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Learning in Leaps: Spontaneous Self-Derivation through Memory Integration in Young Adults

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Abstract

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The present research was an examination of spontaneous (unprompted) self-derivation in young adults (18-22 years old). We investigated young adults' integration of separate memory representations and subsequent self-derivation of new knowledge without an explicit prompt. In Experiment 1, participants were exposed to 16 sets of four stem facts (two stem-fact pairs) that could be integrated with one another to self-derive novel integration facts. For half of the fact sets, participants were given an explicit prompt to integrate the facts (test condition), and for the other half, participants were asked a semantically-related distractor question (no-test condition) that did not explicitly prompt them to integrate the facts. Experiment 2 was a control experiment in which stimulus sets were tested to ensure that integration was necessary for participants to generate the novel integration facts. Participants were given either both members of a stem-fact pair or only one member of a pair and then asked an integration question. We found a significant difference in self-derivation performance between the test and no-test conditions in Experiment 1, and in Experiment 2, we found that participants were unlikely to answer the integration question without exposure to both stem facts in a pair. These results suggest that young adults do not capitalize on unprompted opportunities to self-derive as well as they do explicitly prompted opportunities to self-derive, and the mechanism of this difference in performance is likely due to underlying memory integration processes. This work may have important implications for academic outcomes, particularly in highlighting the importance of appropriate scaffolding for classroom learning.

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The ability to extend existing knowledge and self-generate new knowledge underlies vital cognitive, professional, and academic skills. Critically, to build and expand a semantic knowledge base, one must be able to identify and capitalize on opportunities to extend knowledge beyond information that is directly provided. One such method by which the semantic knowledge base is extended is self-derivation through memory integration. Self-derivation of new semantic knowledge has been observed in children as young as 4 years old (e.g., Bauer & Larkina, 2017; Bauer & San Souci, 2010), which is consistent with the suggestion that self-derivation is likely linked to other important later-developing cognitive processes. In fact, evidence suggests that self-derivation performance is related to cognitive skills such as working memory, verbal comprehension, abstract reasoning, and mathematical performance (Esposito & Bauer, 2017; Esposito & Bauer, 2018; Varga & Bauer, 2017b; Varga, Esposito, & Bauer, 2019). In addition, self-derivation is a productive process that allows for quick and long-lasting knowledge generation. For example, a study by Bauer and Jackson (2015) suggests that information newly self-derived through memory integration is rapidly assimilated into the knowledge base. Further, self-derived knowledge appears resilient over time (at least one week) in young adults, suggesting that self-derivation allows for long-term storage of new knowledge (Varga & Bauer, 2017a). This rapid, long-term extension of knowledge may have important implications for academic outcomes. In fact, retention of self-derived facts is uniquely predictive of GPA for at least 2 years after test (Varga et al., 2019). Therefore, self-derivation is a productive process that permits rapid and stable knowledge extension and may be vital for academic outcomes. Consequently, it warrants comprehensive study, particularly in terms of how it may unfold and function in a real-world setting such as a classroom.

It is yet unknown how self-derivation unfolds when there is not an explicit prompt to integrate, because all prior work has included an explicit prompt. Outside of a laboratory setting, opportunities to self-derive are rarely explicitly prompted. Even when self-derivation *is* prompted, a wide range in performance is observed (approximately 3-93% correct across studies; e.g., Varga & Bauer, 2017a). This range in performance reflects the marked individual differences associated with self-derivation. It is possible that the extent to which self-derivation can be accomplished *spontaneously* is one source of individual differences contributing to the range in performance. Such a finding would have numerous important implications; as stated previously, although there are many opportunities to self-derive in real-world settings, they are rarely prompted. For example, classrooms often expect students to integrate multiple episodes of learning throughout a semester without explicit direction on whether or how information is related across lessons. Examining whether individuals integrate and self-derive knowledge without prompting is therefore critical, particularly given the relation between self-derivation and academic outcomes such as college GPA and performance on standardized tests in elementary school (Esposito & Bauer, 2017; Varga et al., 2019). Accordingly, in Experiment 1 of the present study, we examined young adults' (18-22 years) performance on a test of spontaneous self-derivation. In Experiment 1, we also tested potential predictors of spontaneous self-derivation suggested by previous research, such as working memory (Varga et al., 2019) and verbal comprehension (Esposito & Bauer, 2017). Experiment 2 served as a follow-up study in which we examined whether memory integration and subsequent self-derivation was actually necessary to successfully answer the integration questions asked in Experiment 1.

The ERISS Model

Self-derivation unfolds in a temporally-ordered sequence of processes. The five component steps of self-derivation are encompassed in the ERISS (Encoding, Reactivation, Integration, Selection, and Self-Derivation) model (Bauer & Varga, 2017; see Fig. 1). Self-derivation begins with *encoding* information across different episodes of learning, *reactivating* relevant and related information in memory, *integrating* the related information into one memory representation, *selecting* task-relevant information, and finally *self-deriving* novel knowledge from the integration of provided information. For example, during the first encoding phase, a participant may learn the fact "*wombats are marsupials*" (Stem fact 1). In the second encoding phase, they learn a second, related fact "*marsupials keep their babies in pouches*" (Stem fact 2). Subsequently, when asked, "*where do wombats keep their babies?",* a participant can self-derive the novel integration fact "*Wombats keep their babies in pouches"* by integrating the two facts presented during the two encoding phases. The ERISS model is the framework through which explicitly prompted and spontaneous self-derivation are examined. In the current study, we examined self-derivation performance when the selection stage of the ERISS model was not explicitly prompted.

Spontaneous Self-Derivation: Previous Research

Despite previous research examining self-derivation (e.g., Bauer & Larkina, 2017; Varga & Bauer, 2017a/b) and related productive processes such as analogy and deduction (e.g., Jablansky, Alexander, Dumas, & Compton, 2015; Schlicting, Guarino, Schapiro, Turk-Browne, & Preston, 2016; Wright & Howells, 2008), spontaneous self-derivation (aka, self-derivation of new semantic knowledge without explicit prompting) has not been directly tested.

Spontaneous self-derivation has been indirectly examined in adults. An event-related potential (ERP) study by Varga and Bauer (2017b) found differential neural responses following presentation of a second stem fact in cases of successful versus unsuccessful self-derivation. Specifically, self-derivation trials were back-sorted into roughly equal groups based on whether the participants successfully or unsuccessfully self-derived the novel fact. When self-derivation was unsuccessful, neural activity was roughly at baseline at frontocentral and centroparietal electrode sites following presentation of Stem fact 2 (the first opportunity to integrate). In contrast, when self-derivation was successful, there was marked negative deflection during encoding of Stem fact 2 (Varga & Bauer, 2017b). This performance-dependent differential activity during the Stem 2 encoding phase was thought to reflect recruitment of information processing resources and the beginning of memory integration processes. Therefore, the process of integration and subsequent self-derivation in young adults may spontaneously begin at presentation of the second stem fact.

The idea that memory integration begins at encoding is supported by functional magnetic resonance imaging (fMRI) studies. For example, data suggest that successful performance on inferential reasoning tasks relies on hippocampal-dependent memory integration, or formation of associations, at time of encoding (e.g., Zeithamova, Schlicting, & Preston, 2012). Thus, memory integration at encoding has been observed using multiple neural methods. However, in terms of self-derivation, it is not yet known whether the previously observed integration processes at encoding are sufficient to produce successful self-derivation without subsequent prompting. Thus, the present study builds upon previous self-derivation research by directly examining the process of spontaneous self-derivation in a group of young adults.

The Current Study

In Experiment 1 of the current research, we introduced a novel behavioral paradigm to examine spontaneous self-derivation through memory integration. This paradigm is *recursive integration.* Recursive integration is the sequential integration of four related facts to produce a novel integration fact (Fig. 2). We used recursive integration to assess spontaneous self-derivation in young adults (18-22 years). We selected this age range because self-derivation performance is generally high in adults. Further, previous child studies suggest that children may not integrate until they are explicitly prompted (e.g., Bauer & Varga, 2013; Bauer, Varga, King, Nolen, & White, 2015), and so we expected floor effects in tests of spontaneous self-derivation in children.

