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International Journal of Science Education
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713737283

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Phyllis Baudoin Griffard; James H. Wandersee

To cite this Article Griffard, Phyllis Baudoin and Wandersee, James H.(2001) 'The two-tier instrument on photosynthesis: what does it diagnose?', International Journal of Science Education, 23: 10, 1039 — 1052
To link to this Article: DOI: 10.1080/09500690110038549
URL: http://dx.doi.org/10.1080/09500690110038549

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INT. J. SCI. EDUC., 2001, VOL. 23, NO. 10, 1039-1052

The two-tier instrument on photosynthesis: what does it diagnose?

Phyllis Baudoin Griffard, Department of Natural Sciences, University of Houston-Downtown, One Main Street, Houston, TX 77002, USA; e-mail: griffardp@zeus.dtuh.edu; James H. Wandersee, Louisiana State University, USA

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The goal of this study was to understand how six college biology students complete the tasks of a traditional paper and pencil instrument designed to detect alternative conceptions about photosynthesis. Participants responded to relevant items in a two-tier diagnostic instrument in a think-aloud task. Responses to the traditional content question (first tier) were correct more often than reasons (second tier). However the participants' verbal data indicated that they relied upon test-taking strategies, not retrieval from memory, to choose their reasons. Some distractors caused participants to accept incorrect propositions being considered for the first time (rather than eliciting a misconception from extant knowledge). They also considered relevant exceptions and subtle language cues that justified their choices of incorrect reasons. Participants voiced concerns about the conscientiousness with which students complete such instruments. These findings raise concerns about the validity of using such instruments for diagnosing alternative conceptions.

Introduction

A very active area of science education research in the 1980s was concerned with alternative conceptions about scientific phenomena (Wandersee *et al.* 1994). The Alternative Conceptions Movement (ACM) prompted studies that employed both nomothetic and idiographic methodologies. The nomothetic studies, more typical of the 'quantitative' researcher, employed an experimental approach, usually using a written survey, large samples and inferential statistics, and compared students' conceptions to those currently held by the science community. Idiographic studies, more typical of the 'qualitative' researcher, employed ethnographic research methodologies such as clinical interviews with fewer participants and reported rich understanding of these few students' conceptual frameworks regarding the phenomenon under study. These researchers do not evaluate the conception according to the scientifically held view; rather, they adopt the position that personal, idiosyncratic views of reality are the norm and that they evolve. The ACM has involved researchers operating at many points on the qualitative/ quantitative methodology spectrum.

A variety of research approaches has sought to illuminate students' alternative conceptions about photosynthesis. Alternative conceptions have been revealed by studying documents such as textbooks (Barass 1984, Storey 1989) and by administering a variety of paper and pencil instruments to large sample sizes. Wandersee

International Journal of Science Education ISSN 0950-0693 print/ISSN 1464-5289 online © 2001 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/09500690110038549

(1983) conducted a nationwide cross-age survey using multiple choice and open-ended questions to reveal an alternative conception common from elementary to university level that plants obtain their nutrition from the soil. Eisen and Stavy (1988) administered an instrument with 14 open-ended questions about oxygen release, respiration, autotrophic feeding, and sunlight energy to high school and college students. Both of these studies depend on the use of common language for interpretation of terms like 'food', 'respiration' and 'energy', thus variation in how the participants construed the meanings of the questions confound the findings reported.

Primary reports of alternative conceptions about photosynthesis were followed by some that applied or correlated this knowledge with other learning activities. The learning of photosynthesis (as measured by concept map evaluation and traditional exam) was correlated with study strategies by Hazel and Prosser (1994). One practical case study observed how a teacher attempted to alter her students' alternative conceptions about photosynthesis (Smith and Anderson 1984), but it relied solely on classroom and teacher planning observations. No student interviews were done. Knowledge of student alternative conceptions in photosynthesis was also used as a basis for developing remedial instruction (Amir and Tamir 1994). In that study the researchers used graphs of photosynthetic rates and limiting factors, thus the results may have been confounded by the ability of the subjects to interpret graphical data.

