Supporting Information

Questions for Classroom Response Systems and Teaching Instrumental Element Analysis

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Concerning Questions – A Supplementary

A. The structure of questions

Kelley[1] noticed “A key to understanding what questions is to understand what answers are.” Thus, to use questions effectively, the expected answer should be taken into account from the beginning. Worley[2] addressed some confusion about the difference between close-ended and open-ended questions (OEQs) and proposed a favorable mode for the characterization of questions: a differentiation between the grammatical form and the conceptual content. Table S1 demonstrates this with examples from analytical chemistry. Note the development in the nature of the questions from 1 to 4 in a manner that might be observed during a classroom question-answer cycle between a lecturer and students. Furthermore, Worley[2] argued for the use of grammatically closed and conceptually open questions (example 3 in Table S1), which are to be followed by asking for explanations for the answers given by students. This emphasizes the need for reasoning within the question-and-answer sessions, especially in formative educational settings.

Table S1. Distinction between questions according to Worley[2] with examples from analytical chemistry.

	Grammatically closed (elicits short responses)	**Grammatically open** (elicits longer responses)
Conceptually closed (contains or invites no tension/conflict/controversy in the concept(s))	*1. Is gravimetry an absolute method?*	*2. Why is gravimetry an absolute method?*
Conceptually open (contains or invites tension/conflict/controversy in the concept(s))	*3. Is gravimetry an absolute method because it determines the mass and not concentration of the analyte?*	*4. What are the benefits of gravimetry as an absolute method?*

Table S2. Common question types for CRS with examples of close content proximity.

Type	**Subtype**	**Examples**		
Multiple-choice question (MCQ)	'True' MCQ: Multiple options may be keys	*1. Which is an absolute method?*		(stem)
		A	*ICP-MS*	(distractor)
		B	*Gravimetry*	(key)
		C	*Flame-AAS*	(distractor)
		D	*Titration*	(key)
	Single-choice question (SCQ): only one option is the key	*2. Which is an absolute method?*		(stem)
		A	*ICP-MS*	(distractor)
		B	*Gravimetry*	(key)
		C	*Flame-AAS*	(distractor)
		D	*ICP-OES*	(distractor)
	Alternative choice or two-sided question	*3. What kind of method is gravimetry?*		
		A	*Absolute method*	
		B	*Relative Method*	
	Two-sided question in a true/false mode	*4. Assess the statement "Gravimetry is an absolute method."*		
		A	*True*	
		B	*False*	
Open-ended question (OEQ)	Text input	*5. Name an absolute method.* *[text input required]*		
		6. Is gravimetry an absolute method? *[text input required]*		
		7. Why is gravimetry an absolute method? *[text input required]*		
	Numerical input	*8. What is the gravimetric factor of AgCl for the determination of Ag?* *[numerical input required]*		

While this guides how CRS questions may initiate further fruitful discussions of a topic, for CRSs a different classification of questions is often adapted based on technical aspects driven by the form and type of answers expected (Table S2). Multiple-choice questions (MCQs, questions 1-4) consist of a stem with the description of the problem, the (often implicit) task and a number of different options. The recommended number of presented options is between two and four, but not limited in general. In context with exams, for questions with numerical options (e.g. “0.2 mol”) ten options were suggested to further reduce success rates by guessing[3]. Correct options are called keys and the others distractors. Several subtypes of MCQs can be distinguished. In single-choice questions (SCQs, question 2) only one option is correct. Two-sided questions (questions 3 and 4) have two distinctively contrary options (e.g. true/false, yes/no). The distinction between MCQs, SCQs, and two-sided questions lays in the technical realization with CRSs, e.g. whether more than one option can be selected. Another type are OEQs, also called short answer questions, which prompt a response not fixed by given options, but require free input of text (questions 5-7), numbers (question 8), or even drawings. Depending on the system used, numerical input or drawing overlays may be specifically accepted and evaluated.[4-6]