In addition to introducing the first direct test of spontaneous self-derivation, we also examined possible individual differences that may correlate with spontaneous self-derivation performance in Experiment 1: the Woodcock-Johnson III Cognitive Abilities tests of verbal comprehension, working memory, and decision speed. Verbal comprehension and working memory measures were included due to their previously demonstrated relation to explicitly prompted self-derivation (e.g., Varga & Bauer, 2017b; Varga et al., 2019). It is likely that these measures correlate with spontaneous self-derivation as well, as we expect that spontaneous and explicitly prompted self-derivation rely on the same cognitive mechanisms. The decision speed task was included because previous research has demonstrated that quicker reaction times when indicating an answer during test may be associated with higher self-derivation performance (Varga & Bauer, 2017a), and decision speed is a possible mediator of this relation.

In Experiment 1, we expected that young adults would perform significantly better when self-derivation was explicitly prompted compared to when self-derivation must be accomplished spontaneously. Further, we expected that measures of working memory, decision speed, and verbal comprehension would be related to spontaneous self-derivation performance.

We also performed a control study (Experiment 2) to ensure that successful performance in Experiment 1 was due to integration of stem facts rather than relying on another memory mechanism or prior knowledge of stem facts. To do so, we performed 1- and 2-Stem testing of our stimulus sets, which took place after data collection for Experiment 1 had been completed. In the 2-Stem condition, participants received both stem facts in a pair (e.g., both A1 *and* A2), and they were asked the corresponding integration question (A/B1 integration fact or B integration fact). In the 1-Stem condition, participants received only one out of the two stem facts in a pair (either A1 *or* A2, or either B1 *or* B2), and then they were asked the integration question. We expected lower performance in the 1-Stem condition; previous studies have found 15-20% correct 1-Stem and 40-50% correct 2-Stem (e.g., Varga & Bauer, 2017a). We expected our results to align with previous findings, suggesting that successful performance on the test of self-derivation in Experiment 1 relied on the mechanism of integration.

Experiment 1

Methods

Participants

A total of 34 young adults participated in the study. A major change in study protocol led to the exclusion of the first 6 participants, and so the final sample was 28 undergraduate students (19 female) enrolled in introductory psychology courses at a selective private university. The participants were between 18-22 years old (*M* = 19.06, *SD* = .96). All participants were native English speakers, although many participants (86%) had been exposed to languages other than English in their homes or educational settings.

The final sample of participants was 36% Asian, 50% White/Caucasian and 14% Black/African American, according to self-report. Approximately 7% were of Hispanic descent. For this study and the subsequent experiment, all protocols and procedures were approved by the Emory University Institutional Review Board, and written informed consent was attained at the beginning of each session. Participants were compensated with SONA credit, which served as class credit for their psychology course(s).

Measures

Stimuli. The stimuli were 48 stem facts (A1, A2, and B2) and 32 novel integration facts (A/B1 and B), which could be self-derived from integrating the stem facts. Fact length ranged from 3 to 9 words. The sequential integration of these facts is a novel paradigm known as *recursive integration* (Fig. 2). A1 and A2 are the first two facts, which can be integrated to self-derive novel information (A/B1). This first step, “initial integration,” is the way in which self-derivation has been explicitly tested in previous research. In the novel recursive integration paradigm introduced in this study, the newly self-derived integration fact A—which also serves as B1—can be integrated with the B2 fact to derive another novel integration fact (B). These four facts (A1, A2, B1, and B2) served as a stimulus set. For example, a stimulus set about fruit was *Apricots are also called golden apples* (A1) and *The seeds of golden apples taste like almonds* (A2), which could be integrated to self-derive *Apricot seeds taste like almonds* (A/B1). This integration fact could then be secondarily integrated with *The fruit seeds that taste like almonds are called "stones"* (B2) to self-derive the novel fact *Apricot seeds are called "stones"* (B). In this manner, 3 provided facts and 2 novel integration facts formed a stimulus set. Stimuli for this study consisted of 16 of these stimulus sets. Stimulus sets were audio recorded by a female native English speaker and presented serially using the recordings and associated images during the study.

Stimulus sets were created based on facts used in previous studies of self-derivation. All facts were true, but previously unknown to participants.

Cognitive measures. Cognitive measures were included to assess possible correlates of spontaneous self-derivation performance. These measures included tests of working memory, verbal comprehension, and decision speed (Woodcock-Johnson III Test 7 "Numbers Reversed", Test 1A-D "Verbal Comprehension", and Test 16 "Decision Speed", respectively; Woodcock, McGrew, & Mather, 2001).

Procedure

The procedure was within-subjects and consisted of three phases: encoding, cognitive assessments, and testing. All sessions began with Encoding phase I. There was then a 10-12-minute buffer period, Encoding phase II, Test phase I, another 4-5-minute buffer, Encoding phase III, a final 5-7-minute buffer, and Test phase II (Fig. 3). The same experimenter (JTW) tested all participants.

Encoding phases. Participants were told that we were interested in how memory develops across the lifespan. They were instructed to press the spacebar on a laptop computer to begin a PowerPoint® presentation of stimuli, pay attention to the facts presented, and let the experimenter know when they saw a blank gray screen with a fixation cross.

In the encoding phases, stimuli were presented audio-visually on the computer screen with paired pictures (Fig. 4) and audio recordings. Each fact was presented for 5.7 seconds, as that is the minimal amount of time that allowed all facts to be presented in completion (i.e., the longest fact recording was 5.6 seconds). At the end of each encoding phase, there was a blank gray screen with a black fixation cross to indicate to the participant to stop.

There were three encoding phases in each session. In Encoding phase I, the A1 or A2 facts were presented along with 8 distractor facts (facts that could not be integrated with any other information in the study). There was then a 10-12-minute buffer, and then in Encoding phase II, A1 or A2 facts were presented (whichever had not yet been seen). Previous research indicates that information is not retained in working memory and is not otherwise immediately accessible for longer than approximately 10 minutes (e.g., Reed & Squire, 1998), and so the buffer activities helped to ensure that successful self-derivation performance required memory integration rather than merely requiring a high working memory capacity. The B2 facts were presented in Encoding phase III.

There were four versions of the presentation. The first two encoding phases were counterbalanced across versions such that the A1 and A2 facts from each stimulus set were presented in the first encoding phase equally often. The third encoding phase, in which the B2 facts were presented, was administered after Test phase I (the initial integration test phase). The order of stimulus sets within encoding phases was randomized across versions to minimize primacy, recency, and serial position effects.

Test phases. There were two testing phases during which participants were asked to self-derive integration facts (A/B1 and B). In the first testing phase, stimulus sets were split into test and no-test conditions. In the test condition, participants were explicitly prompted to self-derive the A/B1 fact for the stimulus sets. This is the typical means of testing self-derivation explicitly. For stimulus sets in the no-test condition, participants were asked a semantically-related non-integration question. For instance, if the apricot fact (Fig. 2) was in the test condition, the question in Test phase I was *What do apricot seeds taste like?* In the no-test condition, the question was *Where do apricots grow?* This non-integration question in the no-test condition was included as a control, to ensure that better performance in the test condition was not merely due to reactivation of the stem facts in memory.

In the second testing phase (the recursive integration test phase), participants were explicitly prompted to self-derive (they were asked final integration questions) for all stimulus sets. We then tested for correct selection of integration facts from among distracters (forced-choice testing). All forced-choice questions had three alternatives, one of which was correct (thus 33% correct would be expected by chance). Participants used a pen to record their answers on a response sheet. Finally, we asked the participants stem-fact questions about all the facts they had seen (48 facts in total) to ensure that they had encoded the information that was presented. All testing was verbal, with the exception of the forced-choice section in Test phase II (recursive integration test phase), which was written. Participants were given approximately 30 seconds to respond before they were prompted with, “do you want to take a guess or move on?” If they chose to move on without guessing, their response was recorded as “no answer.”

