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Investigation into the intersection between response process validity and answer-until-correct validity: development of the repeated attempt processing issue detection (RAPID) method

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With the already widespread nature of multiple-choice assessments and the increasing popularity of answer-until-correct, it is important to have methods available for exploring the validity of these types of assessments as they are developed. This work analyzes a 20-question multiple choice assessment covering introductory undergraduate chemistry topics which was given to students in an answer-until-correct manner. Response process validity was investigated through one-on-one think-aloud interviews with undergraduate chemistry students. Answer-until-correct validity was also explored using an analysis of partial credit assignments. Results indicated the convenience of the quantitative partial credit method came at great cost to the precision of validity issue detection and is therefore not a valid shortcut to more rich qualitative approaches. The repeated attempt processing issue detection (RAPID) method is a novel method developed as a combination of response process and answer-until-correct validity. Results from this new method revealed validity issues that were undetected from the use of either approach individually or in concert.

Introduction

Assessment validity

One of many considerations that must be made when developing an assessment is ensuring the assessment produces data with evidence of high validity. Assessment validity is defined as "the degree to which evidence and theory support the interpretations of test scores entailed by proposed uses of tests" (American Educational Research Association, 1999; Arjoon *et al.*, 2013). An assessment that produces data with evidence of high validity does an accurate job of measuring what it was designed to measure. Or, more alarmingly, an assessment with an abundance of validity issues does a poor job reflecting the students' understanding. To minimize the risk of flawed assessment results, many types of validity investigation methods have been developed. Because these many methods exist, the optimal way of showing high assessment validity will vary based on the format, content, and context of the assessment (Wren and Barbera, 2013; Kreiter, 2015; Lewis, 2022; Lazenby *et al.*, 2023).

Response process

One method for investigating the validity of items within an assessment is the analysis of students' response processes. Response process centres around the steps the student takes to arrive at their response and investigates the degree to which the student's process aligns with the response they choose (Kreiter, 2015; Deng *et al.*, 2021). During forced-response item construction, the responses are formulated based on the correct process (correct answer) and specific, common incorrect processes (distractors). In research, these incorrect processes would ideally be determined by a qualitative analysis of common student mistakes as they engage with the item stem as an open-response question. However, in the typical classroom, it is more practical for incorrect distractors to be developed by utilizing the experience of an instructor who has worked with students and is familiar with the errors they tend to make.

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During a response process study, investigation into the process a student articulates within a single attempt when solving the item should reveal that only a student with a correct process and understanding will select the correct answer. Alternatively, students with incorrect processes and understandings will select the distractors. While this view of response process may suffice for some applications, it can also be explored more richly by not only ensuring students with an incorrect process and understanding select an incorrect response, but also that the incorrect process used by the student aligns with the process proposed during item construction (coined "enhanced response process validity" for differentiation here). The utilization of enhanced response process validity is particularly necessary if a deeper understanding of student misconceptions is desired. This is because traditional response process validity analysis only allows for claims of whether a mistake had been made; whereas enhanced response process validity allows for claims about what mistake had been made.

A fictitious example item showing item construction followed by examples of artificial student responses that might be collected during think-aloud interviews is shown in Fig. 1. This fictitious item was designed with five responses (as opposed to the four responses used for the actual study) to demonstrate the various validity threats more easily. Both the process assignment as well as the enhanced response process validity assignment are provided. These fictitious student responses are provided to illustrate the potential array of response process validity classifications; there are many other possible pathways (and other incorrect responses/processes) a student may follow.

As response process validity issues can arise from correct or incorrect responses, full response process analysis could require an analysis of all student responses. Coupling this with the time and resource investment to conduct and transcribe interviews, it is not surprising that response process validity investigations are less commonly used compared to other measures for validity. Examples of investigation into single-attempt response process validity can be found in the literature however, the reporting is relatively scarce compared to other validity methods (Adams *et al.*, 2008; Stains *et al.*, 2011; Wren and Barbera, 2013; Brandriet and Bretz, 2014; Schwartz and Barbera, 2014; Trate *et al.*, 2019). It is possible that recent chemistry education publications regarding response process will lead to an increase in its popularity within the field (Deng *et al.*, 2021; Balabanoff *et al.*, 2022).

Answer-until-correct and partial credit analysis

An extension of multiple-choice assessments is answer-until-correct. Answer-until-correct methods use immediate feedback to allow students to reengage with a problem until they arrive at the correct answer (Pressey, 1926; Epstein *et al.*, 2001). By allowing repeated attempts on each problem, students are given multiple opportunities to improve their process and learn the material (Bangert-Drowns *et al.*, 1991; DiBattista, 2013). Answer-until-correct methods also allow an alternative approach to scoring where credit can be awarded to students based on how many attempts are required to arrive at the correct option (as opposed to assigning partial credit to each response). This immediate correction of students' incorrect response choices can minimize the risks of students solidifying incorrect information (Skinner, 1974; Brown *et al.*, 1999; Brosvic *et al.*, 2005; Roediger and Marsh, 2005). Other work has found additional benefits of answer-until-correct methods including promotion of

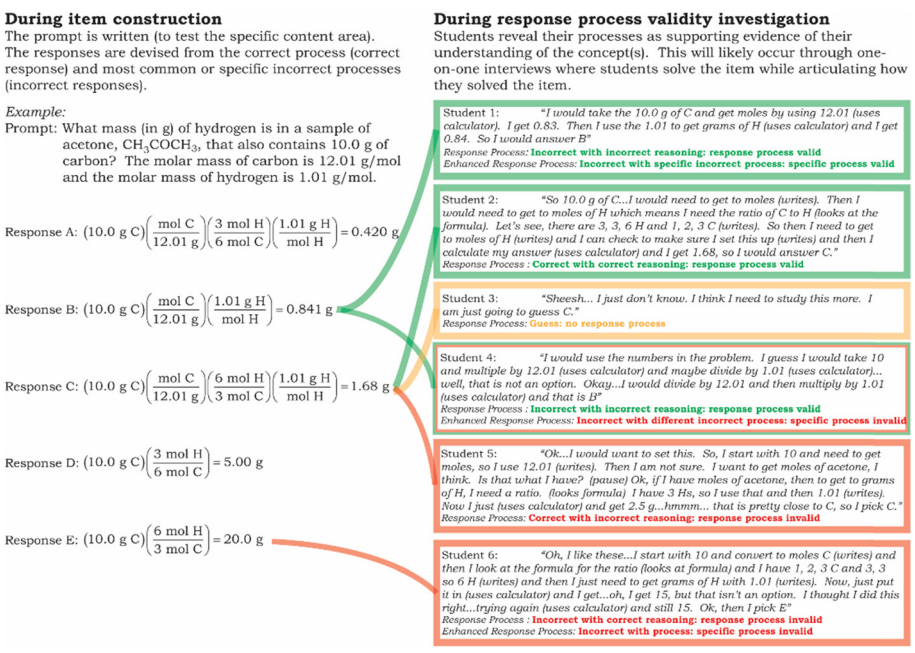


Fig. 1 Fictitious example item showing item construction and single-attempt response process validity (with artificial student responses). Evidence for response process validity is in green, no response process in orange, and potential response process validity issues in red. For incorrect responses, enhanced response process validity is also provided.

learning, student appreciation, and creation of assessments which have questions build off of one another because the correct answer to the previous questions can always be found (Epstein, 2002; Dibattista *et al.*, 2004; Clariana and Koul, 2005; Slepkov and Shiell, 2014; Attali, 2015; Schneider *et al.*, 2018; Pinhas, 2021). Another commonly cited advantage is that partial credit based on number of attempts can be awarded without making assumptions about the processes used by students to arrive at their response (Pressey, 1950; Epstein *et al.*, 2002). However, while avoiding some assumptions about incorrect responses, answer-until-correct does rely on the assumption that as students engage with the immediate feedback, they are correcting their flawed thought processes. This means for an answer-until-correct assessment to be valid; students must use the immediate feedback to build a more complete understanding of the intended concepts ultimately arriving at the correct process and the correct response.

A means to arrive at the sequential improvement of a student's process could be investigated through a merging of multiple responses for each item and a partial credit assignment for each response. Therefore, prior to completing this method of answer-until-correct validity, partial credit must be assigned to each response. This can be done during the test construction (when the process for each response is developed and justified) or following the test construction. When used for validity studies, it is also important to consider agreement between raters of partial credit assignment (Murphy *et al.*, 2023a; 2023b). For the example used in Fig. 1 (and used again here), partial credit is assigned based on using a scale of full credit, $\frac{3}{4}$ credit, $\frac{1}{2}$ credit, $\frac{1}{4}$ credit and no credit. As shown in Fig. 2, for an item to be valid using the sequential partial credit analysis method, a student would be expected to show a progressive increase in the assignment of partial credit for each response in sequence (noted in the figure for artificial students A–C in green/blue). An issue for validity would be cited when the sequence of responses did not show a progressive improvement in partial credit (shown in the figure for artificial students D and E in red/orange). What is not detected through this method is the incorporation of any processing and/or guessing. Assumptions can be made about student process (especially when using process-oriented assessment items), but the assumption of student process based on response selection may not always be valid (Ralph and Lewis, 2019). Because this type of analysis is conducted only using students' response sets, not their think-aloud protocols of their processes, it does not account for details of the single-attempt response process which will be expanded upon in the next section.

