

**Investigating the Cognitive Attributes Underlying Student Performance on the SAT®  
Critical Reading Subtest: An Application of the Attribute Hierarchy Method**

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Paper presented at the 2007 annual meeting of the  
**National Council on Measurement in Education**  
Chicago, Illinois  
April 9, 2007

### **Acknowledgement**

The research reported in this study was conducted with funds provided to the first author by the College Board and by the Social Sciences and Humanities Research Council of Canada (SSHRC). We would like to thank the College Board and SSHRC for their support.

The authors are solely responsible for the methods, procedures, and interpretations expressed in this study. Our views do not necessarily reflect those of the College Board or SSHRC.

### Abstract

Educational assessments are designed to facilitate teaching and learning. To achieve this purpose, the psychology underlying student performance must be well understood because most tests are based on cognitive problem-solving tasks. This calls for the integration of cognitive psychology with educational assessments. The present study illustrates the use of the attribute hierarchy method (AHM; Leighton, Gierl, & Hunka, 2004) by applying this psychometric procedure to student response data from the SAT Critical Reading subtest. The AHM is a psychometric approach which integrates cognitive psychology with educational measurement. The results of the study indicate that, with the AHM, cognitive diagnostic information can be extracted from SAT Critical Reading subtest to enhance score reporting and, potentially, guide teaching and learning. Moreover, in the framework of the AHM, important information about the construct underlying student performance on the SAT Critical Reading subtest can be identified and evaluated.

## **Investigating the Cognitive Attributes Underlying Student Performance on the SAT Critical Reading Subtest: An Application of the Attribute Hierarchy Method**

### **INTRODUCTION**

Educational assessments are designed to facilitate teaching and learning. However, due to the disjunction between cognitive psychology and educational measurement, most large-scale assessments typically yield limited information regarding why some students perform poorly or how instructional conditions can be modified to improve teaching and learning (National Research Council, 2001). Researchers and practitioners are now devoting more time and attend to the integration of cognitive psychology and educational assessment. Several models towards this integration have been proposed. These models include, but are not limited to, the rule-space approach (Tatsuoka, 1995), the tree-based regression approach (Sheehan, 1997), the cognitive design system (Embretson, 1998), evidence-centered design (Mislevy, Steinberg, & Almond, 2002), and the Attribute Hierarchy Method (AHM) (Leighton et al., 2004). These models differ in the way cognitive information is used, but they all attempt to identify the cognitive components and processes that affect student performance on tests, resulting in cognitive diagnostic feedback that can guide teaching and learning. Moreover, the first four procedures have been applied in operational testing programs and promising results have been produced (Gorin, 2002). However, as a newly-proposed model with promising features, the AHM has never been applied in an actual testing situation. Thus, the present study helps address this limitation by illustrating how the AHM can be used to model and report on the cognitive attributes that underlie student performance on the the SAT Critical Reading subtest.

### **The Attribute Hierarchy Method**

The AHM (Leighton et al., 2004; See also Gierl, Cui, & Hunka, in press; Gierl, Leighton, & Hunka, 2000) is a cognitively-based psychometric method which classifies examinees' test item responses into different *attribute mastery patterns* according to a

cognitive model of task performance. In the AHM, cognitive attributes are assumed to be hierarchically related. This assumption better reflects the characteristics of human cognition because skills do not operate in isolation but belong to a network of interrelated competencies (e.g., Anderson, Douglass, & Qin, 2005; Kuhn, 2001). A cognitive attribute in the AHM is a description of the procedural or declarative knowledge needed to perform a task in a specific domain. For the present study, *attribute* is used as an umbrella term to refer to the cognitive processes and skills employed by students to correctly answer SAT Critical Reading items.

One strength of the AHM lies in its facility to guide test development. Once the attribute hierarchies are identified for a content domain, test developers can create items according to the *hierarchical organization of the attributes*. By doing so, the test developer achieves maximum control over the specific attributes measured by each item. The AHM also offers a more convenient way of providing cognitive feedback to students. This feedback is achieved by mapping examinees' observed response patterns onto their expected response patterns derived from the attribute hierarchy. A student with a certain observed response pattern is expected to have mastered the attributes implied by the corresponding expected response pattern. Similarly, a student may need more work on the attributes not mastered.

## **METHOD**

### ***Instrument***

Student response data from 20 passage-based items on the March 2005 administration of the SAT Critical Reading subtest were used. The SAT Critical Reading subtest is designed to measure students' critical reading ability or the ability to construct a coherent meaning representation of texts (passages, item stems, and response options). Critical reading ability is required for success in college and it involves text-based processing, knowledge-based processing, cognitive reasoning and problem solving, and metacognitive executive skills (Burton, Welsh, Kostin, & van Essen, 2003; VanderVeen,

2004).

### ***Procedures***

The study was conducted in two stages. In the first stage, the *substantive* features of the SAT critical reading items were analyzed. This stage involves the specification of attribute hierarchies, the identification of cognitive attributes used by students, and the validation of the attribute hierarchies using student verbal reports and the hierarchy consistency index (*HCI*). The second stage is the *psychometric* analysis of the students' responses to the test items. This stage involved the generation of attribute patterns and expected response patterns, calculation of attribute probabilities for examinees, and cognitive feedback.

#### ***Stage 1: Substantive Analysis***

***Specification of attribute hierarchy.*** The AHM starts with the specification of the attribute hierarchy using the cognitive attributes measured by the test items. In the present study, three attribute hierarchies with different grain sizes were specified for the SAT Critical Reading items. These hierarchies were based on reading theories and research results related to the SAT Critical Reading subtest.

Hierarchy 1 is based on the model proposed by VanderVeen et al. (in press) for the SAT Critical Reading items. The model contains five cognitive attributes (see Table 1) which can be ordered hierarchically. Specifically, the first two cognitive attributes can be considered lower-level in comparison to the latter three attributes. This interpretation is warranted because the first two attributes deal with smaller information units and less inferences are involved in comparison to the latter three cognitive attributes. To fit the hierarchical relationship among the five attributes in the AHM, two amendments were made. The first amendment required an attribute that measures the examinees' basic language knowledge, such as basic vocabulary and grammatical knowledge, be added. This attribute is assumed to be mastered by all examinees who take the SAT and it is the prerequisite for all other attributes. The second amendment required the attributes of

“understanding the situation implied by a text” and “understanding the content, form and function of larger sections of text” be combined into one attribute as they are essentially indistinguishable. This consolidation occurred because a student must have a global understanding of larger sections of text to understand the situation implied by a text. Hierarchy 1 is specified in Figure 1a. The five cognitive attributes in Hierarchy 1 include: (A1) basic language knowledge, (A2) determining the meaning of words, (A3) understanding the content, form and function of sentences, (A4) understanding the content, form and functions of larger sections of text, and (A5) analyzing author’s purposes, goals and strategies.