None of the studies located reported qualitative data such as interviews as their primary mode of uncovering alternative conceptions about photosynthesis, nor the use of triangulation measures to insure validity. One study compared multiple choice responses to a state-administered high school achievement test to responses from the same students to essay questions across the science disciplines, including a biology question concerning photosynthesis and respiration (Yarroch 1991). In reporting the development of a two-tier diagnostic for alternative conceptions about photosynthesis and respiration, the researchers state only that interviews assisted them in their instrument development but did not report specifically on these interviews (Treagust and Haslam 1986, Haslam and Treagust 1987). Their goal was not to identify alternative conceptions, but rather to determine how widespread the reported ones are in their student population.

These and other researchers have recognized the difficulty in uncovering an alternative conception by a traditional instrument since the reason behind a student's selection is not evident. Thus the power of a diagnostic instrument seems to depend on its ability to externalize the student's reason for his/her choice. The two-tier approach advocated by Tamir (1989) and Treagust (Treagust and Haslam 1986, Haslam and Treagust 1987, Peterson and Treagust 1989, Treagust and Mann 2000) is, on the surface, a great improvement over the traditional multiple choice instrument. The first tier of each item (a traditional forced-choice question) is followed by the student's justification either in a multiple-choice form or in a free-response. What remains unknown is the degree to which the very nature of forced choice instruments and two-tier instruments in particular provides clues to correct answers that participants would not have had in an open-ended survey or interview. Students may also rely on logic, key words, or other less valid means rather than turning solely to their conceptual understanding to answer the questions (Yarroch 1991). Such concerns about instrument validity led to a study of the effect of altering the format of the first tier (Tamir 1989). That study concluded

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that forced-choice items provide clues to the subject that can confound the diagnosis of the alternative conception.

This concern is the rationale of the study described here, whose goal was to better understand how students approach such written tasks. Selected upper level college biology students were observed while thinking aloud as they responded to a subset of the items about photosynthesis on Treagust's two-tier instrument. These verbal data as well as data from the interview that immediately followed the task completion were analysed for congruence with the approaches the instrument developers assumed that students take. The findings raise concerns about the validity of such a means to identifying alternative conceptions.

Methods

Instrument

The instrument developed by Haslam and Treagust was obtained from Dr Treagust. Of the 13 items designed to test for students' conceptions of photosynthesis and respiration, four items specifically targeting photosynthesis were chosen, transcribed verbatim, and duplicated for each student. Each item consisted of a traditional multiple choice question followed by a multiple choice question about their reason for their choice. The distractors for both tiers were based on alternative conceptions identified in essay exams, interviews and the research literature. This second tier also included a blank into which the subject could choose to write in an answer.

Participants

All six participants were sophomore, junior or senior pre-medical students at a liberal arts university in the southern USA (table 1). All had been students of PBG's Molecular, Cellular and Developmental Biology (MCDB) course in the previous academic semester, and all but one were high-achieving based on grade point average (GPA). This sophomore level course is one of four required biology courses in a two year core for biology majors. Photosynthesis and respiration had been the final topics studied in the course.

Think-aloud/interview sessions

The nature of the study was not disclosed to the participants until their arrival at the study site. Each session was audio-recorded. The parts of the sessions relevant to this study were transcribed in their entirety. The sessions began by having the students do a 'warm-up' exercise in which they were to think aloud (Ericsson and Simon 1993) as they determined the number of hours then remaining until midnight, 1 January 2000. The participants then began the main task of the interview: completion of the four items of the two-tier diagnostic while thinking aloud. They were told to take as much or as little time as they needed and that the observer would say nothing except to remind them to keep talking or to explain further. After completing the tasks each subject was interviewed, during which time each was asked to elaborate on some of the observations. At that time they were debriefed about the purpose of the study, and their questions were entertained.

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Table 1. Description of participants.

Participant	*GPA*	Course grade	*Description of participant*
Myra	3.8	A	Asian-American female, senior, earned highest percentage in class, quiet, confident
Liz	2.9	C+	Caucasian female, junior, Psychology major, bouncy, impulsive, often tardy
Mark	3.8	B+	Caucasian male, junior, learns traditionally, perhaps by rote, conscientious
Maria	3.8	B	Hispanic-American female, sophomore, quiet, youngest in class, learns visually
Mike	3.7	B+	Caucasian male, junior, hard working, detail-oriented, anxious about grades
Patrick	3.4	A	Caucasian male, junior, driven, outgoing, good student, good self-esteem

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Those who asked how well they did were debriefed about their responses as well. After each session the participants were asked not to discuss the activity with other students from the class even though they had not been told whom the other participants were.