The analysis that would then follow would consider the sequence of the responses based on expert assigned partial credit. Continuing with the example from Fig. 2, each response set is provided with the numeric analysis that would provide the assignment of valid *vs.* invalid processes using this partial credit analysis (Table 1).

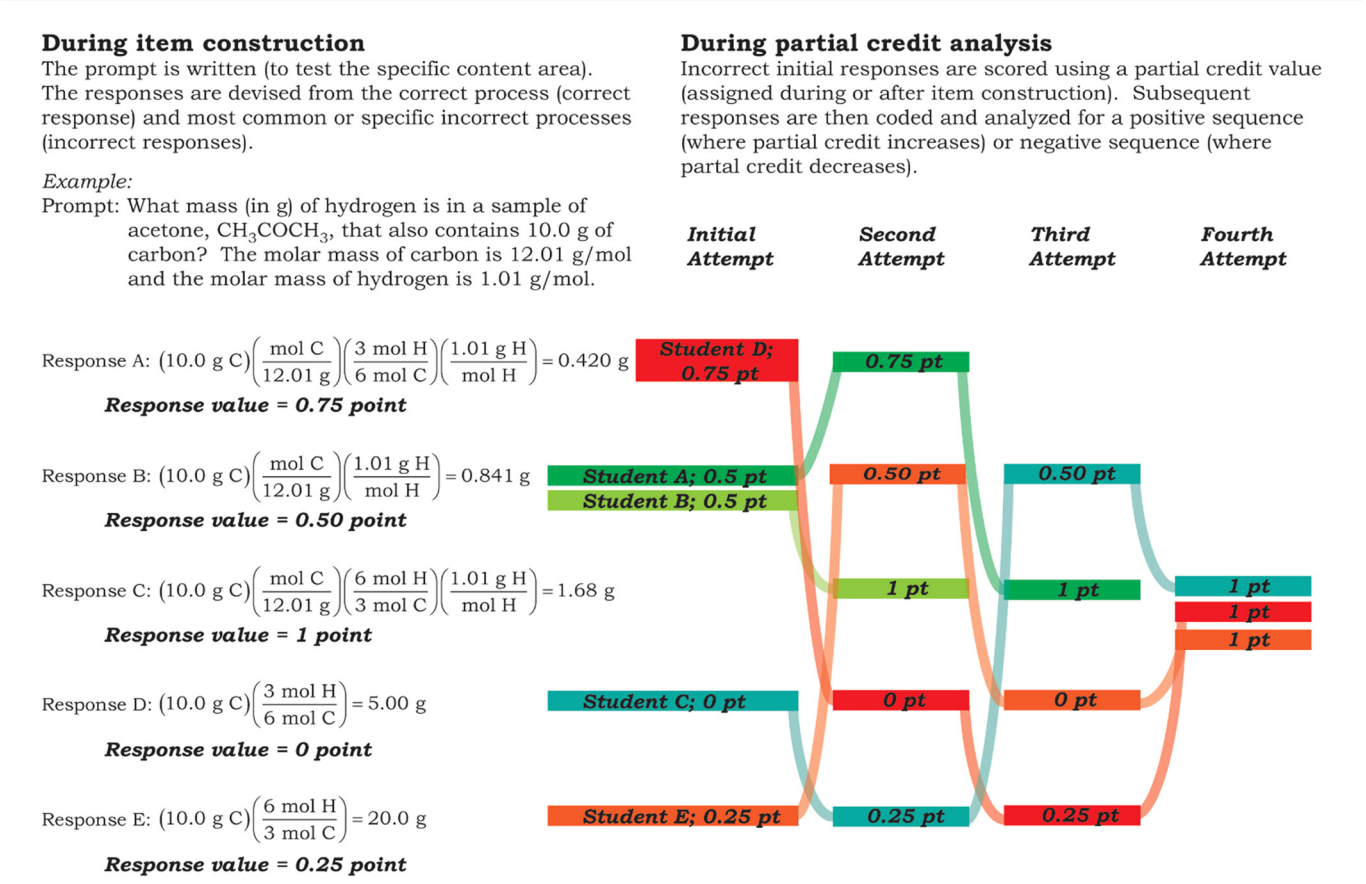


Fig. 2 Possible pathways of partial credit analysis with valid response sets (green/blue) and invalid response sets (red/orange).

Table 1 Hypothetical example of numeric processing of response sets for partial credit analysis

	Response value				Change in values				
Student (color)	Initial response	Second response	Third response	Fourth response	Initial to second	Second to third	Third to fourth	Constant improvement	Valid partial credit process
A (green)	0.50	0.75	1.00		+0.25	+0.25		Yes	Valid
B (light green)	0.50	1.00			+0.50			Yes	Valid
C (blue)	0.00	0.25	0.50	1.00	+0.25	+0.25	+0.50	Yes	Valid
D (red)	0.75	0.00	0.25	1.00	**−0.75**	+0.25	+0.75	No	Invalid
E (orange)	0.25	0.50	0.00	1.00	0.25	**−0.50**	1.0	No	Invalid

Intersection of response process and partial credit analysis

While previous work has made progress in validating the theory and implementation of answer-until-correct in general, and in methods for single-attempt response process validity on traditional multiple-choice assessments, no exploration of the relationship between these two concepts could be found (Towns, 2014; Slepkov *et al.*, 2016). Now that the limitations of these methods have been discussed, the theoretical effect of merging these methods can be explored. As is shown in Fig. 3, a limitation with single-attempt response process validity is it only analyses individual attempts for potential threats. When a student engages with an item once (*i.e.*, traditional, single response assessment), this method fulfils the purpose of this level of item validity. However, when students engage with an item multiple times, as when using answer-until-correct assessment, a set of responses or attempt sequences is generated (as shown in Fig. 3). A necessary element of an attempt sequence is the student is expected to reengage with the item between attempts. One example of a student not reengaging after an initial incorrect response is: "*...Because I feel like earlier I was off by a little margin*". In this example the student selected the closest response to their initial attempt only because of the proximity to their first answer. This student did not utilize the knowledge of their initial incorrect response to reengage with the item. This issue of reengagement is expanded upon in Appendix 1.

When students do reengage, attempt sequences still need to be evaluated for validity. This can potentially be accomplished by considering a partial credit analysis of each response and combined in the attempt sequence (as shown in Fig. 3). However, this method does not consider any student processing, only assumed processing through assigned partial credit value (assigned to the incorrect responses). Therefore, a new method was developed to examine the processing progression within an attempt sequence, which we called "Repeated Attempt Processing Issue Detection" or RAPID (also shown in Fig. 3).

To demonstrate the theoretical need for this new RAPID method Fig. 4 demonstrates an example process (used by Student I) which could result in missed validity issue detection. Student I would not have been flagged as an answer-until-correct validity issue despite an answer-until-correct validity issue being present. In this case the misdetection was caused by a response process issue present in the student's initial attempt which misaligned the student's process with the partial credit of their answer choice (as shown with a red outline). To correctly flag this answer-until-correct validity issue, a different method is required which overcomes the potential interaction between single-attempt response process and answer-until-correct validity issues.

Alternatively, the process used by Student II in Fig. 4 shows how a validity issue could be overlooked when using only single-attempt response process. For this student, each individual attempt has the students' thought process align with their answer selection but how the student engaged with the answer-until-correct feedback constitutes a threat. The student's initial attempt is nearly correct with only a small mistake of inverting the mole ratio. However, once they discover this response is incorrect, rather than correcting their mistake, they move in the wrong direction and start making additional mistakes. In this case the feedback provided by the answer-until-correct format did not help the student and should be flagged as a validity issue. This shows the use of only single-attempt response process to search for validity issues within a multiple-attempt assessment is insufficient.

Both example misdetections using only traditional methods shows the need for a new method (like RAPID) which looks at the intersection of single-attempt response process validity and answer-until-correct validity and investigates the progression of students' processes through multiple attempts of a single task.

Research questions

This project set out with the goal of answering the following research question:

(1) How does the newly developed RAPID method perform in detecting validity issues compared to single-attempt response process validity and a quantitative approach to answer-until-correct validity?