Cognitive assessments. Cognitive assessments were administered during the buffer periods between encoding and testing phases. Woodcock Johnson Tests III 1A, 1B, and 7 (half of the verbal comprehension tasks and the working memory task) were presented between Encoding phases I and II (the A1 and A2 encoding phases). Woodcock-Johnson Test 16 (decision speed) was administered after the initial integration test phase, and Tests 1C and 1D (the second half of the verbal comprehension) were administered after the B2 Encoding phase. In this manner, the cognitive assessments acted as buffers throughout the session.

Data Analysis Strategy

Scoring. Initial self-derivation performance was scored by assessing how many of the 8 open-ended integration questions a participant answered correctly in the initial integration test phase (Test phase I). These questions were scored such that 0 = incorrect and 1 = correct. Therefore, the initial integration test phase was scored on a scale of 0-8, such that the maximum possible score was 8, and the minimum was 0. For Test phase II, open-ended and forced-choice self-derivation scores were created by assessing the number of open-ended and forced-choice questions a participant had answered correctly during the recursive integration test phase (Test phase II). Open-ended and forced-choice scores could be either 0 (incorrect) or 1 (correct), as in the initial integration test phase. Therefore, the highest a participant could score on a given stimulus set was 1 and the lowest was 0 in both open-ended and forced-choice. The maximum possible score in the recursive integration test phase was 16 for both open-ended and forced-choice scores; the minimum score was 0. A total recursive integration score was also created by giving a participant a 1 (correct) if they answered a question correctly *either* open-ended *or* forced-choice (or both). If they answered both the open-ended *and* the forced-choice question incorrectly, they received a 0. This total score was created to avoid repetitive information in scoring (e.g., if a participant had already received a point for answering a question correctly open-ended, we did not want to double-count that question by giving them a second point for answering it correctly forced-choice). Memory for the 48 stem facts was also assessed using a 0 = incorrect, 1 = correct scale.

Analysis. Data were divided into test and no-test conditions based on whether participants were explicitly prompted to self-derive the A/B1 fact in the initial integration test phase (test condition = prompted to self-derive; no-test condition = not prompted to self-derive; within-subjects). A paired *t*-test was used to assess differences in recursive integration performance between the test and no-test conditions. I conducted an independent but parallel analysis of open-ended and total scores. These two measures had to be analyzed separately because they are not independent of one another; a participant was more likely to answer a forced-choice question correctly if s/he had already answered it correctly open-ended, and so open-ended score could influence total score. I used simple linear regression to examine whether performance in the initial integration test phase predicted performance in the recursive integration test phase. In addition, I examined memory for stem facts by averaging all participants' performance on the 48 open-ended stem-fact questions. We anticipated average stem-fact performance above 50%, which would address whether failure in self-derivation was merely due to poor recall of stem facts. Memory for stem facts (average stem-fact recall) was also analyzed as a predictor of self-derivation performance using simple linear regression. Relations between cognitive assessments and spontaneous self-derivation scores were examined using both Pearson correlations and simple linear regression.

Results

Results will be presented in three sections: initial and recursive integration, stem-fact recall, and cognitive correlates of recursive integration.

Initial Integration and Recursive Integration

Average initial integration was calculated from the score in Test phase I (which thus only included stimuli in the test condition). Average initial integration score was 65% ($M = .65$, $SD = .24$).

We examined spontaneous self-derivation performance by comparing test (prompted self-derivation) and no-test (unprompted self-derivation) conditions in the recursive integration test phase (Test phase II). Average open-ended recursive integration score was 55% ($M = .55$, $SD = .23$). Average forced-choice recursive integration score was 85% ($M = .85$, $SD = .12$), and average total recursive integration score was 87% ($M = .87$, $SD = .11$). Means and standard deviations of open-ended and total recursive integration scores in the test and no-test conditions are presented in Table 1. Additionally, a one-sample *t*-test revealed that forced-choice performance was significantly above chance ($t(27) = 23.6$, $p < .000$).

Results of paired *t*-tests indicated that there was a significant difference between the test and no-test conditions both for open-ended recursive integration scores ($t(27) = -2.71$, $p = .011$; Fig. 5) and for total recursive integration scores ($t(27) = -2.74$, $p = .011$; Fig. 5), which is consistent with the suggestion that lack of explicit prompting interferes with successful self-derivation performance. The size of the effect for open-ended scores was moderate ($d = .34$), and the size of the effect for total scores was small ($d = .13$).

Initial and recursive integration performance were related. Specifically, initial integration predicted both open-ended recursive integration score ($R^2 = .621$, $B = .733$, $p < .000$) and total recursive integration score ($R^2 = .611$, $B = .366$, $p < .000$). The relation between the initial integration score and recursive integration score held in open-ended questioning for items that had been in the test condition ($R^2 = .548$, $B = .737$, $p < .000$) and in the no-test condition ($R^2 = .562$, $B = .729$, $p < .000$) individually. The initial integration score also significantly predicted total recursive integration score both for items that had been in the test condition ($R^2 = .394$, $B = .254$, $p < .000$) and items that had been in the no-test condition ($R^2 = .525$, $B = .478$, $p < .000$).

Stem-Fact Recall

Average stem-fact recall was assessed to ensure that differential self-derivation in the test and no-test conditions was not merely due to differences in recall of the stem facts. Average stem-fact recall was 69% ($M = .69$, $SD = .19$). A paired *t*-test revealed that there was no difference in stem-fact recall between the test and no-test conditions ($t(27) = .561$, $p = .579$; Fig. 6), consistent with the idea that differences between test and no-test conditions were not due to differences in memory for stem facts.

Stem-fact recall was significantly related to both open-ended and total recursive integration scores ($R^2 = .716$, $B = .997$, $p < .000$; and $R^2 = .661$, $B = .482$, $p < .000$, respectively).

Cognitive Correlates of Recursive Integration

Verbal comprehension scores calculated from Woodcock-Johnson III Test 1 predicted both open-ended ($R^2 = .207$, $B = .022$, $p = .015$) and total ($R^2 = .430$, $B = .016$, $p < .000$) recursive integration scores. However, scores on Woodcock-Johnson III Test 7 (working memory) did not predict open-ended ($R^2 = .009$, $B = .005$, $p = .623$) or total ($R^2 = .020$, $B = -.004$, $p = .474$) scores. This non-significant relation held for both open-ended and total scores for Woodcock-Johnson III Test 16 (decision speed; $R^2 = .002$, $B = .003$, $p = .814$; and $R^2 = .041$, $B = .006$, $p = .303$, respectively).

Discussion

Overall, in Experiment 1 we found that adults perform worse on tests of spontaneous self-derivation than they do on tests of explicit self-derivation. In other words, adults capitalize less often on opportunities to self-derive when they are not prompted compared to when they are explicitly prompted. Further, we found that spontaneous self-derivation performance is related to verbal comprehension ability but not to working memory or decision speed. Finally, the observed difference between spontaneous and explicit self-derivation was not driven simply by memory for stem facts; stem-fact recall was not significantly different between conditions. Rather, the difference between conditions suggests a difference in the underlying component of integration.

Our results in Experiment 1 suggest that successful self-derivation performance relies on integration of stem facts. However, it is vital to ensure that integration is a necessary component of successful performance on our test of self-derivation. Thus, we conducted Experiment 2 as a control experiment to ensure that participants needed to be exposed to both members of the stem-fact pairs to answer the final integration questions. To do so, we presented participants with either one or two stem facts from each integration pair (i.e., either A1 or A2 *or* either B1 or B2) and compared participants' performance on the respective integration questions (either A/B1 integration or B integration; see Fig. 2).

Experiment 2

Methods

Participants

A total of 10 young adults participated in the study. None of the participants was excluded, and so the final sample was 10 young adults (8 female) between 18-22 years old (*M* = 19.35, *SD* = .92) enrolled in introductory psychology courses at a selective private university. The sample for Experiment 2 was drawn from the same pool of participants as Experiment 1, indicating that the participants in the two experiments represent the same population. However, none of the participants in Experiment 2 had participated in Experiment 1. All participants were native English speakers.