As most attributes in Hierarchy 1 collapse across multiple cognitive processes and may affect the precision of cognitive feedback if used for diagnostic purpose, changes were made to these attributes to form Hierarchy 2. The attribute “determine the meaning of words” was decomposed into two attributes with different cognitive demands. The first attribute involves the recognition and retrieval of simple words and it could be regarded as part of basic language knowledge. Thus, it was included in the prerequisite attribute discussed in Hierarchy 1. The second attribute involves the determination of the meanings for more difficult words which requires the comprehension of contextual information. Also, A3 and A4 in Hierarchy 1 can be broken into two separate attributes with different amount of inferences. For A3, the first attribute (A3a) involves literal understanding of sentences with minimal amount of inferences while the second attribute (A3b) requires the reader to use their experience and background knowledge to make inferences in order to build coherence at the sentence level. Similarly, the first attribute that can be extracted from A4 (A4a) involves little inference while the second attribute (A4b) requires the reader to use their experience and world knowledge to make inferences in order to summarize and evaluate larger sections of text. Attributes A3a and A4a can also be regarded as lower-level attributes than A3b and A4b, respectively. Moreover, A4b can be regarded as higher level than A3b because A4b requires the processing of larger information units than A3b.

Hierarchy 2 is specified in Figure 1b.

As reading is an interactive process, a cognitive model of reading task performance should take both the reader factor and the text factor into account. However, in the VanderVeen et al. (in press) model, the text factor is not accounted for. To address this omission, two additional attributes were included in Hierarchy 3 to account for the effect of text difficulty. These two attributes are (A6) understanding text with difficult vocabulary and (A7) understanding text with complex syntactic structure. These two attributes are included because vocabulary difficulty and syntactic complexity are two important indicators of text difficulty (e.g., Smith, 2004; Veenman & Beishuizen, 2004). Hierarchy 3 is shown in Figure 1c. A summary of the cognitive attributes involved in the three hierarchies is presented in Table 2.

***Validating the attribute hierarchies using student verbal reports.*** A verbal report study (Ericsson & Simon, 1993; Leighton, 2004) was conducted to validate the cognitive attributes, and their interrelationships, in the three hierarchies. Eight first-year undergraduate students were recruited for the verbal protocol study. First-year undergraduate students were selected as the target participant group because, at the time of data collection (September 2006), these students were most like high school students who take the SAT toward the end of the 12<sup>th</sup> grade.

After the verbal report data were collected, two graduate students in cognitive psychology, who have experience in conducting verbal report study and who are familiar with reading comprehension and the assessment of reading, coded the cognitive attributes in the three hierarchies from the verbal reports data. The coders were also instructed to identify any additional cognitive attributes that occurred frequently and consistently in the verbal report data but were not included in the three hierarchies. These additional cognitive attributes, if found, were used to revise the three attribute hierarchies. Disagreements during coding were resolved through discussion.

***Validating the attribute hierarchies using the HCI.*** The three attribute hierarchies

were also validated using the *HCI* on large samples of SAT examinees. The *HCI* for the AHM was proposed by Cui, Leighton, Gierl et al. (2006). It examines the degree to which the observed response patterns are consistent with the attribute hierarchy. The *HCI* for examinee  $i$  is given by

$$HCI_i = 1 - \frac{2 \sum_{j=1}^J \sum_{g \in S_j} X_{ij} (1 - X_{ig})}{N_c}, \quad (\text{Equation 1})$$

where  $J$  is the total number of items,  $X_{ij}$  is examinee  $i$ 's score (1 or 0) to item  $j$ ,  $S_j$  includes items that require the subset of attributes of item  $j$ , and  $N_c$  is the total number of comparisons for correct-answered items by examinee  $i$ . The values of the *HCI* range between  $-1$  and  $+1$ . The mean of the *HCI* can be used as indicators of the overall model-data fit. As a preliminary guideline, a mean below 0.3 suggests poor model-data fit, a mean between 0.3 and 0.6 suggests moderate model-data fit, and a mean above 0.6 suggests good model-data fit. We are currently conducting research to validate these guidelines.

The response data from two random samples of 2,000 examinees who took the March 2005 administration of the SAT were used for calculating the *HCI*s. The hierarchy which provided the best model-data fit was used for analyzing student response data in the next stage. In cases where two hierarchies fit the data equally well, the more parsimonious model with less cognitive attributes would be used.

## **Stage 2: Psychometric Analysis of Student Response Data**

**Generation of attribute patterns and expected examinee response patterns.** After the hierarchy which provided the best model-data fit was identified, the examinees' observed attribute patterns were compared to the expected response patterns. The attribute patterns refer to the combinations of attributes that are consistent with the hierarchy. Corresponding to each attribute pattern is an expected response pattern—these patterns are

generated by matching the attribute patterns with the cognitive attributes measured by the items. If an attribute pattern includes the cognitive attributes required by an item, then the examinee who has such an attribute pattern are expected to answer this item correctly. Conversely, if at least one of the cognitive attributes required by the item is missing in an examinee's attribute pattern, then the examinee should not answer this item correctly.

***Estimation of attribute probabilities.*** To extract information about students' mastery of specific cognitive attributes, a neural network was used to calculate the probabilities that examinees possess specific attributes. To use the neural network, the relationships between the expected response patterns and their associated attribute patterns were established by presenting each pattern to the network repeatedly until it "learned" each association (Gierl, Cui, & Hunka, 2007). After the network learned the associations successfully, a set of weight matrices were produced. These weight matrices were then used to obtain the probabilities of the individual attributes for any observed response pattern. A probability close to 1 indicates that the corresponding attribute is likely to be mastered by the examinee. Conversely, a probability of close to 0 indicates that the corresponding attribute is likely not to be mastered by the examinee.

***Descriptive score reports and diagnostic feedback.*** Descriptive score reports were created for a sample of students to demonstrate how attribute probabilities can enhance the cognitive diagnostic feedback examinees receive during score reporting.

## RESULTS

### ***Substantive Analysis***

#### ***Results from the Verbal Report Study***

The frequencies of occurrence for each cognitive attribute, as used by the eight think aloud study participants, are summarized in Table 3. All attributes in each hierarchy were used, but to differing degrees, by the participants. Moreover, two additional attributes were discovered. These two attributes are (A8) using rhetorical knowledge and (A9) evaluating response options. Among the attributes, attributes A3, A4, A3a, A4a, and A9

were used more frequently (i.e., their use exceeded 10%). In fact, these attributes were used in almost every item. On the other hand, attributes A2, A4b, A6, and A7 were used less frequently (i.e., less than 5% occurrences), as these attributes were used in only a small number of items.

As the AHM uses only dichotomous values to conduct the psychometric analysis, meaning the attribute can only be deemed absent (i.e., a value of 0) or present (i.e., a value of 1), the frequencies of the cognitive attributes had to be transformed into 0s and 1s. In determining whether a cognitive attribute was measured by a test item, two considerations were made. First, if a cognitive attribute is coded as 1, then its prerequisite would also be coded as 1. Second, as eight students were included in the verbal report study, we felt that if at least half of the participants used a cognitive attribute, then this cognitive attribute could be deemed prevalent enough to be regarded as present. Of course, other decision rules could be used to recode the data. Using these two considerations, the recoded cognitive attributes measured by the test items are summarized in Table 4.