Data analysis

Analysis of the data, including transcripts, was facilitated by the use of NUD*IST software (Non-numerical, Unstructured Data system for Indexing, Searching and Theorizing) (QSR Corporation).

Results and discussion

Need for warm-up

The warm-up exercise seemed to be necessary to establish the ground rules since most immediately looked to the researcher for feedback, information (e.g. 'how many days are in November?'), or approval that they had finished the task to the satisfaction of the investigator. The warm-up also provided clues to the anxiety level of each subject. Liz was most nonchalant about the warm-up, while Mike worked through many fits and starts and revealed his awareness of the investigator's presence and of being recorded. The amount of time it took for them to complete the task ranged from 10 minutes (Liz) to almost an hour (Mike). The asterix (*) indicates the most correct answer. [Brackets] indicate where omitted words have been inserted by the authors for clarity. Italics indicate their audible emphasis or, if illustrative of a point, an emphasis added by the authors. ''Double quotes'' indicate where the student was reading from the two-tier instrument.

Responses to the tasks

Tallies of the students' responses to the two-tier test on photosynthesis are inserted in the actual items below. The numbers to the left of the choices indicate the number of participants (out of 6) who made this choice.

0 (1) Glucose + oxygen $\xrightarrow[\text{light energy}]{\text{chlorophyll}}$ Carbon dioxide + water.

6* (2) Carbon dioxide + water $\xrightarrow[\text{light energy}]{\text{chlorophyll}}$ Glucose + oxygen.

0 (3) Carbon dioxide + water + energy $\longrightarrow$ Glucose + oxygen.

The reason for my answer is because:

2 (a) The green pigment called chlorophyll combines with the carbon dioxide in the presence of light energy and produces glucose and water.

3* (b) The energy from sunlight is used by plants containing chlorophyll to combine carbon dioxide and water to form glucose and oxygen.

0 (c) Glucose and oxygen are combined in the presence of chlorophyll and light energy to form carbon dioxide and water.

1* (d) ———————————————————————————————

Figure 1. Which of the following equations best represents the overall process of photosynthesis?

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On item 1 (figure 1), all participants gave the 'correct' answer but also gave three different reasons. Only four of the six students gave both the correct answer and reason on paper. Myra, Mark and Maria chose the correct reason B, while Patrick supplied a correct reason verbally. His written answer in the blank section was so unclear ('don't start w/ glucose, need chlorophyll and light energy so not (1) or (2)') that it probably would have been scored as incorrect by a researcher in the original survey. However it is possible that Patrick would have been clearer in his written justification if he were not being recorded. In his verbal report he said:

> I don't think [reason B] is right because as I recall they don't use the water, *it's not combining with the carbon dioxide*. It's just used for the hydrogen pump. The reason I chose [choice 2] is because the light energy hits the chlorophyll, excites the electron transport chain, which is a cascade of reactions, and the carbon dioxide is put together to yield glucose and oxygen. But the reason I wouldn't say [choice 3] is I don't recall that the water at any [point] actually combines with carbon dioxide. Hmm. And I didn't choose 1 and 3 because, [on choice] 1, you don't start with glucose, and [on choice] *2 you have to have light energy and you have to have chlorophyll*. [emphasis added]

Thus his detailed knowledge of the separation of 'water consumption' from 'carbon dioxide fixation' prevented him from choosing the correct reason B, which assumes knowledge of only the general equation for photosynthesis and not the details of the individual biochemical processes. The two students who incorrectly chose reason A (Liz and Mike) may have done so carelessly, as there is no evidence of an alternative conception in their transcripts. Liz finished the entire instrument quickly and did not make many comments as she worked.

After the warm-up task, Mike's anxiety was obvious. This may have prevented him from thinking clearly about the reasons for his answer to item 1, as evident in his comment in the interview: 'I have to admit [during] the warmup, that was where I was [thinking], ''oh I'm not going to be able to do this. I can't believe she called [on me to participate]''.'