The sample of participants was 50% Asian, 40% White/Caucasian and 10% Black/African American, according to self-report. 20% were of Hispanic descent. All protocols and procedures were the same as in Experiment 1.

Measures

The measures were the same as in Experiment 1, but an additional cognitive assessment was added. The additional assessment was Woodcock-Johnson III Cognitive

Abilities Test 9 (Passage Comprehension). We included the additional cognitive assessment because we wanted a task that required considerable cognitive load during the buffer period of Experiment 2, as the amount of information presented in Experiment 2 was substantially less than that presented in Experiment 1.

Procedure

The procedure was within-subjects and consisted of three phases: encoding, cognitive assessments, and testing. All sessions began with Encoding phase I. There was then a 12-15-minute buffer period, Encoding phase II, another 8-12-minute buffer, and Test phase I. The same experimenter tested all participants.

Encoding phases. Instructions and stimuli presentation were the same as in Experiment 1. There were two encoding phases. In Encoding phase I, the participants were exposed to 12 stem facts and 5 distractor facts. Of the 12 stem facts, 4 were in the 1-Stem condition and 8 were in the 2-Stem condition. These stem facts were either from the A stem-fact pair (A1 or A2) *or* the B stem-fact pair (B1 or B2). In the second encoding phase, the participants were exposed to 5 more distractor facts, 4 more stem facts in the 1-Stem condition, and the other member of the stem-fact pair for the 8 stimulus sets in the 2-Stem condition. Thus, for each participant, 8 stimulus sets were presented in the 1-Stem condition and 8 stimulus sets were presented in the 2-Stem condition. The two encoding phases were counterbalanced such that the A1 and A2 or B1 and B2 facts from each stimulus set were presented in the first encoding phase equally often. There were eight versions of the presentation, and the order of stimulus sets within encoding phases was randomized across versions to minimize primacy, recency, and serial position effects.

Test phase. In the test phase, participants were explicitly prompted to self-derive integration facts (A/B1 or B integration facts) in an open-ended format. We then tested for selection of integration facts from among distracters (forced-choice testing). All forced-choice questions had three alternatives, one of which was correct (thus, 33% correct was expected by chance). Forced-choice questions were only asked if a participant had answered the question *incorrectly* open-ended. Finally, we asked the participants stem-fact questions about all the facts they had seen (24 facts in total) to ensure that they had encoded the information that was presented. All testing was verbal. Participants were given approximately 30 seconds to respond before they were prompted with, “do you want to take a guess or move on?” If they chose to move on without guessing, their response was recorded as “no answer.”

Cognitive assessments. Cognitive assessments were administered during the buffer periods between encoding phases and the test phase. Woodcock Johnson III Tests 1A, 1B, 1C, 1D, and 7 (tests of verbal comprehension and decision speed) were presented between Encoding phases I and II. After Encoding phase II, Woodcock-Johnson III Test 9 (passage comprehension) and Test 16 (decision speed) were administered. In this manner, the cognitive assessments acted as buffers throughout the session.

Scoring and Data Analysis Strategy

Self-derivation performance in both 1-Stem and 2-Stem conditions was scored in a binary manner as in Experiment 1 (0 = incorrect, 1 = correct). The maximum possible score a participant could receive was 16 open-ended and 16 forced-choice; the minimum was 0 for both open-ended and forced-choice. Half of the points could be accumulated in the 1-Stem condition, and the other half of the points could be accumulated in the 2-Stem condition. Average score on stimulus sets in 1-Stem and 2-Stem conditions was compared, and a one-tailed *t*-test was used to examine the difference in performance between 1-Stem and 2-Stem. Memory for the 24 stem facts was also assessed using 0 = incorrect, 1 = correct.

Results and Discussion

1-Stem and 2-Stem conditions were compared to ensure that both members of a stem-fact pair had to be provided for participants to answer the A/B1 and B integration questions correctly (see Fig. 2). Participants scored an average of 32.5% correct in 1-Stem (*M* = .33, *SD* = .23) and 50% correct in 2-Stem (*M* = .50, *SD* = .23). A one-tailed *t*-test revealed that performance was significantly lower in the 1-Stem condition compared to the 2-stem condition (*t*(9) = 1.871, *p* = .047). The effect size was moderate (*d* = .23). Although the difference was significant, participants scored nominally higher on average in the 1-Stem condition than that reported in previous studies (e.g., Varga & Bauer, 2017a). Further examination revealed that 3 stimulus sets were problematic in this regard, with more than 66% correct on average in 1-Stem, whereas the other 13 stimulus sets displayed fairly typical patterns of 1-Stem and 2-Stem performance (Fig. 7). Removal of the 3 problematic stimulus sets revealed 1-Stem testing results that aligned with previous research, with 23% correct in 1-Stem on average (*M* = .23, *SD* = .18) and 42% correct on average in 2-Stem (*M* = .42, *SD* = .25). A one-tailed paired *t*-test revealed that the significant difference between 1- and 2-Stem conditions remained after removal of the 3 problematic stimulus sets (*t*(9) = 2.172, *p* = .029), with a moderate effect size (*d* = .22). These data demonstrate that, for most of the stimulus sets, integration of stem facts was necessary to answer the final integration question correctly. However, a different pattern was observed in forced-choice. Average forced-choice performance was 55% in 1-Stem ($M = .55$, $SD = .23$) and 63% in 2-Stem ($M = .63$, $SD = .29$). A one-tailed paired *t*-test revealed that there was not a significant difference between 1-Stem and 2-Stem forced-choice performance ($t(9) = -.264$, $p = .798$). The difference remained non-significant even after removal of the 3 problematic stimulus sets ($t(9) = -.360$, $p = .364$).

As in Experiment 1, average stem-fact recall was assessed to ensure that different self-derivation scores in the 1- and 2-Stem conditions were not due to differences in recall of the stem facts. Average stem-fact recall was approximately 68% ($M = .68$, $SD = .19$), which is similar to the results of Experiment 1. A paired *t*-test revealed that there was no difference in stem-fact recall between the 1-Stem and 2-Stem conditions ($t(9) = -1.48$, $p = .17$), consistent with the idea that differences between 1- and 2-Stem conditions were not due to differences in memory for stem facts.

In summary, we found in Experiment 2 that exposure to both facts in a stem-fact pair was necessary to answer most integration questions correctly. Although performance on 3 of the stimulus sets was unusually high, likely demonstrating the influence of participants' prior knowledge, performance was typical across 1-Stem and 2-Stem conditions for the other 13 stimulus sets. These data suggest that memory integration and subsequent self-derivation are necessary to correctly answer most of the integration questions in Experiment 1. However, forced-choice results across the 1- and 2-Stem conditions suggest that the forced-choice and total scores in Experiment 1 must be interpreted with caution; the forced-choice format may have allowed participants to guess the correct answer fairly accurately even without memory integration and subsequent self-derivation, likely due to some improbable distractor options in forced-choice testing (e.g., for the integration question, “how is the largest organ in the body healed?”, one of the answer choices was “by eating almonds”). Nonetheless, the results of Experiment 2 provide support for the interpretation that self-derivation is required for high performance at least on open-ended questioning in Experiment 1.

General Discussion

This study was the first investigation of spontaneous, or unprompted, self-derivation through memory integration. Self-derivation is a vital productive process, contributing to one’s semantic knowledge base and allowing one to extend existing semantic knowledge without explicit instruction. Previous work has validated the real-world outcomes of self-derivation, including its relation to academic achievement such as GPA and mathematical performance (Varga, et al., 2019; Esposito & Bauer, 2017), as well as links to important cognitive skills such as inductive reasoning and verbal comprehension (Varga et al., 2019; Varga & Bauer, 2017). Despite substantial work examining self-derivation, previous studies have exclusively investigated explicitly prompted self-derivation. The present study sought to extend previous work with a direct investigation of spontaneous self-derivation in young adults. We expected that spontaneous self-derivation would be challenging even for young adults, and thus we predicted better performance in an explicitly prompted (“test”) condition compared to an unprompted (“no-test”) condition. Further, we predicted that verbal comprehension and working memory would be related to self-derivation performance, in line with previous findings.