In addition to evaluating the veracity of the cognitive attributes, we also evaluated their hierarchical relationships during the protocol analysis. For Hierarchies 2 and 3, attribute A3a was found to be the prerequisite of attributes A2, A3b, A4a, A5, and A8 because the participants must possess A3a before they could use other attributes to process the text. For similar reasons, attribute A4a was the prerequisite of A4b. As A3a and A4a were coded, respectively, as A3 and A4 in Hierarchy 1, A3 is considered the prerequisite of A2, A4, and A5.

By way of a short illustration, excerpts from student verbal reports for Item 14 are displayed below to indicate how the relationship between A3a and A3b was validated. Item 14 measures attributes A3a and A3b. All eight students correctly answered this item. The item requires the students to understand the sentence *“The practice has been to treat the arts in chamber-of-commerce, rather than in creative, terms.”* To produce the item correct, students need to draw inferences about the sentence (A3b). However, they must

first understand the literal meaning of the sentence (A3a). The verbal reports by G.A. and K.R. illustrate the prerequisite relationship between A3a and A3b:

**G.A.:** ...cause, **chamber-of-commerce, you go there when you want to start a business (A3a).** So, **the business which would be a commercial thing, if it is cultural, it is definitely the commercialization of culture (A3b).** I don't know, it's just a logical thought process to get to A.

**K.R.:** The practice, what's the practice. The practice has been to treat the arts in chamber-of-commerce, rather than in creative, terms" That talks about the government, I think. **Chamber-of-commerce is government and it's saying the practice means what they have been doing, I mean, like, rather than in creative terms, treat the arts, treat the arts in government terms, rather than in creative terms (A3a).** ... Arts in chamber-of-commerce terms, rather than in creative terms, We are not being creative of the arts. **We are making money, maybe, that's what they mean. Commercialization...that's what commercialization means (A3b).** And money, make money. ... The commercialization rather than creative terms, I just go with A.

In these reports, both students started by understanding the key word "chamber-of-commerce" in terms of its literal meaning. G.A. understood it as a place where you go to start a business and K.R. understood it as a government institution. Based on this understanding, they could then infer that the "practice" refers to "commercialization of culture." Data to support our interpretation for other prerequisite relationships among attributes is provided in the Appendix. Based on the verbal report results, our initial three hierarchies revised by adding the two additional attributes and by changing the relationship between A2 and A3 in Hierarchy 1 and the relationship between A2 and A3a in Hierarchies 2 and 3. The revised hierarchies are displayed in Figure 2.

### ***Results from HCI Analysis***

The mean *HCI* values for the three revised hierarchies are summarized in Table 5. These values suggest moderate model-data fit for all three hierarchies. From Hierarchy 1 to Hierarchy 2, the mean *HCI* values for both samples increased by 0.11. However, from

Hierarchy 2 to Hierarchy 3, the mean *HCI* values for both samples only increased by 0.02. In other words, Hierarchy 2 improved model-data fit considerably but Hierarchy 3 did so only negligibly. Given the fact that Hierarchy 2 involves less attributes and inter-attribute connections and, thus, is more parsimonious than Hierarchy 3, Hierarchy 2 was regarded as the best among the three hierarchies and, thus, was used for analyzing student response data.

### ***Psychometric Analysis***

#### ***Analyzing Student Response Data with the AHM***

Next, student response data were analyzed using the AHM. To begin, attribute patterns and expected response patterns based on Hierarchy 2 were generated. Then, the attribute probabilities were estimated for a random sample of 15 students who took the March 2005 administration of the SAT, as an illustration (in a actual testing situation, the attribute probabilities for all 2,000 students would be estimated). As attribute probability values range from 0 to 1, values of 0 to 0.499 are regarded as non-mastery, values of 0.5 to 0.799 as partial mastery, and values of 0.8 to 1 as mastery in the present study. Again, other classification ranges could be proposed and used—our non-mastery to mastery score ranges merely serve to illustrate our reporting approach. The results of the estimation are displayed in Table 6. Table 6 also summarizes the numbers of masters, partial-masters, and non-masters for each of the nine cognitive attributes in Hierarchy 2 (the last three rows of the table) and for each of the 15 examinees (the last three columns of the table).

A general finding apparent: The higher the total score, the more attributes a certain examinee masters. This finding gives some legitimacy for reporting a total score to students, as is done in most operational testing programs. However, in some cases, examinees who received a lower total score may have mastered more cognitive attributes than those who received a higher total score. For example, examinee 14 received a total score of 8, while the attribute probabilities indicate that this examinee has mastered five attributes, partially mastered one attribute, and lacks three attributes. Examinee 15, on the other hand,

received a total score of 6, mastered seven attributes, partially mastered one attribute, and lacks only one attribute. Such results indicate that only providing an examinee with a single total score may, sometimes, misrepresent their cognitive skill profiles.

Table 6 also indicates that examinees with the same total scores may possess different cognitive attributes. For example, examinees 1 and 2 both received a total score of 13 out of 20. However, because their response patterns are different (“11110001110100111011” for examinee 1 and “11101101111000011101” for examinee 2), the estimated attribute probabilities indicate the two examinees have mastered different cognitive attributes. Examinee 1 has mastered attributes A1, A3a, A3b, A4a, A8, and A9, partially mastered attributes A2 and A4b, but lacks attribute A5. Examinee 2 mastered all attributes but A4b. Such results suggest that students who obtained the same total score on a test do not necessarily have the same cognitive skill profiles, especially when a test measures a variety of cognitive attributes.

### ***Score Reporting and Providing Diagnostic Feedback***

A key advantage of the AHM is that it provides a specific method for diagnostic score reporting, as examinees receive individualized score reports based on their attribute mastery levels. The score reports produced by the AHM not only have a total score but also have detailed information about what cognitive attributes were measured by the test and the degree to which the examinees have mastered these cognitive attributes. Also, because attributes are hierarchically related (e.g., A3a and A3b), the score reports can reflect such relationships among the attributes and this information can be conveyed to the examinee, and their instructors. To demonstrate how the AHM can be used to report test scores and provide diagnostic feedback, four examinees were chosen from the 15 examinees whose response data were used in estimating attribute probabilities in a previous section. The four examinees are examinees 5, 1, 8, and 12.

Examinees 5 and 1 are chosen to demonstrate how detailed information regarding the examinees’ attribute mastery can be provided to the examinees. Examinee 5 correctly

answered 19 items out of 20. According to the estimated attribute probabilities, this examinee has mastered all nine attributes in Hierarchy 2. Examinee 1 correctly answered 13 items. According to the estimated attribute probabilities, this examinee has mastered attributes A1, A3a, A3b, A4a, A8, and A9, partially mastered attributes A2 and A4b, but lacks attribute A5. Thus, this examinee is considered to lack the ability to analyze author's purposes, goals and strategies. Moreover, this examinee may not efficiently determine the meaning of difficult words from context (A2), or understand larger sections of text by making inferences or integrating background knowledge (A4b). These results demonstrate that the score reports from the AHM provide detailed information to the examinees about their cognitive attribute mastery levels. Such information can be used by examinees to improve specific cognitive skills, and thereby, increasing their test performance.