Preamble

To properly compare the RAPID method against other validity issue detection methods, all three methods (response process, partial credit analysis, and RAPID) were conducted and will be discussed in this work. To present this work with a clear delineation between the methods, the full methods and results of response process validity and the partial credit analysis for answer-until-correct validity will first be discussed. These results served as the baseline against which the RAPID method would be compared.

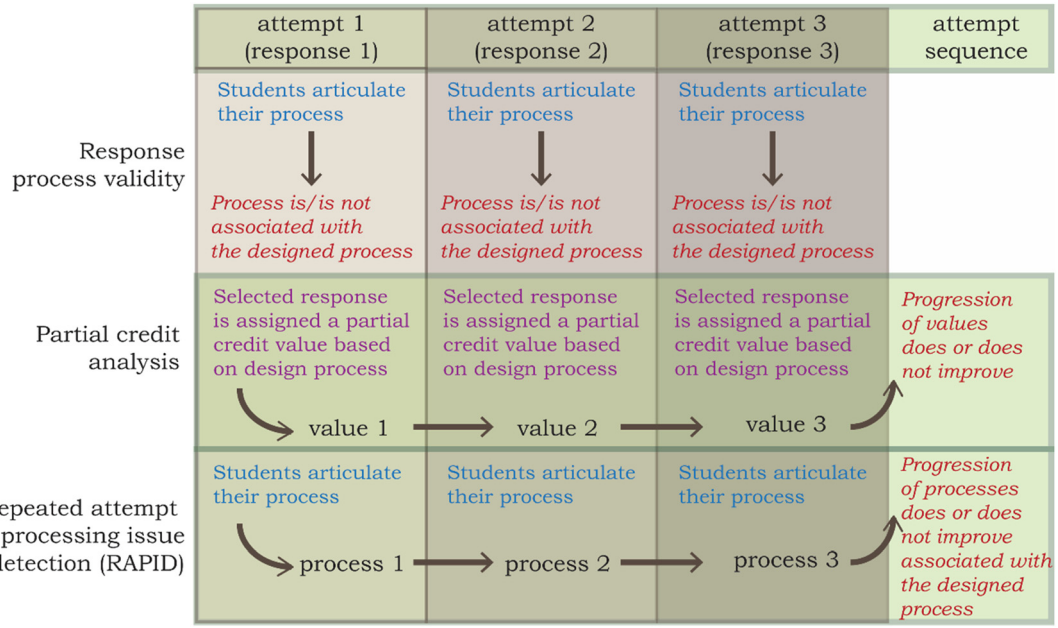


Fig. 3 Comparison of the methods of single-attempt response process validity, partial credit analysis, and RAPID. Coding in figure: blue text = information from think-aloud interviews; purple text = responses; red text = results available from each method.

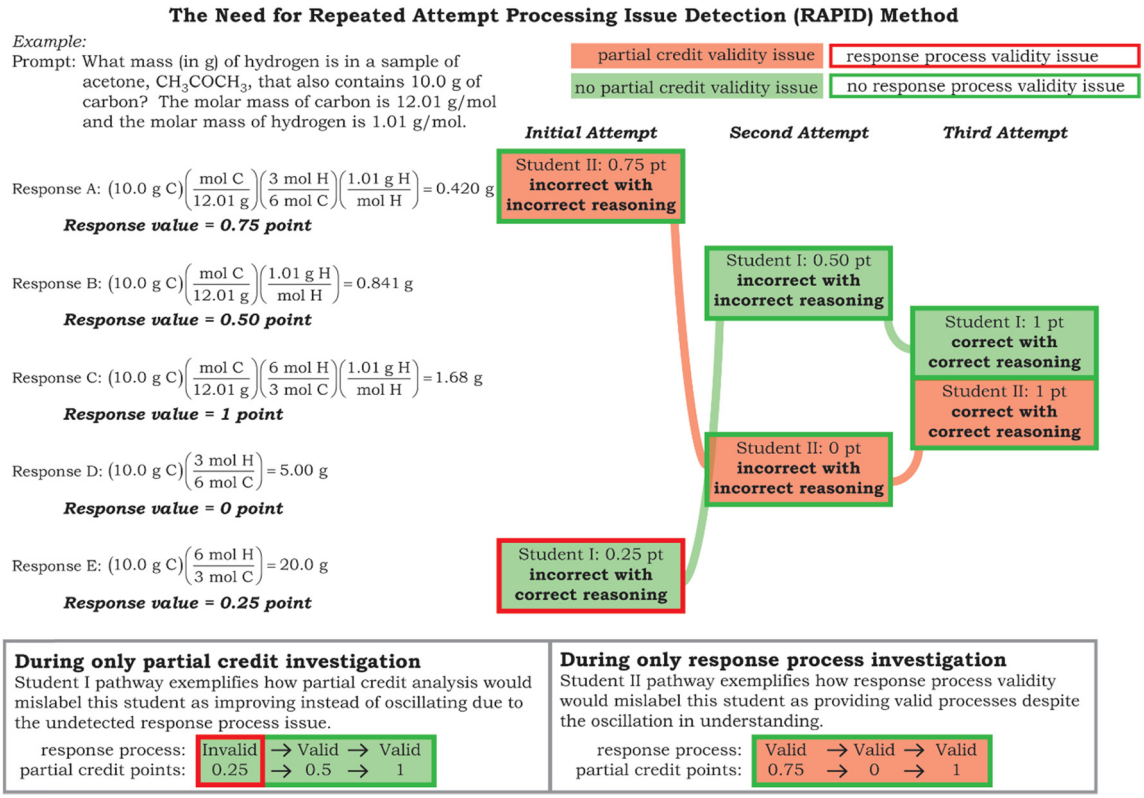


Fig. 4 The need for the RAPID method (where answer-until-correct and single-attempt response process validity missed detection).

With these baselines being set, the "Methodology" and "Results" section strictly explore where the previous methods failed, how RAPID was conducted, and how RAPID compares against the other approaches. In order to understand the value and deficiencies of response process validity and partial credit analysis compared to the use of RAPID, and to ensure a reasonable comparison of results between methods, the same assessment was used for all methods. All of the compared results also shared the same sample.

Sample

All of the methods conducted used data collected through think-aloud interviews where students worked through a 20-question assessment while verbalizing their thought processes. The assessment covered introductory chemistry concepts and was in a multiple-choice format with four responses. The students worked through the questions in an answer-until-correct style. Answer-until-correct was conducted by having students select their initial response followed by the interviewer telling them whether that response was correct or incorrect. If incorrect, the students reattempted the problem and selected another answer choice. This process was repeated until the student arrived at the correct answer at which point they moved on to the next question.

Interviews were performed with 53 students at three different institutions. All students were current general chemistry students who were in the final weeks of their course. The first institution is classified as a large urban research-intensive institution and interviews were conducted in-person with 22 students. At the second institution (a Hispanic serving comprehensive university) and third institution (a small comprehensive university with bachelor level science programs), the interviews were conducted digitally over video-conference software (Trate *et al.*, 2020). Participating students from the second and third institution worked through the same paper assessment as the students from the in-person institution with on-site assistance from one of the authors. Digital interview participants would verbalize their thought process and answer selection with the interviewer simply informing them whether they were correct or incorrect. Fourteen students were digitally interviewed from the second, and seventeen students were digitally interviewed from the third institution. Full details on the remote interviews and sample can be found in previous work (Trate *et al.*, 2020). All interviews were digitally recorded and later transcribed for analysis. All students who participated consented to do so through an IRB approved consent form and protocol at each institution.

Response process validity

Response process method

Response process validity analysis for this work followed the process of think-aloud one-on-one interviews conducted with students so that the students' thought processes could be collected and compared against their final answers. Further information on how this data was collected can be found in the "Sample" section. Investigation into response process was conducted on each of the attempts made by each student. Therefore, each attempt was assigned a single code and in the event of multiple codes being applicable the code most related to the students' final answer selection was used. With 20 questions × 53 students, 1060 first attempts were initially analysed. However, because the assessment was taken as answer-until-correct, 251 second attempts and 113 third attempts were also investigated. Eight possible classifications were used in the analysis of the responses (described in Table 2). These codes are based on what has been previously reported in the literature (Trate *et al.*, 2019). Of these codes, elimination, correct answer for the wrong reason, and wrong answer but had the right reason would all be classified as potential issues as they indicate the student was either using an incorrect process to arrive at the correct response or was using the correct process but not arriving at the correct response. Totally correct and totally incorrect both support item validity as the assessment correctly matches correct/incorrect answers with correct/incorrect processes respectively. Codes of guessing, incorrect but strategy cannot be determined, and correct but strategy cannot be determined were not used to support or refute response process validity as the student's process was either not present (guessing) or could not be determined. All codes were initially assigned by a single rater, and a sample consisting of eight questions were distributed to five raters to ensure reasonable code assignment. The questions distributed were specifically selected to represent a variety of codes. Each of the raters were chemistry content experts and part of the research project. Initially, a 71% agreement was found between raters. Following independent coding, codes were discussed until consensus was reached. As consensus always aligned with the original rater, no changes were made. Disagreements in initial assignment were primarily based on the primary rater being more likely to assign cannot be determined codes. It should also be noted that the enhanced response process validity was not conducted in this work as the scope of this work was only to look at whether students had made mistakes, and not at what mistakes had been made.