There are several major findings from the present work. First and foremost, we found a significant difference between test and no-test conditions in Experiment 1, indicating that young adults perform significantly worse on tests of self-derivation when they are not explicitly prompted to integrate and subsequently self-derive the information. However, performance in the unprompted condition was still remarkably high. This finding contributes to previous indirect examinations of spontaneous self-derivation in young adults. For example, Varga and Bauer (2017b) found neural evidence of memory integration processes beginning at presentation of a second stem fact in young adults, which was interpreted as the early neural stages of self-derivation. The current work further clarifies this finding. Specifically, it suggests that the neural activity identified by Varga and Bauer (2017b) likely reflects integration of multiple memory representations, which is a necessary step in successful self-derivation (Bauer & Varga, 2017), but this process of integrating memory representations may not always be sufficient to produce novel, self-derived facts without a prompt. In other words, the high performance in both conditions in Experiment 1 suggests that adults are capable of integrating both with and without an explicit prompt; however, the significantly higher performance in the explicitly prompted condition is consistent with the idea that memory integration at encoding may not always lead to successful self-derivation without appropriate scaffolding later on. Thus, the current study's finding of a significant difference in prompted and unprompted self-derivation further elucidates the time course of self-derivation.

The finding of a significant difference in prompted and unprompted self-derivation is critical in application to real-world contexts such as academia. The results of the current work suggest that the standard classroom model may present a challenge for many individuals even as late as young adulthood. Classes often assume students will integrate material across multiple episodes of learning without explicitly stating whether the material is related or how it is related. Considered within the framework of the present study, this typical classroom practice may not allow students to fully integrate and critically apply or extend information that is presented to them. Therefore, the current work on spontaneous self-derivation may suggest important implications for student outcomes and academic practices in general. For example, school curriculums with more explicit lesson structure and consistent reminders about how information is related throughout a semester might be associated with better student outcomes.

The finding from the current study that suggests spontaneous self-derivation likely has implications for academia is in line with previous research on self-derivation (e.g., Varga & Bauer, 2017a) and related productive processes, such as analogy (e.g., Spalding et. al, 2008). For example, analogical reasoning is linked to expertise in STEM domains (Alexander, 2017; Dumas, Alexander, & Grossnickle, 2013; Dunbar, 2001; Resnick, Davatzes, Newcombe, & Shipley, 2017). Additionally, the development of relational reasoning has been linked to STEM skills such as the ability to solve simple mathematical equations in elementary school (Farrington-Flint, Canobi, Wood, & Faulkner, 2007). Further, productive processes such as associative inference are associated with increased memory for events or stimuli (Schlicting & Preston, 2015), and transitive inference is linked to general cognitive skills that are useful in academia, such as scientific thinking (Wright & Howells, 2008). Therefore, the present research adds to a large body of work that suggests productive processes are vital underpinnings of academic skills and outcomes.

Another major finding from the present study is that recall of stem facts did not differ for spontaneous compared with explicitly prompted self-derivation. These results can be viewed from two perspectives, as the direction of the relation is not certain. First, it is possible that these data suggest that prompts do not improve participants' memory for stem facts. Such a finding is interesting, as it indicates that spontaneous and explicitly prompted self-derivation similarly allow participants to recall a high number of the previously integrated facts. If the similar stem-fact recall in the test and no-test conditions indicate that both spontaneous and explicit self-derivation allow participants to remember a high number of the facts on which integration and self-derivation is based, it provides evidence consistent with the idea that spontaneous and explicit self-derivation rely on similar cognitive mechanisms. However, future research is required to further distinguish the potential overlap in mechanisms underlying spontaneous and explicit self-derivation, particularly in regards to developmental trends.

Alternatively, the finding that stem-fact recall did not differ between conditions could also suggest that simply reactivating the presented information did not account for the observed performance difference in spontaneous versus prompted self-derivation conditions. This finding suggests that the difference in spontaneous and explicitly prompted self-derivation is due to the mechanism of integration and subsequent self-derivation rather than an effect of reactivation of the presented information alone. Additionally, the results of Experiment 2 provide further evidence that the difference between the test and no-test conditions resulted from integration processes, as exposure to both facts in a stem-fact pair was necessary for successful performance on integration questions for most stimulus sets. Thus, our results suggest that the observed performance difference between conditions was due to differences in the underlying integration component of self-derivation.

Finally, a third major finding of the present work is that verbal comprehension performance was related to both spontaneous and explicitly-prompted self-derivation performance, but working memory and decision speed did not explain significant variance in either spontaneous or explicitly-prompted self-derivation performance. Verbal comprehension has been linked to self-derivation performance in previous studies of young adults (e.g., Varga et al., 2019) and so the finding that verbal comprehension relates to spontaneous self-derivation performance is not surprising. However, it is worth noting that in this study verbal comprehension performance related to *spontaneous* self-derivation in addition to prompted self-derivation. The link between verbal comprehension and spontaneous self-derivation may suggest that the previously-identified association between verbal comprehension and self-derivation is not merely a reflection of participants' ability to understand and actively process the question asked of them. Rather, the link between verbal comprehension and spontaneous self-derivation may suggest that verbal comprehension and self-derivation rely on similar structural mapping processes, such as the identification of relational commonalities among multiple memory representations or events (see Gentner, 1983). In other words, the finding that verbal comprehension relates to *spontaneous* self-derivation precludes the idea that verbal comprehension abilities only influence the prompting or selection stage of self-derivation (the question; see Fig.1). The Woodcock Johnson III Test of verbal comprehension is composed of four sub-tests, three of which rely on comparison or structural alignment (i.e., there is a test of vocabulary, synonyms, antonyms, and analogies; vocabulary assesses crystallized knowledge, but the other three sub-tests rely on comparison and reasoning abilities). Thus, both self-derivation and the assessment of verbal comprehension used in the present study may measure structural mapping. Consequently, the observed relation between verbal comprehension and self-derivation may be a product of general structural mapping abilities predicting both verbal comprehension and self-derivation. This is a possible direction for future research. For example, developmental precedence could be examined to determine whether development of general structure mapping abilities predicts both verbal comprehension and spontaneous self-derivation development.

The present research contributed to our understanding of self-derivation, particularly as it would typically unfold in a real-world setting. However, there are a few limitations to the current study to be addressed in future studies. First, application to academic settings must be interpreted with caution, as the current study took place in the laboratory. Nonetheless, the current study helped to inform the application of self-derivation to academic settings. In addition, 1-Stem testing in Experiment 2 revealed that 3 of the 16 stimulus sets in the current work could be answered correctly most of the time without exposure to both stem facts (i.e., correct responses did not necessarily depend upon integration and self-derivation). However, the results of Experiment 1 are significant even with inclusion of these problematic stimulus sets, and therefore the problematic stimulus sets are included in reported analyses to offer a conservative estimate of the effect in the current work.

Additionally, the present work does not allow for examination of developmental trends, as only young adults were included in the sample. Spontaneous self-derivation across different developmental stages is therefore a future direction. Indirect examinations of spontaneous self-derivation have revealed a potential developmental difference in the process of self-derivation such that children do not appear to integrate and subsequently self-derive without a prompt (e.g., Bauer et al., 2015), whereas adults begin to integrate information at encoding (Varga & Bauer, 2017b). For example, a study by Varga and Bauer (2013) found that when 6-year-olds were presented with stem facts and tested for self-derivation in the same session, they self-derived new knowledge and retained the newly self-derived knowledge over a delay of one week (63% correct on average at first test, and 60% correct after the one-week delay). However, if the one-week delay occurred *before* participants were tested for self-derivation, they performed significantly worse (21% correct on average). These results suggest that the one-week delay before test inhibited integration and subsequent self-derivation, as the prompt to integrate occurred too long after the information had been presented. Thus, 6-year-olds may not integrate and self-derive knowledge until they are prompted. Additionally, Bauer and colleagues (Bauer, et al., 2015) found that 6-year-olds' self-derivation performance was enhanced by hints before test, but not by hints between encoding phases (i.e., between presentation of Stem 1 and Stem 2 facts). In other words, 6-year-olds did not perform better when a hint indicated that a forthcoming fact would be related to a previously presented fact, but they *did* perform better when they had already been exposed to both of the facts and were primed to integrate them with a hint (Bauer et al., 2015). These results further suggest that memory integration does not occur spontaneously in 6-year-olds, even when they are given a hint; rather, integration and self-derivation occur only when participants are prompted to integrate (e.g., with a question). Thus, previous research suggests that children are even less likely than adults to capitalize on opportunities to spontaneously self-derive. Future studies should thus examine spontaneous self-derivation performance in children, as it may be relevant both to academic settings and to the development of productive processing skills.