Examinees 8 and 12 are chosen to demonstrate how the hierarchical relationships among cognitive attributes can be incorporated into score reports to increase the specificity of diagnostic feedback. Examinee 8 correctly answered five items. The estimated attribute probabilities indicate that this examinee has mastered five attributes (A1, A2, A3a, A4a, and A8), but lacks three attributes (A3b, A4b, A5). As both attributes A3b and A4b represent the inferential text comprehension, the absence of these two attributes suggests that the examinee's comprehension of text rests at a literal level while he has difficulty in understanding text inferentially. Examinee 12 only answered three items correctly. The estimated attribute probabilities indicate that this examinee only mastered three attributes (A1, A3a, and A8), partially mastered one attribute (A4a), and lacks the other five attributes. As the examinee lacks both attributes A3b and A4b, the same diagnostic feedback provided to examinee 8 can be provided to this examinee. Moreover, as the examinee only partially mastered attribute A4a and did not master attribute A4b, which both deal with larger sections of text, the conclusion may be drawn that this examinee can only process text at the sentence level, but may have difficulty in processing larger sections of text (A4a, A4b). Descriptions of the cognitive strengths and weaknesses

for the four examinees are summarized in Table 7. A sample score report for examinee 8 is displayed in Figure 3.

### CONCLUSIONS AND DISCUSSION

The purpose of the study was to investigate the cognitive attributes underlying student performance on the SAT Critical Reading subtest using the AHM. It also serves as the first application of the AHM to data from an operational testing program. The study was conducted in two stages. In the first stage, the *substantive* features of the SAT critical reading items were analyzed. Three attribute hierarchies for the SAT Critical Reading subtest were identified. Then, a verbal report study was conducted to validate and, when required, revise the three attribute hierarchies. Next, an *HCI* analysis was conducted to further validate the three revised hierarchies on large samples and to select the best-fitting hierarchy for analyzing examinee response data. Based on the *HCI* results, Hierarchy 2, due to its model-data fit and parsimony, was selected for analyzing examinee response data.

In the second stage, a *psychometric* analysis of the response data from 15 examinees on the March 2005 administration of the SAT was conducted. Probabilities for the nine attributes in Hierarchy 2 were calculated for the sample of examinees. Based on these attribute probabilities, descriptive score reports were composed for four examinees to demonstrate the facility of the AHM in providing diagnostic feedback.

From the present study, the advantages of the AHM over traditional psychometric scoring methods are apparent. First, in addition to providing a total score, the AHM provides more detailed cognitive diagnostic information to the examinees. The information allows examinees to focus their efforts on remedying attributes they have not mastered. In other words, the AHM may be instrumental in improving student learning.

Second, the AHM provides useful information for construct validation. The AHM requires a substantive analysis, which can include a verbal report study, to probe the specific cognitive skills measured by each item. For example, in the present study, we

found that (A8) using rhetorical knowledge and (A9) evaluating response options were two important attributes measured by the test items. If *HCI* results indicate good fit between the attribute hierarchies and the observed response data, then clear evidence about the construct validity of the test can be obtained.

Third, the AHM provides information for researchers to further investigate the nature of reading ability and, thereby, develop cognitive theories in reading. For example, once examinees strengths and weaknesses in reading are reliably and validly identified, remediation techniques specific to each cognitive attribute may be developed. Then a pretest-posttest experimental study could be conducted to produce contrasting subscores on the component attributes and the total score. By regressing the posttest subscores and total score on the pretest scores, the treatment interaction can be determined. The relative contributions of treatments targeting the component attributes to the total score can be contrasted, and inferences drawn about which component attributes are most efficient in their contribution to reading ability (VanderVeen et al., in press).

To conclude, the AHM draws on information from students, assessment specialists, and cognitive psychologists and, in turn, yielded information to benefit these three groups. In other words, the AHM serves to unify the different components of educational assessment, including instruction, cognitive theory, and assessment. However, it must be noted that the links among these different components are weak, at the current stage. For example, few large-scale tests are developed with the guidance of an explicit cognitive model. Therefore, these links must be strengthened in the future. The present study provides a short illustration of how these links can begin to be formed.

**Table 1**

*The Five Cognitive Attributes in VanderVeen et al.'s (in press) Cognitive Model of the SAT Critical Reading Subtest*

<b>Skill Category</b>	<b>Description</b>	<b>Comment</b>
Determining the Meaning of Words	Student determines the meaning of words in context by recognizing known words and connecting them to prior vocabulary knowledge. Student uses a variety of skills to determine the meaning of unfamiliar words, including pronouncing words to trigger recognition, searching for related words with similar meanings, and analyzing prefixes, roots, and suffixes.	This skill category includes more than just lexical access, as word identification and lexical recall are combined with morphological analyses.
Understanding the Content, Form, and Function of Sentences	Student builds upon an understanding of words and phrases to determine the meaning of a sentence. Student analyzes sentence structures and draws on an understanding of grammar rules to determine how the parts of speech in a sentence operate together to support the overall meaning. Student confirms that his or her understanding of a sentence makes sense in relationship to previous sentences, personal experience, and general knowledge of the world.	This skill category focuses on the syntactical, grammatical, and semantic case analyses that support elementary proposition encoding <i>and</i> integration of propositions across contiguous sentences.
Understanding the Situation Implied by a Text	Student develops a mental model (i.e., image, conception) of the people, things, setting, actions, ideas, and events in a text. Student draws on personal experience and world knowledge to infer cause-and-effect relationships between actions and events to fill in additional information needed to understand the situation implied by the text.	This skill category is a hybrid of the explicit text model and the elaborated situation model described by Kintsch (1998). As such, category three combines both lower level explicit text interpretation and higher level inferential processes that connect the explicit text to existing knowledge structures and schemata.

<b>Skill Category</b>	<b>Description</b>	<b>Comment</b>
Understanding the Content, Form, and Function of Larger Sections of Text	Student synthesizes the meaning of multiple sentences into an understanding of paragraphs or larger sections of texts. Student recognizes a text's organizational structure and uses that organization to guide his or her reading. Student can identify the main point of, summarize, characterize, or evaluate the meaning of larger sections of text. Student can identify underlying assumptions in a text, recognize implied consequences, and draw conclusions from a text.	This skill category focuses on the integration of local propositions into macro-level text structures (Kintsch & van Dijk, 1978) and more global themes (Louwerse & Van Peer, 2003). It also includes elaborative inferencing that supports interpretation and critical comprehension, such as identifying assumptions, causes, and consequence and drawing conclusions at the level of the situation model.
Analyzing Authors' Purposes, Goals, and Strategies	Student identifies an author's intended audience and purposes for writing. Student analyzes an author's choices regarding content, organization, style, and genre, evaluating how those choices support the author's purpose and are appropriate for the intended audience and situation.	This skill category includes contextual and pragmatic discourse analyses that support interpretation of texts in light of inferred authorial intentions and strategies.