Thus item 1 did not definitively diagnose alternative conceptions in the two students who chose incorrect reasons. Rather, impulsiveness and anxiety seem to have prevented Liz and Mike, respectively, from choosing carefully. It is still possible that they had the alternative conception but that it was masked by these affective conditions.

As perhaps intended by the researchers, words like 'chlorophyll' and 'light energy' seemed to have steered some participants to the 'correct' choices and may be cues that test-wise students such as Myra seek:

> *Myra:* OK, I'm going to pick #2, because chlorophyll is there ... And it seems like it should be part of the overall process. I was having a hard time deciding between #2 and 3, because I think energy, the light energy would be more of a catalyst that goes on the arrow instead of a reactant. And also I picked 2 because of chlorophyll.

Like Myra, Mark considered choosing (3), which is not incorrect as stated. Mark said:

> And this one's kind of worded funny, but I'm going to eliminate that one too because energy is not something we add, well I guess we could add light energy. But I'm gonna go with 2.

Haslam and Treagust's rationale for including choice (3) (in which 'energy' is an input) is unclear. Their assertion that this statement is incorrect seems to contradict another statement in their set of propositions (R7) which shows 'energy' on the products side in the summary equation for respiration. The investigators themselves may not have resolved light energy's role for themselves, since light is not a catalyst (renewable, unchanged by the process) as suggested by its placement above the arrow, rather than as an input as in choice (3).

On the item shown in figure 2, all chose the correct answer and reason, however knowledge of the details and possible exceptions to these generalizations nearly caused two students to reconsider their answers. Regarding choice (4) in the first tier, Myra said:

> I know you need light, but I know there's part of photosynthesis that doesn't need light. Anyway, I wouldn't pick that answer.

Upon reading reason (c), Patrick said:

> Hmm well maybe, I don't know. I don't recall ever studying an organism that used a different compound other than carbon dioxide. I mean there may be some strange one, like maybe a sulfur algae, or something I don't know. But I'm gonna wait for that one.

Patrick was aware of unusual organisms that exhibit variations to the generalized photosynthesis scheme, but his reference was to chemosynthesis, which is a variation of the light, not the dark, reactions. Additionally, early in the session, Maria

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6* (1) Amount of oxygen.
0 (2) Amount of carbon dioxide.
0 (3) Amount of chlorophyll.
0 (4) Amount of light.
The reason for my answer is because:
0 (a) Photosynthesis can take place with no light energy.
0 (b) Non-green plants like fungi which do not contain chlorophyll or similar pigments can also photosynthesize.
0 (c) Photosynthesis cannot take place without carbon dioxide.
6* (d) Oxygen is not required for photosynthesis, it is a by-product of photosynthesis.
0 (e) _____

Figure 2. Which of the following factors is not important for the process of photosynthesis?

could not recall whether oxygen was a product of photosynthesis, but eventually made the correct choice, indicating she used clues imbedded in the instrument to jog her memory. In spite of these concerns, item 2 seems to be most valid of the four chosen for this survey since the students' responses and their concurrent think-aloud comments were most consistent with those responses expected of students who did not hold the alternative conceptions. However, this question really does not seem to be aimed at uncovering one of the well-documented alternative conceptions. Rather its purpose seems to be to reveal a slip, or a tendency to rely on the use of a proposition by habit because of its familiarity in another context, namely respiration. There is tendency for concepts common to both respiration and photosynthesis to preferentially elicit the respiration schema rather than photosynthesis schema. This response may thus be due to a common processing error rather than to a well-held belief about an oxygen requirement for photosynthesis. This propensity has been reported elsewhere (Griffard 1999, Griffard and Wandersee 2000).

On the item shown in figure 3, all gave the correct answer, but only four of these six chose the correct reason. Mark's response was typical of the correct responses, most of which acknowledged that plants' removal of carbon dioxide is not a benefit to the plants *per se* and that energy cannot be 'produced':

> They don't really produce energy, they convert the energy from light to chemical energy. And the removal of carbon dioxide from the air I guess can be important but I wouldn't really call it a benefit, so I guess I'll go with 2.