Finally, future research should address what form of memory integration underlies spontaneous self-derivation. Memory integration occurs at multiple levels, such as the low-level integration of features of one's surroundings that allows one to generalize to a new environmental context, or the active, goal-directed integration of information in the pursuit of acquiring new knowledge. In the present study, we sought to examine memory integration with the goal of acquiring new factual knowledge. It is likely that, at least at times, this type of integration is an active, goal-directed process, particularly when the relational aspect of the task must be detected spontaneously (e.g., without an explicit prompt cueing integration; Varga & Bauer, 2017a). In support of this conclusion, previous work suggests that explicit awareness of the opportunity to integrate is associated with longer reaction times on unsuccessful self-derivation trials, likely reflecting an active search through memory in an attempt to distinguish relevant information (Varga & Bauer, 2017a). Therefore, memory integration occurring in service of self-derivation is likely a goal-directed form of integration that may rely on active processing of integrable material for successful performance. However, the current work did not include a measure of participants' metacognitive awareness or a measure of the form of memory integration that participants were using. Thus, examining whether spontaneous integration and subsequent self-derivation is a low-level or more active, higher-level process is a direction for future research.

In conclusion, the current work contributes multiple important findings to the literature on self-derivation and productive processing in general. The finding that young adults perform worse on tests of spontaneous compared with explicit self-derivation, regardless of a more general test of memory for the presented information (stem facts), adds to a growing body of literature on the challenges and individual variation in memory integration and productive self-generation of knowledge. This finding is also important in terms of academic outcomes, as spontaneous self-derivation may be a knowledge self-generation technique applied often in a typical classroom setting. The results of the current work suggest that young adults readily spontaneously self-derive without explicit prompting, which is encouraging in terms of young adults' ability to apply self-derivation in academic settings. However, the results also suggest that without proper support such as an explicit demand to self-derive, many individuals may not capitalize well on opportunities to self-derive new knowledge. Impaired performance without an explicit prompt would hinder individuals' performance in real-world settings such as classrooms. Additionally, the current work adds to previous research on the relation between verbal comprehension and self-derivation. The fact that the relation between verbal comprehension and self-derivation exists even when there is no prompt (e.g., a question) suggests that the relation exists not only due to active processing of the provided prompts. Rather, verbal comprehension tasks and self-derivation may rely on similar structural and relational alignment processes. Thus, the current work adds findings to a body of literature on productive processes and relational reasoning more generally, and further suggests that there may be critical consequences for the unscaffolded application of productive processes in academic settings.

Author's Note

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Tables

Table 1

Descriptive Statistics of Recursive Integration Performance by Condition and Question

Type

No-Test Condition	**Mean**	**(SD)**
Open-Ended (*n*=28)	.51	.24
Total (*n*=28)	.83	.16
Test Condition		
Open-Ended (*n*=28)	.59	.24
Total (*n*=28)	.90	.10

Figures

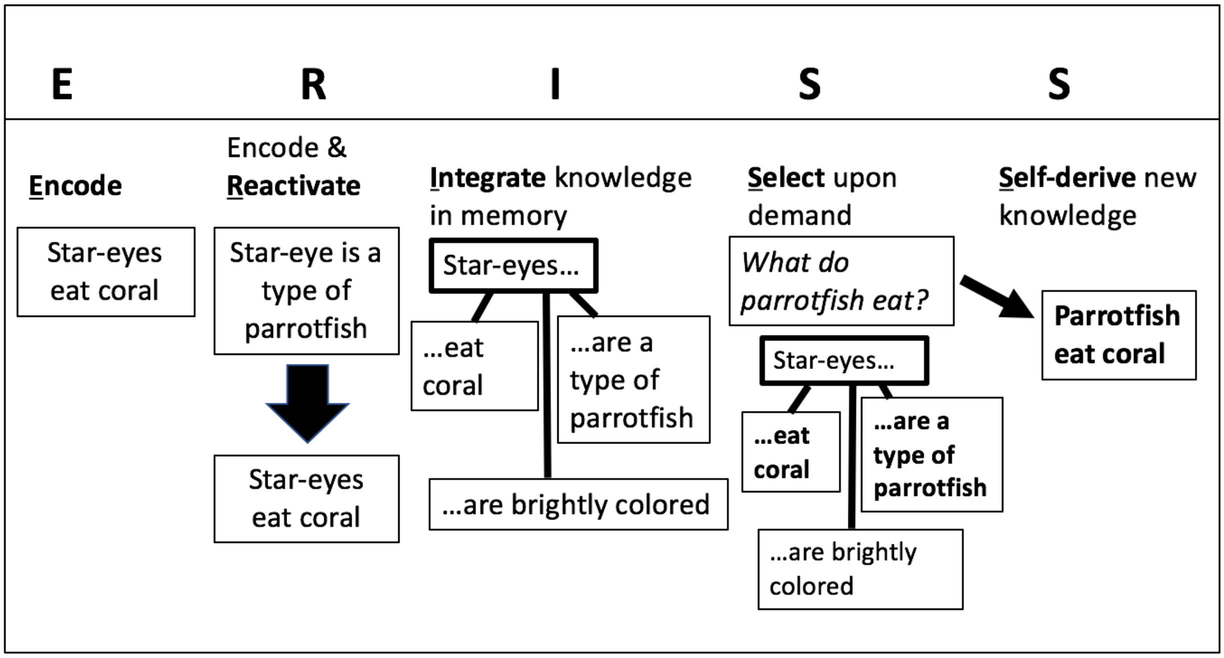

Fig. 1. Schematic of the ERISS model (Bauer & Varga, 2017).

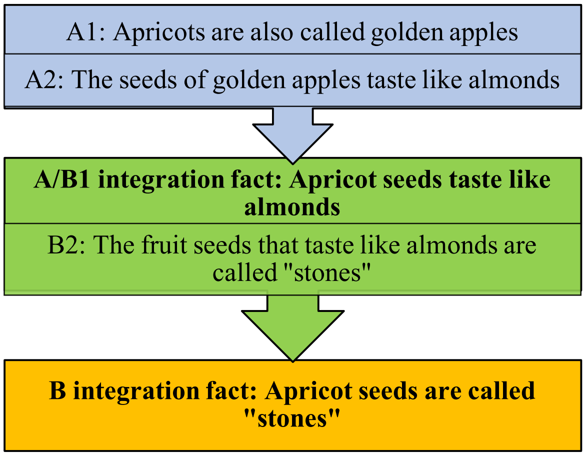

Fig. 2. Model of the sequential integration of stem facts within stimulus sets. Non-bolded facts are presented in encoding phases; bolded facts are the novel integration facts that can be self-derived.