Response process results

Response process validity coding of the interviews revealed the distribution of codes shown in Table 3. These results indicate that response process validity issues represented a relatively small proportion of the overall attempts (2.1% + 1.4% = 3.5%).

Table 2 Codes used to analyse response process validity

Code	Explanation
Totally correct	Selected correct answer with correct reasoning and correct conceptual understanding
Totally incorrect	Selected incorrect answer with incorrect reasoning and incorrect conceptual understanding
Guessed	Selected correct or incorrect answer by guessing, without any process
Elimination	Eliminated choices without any content knowledge
Correct answer for the wrong reason	Used a process that was wrong but that led them to a correct answer
Wrong answer but had the right reason	Used a process that was correct but selected an incorrect answer
Incorrect but strategy cannot be determined	Selected incorrect answer with a process which cannot be determined
Correct but strategy cannot be determined	Selected correct answer with a process that cannot be determined

Table 3 Counts and percentages of each response process validity code which was assigned

	Response process validity issues	Count	Percent (%)
Totally correct	No	841	59.1
Totally incorrect	No	264	18.5
Elimination	Yes	30	2.1
Correct answer for the wrong reason	Yes	20	1.4
Wrong answer but had the right reason	Yes	0	0.0
Guessed	Cannot determine	208	14.6
Incorrect but strategy cannot be determined	Cannot determine	23	1.6
Correct but strategy cannot be determined	Cannot determine	38	2.7

However, a proportion of attempts was not used to support or refute validity as 14.6% of attempts did not use a response process (coded as guessing) and in 4.3% (1.6% + 2.7%) the process used could not be determined (coded as correct/incorrect but strategy cannot be determined).

While knowledge of the overall detection of response process codes is informative, it is more important to consider the concentration of potential issues by item. As shown in Table 4, only eight of the 20 questions showed any response process validity issues, however, questions 11 and 13 had a higher concentration (exceeding 10%) of the elimination code.

While not clear from the coding data, another item of note is question 20. In interviews it was observed that many students were unable to apply appropriate thought processes because they were confused by the question prompt and expected task. This perhaps could be seen in the first attempt data in the higher number of ''cannot be determined'' codes but was most evident in the interviews where students articulated not being sure what the question was asking and continued to guess for all of their attempts. One example of this is shown in Fig. 5.

The analysis of students' first attempts for response process validity on each item can be further expanded to look at how response process issues may evolve over multiple attempts. Although on the students' first attempts, only 2% showed validity issues (Fig. 6), on the second attempt this increased to 4%, and by the third attempt it further increased to 12%. This shows that as the attempt number increases, issues become more prevalent which supports that an investigation of response process validity on answer-until-correct testing format could reveal valuable (and often missed) validity issues. Additionally, because the second and third attempts only include students who were incorrect initially, special attention should be paid to the prevalence of response process validity issues with lower performing students. This also suggests the impact could be even greater on more difficult assessments where more students may require second and third attempts, although this was outside of the scope of this work.

Of the attempts flagged for response process issues, all fell into ''elimination'' and ''correct for the wrong reason''. The final response process validity issue which was searched for was ''wrong answer but had the right reason'', which was not observed in this dataset. For an attempt to be flagged with the code of elimination, the student needed to arrive at their answer not based on articulated chemistry reasoning but rather by removing the other answer choices based on arbitrary reasoning.

One example of elimination which was observed in this sample is shown in Fig. 7 for a student's third attempt on question 3. Here the student eliminated the answer based

Table 4 Percent of first attempts by question showing the prevalence of each response process validity code[a]

Question	Totally correct	Totally incorrect	Correct answer for the wrong reason	Elimination	Correct but strategy cannot be determined	Incorrect but strategy cannot be determined	Guessed
1	92	8					
2	79	17			2		2
3	70	26			4		
4	85	11	2		2		
5	75	4			4	2	15
6	83	8			6		4
7	68	15	2		4	2	9
8	79	4	2		4	2	9
9	66	17	2		2		13
10	45	30	2	2		6	15
11	64	8		23	2		4
12	64	28			4		4
13	47	36		11	2		4
14	75	19			4		2
15	60	25	2	2	4		8
16	75	23				2	
17	79	15					6
18	74	9			2		15
19	45	40			6		9
20	47	40			4	6	4

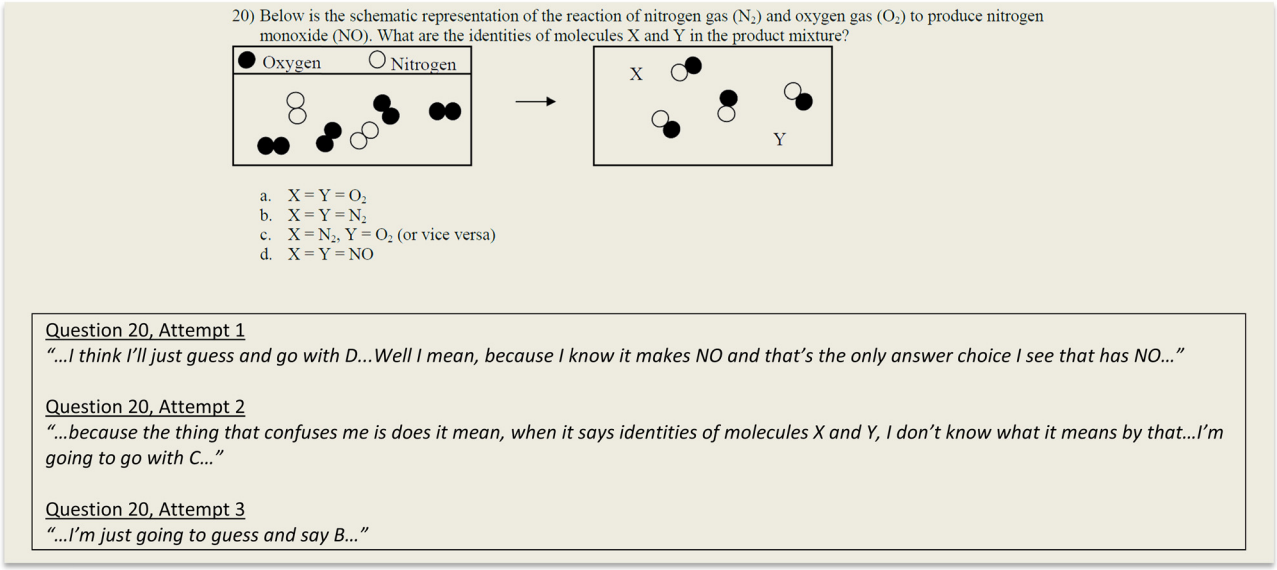


Fig. 5 Example of student being confused by the prompt of question 20.

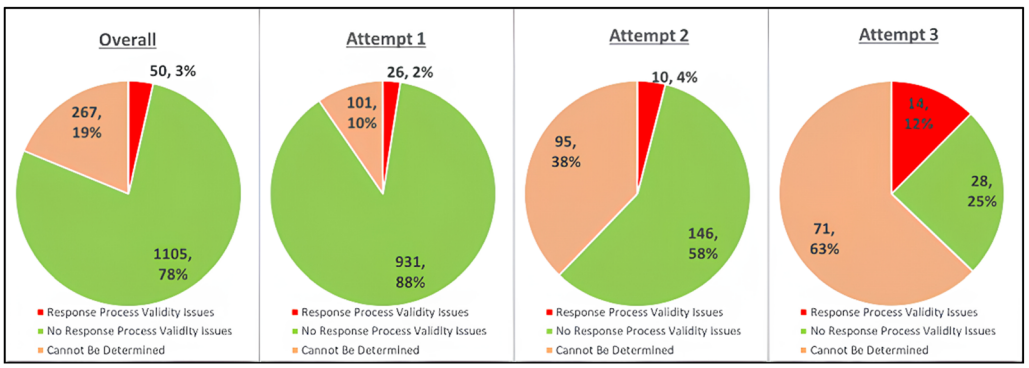


Fig. 6 The counts of student attempts (and more broadly over all of their attempts) which were not flagged as response process validity issues (totally correct and totally incorrect, in green); flagged as potential response process validity issues (elimination and correct answer for the wrong reason, in red); and could not be determined (guessing, incorrect but strategy cannot be determined, and correct but strategy cannot be determined in orange).

on the response being larger than the other response options. It's important to note that this elimination required students to eliminate response options without articulating any chemistry reasoning. For example, had the student articulated that the molar mass for a compound this small could not reasonably be that large, they would not be coded as using elimination.