**Table 2***Summary of Cognitive Attributes*

A1	Basic language knowledge, such as word recognition and basic grammar.
A2	Determining word meaning by referring to context
A3	Understanding the content, form and function of sentences
A3a	Literal understanding of sentences with minimal amount of inferences
A3b	Understanding sentences by making inferences based on the reader's experience and background knowledge.
A4	Understanding the content, form and function of larger sections of text
A4a	Literal understanding of larger sections of text with minimal amount of inferences
A4b	Understanding larger sections of text by making inferences based on the reader's experience and world knowledge; building coherence across, summarizing, and evaluating larger sections of text.
A5	Analyzing author's purposes, goals and strategies.
A6	Understanding text with difficult vocabulary
A7	Understanding text with complex syntactic structure

**Table 3***Frequencies of Cognitive Attributes Used by the Eight Verbal Report Participants*

Item	A2	A3	A4	A5	A3a	A3b	A4a	A4b	A6	A7	A8	A9
1	2	7	2	2	5	2	2	1	1	0	0	2
2	0	2	0	1	1	2	0	0	0	0	8	1
3	1	2	7	2	2	0	4	3	1	0	0	2
4	0	4	8	3	4	0	6	3	0	0	0	0
5	0	3	7	4	3	3	7	2	0	0	0	3
6	4	5	4	2	5	2	4	1	5	0	0	6
7	1	0	3	6	0	0	3	0	2	0	4	5
8	0	0	7	3	0	0	6	2	0	0	0	2
9	4	6	3	0	5	3	3	0	1	0	1	2
10	0	7	1	1	6	5	1	1	0	0	0	1
11	4	2	1	6	2	6	1	0	0	0	3	7
12	0	4	2	1	4	4	2	0	4	3	0	5
13	0	6	6	4	6	0	6	4	5	4	1	7
14	0	7	4	0	7	6	4	0	0	0	5	1
15	3	2	6	4	2	5	6	2	4	7	7	8
16	0	3	5	4	3	0	5	5	0	0	0	7
17	2	7	4	0	6	4	4	2	6	0	1	5
18	0	6	8	2	6	2	8	4	0	0	0	2
19	0	8	1	2	7	2	1	5	0	0	0	1
20	0	7	1	1	7	6	1	0	0	0	4	4
Total	21	88	80	48	81	52	74	26	29	14	34	71
Percentage	3.4	14.2	12.9	7.8	13.1	8.4	12.0	4.2	4.7	2.3	5.5	11.5

**Table 4***Cognitive Attributes Measured by the 20 Test Items*

Item	A2	A3	A4	A3a	A3b	A4a	A4b	A5	A6	A7	A8	A9
1	0	1	0	1	0	0	0	0	0	0	0	0
2	0	0	0	1	0	0	0	0	0	0	1	0
3	0	1	1	1	0	1	0	0	0	0	0	0
4	0	1	1	1	0	1	0	0	0	0	0	0
5	0	1	1	1	0	1	0	1	0	0	0	0
6	1	1	1	1	0	1	0	0	1	0	0	1
7	0	1	0	1	0	0	0	1	0	0	1	1
8	0	1	1	1	0	1	0	0	0	0	0	0
9	1	1	0	1	0	0	0	0	0	0	0	0
10	0	1	0	1	1	0	0	0	0	0	0	0
11	1	1	0	1	1	0	0	1	0	0	0	1
12	0	1	0	1	1	0	0	0	1	0	0	1
13	0	1	1	1	0	1	1	1	1	1	0	1
14	0	1	1	1	1	1	0	0	0	0	1	0
15	0	1	1	1	1	1	0	1	1	1	1	1
16	0	1	1	1	0	1	1	1	0	0	0	1
17	0	1	1	1	1	1	0	0	1	0	0	1
18	0	1	1	1	0	1	1	0	0	0	0	0
19	0	1	0	1	0	1	1	0	0	0	0	0
20	0	1	0	1	1	0	0	0	0	0	1	1

**Table 5***A Summary of the HCI Values for the Three Attribute Hierarchies*

	Hierarchy 1		Hierarchy 2		Hierarchy 3	
	Sample1	Sample 2	Sample1	Sample 2	Sample1	Sample 2
Mean HCI	0.44	0.45	0.55	0.56	0.57	0.58

**Table 6**

*Attribute Probabilities for a Random Sample of 15 Students Who Wrote on the 20 SAT Critical Reading Test Items in March 2005*

Examinee	Student Response Data	Total Score	Attribute Probabilities											
			A1	A2	A3a	A3b	A4a	A4b	A5	A8	A9	M	PM	NM
1	11110001110100111011	13	0.999	0.733	0.990	0.998	0.982	0.582	0.003	0.987	0.998	6	2	1
2	11101101111000011101	13	0.997	1.000	0.999	0.994	0.993	0.218	0.999	0.994	1.000	8	0	1
3	11111101111100000000	11	0.998	1.000	0.999	0.994	0.987	0.019	0.999	0.989	1.000	8	0	1
4	11111101110011010110	14	0.999	0.998	0.999	0.998	0.999	0.998	0.988	0.986	1.000	9	0	0
5	11111111111111111110	19	0.999	0.996	0.998	0.995	0.999	0.985	0.998	0.994	1.000	9	0	0
6	11111110101100101011	14	0.998	0.980	0.998	0.800	0.909	0.381	1.000	0.998	1.000	8	0	1
7	10110011110001000101	10	0.999	0.995	0.999	0.998	0.999	0.741	0.930	0.347	0.913	7	1	1
8	01110000100000100000	5	0.994	1.000	0.813	0.026	0.905	0.042	0.013	0.997	0.003	5	0	4
9	11111001111111111110	17	0.999	0.992	0.998	1.000	1.000	0.997	0.985	0.981	0.999	9	0	0
10	11110010000101011100	10	0.999	0.005	0.999	0.492	1.000	0.959	0.999	0.931	1.000	7	0	2
11	11111001011101111010	14	0.999	0.011	0.998	0.994	1.000	0.460	0.999	0.997	0.999	7	0	2
12	11010000000000000000	3	0.999	0.015	0.995	0.013	0.690	0.013	0.015	0.998	0.033	3	1	5
13	11011010110111011111	15	0.998	0.998	0.999	0.987	0.991	0.986	1.000	0.994	1.000	9	0	0
14	10101100100010110000	8	0.998	0.998	0.967	0.005	0.761	0.085	0.879	0.000	1.000	5	1	3
15	01100000101010000100	6	0.998	1.000	0.987	0.098	0.977	0.930	0.657	0.989	0.838	7	1	1
M			15	11	15	10	13	6	11	13	13			
PM			0	1	0	0	2	2	1	0	0			
NM			0	3	0	5	0	7	3	2	2			

Note. In Table 6, M indicates Mastery, PM indicates Partial Mastery, and NM indicates Non-Mastery.