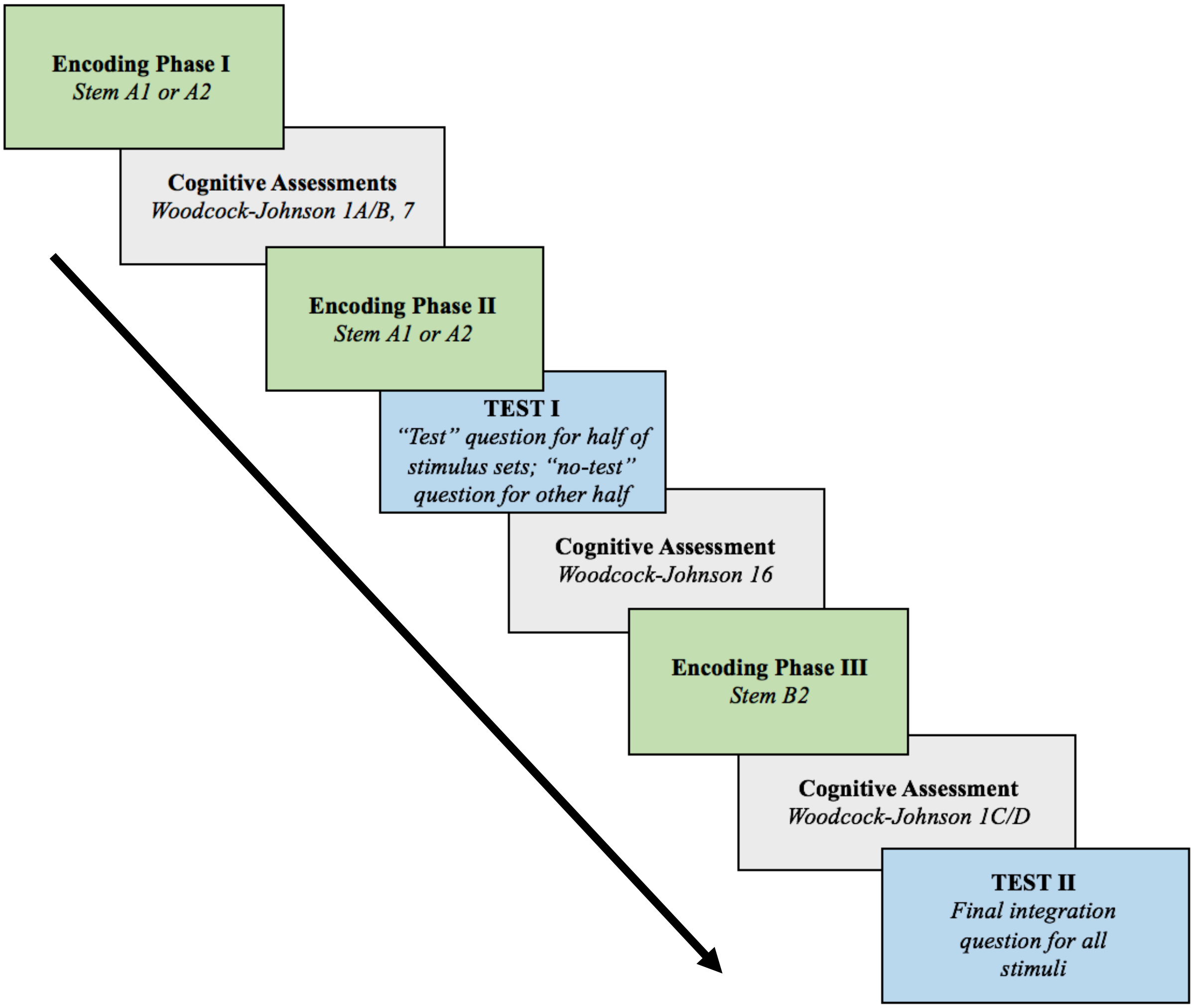

Fig. 3. Schematic of a typical session in Experiment 1.

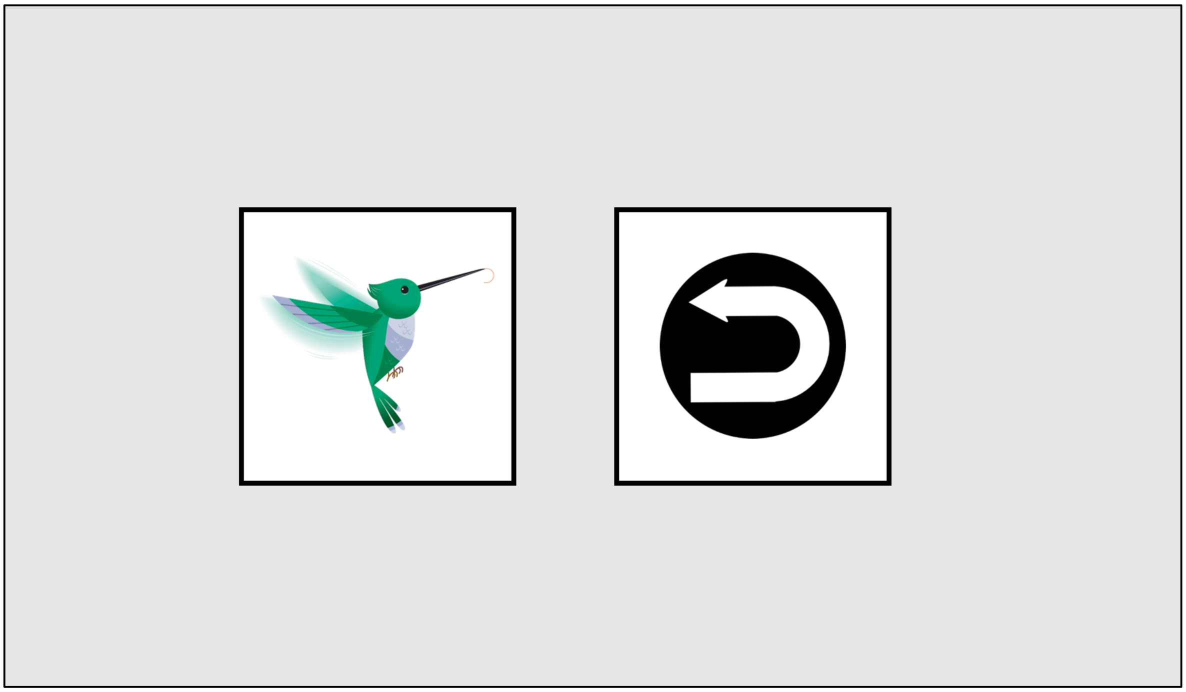

Fig. 4. An example of how stimuli are presented in encoding phases in both experiments. The fact “Hummingbirds are the only bird that can fly backwards” was presented using these paired images and an audio recording of the fact.