B. The cognitive dimension

There is a strong endorsement for 'challenging problems' or so-called 'concept(ual) questions' in the context of CRSs in the literature[7, 8]. The intention can be best understood by contrasting to what these questions ought not to be: promoting plain rote learning, recognition, or numerical problem solving. Table S3 provides a simplified list of the revised version of the involved cognitive dimension by Krathwohl[9]. This may form the basis from which the cognitive demand of questions can be realized, reflected, and if needed revised to improve the alignment with the learning objectives and process goals[8] during the development of questions. For example, there are certainly many instances when rote learning is required and respective questions in demand. However, in many other cases this needs be complemented with other questions to promote different course objectives. Noteworthy are critiques[10-12] of this framework, especially the distinction between deep and surface learning (also higher and lower order thinking).

The first six questions in Table S2 may clearly fall in the dimension “remember”, while question 7 could be associated with the dimension “understand.” However, association of a question with a cognitive domain is highly situation related. If the lecturer previously explained specifically why gravimetry is an absolute method, question 7 would be attributed to the dimension “remember” (implying attention of the students at that time and retention). This holds up even for the most complex questions: If the correct answer to a particular question is known it is just an issue of remembering. Especially with MCQs, there is tendency that instead of remembrance only recognition (e.g. from similarity) is required because phrased options are on display. However, in general all domains are accessible with MCQs.

Table S3. The cognitive dimension and typically associated verbs, adapted from[9, 13]. Note that the associated domain is highly context-related; using typical verbs does not guarantee that the associated domain is met.

Dimension	Grammatically closed (elicits short responses)
Remember *Retrieving relevant knowledge from (long-term) memory*	*list, define, identify, label, collect, name, recognize[a], recall*
Understand *Determining the meaning of instructional messages, including oral, written, and graphic communication*	*describe, contrast, predict, associate, distinguish, estimate, discuss, extend, interpret, exemplify, classify, summarize, explain*
Apply *Carrying out or using a procedure in a given situation*	*demonstrate, calculate, complete, illustrate, modify, relate, change*
Analyze *Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose*	*separate, order, connect, categorize, arrange, analyze, divide, compare, differentiate, organize, infer, attribute*
Evaluate *Making judgments based on criteria and standards*	*assess, decide, rank, grade, test, measure, recommend, evaluate, convince, check, critique, select, judge, discriminate, support, conclude, debate*
Create *Putting elements together to form a novel, coherent whole or make an original product*	*develop, plan, produce, combine, integrate, rearrange, substitute, create, design, invent, speculate, compose, formulate, prepare, generalize, rewrite, generate*

[a]Notwithstanding other characteristics, all questions may fall into the dimension "remember" if an option of a MCQ is recognized as correct or best. "Recognize" may also be put as an additional domain for MCQs above "remember".

Allow me to further illustrate these points with two non-chemical, but Swiss multiple-choice questions (Fig. S1). The top question provides actual Canton emblems as options, the bottom question a variation of the same color scheme. Whenever I put these questions to an audience with just seconds to respond, the bottom question results in a lower correct response rate than the top question. The demand for recognition, association, and exclusion of options is different for those two questions. Again, whether or not it makes sense to ask one question or another depends on the situation and the learning goal. Another possibility would be to let students draw the emblem. For Chemistry, the questions displayed in Fig. S1 may translate into questions for a reaction product and options with very different compounds (top questions) or compounds in close structural proximity (bottom question).

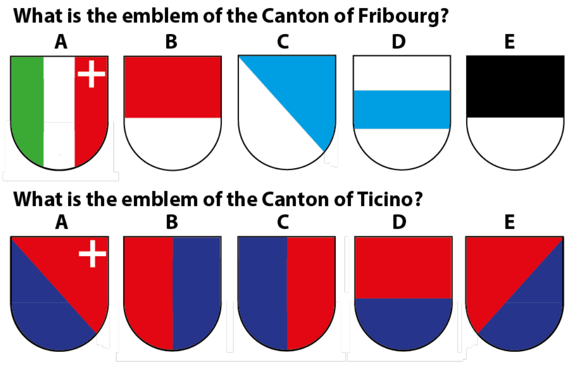

Fig. S1. Two exemplary, non-chemical, but Swiss multiple-choice questions. The options for the top question represent actual emblems of Cantons, the options for the bottom question variations of the Ticino emblem next to the correct emblem.