**Table 7***Sample Descriptive Score Reports for Examinees 5, 1,8, and 12*

Examinee	Total Score	Description of Performance
5	19	You have mastered the nine cognitive attributes of reading measured by the test. You are proficient in understanding texts of different length at both literal level and inferential level. You are also proficient in analyzing author's purpose, goals, and strategies in the text. You are skillful in determining the meaning of unfamiliar words from context and you have a good understanding of the rhetorical devices used in the text. In addition, you have good ability in evaluating response options to get the correct answer.
1	13	You have mastered six, and partially mastered another two of the nine cognitive attributes of reading measured by the test. You are proficient in understanding texts of different length at literal level. Although you can incorporate inferences and background knowledge in comprehending text, you need strengthen this ability when reading larger chunk of text. You have a good understanding of the rhetorical devices used in the text and a good ability in evaluating response options to get the correct answer. There is still room for improving your skill in determining the meaning of unfamiliar words from context. Attention should also be paid to improve your ability to analyze author's purpose, goals, and strategies in the text.
8	5	You have mastered five of the nine cognitive attributes of reading measured by the test. You are proficient in understanding texts of different length at literal level. You are skillful in determining the meaning of unfamiliar words from context and you have a good understanding of the rhetorical devices used in the text. However, you need to improve your ability to incorporate inferences and background knowledge in comprehending a text. Attention should also be paid to improve your ability to analyze author's purpose, goals, and strategies in the text and to evaluate response options when answering the passage-based questions.
12	3	You have mastered three of the nine cognitive attributes of reading measured by the test. You are proficient in understanding sentences at literal level. You have a good understanding of the rhetorical devices used in the text. However, you should learn how to incorporate inferences and background knowledge into comprehending texts of different lengths. Moreover, you need to improve ability in reading larger chunks of text. You also need to improve your skill in determining the meaning of unfamiliar words from context. Attention should also be paid to improve your ability to analyze author's purpose, goals, and strategies in the text and to evaluate response options when answering the passage-based questions.

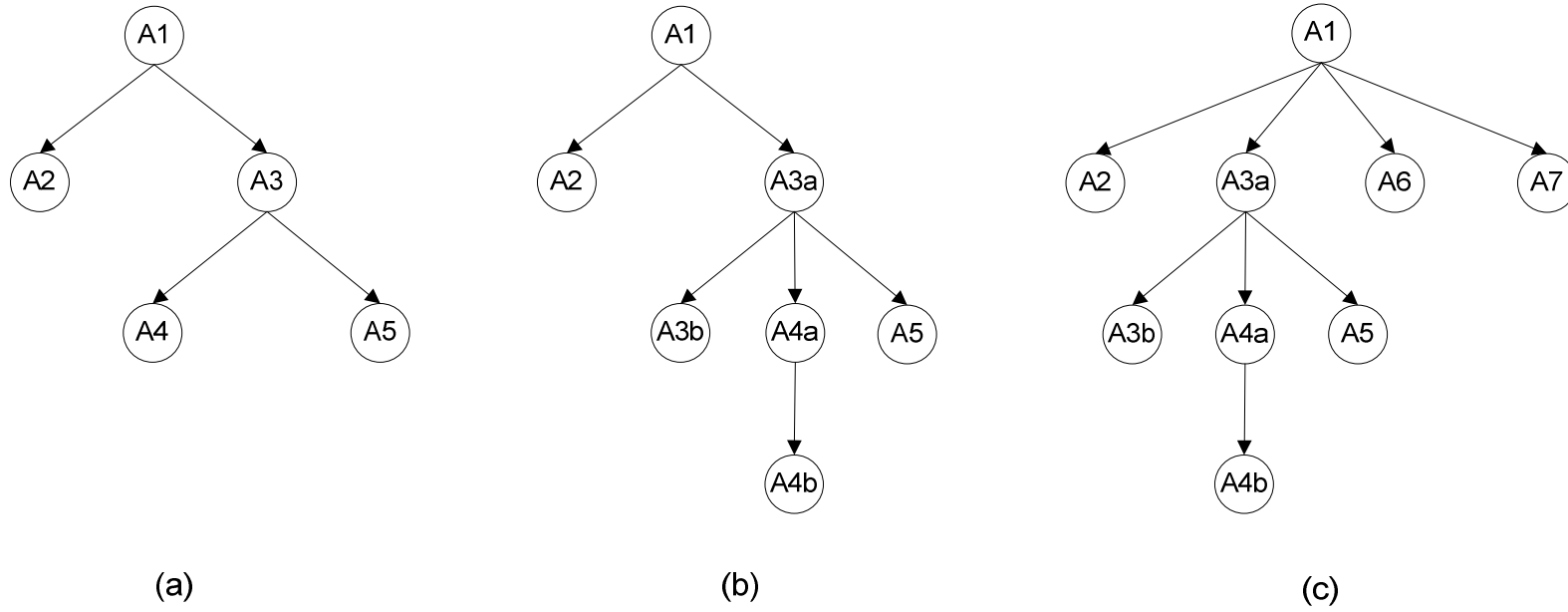
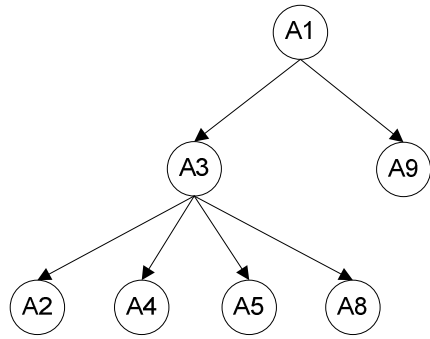
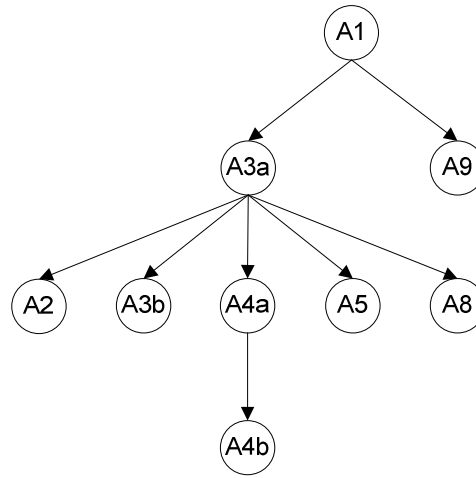


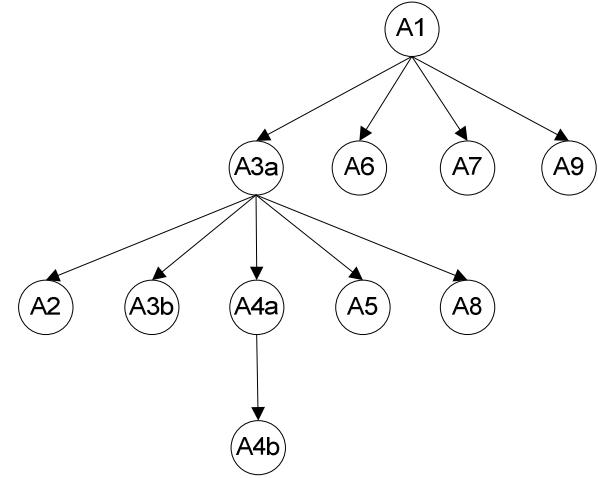
Figure 1. The three initial hierarchies.