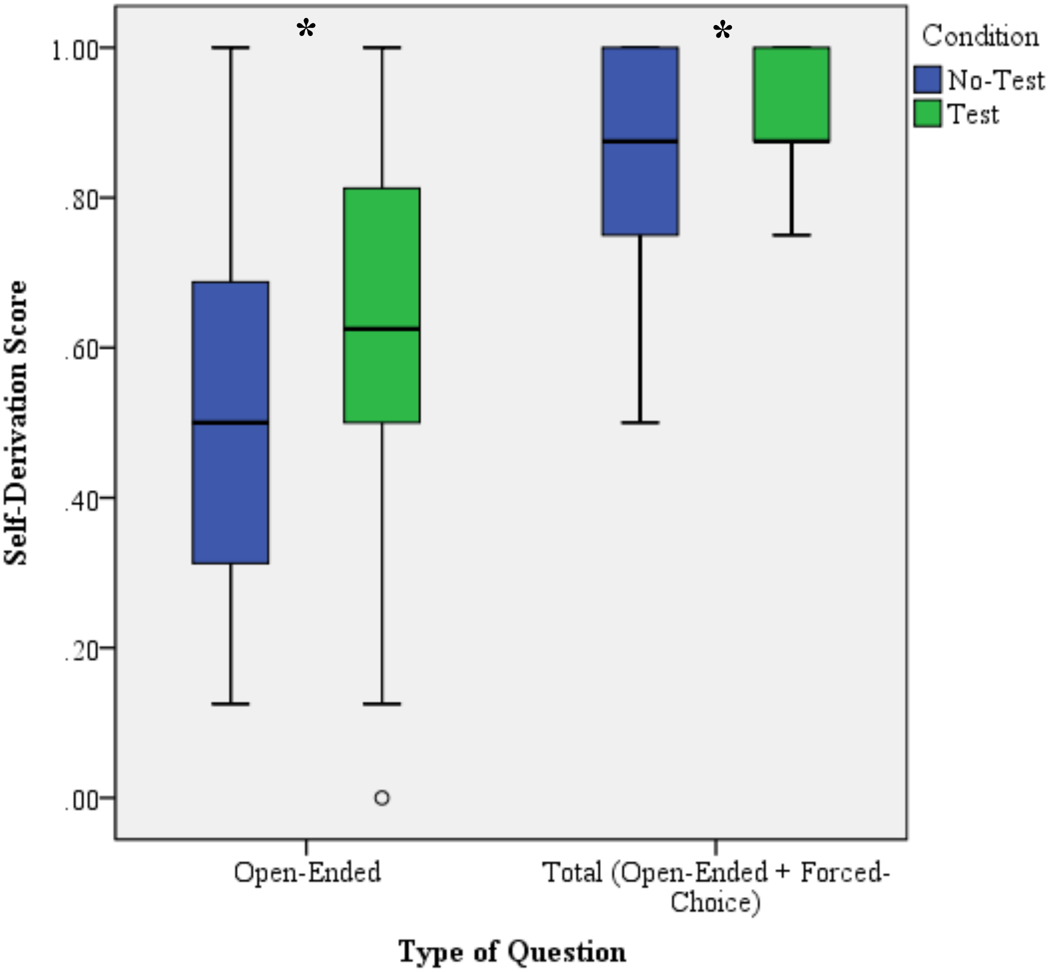

Fig. 5. Open-ended and Total (open-ended + forced-choice) self-derivation scores in the test and no-test conditions in Experiment 1. There was a statistically significant difference between conditions in both open-ended and total questioning.

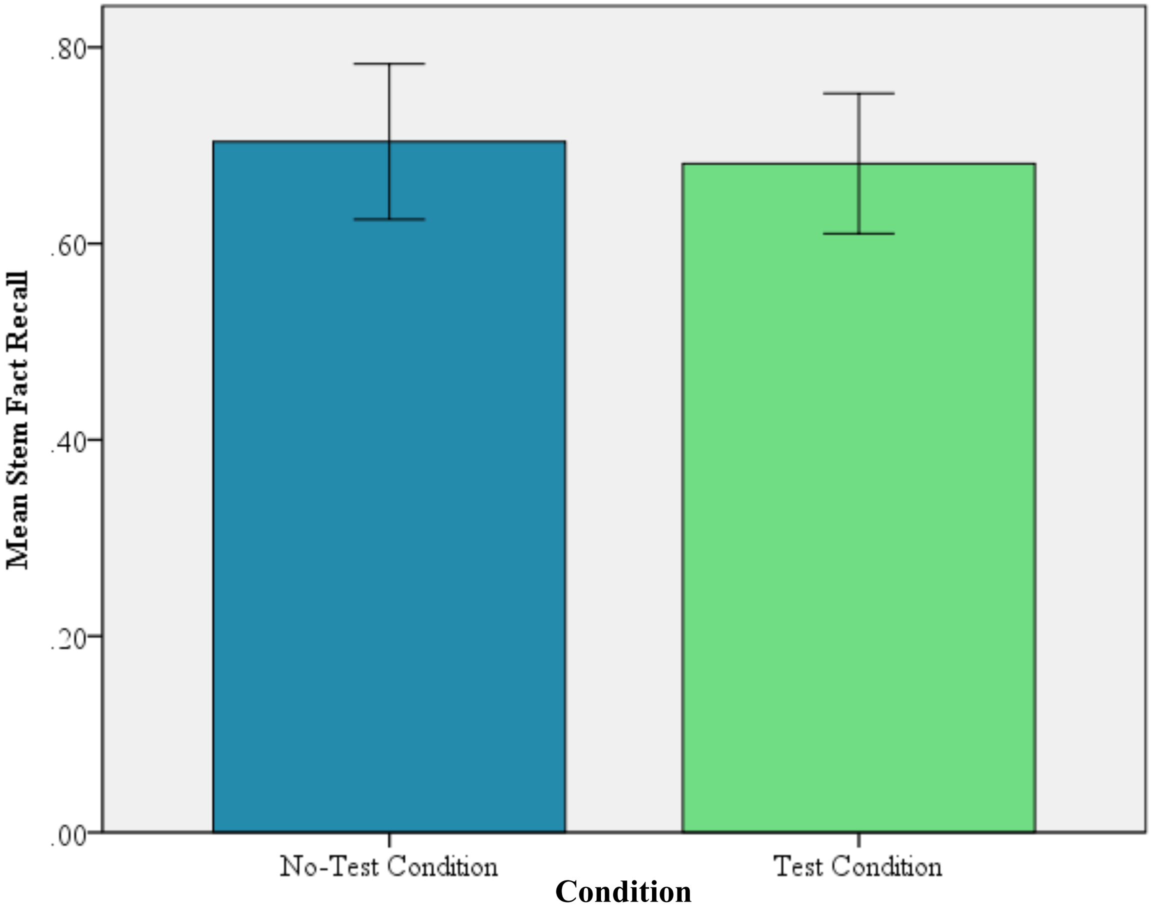

Fig. 6. Average stem-fact recall in the test and no-test conditions in Experiment 1. There was not a significant difference between conditions in stem-fact recall. Error bars represent +/- 2 standard errors.

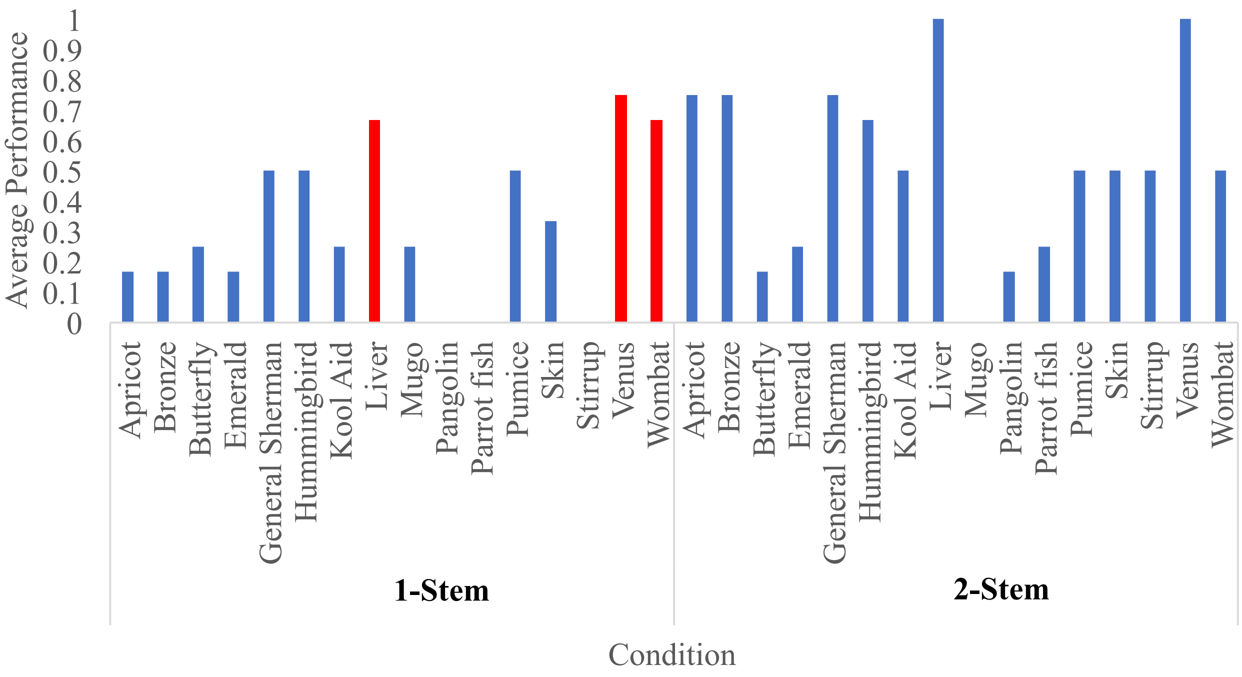

Fig. 7. Average performance on the 16 stimulus sets in 1-Stem and 2-Stem conditions in Experiment 2. The 3 stimulus sets on which participants demonstrated unusually high performance (>66% correct) are highlighted in red.