Myra and Liz were the two participants who chose the 'incorrect' reason A. Liz completed the task hurriedly, giving no evidence of whether she had the alternative conception that her response diagnosed. On the other hand Myra chose reason A because in her view reason B was merely a restatement of her first tier choice, a tautology which did not qualify for her as a true reason. She said:

> Alright, my reason would be A, because it does support the answer that I chose: ''Photosynthesis provides energy for plant growth'', which is the chemical energy that they converted from light. And I wouldn't choose B because . . . ''. During photosynthesis energy from the sun is converted and stored in glucose molecules''. . .That does support the answer I gave, but [pauses] yes, it's pretty much restating the answer I gave, so I don't think that would be a reason. It's basically saying the same thing.

This is but one example illustrating how participants would be categorized as wrong for looking deeper into the question than was intended. Ironically this

0 (1) Removal of carbon dioxide from the air.
6* (2) Conversion of light energy to chemical energy.
0 (3) Production of energy.

The reason for my answer is because:

2 (a) Photosynthesis provides energy for plant growth.
4* (b) During photosynthesis energy from the sun is converted and stored in glucose molecules.
0 (c) Carbon dioxide is taken in by the leaf through the stomates during photosynthesis.
0 (d) _____

Figure 3. The most important benefit to green plants when they photosynthesize.

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		Photosynthesis	*Respiration*
	(1)	Takes place in green plants only.	Takes place in animals only.
1	(2)	Takes place in all plants.	Takes place only in all animals.
2*	(3)	Takes place in green plants in presence of light energy.	Takes place in all plants and in all animals at all times.
3	(4)	Takes place in green plants in presence of light energy.	Takes place in all plants only when there is no light energy and all the time in all animals.

The reason for my answer is because:

	(a)	Green plants photosynthesis and do not respire at all.
	(b)	Green plants photosynthesize during the day and respire at night (when there is no light energy at all).
1*	(c)	Because respiration is continuous in all living things. Photosynthesis occurs only when light energy is available.
3	(d)	Plants respire when they cannot obtain enough energy from photosynthesis (e.g. at night) and animals respire continuously because they cannot photosynthesize.
2	(e)	_____

Figure 4. Which of the following comparisons between the processes of photosynthesis and respiration in green plants is correct?

item violates the convention that tautology is not a valid justification in a two-tier instrument (Tamir 1989).

On the item shown in figure 4, only two of six (Patrick and Myra) gave both the correct answer and a correct reason. This item drew the most incorrect responses. Those who chose response (4) (Liz, Mark and Maria) may have an alternative conception that 'respiration helps meet the energy needs when there is no light available', although Mark showed acceptance of the correct choice (3) before encountering the previously unconsidered proposition posed in choice (4):

> OK. Let me think about this for a second. If photosynthesis takes place in green plants in the presence of light energy, I guess that's true. And ''it takes place in all plants and in all animals at all times''. *That sounds pretty good* [evidence of acceptance of the correct choice]. And [choice] 4, which says, ''takes place in green plants in the presence of light energy, and [respiration] ''takes place in all plants even when there is no light energy and all the time in all animals''! OK, I'm gonna go with [choice] 4 [and reason D].

Although Maria's economy of explanation in the transcript does not overtly indicate her debate between choices (3) and (4), her pauses indicated a tentative acceptance of choice (3) before reading choice (4). Furthermore, her verbal reasoning doesn't distinguish rationale for choice (4) over (3). She said that she chose (4) 'because I know respiration takes place in animals all the time'.

Myra and Liz made similar comments about light not being required directly for carbon fixation. Myra was more confident about this than Liz was and took the time to rephrase the reason and enter a correct written response into the blank for choice E. She explained her reasoning as she did so:

> So #3 [is what I choose]. OK, for #2, respiration also occurs in plants. That's why I didn't pick that. And (4)... the photosynthesis part is right, [but] respiration happens in plants even when there is light energy. So that's why I wouldn't pick (4) ... I'm not

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> sure about [reason C]. The first sentence looks fine, but parts of photosynthesis can happen when there is not light available' ... Both plants and animals respire all the time, so I wouldn't pick [D]. But then I wouldn't pick [C] either because photosynthesis does happen when light energy is not available, so I guess I'll write my own answer. ...because I have a problem with this 'only' right there. ''Photosynthesis occurs 'only' when light energy is available''. And I think it occurs at other times as well.