(a)



(b)



(c)

Figure 2. The three revised hierarchies.

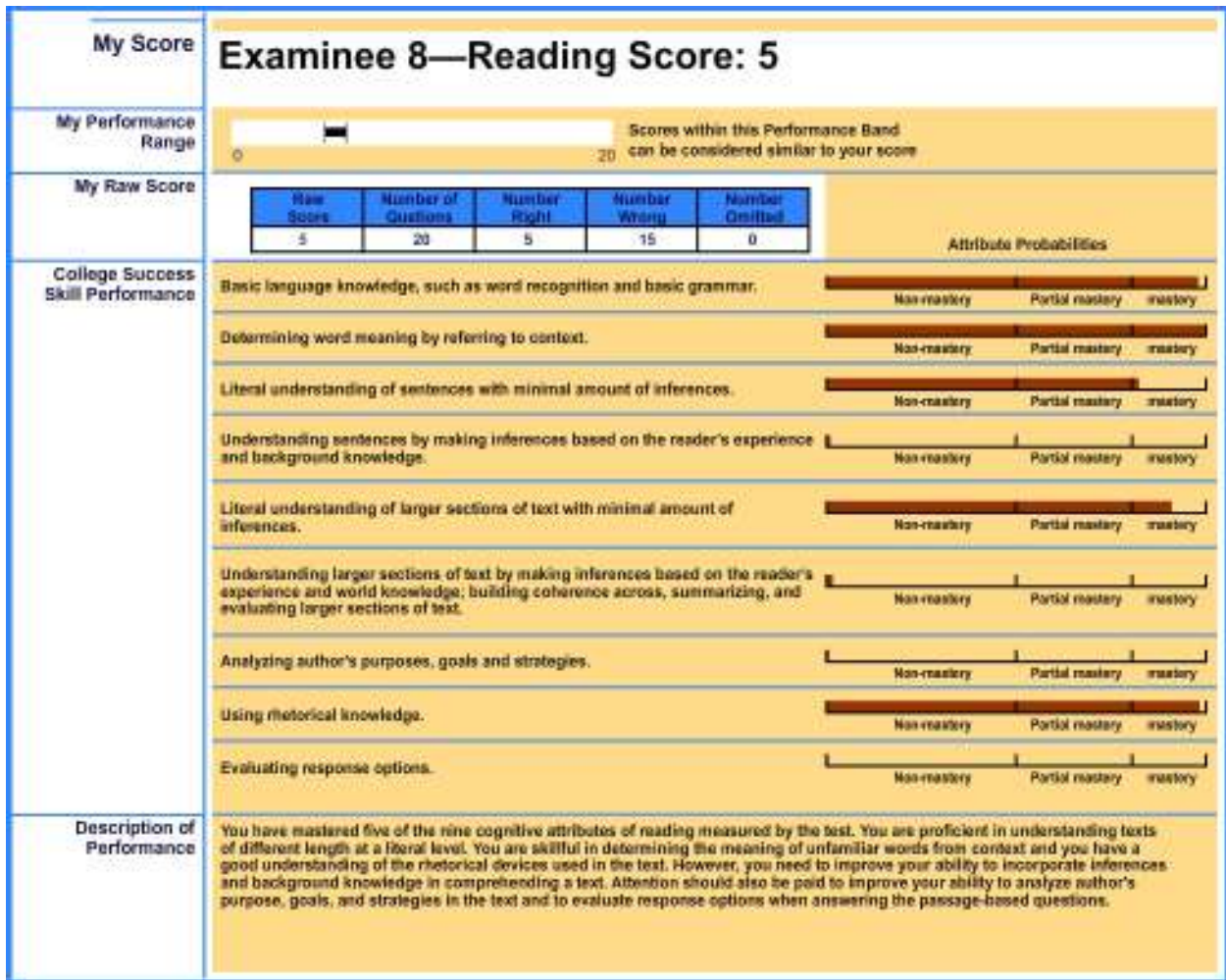


Figure 3: A sample score report for examinee 8<sup>1</sup>.

<sup>1</sup> This sample score report is not used by the College Board. It is displayed here for an illustration of how cognitive feedback can be provided to examinees using the AHM.

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## APPENDIX

The verbal reports in the appendix provide evidence to support our validation of the relationships among cognitive attributes.

### Attribute A3a and A2

Item 9 measures attributes A3a and A2. Five students got this item correct. In this item, students are required to determine the meaning of the word “death” by referring to a wider context (A2). However, when solving this item, the students need, first, be able to understand the literal meaning of the sentences that are related to this word (A3a). These sentences include:

- (1) *After 50 years of life and 20 years of death, the great Adler and Sullivan Auditorium in Chicago is back in business again.*
- (2) *Closed after that, it settled into decay for the next 20 years.*

Understanding these two sentences will lead the students to rule out the two plausible distractors “demolition” and “flagging attendance,” and select the correct one “neglect.” Consider the verbal reports provided by students D.C. and P.B.:

**D.C.:** They weren’t demolishing, like it hasn’t been demolished yet (A3a). Uh, neglect, I chose neglect because it talked about **until 1967, and said, oh, here it is, closed after that, it settled into decay for the next 20 years (A3a). It was neglected (A2).** So it had to be that.

**P.B.:** So death is really, what it’s saying or the essence of **what it’s talking about in the paragraph is a time when it was unoccupied or it was not being used, or ignored (A3a).** So flagging attendance, no, because **it’s closed (A3a).** So I would say neglect because it’s being rejected by the general public during the...or after the war. **So I would say neglect (A2).**

In both cases, the students understood the above two sentences and got the correct meaning for the word “death.” On the contrary, failure to understand these two sentences would lead the students to select a wrong option. Consider the verbal report provided by L.G.:

**L.G.:** Based on the 1<sup>st</sup> sentence of the passage, death here contrasted “life” and “is back in business”. I think it refers to the demolition, which is C.

Obviously, the student failed to understand or did not notice the second sentence listed above. Therefore, she chose “demolition” rather than “neglect.”

### Attribute A3a vs. A3b

Item 14 measures attributes A3a and A3b. All eight students correctly answered this item. The item requires the students to understand the sentence *“The practice has been to treat the arts in chamber-of-commerce, rather than in creative, terms.”* To get the item correct, the students need to draw inferences about the sentence (A3b). However, they need first understand the literal meaning of the sentence (A3a). The verbal reports by G.A. and K.R. indicate the prerequisite relationship between A3a and A3b:

**G.A.:** ...cause, **chamber-of-commerce, you go there when you want to start a business (A3a).** So, **the business which would be a commercial thing, if it is cultural, it is definitely the commercialization of culture (A3b).** I don’t know, it’s just a logical thought process to get to A.