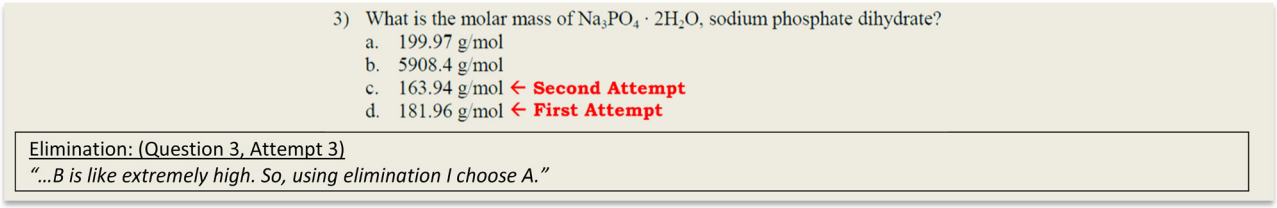
An example of a response process validity issue based on a student selecting the correct answer for the wrong reason is also provided below (Fig. 8). Due to the algorithmic nature of this example, a mathematical representation of their verbalized thought process is also included to demonstrate this student's flawed reasoning leading them to the correct answer.

Despite the clear benefits of response process analysis, an important limitation is that this analysis only considers a single attempt at a time with no connection to other attempts on the item. Therefore, although response process can provide a valuable snapshot of processing validity, it has no mechanism to consider the larger picture of the student's progression in process and understanding over repeated attempts. Therefore, as indicated in the "Preamble" section, the response process analyses were only one part of this larger analysis seeking to compare this approach against alternate options.

Partial credit analysis for answer-until-correct validity

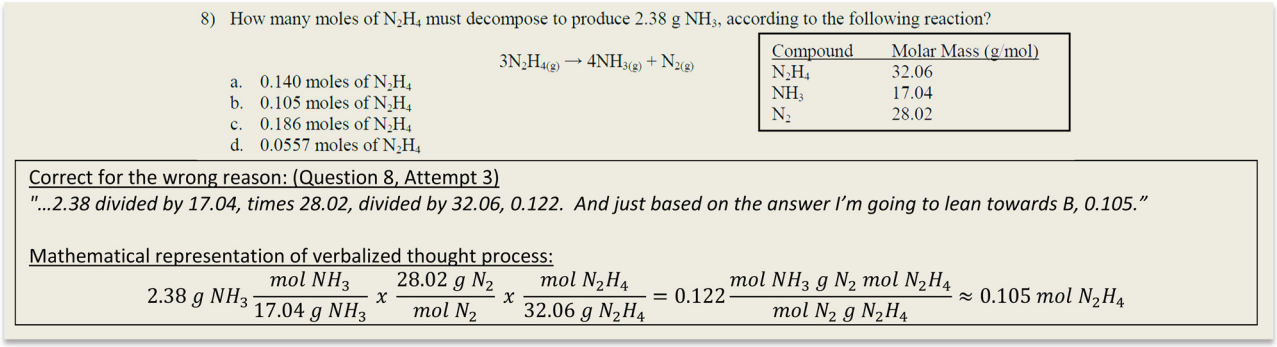
Partial credit analysis method

The partial credit analysis was conducted on attempts where students selected an incorrect answer on their first attempt and tracked their performance over subsequent attempts. This analysis was conducted on the same sample described previously and used for the qualitative response process validity analysis. Of the total 1424 attempts that were collected, only 615 were suitable for partial credit analysis (251 first attempts, 251 second attempts and 113 third attempts). More accurately,


3) What is the molar mass of $Na_3PO_4 \cdot 2H_2O$, sodium phosphate dihydrate?
a. 199.97 g/mol
b. 5908.4 g/mol
c. 163.94 g/mol ← **Second Attempt**
d. 181.96 g/mol ← **First Attempt**

Elimination: (Question 3, Attempt 3)
"...B is like extremely high. So, using elimination I choose A."

Fig. 7 Student using elimination on their third attempt to remove choice b and select choice a. Response choices c. and d. were previously selected on the first two attempts.


8) How many moles of N_2H_4 must decompose to produce 2.38 g NH_3, according to the following reaction?

$$3N_2H_{4(g)} \rightarrow 4NH_{3(g)} + N_{2(g)}$$

Compound	Molar Mass (g/mol)
N_2H_4	32.06
NH_3	17.04
N_2	28.02

a. 0.140 moles of N_2H_4
b. 0.105 moles of N_2H_4
c. 0.186 moles of N_2H_4
d. 0.0557 moles of N_2H_4

Correct for the wrong reason: (Question 8, Attempt 3)
"...2.38 divided by 17.04, times 28.02, divided by 32.06, 0.122. And just based on the answer I'm going to lean towards B, 0.105."

Mathematical representation of verbalized thought process:

$$2.38\ g\ NH_3 \frac{mol\ NH_3}{17.04\ g\ NH_3}\ x\ \frac{28.02\ g\ N_2}{mol\ N_2}\ x\ \frac{mol\ N_2H_4}{32.06\ g\ N_2H_4} = 0.122 \frac{mol\ NH_3\ g\ N_2\ mol\ N_2H_4}{mol\ N_2\ g\ N_2H_4} \approx 0.105\ mol\ N_2H_4$$

Fig. 8 Student coded as correct for the wrong reason on their third attempt to select choice b.

138 two-attempt sequences and 113 three-attempt sequences were analysed, for a total of 251 attempt sequences.

Because partial credit analysis requires partial credit assignment to all responses, for this work each of the four responses for each item was assigned a credit value of either 0, 0.25, 0.5, or 1 by expert raters based on how reasonable the inferred process associated with each response was. The correct answer would be 1, answers derived from close to the correct process would be 0.5 or 0.25 depending on how far they deviated from the correct process, and answer choices resulting from extremely flawed processes would be 0. Of the four possible credit values (0, 0.25, 0.5, 1), each could be assigned as frequently or infrequently as the raters felt appropriate. Five instructors from four institutions who regularly teach general chemistry I as well as one post-doc independently assigned partial credit and then discussed until consensus was reached. For numeric questions, raters were provided the mathematical process used to design each response. The mathematical steps served as the inferred process for students who selected that response.

Partial credit analysis results

Using the partial credit values for each response, students whose answer selection suggested they were close to the correct answer, but the next selection indicated they were further from the correct answer were flagged as possible answer-until-correct validity issues following the method described in Fig. 2 and Table 1. Of the 364 individual attempt sets (251 from first to second attempt +113 from second to third attempt), only 55 (15.1%) showed a transition from a higher credit value to a lower credit value. This conclusion holds true on the question-level as well as is shown in Fig. 9 with each question being far more likely to have students perform the same or better on subsequent attempts. The question with the largest number of students performing worse on later attempts was question 20. This result was not surprising as the response process results previously indicated question 20 had some students struggle to understand what was being asked. With this confusion, many students resorted to guessing which increased the number of students who showed worse performance on later attempts. However, it is important once again to recognize the purpose of this work was not to investigate specific validity threats within this assessment, but rather compare detections between this method, response process, and the newly developed RAPID method.

Methodology

The RAPID method implements a qualitative coding method similar to response process but applies the codes to attempt sequences (*e.g.*, multiple attempts on a single item) instead of individual attempts. An important aspect of an attempt sequence is that students must reengage with the item following each attempt. One example was included prior where a student did not reengage after their initial incorrect response and instead opted to select the closest response to their initial answer. Another pathway a student may take to justify a response without reengagement is also included in Appendix 1. Any evidence for students not reengaging between attempts was flagged as a validity threat prior to RAPID coding.