Myra's and Liz's proposition that the dark reactions do not require light directly is correct. In intact plants the light and dark reactions are so tightly coupled that the light-independence of the dark reactions is only demonstrable under laboratory conditions. These classical experiments are commonly described and illustrated in college-level textbooks and may promote the notion that in nature the dark reactions can function independently of light. Again, a detailed knowledge of the process would have penalized Myra, especially if she would have worded her justification more strongly to emphasize that parts of photosynthesis can proceed in the absence of light. Myra's test-wiseness is again apparent in her 'safe' choice of words for her written justification.

The source of Mike's incorrect answer was altogether different. He was clearly confused while studying this question, which he read and discussed with himself many times before finally making his somewhat arbitrary choice:

> I thought in respiration, when human beings respire, they take in oxygen and give off $C0_2$. It's kind of the reverse process [in] photosynthesis ... Therefore I said that respiration must then only be the giving off of oxygen. Therefore it takes place only in all animals. This exchange during the post-task interview explains his confusion (Note: Inv. abbreviates 'Investigator'.)

Inv. So you're seeing respiration in that case as maybe gas exchange.
Mike Yes, as a gas exchange. And I've never, I don't think I have, if I have, I can't recall, someone referring to a plant as respiring.
Inv. But what about cellular respiration?
Mike Right, I guess [that didn't come to my] mind.

Mike interpreted 'respiration' as breathing, which is not inherently an incorrect proposition. This misinterpretation led him to be very confused as shown by his obvious anxiety and the amount of time he spent on this item. Use of the label 'respiration' is context-dependent and to avoid this needless confusion the developers of the instrument should have specified 'cellular respiration'. The contention that this use of the term signals an alternative conception (Bishop *et al.* 1986, Roth *et al.* 1983) is unwarranted.

Patrick noticed that in the photosynthesis column of item 4 the statements distinguished between 'green plants' and 'all plants'. Apparently the developers of the instrument used a definition of 'plant' that may have included fungi. Students possessing a contemporary definition of 'plant' assume, like Mike, that if a plant is not green it is still photosynthetic, as autotrophism is now considered a criterion for classification as a plant. This did not seem to affect Patrick's answer, but it only exacerbated Mike's confusion while struggling to make sense of item 4. Patrick said, 'I can't think of any plants in which photosynthesis doesn't take place. But respiration doesn't only take place in animals, so that's not it'. Mike said:

> They say ''takes place in green plants''. So what if you get something like a barberry bush or something that has red leaves? A mean I know there's photosynthesis and all, but it's just a different pigment. It's not chlorophyll. Is that correct, or are they still utilizing chlorophyll?

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Although these interpretations did not affect their responses, a slightly different design could have caused the investigator scoring the surveys to wrongly attribute an 'incorrect' response to a non-existent alternative conception.

Metacognitive and affective factors

Following the think-aloud tasks, the students were interviewed about observations made and approaches they seemed to have taken. Most students seemed to treat the survey as an exam, seeking what seemed to be the correct or most logical answer on both tiers rather than generating a response and reason mentally, then looking for them among those offered. Myra questioned the fairness of such a format for an exam, but felt that the instrument would probably function in revealing alternative conceptions. Still she treated the survey as an exam and used test-taking strategies and logic rather than relying solely on her own knowledge:

Myra Having the choices for my reasons kind of confused me a little bit. Because then I would have to go through all the reasons and check it back with my answer. But I would also have to check back the reasons with the original question ...
Inv. You looked to see which one was consistent, and so you used logic. You used test strategies, which is valid.
Myra And it seemed like this wouldn't need a test strategy if my reason was there.

Mike took the most time and was the most verbal of the participants during the think-aloud as well as the interview. He, like Myra, felt that the format was unusual, and questioned whether such an instrument could accurately reveal a student's knowledge. He also questioned the validity of forced choice justifications and he admitted that without a sense of the importance of the data he might not have taken the task seriously. When asked if he would have treated this task differently had he not been a student of the researcher, he said:

> I probably would not have taken the time if it was some person I had never met before just in there [wanting me] to take this test, you know? ... There's no way that this other person giving it in a class of 30 would ever know really what my reason is.