**K.R.:** The practice, what’s the practice. The practice has been to treat the arts in chamber-of-commerce, rather than in creative, terms” That talks about the government, I think. **Chamber-of-commerce is government and it’s saying the practice means what they have been doing, I mean, like, rather than in creative terms, treat the arts, treat the arts in government terms, rather than in creative terms (A3a).** ... Arts in chamber-of-commerce terms, rather than in creative terms, We are not being creative of the arts. **We are making money, maybe, that’s what they mean. Commercialization...that’s what commercialization means (A3b).** And money, make money. ... The commercialization rather than creative terms, I just go with A.

In the above reports, both students started by understanding the key word “chamber-of-commerce” in terms of its literal meaning. G.A. understood it as a place where you go to start a business and K.R. understood it as a government institution. Based on that understanding, they could then infer that the “practice” refers to “commercialization of culture.”

### Attribute A3a vs. A4a

Item 4 measures both attribute A3a and attribute A4a. All eight students correctly answered the item. The item requires the students to understand the literal meaning of a larger section of text (A4a). However, the students need first understand each individual sentence in the text (A3a), as indicated by the verbal reports of L.G. and P.B.:

**L.G.:** ...it mainly focuses on the economic impact of recycling (A4a), which can be seen from these sentences: **They offer mainly short-term benefits to a**

few groups; ...**Diverting money from genuine social and environmental problem; Recycling programs actually consume resources (A3a)**, and the last sentence. I think that last sentence is the main idea of passage 2. ...**It is mainly about the cost of recycling, cost of money and human and natural resources (A4a)**.

**P.B.** Passage 2 ...passage 2 is talking about how it's really only beneficial to a few groups. Um...and its taking away from things that can be considered beneficial ...Does talk about ...**how it's three times more expensive than collecting a ton of garbage. ... and recycling is a waste of time and money (A3a)**. So I am gonna say economic impact because most of them are focusing on the monetary things in passage 2 (A4a).

As indicated above, both students referred to several key sentences in the paragraph and reported how they understood these sentences to get the meaning of the whole paragraph.

### Attribute A3a vs. A5

Item 13 measures attributes A3a and A5. Seven students correctly answered the item. The item requires the students to understand the author's purpose in writing the segment "*temples to bourgeois muses with all the panache of suburban shopping centers*" (A5). To get the item correct, the literal meaning of the following sentence must be understood (A3a):

- (1) *It has seen a few good new theaters and a lot of bad ones, temples to bourgeois muses with all the panache of suburban shopping centers.*

Consider the verbal reports of G.A. and D.C.:

**G.A.:** The last decade has seen city after city...Ok, **it is the last decade,...so the last decade has a few good new theaters, and a lot of bad ones, temples to bourgeois muses, with all the panache of suburban shopping centers (A3a)**, So that is just describing, ...the bad theaters, in this line it is a descriptive of the bad ones, ok, ...**temples to bourgeois muses line could be a dig at the character. And the shopping center thing could be a dig at the appearance (A5)**. Mmm, I'll put a star beside C, cause it might be good.

**D.C.:** Let's see...(read the sentence) they are talking about cities, so description best serves to ...well, before that, in lines before that, **it said, it has seen a few good new theaters and a lot of bad ones (A3a), which really influenced me choosing C because it says deprecate the appearance and character of many new theaters (A5)**. Not all theaters but many of them were bad.

In the above reports, both students first got the literal meaning of the sentence and then they could infer the author's purpose in writing "*temples to bourgeois muses with all the panache of suburban shopping centers.*" On the other hand, failure to understand the sentence might lead the students to select a wrong option, as indicated in the report by P.S.:

**P.S.:** I read the sentence and I didn't know the exact meaning of this word bourgeois, I didn't know what exactly it meant, but I just thought that the answer from the 11<sup>th</sup> question could carry forward to the 12<sup>th</sup> question, So I said that it's A.

Due to word difficulty, P.S. could not understand the sentence. Therefore, she got the item wrong.

### Attribute A3a vs. A8

Item 2 measures attributes A3a and A8. All eight students got the item correct. The item asks what rhetorical strategy was used in the paragraph (A8). To get the item correct, the literal meaning of one or more of the following sentences must be understood (A3a):

- (1) *For him the sounds of the world were the ingredients he mixed into appetizers, main courses, and desserts to satisfy the appetite of his worldwide audience.*
- (2) *He wasn't averse to going out in a boat to catch the fish himself.*
- (3) *He would raise the fowl himself.*
- (4) *But when that musical meal appeared before you none of the drudgery showed.*

Consider the verbal reports provided by K.R. and G.A.:

**K.R.:** So what does he mean, when he is saying all of this. Okay...um...**the sounds of the world were the ingredients, it's talking about how he takes the sound that he hears and it's relating it to food (A3a)**, he wasn't averse to going out in a boat to catch the fish himself. ...Oh, so he ...he didn't like things that he didn't sort of have insistence, creating it, raising the fowl, the chicken, but the music meal appear before you...**Metaphor, through relating food and making food to his making music (A8)**...I think I probably say metaphor...because from rereading, from line 5 to the end, **he is comparing things that aren't shouldn't be compared with music that most people would think. He was comparing food, and like food mostly, and making food, and how you get to what you get to the restaurant from like the farm (A8).**

**G.A.:** ...if you look back line8 to 10, **it's talking about, like, actually going out,**

**and doing things to get the final product, like getting fish by going into the boat and catching it and having a chicken by raising it (A3a).** So, in the end all you have is the fish or the chicken, there is no indication of how you got it. **So to me it is a metaphor of how he got his music, like final product of his music (A8).**

As indicated in the above reports, before the students arrived at their answers, they need first have an understanding of what the sentences were talking about. Then they would realize that the author was comparing different activities to the making of music, which finally led them to get the rhetorical strategy metaphor.

### **Attribute A4a vs. A4b**

Item 16 measures both attribute A4a and attribute A4b. Six students correctly answered this item. The item asks for the author's purpose in writing a paragraph (A5). However, to answer this item, the students have to both understand the literal meaning of the paragraph (A4a) and make inferences about the paragraph (A4b). Consider the verbal reports provided by G.B. and P.B.:

**G.B.:** To answer this question, you have to find what the author meant in the first place. **That wisdom, as it comes, blah-blah, ...is expressing what the author believes to be the economic reasons for people building the new centers of the arts (A4a).** Property values are not being very concerned about. Well, tradition, or perhaps, the older buildings are nicer. Just because you can make the new one shiny doesn't mean it is necessarily better. ...So, primarily the paragraph serves to ...criticize the way in which **cultural buildings are viewed as commodities. That's what it is (A4b).**

**P.B.:** So...**what is this paragraph saying...uh...So, this is all about how to get, you know, more, how to stretch your dollar kind of thing, ...by building cultural centers (A4a).** So, yeah, they are commodity and that's just what the whole paragraph is talking about. Really I think **what the paragraph was conveying was how culture's being destroyed by modern values (A4b),** so criticize the way in which cultural buildings are viewed as commodities, so I picked it which was A.

In both verbal reports, the students first attempted to grasp the literal meaning of the paragraph. Then, based on their understanding of the paragraph, they made further inferences about the paragraph which helped them get the purpose of the author in writing the paragraph.