C. Correct and best options

Tamir discussed the problem of correct vs. best answer in detail[14], which complicates the matter of question development even more. Consider the following MCQ[1]:

Gravimetry is an absolute method because…

- A *it is a primary method.*
- B *quantification is based on stoichiometry, amount of substance, and mass.*
- C *quantification is based on a relationship between signal and analyte amount which can be described by physical constants and universal quantities.*
- D *no calibration is required.*

All four options are "correct" (opposed to unambiguously incorrect), while C can be considered the "best" option. Note that the stem misses (if not provided otherwise) the instruction on whether only one or potentially all options are supposed to be "correct" and selected. Such question may provide opportunities to subsequently discuss shortcomings of particular phrasings of options and emphasize characteristics of specific terminologies or concepts, respectively. If such MCQs are used, students might be instructed to select the *best* answer. This implies that even when they have identified a correct answer, they should consider the other options to find a better response. Although, this question type tends to require more abilities from students, it also introduces ambiguity. Overall, one might find over time that MCQs offering solely correct options and distractors lack a certain richness and usefulness in teaching. Moreover, the example above illustrates the tendency of the correct or best option to be the

[1] Another example from general chemistry: *What is a chemical bond? (A) The interaction between two atoms leading to a state of lower energy. (B) The sharing of one or more electron pairs between two atoms. (C) The interaction between atoms leading to a new chemical entity with distinct properties. (D) Stabilizing interaction between atoms with an energy gain larger than the thermal energy.*

longest. If they lack the specific skill in demand, test-wise students will select the longest option and commonly have a higher success rate than by a random selection.

D. Multiple-choice vs. open-ended questions for classroom response systems

At large, CRSs do not restrict a lecturer to one of the specific question types presented in Table S1; all four can be handled either as MCQ or OEQ. With MCQs several phrased options would be provided. Many CRSs also allow free text responses to OEQ. Similarly, the OEQs in Table S1 could be converted into MCQs by providing options.

With CRSs, it is easy to collect many OEQ responses and their range (content, context, and phrasing) is wider and present more representative overview of students' approach to the question. Nevertheless, there are considerable drawbacks: Since students need to phrase and type their response freely, the response time may increase compared to MCQs. Another hurdle lies in the ad-hoc evaluation of answers, particularly for larger classes with numerous responses. An acceptable response should be possible with a reasonable number of characters. With these shortcomings, CRS rely mostly on suitable MCQs. Nevertheless, MCQs restrict the responses by design to a limited variety, leaving out alternatives and nuances in the phrasing.

It is challenging to encase the complexity of a problem into adequate options of a MCQ, which leads to, as mentioned above, longer best or correct options. This is one particular reason why it is a challenge to design and phrase questions for CRSs. If a complex answer structure or lengthy processing of information, i.e. with multiple steps, is required, a different and even out-of-class activity (weekly worksheets, allocated exercise sessions, one-to-one interactions, etc.) should be considered. Graphical aids can be used to address some forms of complex issues, which are not suitable for a solely text-based approach, e.g. a prediction or evaluation of experimental results in diagram format.

In brief, the variety of MCQ types used for the CRSs in a course should be limited to avoid confusion. Several MCQ types[15] like matching, complex MCQs, or scale-based responses (e.g. Likert-type questions[16]) are not commonly used with CRSs. However, the analysis of OEQ can provide valuable insights into students' reasoning, skill to process information[17] and increase opportunities for students to practice problem-solving. Therefore, it is up to lecturers to balance the use of MCQs and OEQs by considering educational aims, affordance, and demands, respectively.

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