For RAPID coding, each of the attempt sequences was assigned a single code from Table 5. These codes focus on how the student's thought process evolved over multiple attempts

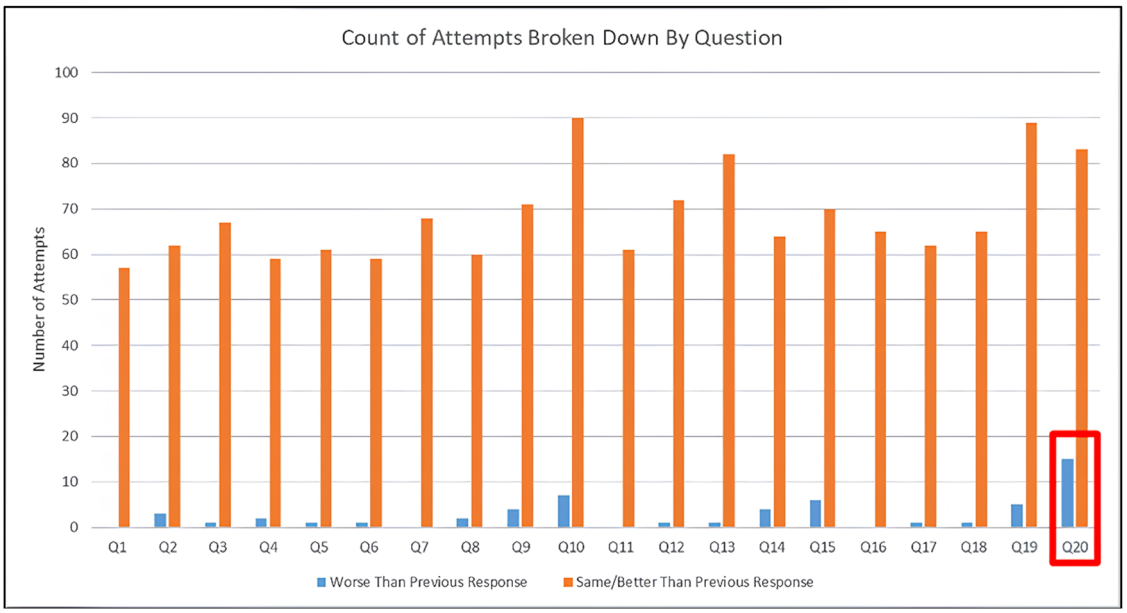


Fig. 9 A comparison of the number of attempts, by question, between answer-until-correct validity issues (Worse than previous response) and non-answer-until-correct validity issues (same/better than previous response).

Table 5 Codes and code criteria under the RAPID method

Code	Explanation
Progression	Student reasoning on the item improves over attempts
Stagnation	Student reasoning on the item does not change over attempts
Regression	Student reasoning on the item gets worse over attempts
Oscillation	Student reasoning on the item varies (with elements of both progression and regression) over attempts
Resort to guessing	Student has no process which could be tracked and guessed instead
Progression with guessing	Student reasoning on the item improves over attempts but guessed for one attempt
Stagnation with guessing	Student reasoning on the item does not change over attempts but guessed for one attempt
Regression with guessing	Student reasoning on the item gets worse over attempts but guessed for one attempt
Oscillation with guessing	Student reasoning on the item varies (with elements of both progression and regression) over attempts but guessed for one attempt
Only 1 attempt was needed	Student answered correctly on their first attempt so answer-until-correct validity cannot be investigated

on a single problem. As such, the development of these codes was based on all of the possible changes to student reasoning which could occur. Initially, coding was completed by a single rater that was then blindly checked with four chemistry content experts to ensure appropriate assignment. Any disagreement was resolved through discussion until consensus was reached and the coding scheme assignment was consistently applied.

Examples of regression, stagnation, progression, and oscillation are shown below. Attempt sequences coded as guessing were not flagged as evidence for or against validity. Students who only articulated guessing for an entire attempt sequence were coded as guessing. However, if a student used two processes (for two attempts) and then resorted to guessing (for the final attempt), the initial attempt set (attempts 1 and 2) were coded but then included the additional component of "with guessing" to complete the attempt sequence code.

Regression: (Question 3, Attempt 1, 2 and 3)

"...Okay then I would do, so there's 3 moles of sodiums, so 3 times the molar mass of Na, 22.99 times 3, plus and then potassium is 30.97 plus, 4 times 16, plus 4 times 1.008, plus 16. So, I got 183.97. This is little bit off... That's the molar mass of sodium phosphate dihydrate....So, I'm just going to do it again, just make sure...2 times 22.99 plus 30.97 plus 5 times 16 plus 4 times 1.008. Okay still I got the same answer...So right then I'm gonna choose D."

"...So, I have to do is take the molar mass of just like sodium phosphate and may be the hydrate part...is not there...so it's 163..."

"Okay, now I know it's not C or D. But B is like extremely high. So, using elimination I choose A..."

Mathematical representation of verbalized thought process

(1) $(22.99 \times 3) + (30.97) + (4 \times 16) + (4 \times 1.008) + 16 = 183.97$
(2) $(30.97) + (4 \times 16) + (4 \times 1.008) + 16 = 115.002$

Stagnation: (Question 8, Attempt 1 and 2)

"...so, I'm going to go ahead and start with the 2.38 grams of the NH_3 and divide that by the molar mass for the NH_3, 17.04 grams. That gives me 2.38 divided by 17.04, 0.14 moles. But that's still the NH_3. So, since I have the 0.14 moles of NH_3, I can multiply it by 3

moles of N_2H_4 and then divide that by the molar mass of N_2H_4...I will plug in that to my calculator, and I get 0.013. Oh, I'm going to go back to this since I had 4, I have to multiply that by 4, so it gives me 0.56. Actually, this will still stay 3...so 32.06 grams times 0.56 multiply that by 3 divide by 32.06...so I got 0.052. So, it's very close to the 0.0557. So, I'm going to choose D...''

''...maybe I will look at just the first step over here...the answer I got 0.14...so I go with answer A.''

Mathematical representation of verbalized thought process:

(1) $2.38/17.04 \times 4 \times 3/32.06 = 0.052$
(2) $2.38/17.04 \times 3/32.06 = 0.013$

Progression: (Question 3, Attempt 1 and 2)

''So first, I need to know the molar mass...3 times 22.99 plus phosphate, 30.97, 4 oxygens, 15.99 times 4...then $2H_2O$. So, 2 times 2 plus 16 times 2. So, 163.007 times 34.016, gives me 5544. So I think my answer will be B, because that's the closest I get to my answer. Just because alone sodium phosphate is already 163. Which is pretty close to the other 3 options, where we don't have H_2O, which is going to...when you multiply it's going to be way bigger.''

''So, based on my interpretation, molar mass for this compound times by the other one. This star is a multiplication, so that's what I did. Maybe I should add them up. So...I think finding the molar mass of each of them is not my mistake. It's the multiplying them together, I should have added them up together. So, if I add them together, so, my new answer is A.''

Mathematical representation of verbalized thought process

(1) $[(3 \times 22.99) + (30.97) + (15.99 \times 4)] \times [(2 + 2 \times 16)] = 5544$
(2) $[(3 \times 22.99) + (30.97) + (15.99 \times 4)] + [(2 + 2 \times 16)] = 197.9$

Oscillation: (Question 3, attempt 1, 2 and 3)

''...is this supposed to be a plus or multiplication? So okay Na_3PO_4 times $2H_2O$. I am going to get molar masses up here. Na is 22.990 times that by 3, gives 68.97. Then phosphate or phosphorus is 30.97 and there's only one of those. 99.94 is the total of those two so far. Oxygen is 16, and times 4, which is 64...And then $2H_2O$. H2O is...18.014, there's two of them so it's 36.028. And I will add this to this number here (99.94 + 64), 163.94...so the closest answer from that would be C''

''...I am pretty sure that we had to multiply these two not add them. So, for that I did...which is 460...I will write, 15.99 times 4, which is 63, plus...no this is really off. Okay, 163.12 multiply by 36.028, which is close to the second answer...''

''So, I'm going to change my answer. I added these two (163.94 + 36.028) and got close to this one. It was 199.968, which is A.''

Mathematical representation of verbalized thought process

(1) $(22.99 \times 3) + (30.97) + (4 \times 16) = 163.94$
(2) $[(22.99 \times 3) + (30.97) + (4 \times 16)] \times [2 \times 18.014] = 5906.43$
(3) $[(22.99 \times 3) + (30.97) + (4 \times 16)] + [2 \times 18.014] = 199.968$

Results

RAPID method

The RAPID coding revealed the counts and percentages shown below in Table 6. Of the students who required additional attempts, nearly half showed progression lending weight to the validity and fundamental tenets of answer-until-correct. Only fourteen total attempts (or about 5%) showed students' processes regressing or oscillating. An additional 16% of student attempts showed stagnation, for which students did not show improvement or regression in their processing. All cases involving regression, oscillation, or stagnation were treated as validity threats as they violate the assumption that repeated attempts aid students in improving their process.