When asked if his answers would have been different, he said:

> Probably not, but you wouldn't have known my reasoning ... [nor] the number of times I had to go back and reread the question. ... Stuff like that I guess is valuable to studies like this.

When he was asked about his confusion on item 4, he said he would not have asked for clarification from a stranger administering the instrument because:

> I would [assume] it's part of the study, that's what they want you to do ... that it's just part of the question. I don't know what I'd do. I don't see myself going up and asking them for help though.

A summary of the results of the paper and pencil task alone indicates that the students' mean number of correct answers with correct reasons (out of 4) was 2.33 (58.3%). The mean number of correct answers in the first tier (3.33) is similar to the mean number of correct answers with correct reasons provided in the verbal data (3.17) (table 2).

The fraction of students providing correct responses to the content question alone was 25% higher than the fraction that answered both tiers correctly. Tamir's

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Table 2. Summary of participants' scores.

Participant	*Correct responses (of 4) first tier*	*Written data alone both tiers*	*With verbal data*
Patrick	4	3	4
Myra	4	2	4
Mark	3	3	3
Maria	3	3	3
Mike	3	2	3
Liz	3	1	2
average:	3.33 (83.3%)	2.33 (58.3%)	3.17 (79.2%)

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(1989) subjects scored about 17% higher if only the first tier was considered. However if the verbal data were also considered, the acceptable reasons were much higher, and there was only a 4% difference between the number correct considering only the first tier and the number correct considering the verbal data as well. It appears that considering only the written answers overestimates the fraction of the student population having an alternative conception.

Conclusions and implications

In conclusion, the two-tier instrument may have diagnosed some alternative conceptions in these students' conceptual frameworks regarding photosynthesis, but perhaps not validly. Aside from the potential pitfalls in interpreting item (4), the fact that half the students chose the same distractor with similar verbal explanations indicates it may have accurately diagnosed a *bona fide* alternative conception or gap in knowledge about plant respiration. In the MCDB lectures on this topic many of the alternative conceptions this instrument sought to reveal were anticipated and addressed because of the instructor's familiarity with the literature. There was emphasis placed on the fact that all cells in all organisms constantly undergo respiration and that the two processes of photosynthesis and respiration are linked physiologically by intra- and extra-cellular gas exchange and ATP production. However the related notion that respiration somehow 'fills in' for photosynthesis in the absence of light was not specifically dispelled. Students may erroneously perceive this to be a corollary of the propositions that photosynthesis occurs only when light is available and that respiration is the only metabolic process of the two to be active at night. This is only a slightly different proposition than the one stating that respiration occurs constantly.

On item 4 Maria, Mark and Liz selected the distractor intended to diagnose an alternative conception that respiration provides for the shortfall of a plant's energy needs in the absence of photosynthesis. Maria and Mark both showed an immediate positive reaction to the correct choice (3). However they chose #4 in spite of their uncertainty about the particular circumstances, perhaps because of its novelty and plausibility. Their haste suggested that the sequence of choices may have affected their choice. Furthermore, the proposition that plants only undergo respiration at night was not a proposition these participants held in their conceptual frameworks prior to the interview. Rather it had been an unconsidered pro-

position that seemed plausible at first glance and therefore was chosen. This item therefore did not validly diagnose an existing alternative conception, but rather created one.

Analysis of the think-aloud protocols and post-task interviews indicates that the students' raw scores on the task underestimated these students' knowledge. This is in contrast with Yarroch's findings (1991) in which the state-administered achievement test overestimated the student's knowledge. Interviews allowed him to conclude that the design of the items themselves, not guessing, led students to a correct answer in the absence of meaningful understanding of the concept being tested. In contrast, students in the current study sometimes chose incorrect justifications. This instrument, designed for secondary students, may not have been a good match with the population being tested since some of the concepts about photosynthesis were oversimplified relative to these students' knowledge of photosynthesis, as the data indicated.

