who contributed cognitive data (*n* = 55 RI Concurrent, *n* = 43 RI Longitudinal, *n* = 55 EOG math Concurrent, *n* = 43 EOG math Longitudinal).

Table 9.

Experiment 2 Summary of Multiple Regression Analysis Explaining Variability in Self-derivation

	Predictor	**ΔR^2**	**β**	**VIF**	***p***
Step 1		.06			.17
	Age		−.12	1.00	.35
	Gender		−.22	1.00	.10
Step 2		.45**			< .001
	Age		−.14	1.00	.16
	Gender		−.05	1.07	.60
	Verbal Comprehension		.66**	1.53	< .001
	$TONI_4$		.11	1.46	.36
	Backward Corsi		−.16	1.17	.13
Total adj R^2	.46**				

Note:

** indicates a $p \leq .001$;

Beta weights are standardized.

Table 10.

Experiment 2 Summary of Multiple Regression Analysis Explaining Variability in Academic Performance

	Predictor	**ΔR^2**	**β**	**VIF**	***p***
Model 1: Concurrent RI ($N = 56$)					
Step 1		.04			.32
	Age		−.04	1.00	.76
	Gender		−.20	1.00	.14
Step 2		.46 **			< .001
	Age		.01	1.03	.91
	Gender		−.03	1.06	.75
	Self-derivation		.27 †	1.90	.06
	Verbal Comprehension		.50 *	1.88	< .001
Total adj R^2		.47 **			
Model 2: Concurrent EOG Math ($N = 55$)					
Step 1		.16 *			.01
	Age		−.10	1.00	.43
	Gender		−.39 *	1.00	.004
Step 2		.22 **			< .001
	Age		−.07	1.04	.56
	Gender		−.26 *	1.08	.03
	Self-derivation		.08	1.88	.61
	Verbal Comprehension		.43 *	1.84	.006
Total adj R^2		.33 **			
Model 3: Longitudinal RI ($N = 43$)					
Step 1		.02			.65
	Age		.08	1.00	.60
	Gender		−.12	1.00	.45
Step 2		.51 **			< .001
	Age		.001	1.16	.99
	Gender		.03	1.05	.78
	Self-derivation		.16	1.88	.29
	Verbal Comprehension		.62 **	1.96	< .001
Total adj R^2		48 **			
Model 4: Longitudinal EOG Math ($N = 43$)					
Step 1		.06			.32
	Age		.22	1.00	.16
	Gender		−.08	1.00	.59
Step 2		.48 *			< .001
	Age		.10	1.16	.39

	Predictor	ΔR^2	β	VIF	*p*
	Gender		.07	1.05	.55
	Self-derivation		.02	1.88	.87
	Verbal Comprehension		.71**	1.96	< .001
Total adj R^2		.49**			

Note:

+indicates $p < 0.06$,

*indicates $p \leq .05$,

**indicates a $p \leq .001$;

Beta weights are standardized.