The question-level analysis of RAPID shows that half of the questions had >10% of students progressing in their reasoning over their attempt sequences (progression or progression with guessing) (green cells in Table 7). However, there were 3 questions of concern which had >10% of students raising RAPID concerns when including guessing (stagnation, stagnation with guessing, regression, regression with guessing, oscillation, oscillation with guessing) (red cells in Table 7). An important consideration when looking at the percentage of students on later attempts by question is the difficulty of the question (*i.e.*, the number of students who needed a second/third attempt). Unsurprisingly, the three questions which had greater than 10% of students in two or more categories (questions 10, 13, and 19) also had some of the highest number of students requiring additional attempts.

Validity issue detection of RAPID *versus* response process and partial credit analysis

Using the results found from response process (both traditional and avoiding reengagement), partial credit analysis, and RAPID, comparisons were conducted to investigate the magnitude of differences in issue detection. To allow for an appropriate comparison, only attempts which were a part of an attempt sequence were compared because both the partial credit analysis and RAPID were not possible on a single attempt. Table 8 shows the attempt sequences that were flagged by at least one of the methods. Using this framework, Table 8 groups false-positive detection as any attempt sequences which were flagged by the partial credit analysis method, but the richer qualitative data used by RAPID suggested were not truly issues. The 29 sequences which were flagged only by partial credit are the result of students following response patterns

Table 6 Reduced counts and percentages of RAPID codes

RAPID code	Count	Percent (%)
Progression + progression with guessing	123	49.00
Stagnation + stagnation with guessing	41	16.33
Regression + regression with guessing	8	3.19
Oscillation + oscillation with guessing	6	2.39
Resort to guessing	73	29.08
Single attempt used	807	

Expanded table can be found in Appendix 2.

Table 7 Percentage of 53 students showing RAPID validity by question. Highlighting indicates greater than 10% of students fell in that classification. No RAPID Validity Concerns include progression or progression with guessing and RAPID Validity Concerns include stagnation, stagnation with guessing, regression, regression with guessing, oscillation, oscillation with guessing

Question Number	1	2	3	4	5	6	7	8	9	10
No RAPID Validity Concerns	8%	15%	2%	9%	6%	4%	13%	2%	2%	9%
RAPID Validity Concerns		2%	6%	2%	2%	2%	2%	2%	8%	11%
Resort to Guessing		2%			6%	4%	8%	8%	15%	28%
Single Attempt Used*	92%	81%	92%	89%	87%	91%	77%	89%	75%	51%
Question Number	11	12	13	14	15	16	17	18	19	20
No RAPID Validity Concerns	4%	17%	13%	13%	15%	21%	13%	8%	13%	28%
RAPID Validity Concerns		6%	17%	6%	8%		2%		21%	9%
Resort to Guessing	8%	8%	8%	2%	8%		2%	9%	13%	11%
Single Attempt Used*	89%	70%	62%	79%	70%	79%	83%	83%	53%	51%

Expanded table can be found in Appendix 2. *Single attempt used indicates the student answered correctly on their first attempt so there is no change in process to track between attempts.

that deeper investigation revealed students were progressing in understanding despite not aligning with partial credit assignments to distractors.

The final 2 false-positive attempt sequences again showed student progression not aligning with the partial credit which was assigned. However, these attempts were also flagged as containing response process issues. These response process issues led to students selecting their response for reasoning inconsistent with what was designed so the students' response process skewed the partial credit analysis. Over all of the flagged attempt sequences, 32.0% constitute false-positive issue detection corrected through the use of response process and RAPID.

Using the implementation of both response process and RAPID, 34.0% of the attempt sequences were described as "Correct Detection". These include sequences which were detected by either the attempt-level analysis (only response process) or both of the attempt sequence-level analyses (RAPID and partial credit analysis). One example of why coding is necessary at both the attempt and attempt-sequence level is the results seen with Q11. Q11 was not detected by RAPID but was detected by response process. This is because the validity threats were always contained within a single attempt and therefore unable to be detected when only coding attempt-sequences. This further revealed that 9.3% of the attempt sequences contained issues at both the attempt-level and the attempt sequence-level.

Furthermore, Table 8 also reveals a considerable percentage (34.0%) of false-negative issue detection. If attempt sequence-level detection was performed using only partial credit analysis, 33 (13 + 20) attempt sequences would have had their issues overlooked. Additionally, even if both response process and partial credit analyses would have been conducted, 20 sequences were not detected by any method besides RAPID.

Limitations

One limitation of this work is each question was treated individually and the effect that feedback from early questions played on performance on later questions was not investigated. This effect on later items that immediate feedback has is an important aspect of answer-until-correct and investigation into this area could reveal more issues through partial credit

Table 8 Comparison of validity issue detection through response process, partial credit analysis, and the RAPID method

Detection classification	Validity issue detected	Attempt sequence count	Attempt sequence percent (%)	Detection classification percent (%)
False-positive *(No RAPID Detection)*	Partial credit analysis only	29	29.9	32.0
	Partial credit analysis and response process	2	2.1	
Correct detection (through suggested implementation using both RAPID and response process)	Response process only	11	11.3	34.0
	Partial credit analysis and RAPID	13	13.4	
	Partial credit analysis, response process, and RAPID	9	9.3	
False-negative *(RAPID detection but missed by partial credit)*	Response process and RAPID	13	13.4	34.0
	RAPID only	20	20.6	

analysis or RAPID. However, an investigation into these answer-until-correct issues would further build off of, not detract from, the work done in this project.

In addition, one interesting finding from this work was the poor performance of the partial credit assigned to distractors on students' second and third attempts. This is a result which deserves further investigation, and a deeper understanding of this phenomenon may reveal an opportunity for developing a more efficient method for answer-until-correct validity issue detection.

Lastly, this new RAPID technique was only applied to one instrument of 20 questions on basic general chemistry knowledge. Employing the technique in additional contexts would allow for further understanding of its potential and/or limitations.

Implications

The results present an opportunity for both researchers and practitioners to evaluate assumptions made when considering the benefits of answer-until-correct assessments. The results of the RAPID coding align with the existing literature showing benefits of answer-until-correct assessments (Brown *et al.*, 1999; Brosvic *et al.*, 2005; Clariana and Koul, 2005; Slepkov, 2013; Attali, 2015; Pinhas, 2021). For this sample of students, 49% of those who required multiple attempts progressed in their reasoning suggesting answer-until-correct assessments are indeed helping students learn. However, to take advantage of the benefits offered through answer-until-correct assessments, steps must be taken to identify and minimize validity threats. To do this for studies where the improved problem-solving process is integral, researchers may want to consider studies incorporating both the response process and RAPID methods. Additionally, as was noted, when more complex items are included in the assessments, the rate of correct first responses will likely decrease, thus increasing the need for investigating the validity of the answer-until-correct assessment.

For practitioners, the need for incorporating this level of validity studies is likely unnecessary. However, when developing items, considering the change in process associated with the various responses and the escalation of understanding expected by students may be considered. Additionally, when incorporating more challenging or complex items, practitioners may want to consider including more elaborate feedback (through a hint or similar feature) to provide students with additional scaffolding to progress to better understanding. Finally, the care that is taken during exam development for creating plausible distractors as well as incorporating the instructor's expert knowledge of their students and the processes they may use to solve problems is critical to note. This task taken on by instructors may often be overlooked or marginalized by outsiders and should be noted as important classroom work.

Finally, it is also hoped that the benefits cited and now further supported from this work of feedback using answer-until-correct formats would encourage course management system designers to include this feature in their quiz or testing platforms. As of the writing of this work, there are still widely used course management systems that do not allow answer-until-correct for each item (and instead require a student to use a second or third attempt on an entire assessment).

Discussion and conclusions

The findings discussed here demonstrate the benefit of using the RAPID method for detection of validity issues on answer-until-correct assessments. This is shown by the misalignment of the issue detection between methods and by the large number of attempts/attempt sequences which were flagged as having validity issues through only one approach. These results suggest that issues could be more reliably and accurately detected through the use of both an attempt-level (response process) and attempt-sequence-level (RAPID) in unison. It is advisable to conduct these codings simultaneously with attempt-level codes being assigned for each attempt within a single question of a single student, followed by a broader RAPID code for the sequence as a whole. This process would lead to only a marginal increase in time investment of the researcher.

While the time investment is even smaller for partial credit analysis, the results presented here suggest that this procedure should not be used. Despite being unsurprising that the results generated from rich qualitative data outperformed the limited quantitative data of distractor selection, how poorly the partial credit approach performed was surprising. Concurrent research into this assessment has shown that the partial credit used in this work provides a reasonable estimate of student proficiency. One possible explanation for this unexpected result is the feedback from answer-until-correct invalidates the partial credit values that were previously assigned to each distractor and only the first response or attempt has a valid partial credit assignment, though this is an area where further investigation would be needed. Regardless of the reasoning behind this result, it must be made clear that these results do not suggest the assignment of partial credit is flawed, only that its use for validity issue detection may be problematic.