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At secondary and college levels educators can expect their students to be able to provide justifications for their answers. This is the goal of the second tier of these instruments. Tamir (1989) found that secondary students' invalid justifications often took the form of tautologies, teleologies and anthropomorphisms. He also found that US students in his studies did not give justifications as valid as their Israeli counterparts, which Tamir attributes to US teachers' dependence on multiple choice exams, which too often measure only recognition, instead of essay exams preferred in Israel. In spite of criticism of tautologous justifications, such a flaw subtly appeared in this instrument and led a particularly good student, Myra, to reject the 'correct' choice in the second tier that she perceived to be a restatement of the first tier.

In addition, the developers of the instrument may have erred in their designation of sunlight as a catalyst (by placement on the arrow) rather than an input. This subtle distinction suggests that they view sunlight in human terms, as a 'renewable resource', when in reality the light energy that arrives on earth is 'consumed' by plants when they convert it to chemical energy (or lost as heat). The plant does not regenerate this light energy like a catalyst would be regenerated, nor is the light unchanged by the process. Students with a good physical chemistry background might be more likely to choose distractor (3) as well since their view of energy in endergonic processes is more often represented as an input than as a catalyst.

No participant appeared to locate and choose his/her own reason among the choices. Rather, each regarded the second tier question as a distinct multiple choice task, and then finalized their choice on the basis of whether it logically follows from their response to the first tier. Therefore the two-tier instrument seems to measure a student's test-taking skills rather than extant knowledge.

In addition to diversity in test-taking ability, students also bring to these tasks different amounts of sincerity, anxiety, persistence and meticulousness that unavoidably confound the data. The method of collecting data impersonally or anonymously may prevent data bias, but more insidious is the often-disregarded fact that reluctant subjects do not care enough to take the surveys seriously. Students who have nothing personally invested in the project and have no relationship with the investigator have little incentive to commit sizable cognitive resources to completing the survey conscientiously. Also, if students know that they are completing a survey as part of a research project, they might have Mike's

reaction and assume their confusion about an item is due to some aspect of the survey's purpose and design. It also seems obvious that any self-contained survey of forced choice questions inherently has clues built into it. Any set of questions with an objective of revealing knowledge gaps about a topic will unwittingly bridge those gaps by having theretofore unconsidered propositions (both true and false) there for the participants' consideration and comparison.

To what end might this two-tier instrument be useful? Developers of such instruments suggest that it would be of value to classroom teachers as a diagnostic tool (Haslam and Treagust 1987, Odom and Barrow 1995). This is not a very ambitious application of the instrument since a self-contained diagnostic tool with proven validity does permit the use of inferential statistics to predict prevalence of an alternative conception in the general population. However, classroom teachers are far better poised to uncover their students' alternative conceptions simply by interacting with them. This instrument is not necessary to uncover alternative conceptions in classrooms except in very formal classroom cultures or exceedingly large lecture classes that constrain these interactions. Furthermore, instruments are necessarily so heavily dependent on word usage for such concepts as 'plant', 'respiration', 'green plant' and 'combines' that they cast doubt that valid conclusions can be reached using such instruments alone.

Advanced students such as college biology majors have maturing conceptual frameworks that are becoming more elaborate as links between their concepts form. College students' ideas are less likely to be completely contrary to the scientifically accepted concept than a younger student's ideas. Instrument items based on scientifically correct propositions about photosynthesis actually diagnose isolated errors in a conceptual framework rather than robust naïve theories about plant nutrition. Using an instrument with these students may diagnose possession of a discrete alternative conception when what is actually lacking is a valid proposition connecting previously unlinked concepts, as seen with item (4). Thus it may be more fruitful to discover where links between concepts have failed to form (i.e. gaps) rather than seeking to identify an intact alternative conception per se. Since these conceptual frameworks are complex networks as individual as the students themselves, the first step in identifying these gaps requires a qualitative approach. Having students think aloud while working on an appropriate task (such as a graphic simulation of the process of photosynthesis) seems to be a valid and practical way to look for these gaps (Griffard and Wandersee 1999). If similar gaps are found among the participants, the research may then take a quantitative turn to determine how common these gaps are, assuming concerns about these diagnostic instruments can be addressed satisfactorily.

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