A consideration not directly addressed thus far is how validity threats should be handled once detected. While this is an important aspect, it was not addressed because how a test designer wishes to respond to items showing validity threats will depend on both the stakes of the assessment as well as the impact of validity threats. For low stakes assessments where the validity threat only had a modest impact on student ability estimation, no action may be required. However, with higher stakes assessments items may need to be omitted or rewritten. A brief example is included in Appendix 4 to show one possible approach to determine the impact of validity threats on the assessment.

While the results show clear advantages to using the RAPID method as opposed to a single traditional validity analysis,

implementation of the method does still require a non-trivial time investment on the part of the researcher. However, as response process alone requires diligent analysis of transcripts from each response already, the added time investment to conduct RAPID coding as well is minimal. Further, if partial credit assignment to individual responses is desirable the completion of this coding can aid in determining appropriate credit values. Even if a response was derived by the test designer through a method which is close to the correct process, if the students who ended up selecting that response did so due to an unexpected pathway the partial credit assignment should be reconsidered. In other words, rather than relying on *assumed* student process, *articulated* student process can be used to determine partial credit.

Appendices

Appendix 1: avoiding reengagement cleaning

An important aspect of repeated-attempt assessments is students are presumed to be reengaging with the item on each attempt. However, two major classifications were found where students did not reengage: double-down or inverted reasoning. As the name suggests, double-down categorization was given to an attempt sequence where the knowledge of any previous incorrect attempt(s) did not lead the student to reevaluate their thought process, but rather the student continued to rely on their previous logic to select a new response. In the example below, this student initially answered 1.0 mol CCl_4 (choice b) for question 7. After being told they were incorrect, the student still felt their process was correct and simply chose the closest answer to their previous attempt (1.5 mol CCl_4).

Double-down: (Question 7, Attempt 2)

"...Because I feel like earlier I was off by a little margin"

Alternatively, other students avoided reengagement with the task by simply inverting their previous reasoning. In other words, knowing their previous logic was incorrect, these students assumed that the opposite of their logic must therefore be correct. One example of this occurring is shown below.

Inverted reasoning: (Question 4, Attempt 1 and 2)

...so, I think it would be C, considering it has the lowest mass..."

"Okay, then I guess it would be the first one, because it would be the largest (mass)."

Of the 251 second attempts and 113 third attempts, only 12 attempts were found to have these engagement issues. Of these attempts, 5 showed students "double-down" and chose the closest response to their previous attempt. The remaining 7 students "inverted" their previous reasoning by choosing the response furthest from their initial attempt, again without reengagement with the problem. For this assessment with this sample, only 3% of the repeat attempts showed these issues which are unique to repeated-attempt assessments.

Appendix 2: RAPID method

The tables below represent expansions off of tables in the primary article. These tables show counts and percentages for each RAPID code prior to codes being binned together. Table 9 depicts the RAPID code distribution for each of the possible codes (rather than the collapse of a code with its "with Guessing" counterpart). Table 10 shows question-level percentages of the codes as opposed to the binning of the codes into RAPID validity concerns and non-answer-until-correct validity concerns.

Table 9 Counts and percentage of RAPID codes

RAPID code	Count	Percent (%)
Progression	122	48.61
Stagnation	25	9.96
Regression	6	2.39
Oscillation	5	1.99
Resort to guessing	73	29.08
Progression with guessing	1	0.40
Stagnation with guessing	16	6.37
Regression with guessing	2	0.80
Oscillation with guessing	1	0.40
Only 1 attempt was needed	807	

Table 10 Percentage of RAPID codes by question for the 53 students

Question Number	Progression	Stagnation	Regression	Oscillation	Resort to Guessing	Progression with Guessing	Stagnation with Guessing	Regression with Guessing	Oscillation with Guessing
1	8%								
2	13%	2%			2%	2%			
3	2%	2%	2%	2%					
4	9%			2%					
5	6%	2%			6%				
6	4%	2%			4%				
7	13%				8%		2%		
8	2%	2%			8%				
9	2%	2%			15%		6%		
10	9%	2%		2%	28%		8%		
11	4%				8%				
12	17%	4%			8%			2%	
13	13%	6%	6%		8%		4%		2%
14	13%		2%		2%		2%	2%	
15	15%	6%		2%	8%				
16	21%								
17	13%	2%			2%				
18	8%				9%				
19	13%	9%	2%	2%	13%		8%		
20	28%	8%			11%		2%		

Appendix 3: comparison of response process validity and the RAPID method

Table 11 classifies all of the attempts used by students in this study by their response process validity and RAPID code. Further investigation is shown in Table 12 which specifically analyses sequences with response process validity issues and shows the type of RAPID code. This revealed no discerning pattern. Both of these tables align with the conclusion

Table 11 The table below shows attempt counts to compare response process validity with RAPID validity codes

	Response process validity issues	No response process validity issues
Progression	5	117
Stagnation	13	12
Regression	4	2
Oscillation	2	3
Resort to guessing	8	65
Progression with guessing	0	1
Stagnation with guessing	3	13
Regression with guessing	0	2
Oscillation with guessing	0	1
Only 1 attempt	24	783

Table 12 Of the students who exhibited response process validity issues, the table below shows the reduced distribution of RAPID validity codes

Attempts which exhibit response process validity issues	Count	Percent (%)
Progression + progression with guessing	5	8.47
Stagnation + stagnation with guessing	16	27.12
Regression + regression with guessing	4	6.78
Oscillation + oscillation with guessing	2	3.39
Guessing	8	13.56
Only 1 attempt	24	40.68

discussed in the primary article that RAPID validity and response process validity must each be investigated.

Appendix 4: assessing the impact of detected validity threats

Following the detection of validity threats within an assessment it may be desirable to better understand the impact the threats have on the assessment results. What follows is a brief example of one of many approaches which could be used to inform if the detected problematic items warrant remediation. This was done through a series of correlations between the assessment where validity threats were found, and assessments which are likely to be an accurate reflection of student chemistry proficiency (standardized national exams).

Sample

The sample in the primary manuscript was composed of rich qualitative data which is limited in that the sample size being analysed scales with the time and resources needed for data analysis. This typically results in smaller sample sizes for the qualitative data making the results more susceptible to sampling errors. With this in mind, when assessing the impact of detected validity threats, it may be beneficial to take advantage of quantitative data which can be more efficiently collected. For this example, a class-wide sample was collected by providing the same 20-question assessment in written form to 284 students. All 284 students were from the first institution because this was the only institution for which final exam scores were available. To implement answer-until-correct to this many students, the commercially available Immediate Feedback Assessment Technique was utilized (Cogna Learn; Epstein Educational Enterprises; Epstein *et al.*, 2001).

Method

The score for each student in the class was calculated and subsequently compared against external measures (two different final exam scores) using R (Meng *et al.*, 1992; Team, 2020). This correlation between the full assessment and external measures served as a baseline. Correlations were also calculated between these external measures and assessment scores calculated after the removal of items containing the most response process validity threats. The threshold for which items to remove was set as any item from the interview data with greater than 10% of any one of the validity issue codes. The external measures chosen were two standardize multiple-choice ACS Exams which together served as the students' final exam (2005 General Chemistry Exam – Paired Questions, First Term | ACS Exams; 2008 General Chemistry Conceptual Exam – Full Year, First Term and Second Term | ACS Exams).

Results

Based on the interview results, items Q11 and Q13 were flagged as the items with the most response process issues. The correlation was initially completed using the assessment score from all 20 items, then repeated using the assessment score without Q11 and Q13. If these correlations statistically differ from one another, that will indicate the two questions were contaminating the assessment score and were therefore harming the validity of the assessment. Correlations were checked for statistical differences using the referenced technique (Meng *et al.*, 1992). As no significant differences were found (shown in Table 13), it was determined that the inclusion of Q11 and Q13 were not *statistically* having a negative impact on the accuracy of the assessment results. Therefore, it may be acceptable to leave these items in the assessment due to the small impact the response process validity threats had on the assessment overall.

Table 13 Correlations between students' performance on the assessment analyzed in this paper (full and with validity issues removed) and final exam scores. Statistical comparison between correlations with and without validity issues is also provided

	r (Pearson product moment coefficient)	Z (p)
Assessment (Full) and *Paired* ACS final	0.640	−0.535 (0.593)
Assessment (Q11 and Q13 removed) and *Paired* ACS final	0.644	
Assessment (Full) and *Conceptual* ACS final	0.604	−0.247 (0.805)
Assessment (Q11 and Q13 removed) and *Conceptual* ACS final	0.606	

Conflicts of interest

There are no conflicts to declare.

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