Applying Cognitive Science to Online Learning

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Abstract
Online educational resources like videos and exercises are playing an increasing role in the education of thousands of students, via both MOOCs and blended education in classrooms. Taking advantage of the progress in scientific research on learning, this paper considers some practical implications that emerge from synthesizing research in cognitive science, presenting actionable instructional tactics that any designer or instructor can take advantage of to improve students’ learning. These target the complementary goals of enhancing both motivation and cognitive processing. Motivation can be increased by fostering students’ beliefs that intellectual capacity is malleable and can be improved through effort and use of effective learning strategies. Cognitive processing can be enhanced by augmenting online videos and exercises with questions and prompts for students to generate explanations: before, during, and after learning. These instructional strategies provide students with direction while allowing them to take charge of their learning, are technically easy to implement, and are applicable to online resources across a wide range of topics.

1 Introduction
Students of all ages are increasingly learning from online educational resources. This can range from completely online education (like the university level videos and assignments in massive open online courses or MOOCs) to blended or hybrid learning, such as complementing in-class instruction with online resources like homework mathematics exercises on Khan Academy’s platform. How can instructors be supported in teaching online, and students be helped to learn effectively?

While there are many answers to this complex question, one approach is to use what has been learned from the past forty years of research in cognitive science (and the learning sciences more generally), which is complementary to the expertise of instructors and course designers. This is challenging for both researchers (in considering how their work might provide practical and actionable improvements for specific online resources) and practitioners (in determining the relative relevance of thousands of published studies).

The current paper considers research on how to increase motivation by encouraging students to view their intelligence as malleable, and how to enhance learning processes by prompting students with questions. Previous literature that similarly considers the practical educational
relevance of cognitive science is cited in the following section, but the current paper aims to
provide several novel contributions. The paper focuses on learning online and in blended/hybrid
environments that use online educational resources. The learning principles reviewed were chosen
to target key challenges in online learning, like ensuring learners remain engaged and active even
without a traditional classroom environment, promoting deep understanding rather than superficial
memory, and supporting students in active construction of knowledge even with minimal direct
feedback.

The paper also synthesizes this research to present concrete, actionable and readily implementable
suggestions for applying this research, targeted at the level of improving learning from an
individual video (tiny.cc/augmentedvideo) and/or interactive exercise
(tiny.cc/augmentedexercise).

Finally, given the complexity and depth of the topic, the paper does not purport to be the final say,
but aims to provide a concrete starting point for further discussion between researchers and
practitioners. A working draft of the paper is available at tiny.cc/cognitivescienceinmoocs, so that
it can evolve in light of feedback and discussion, which is welcomed by email to the author.

1.1 Related resources on Cognitive Science and Educational Practice

The following consider educational implications of cognitive science more generally. [1] is an
Institute of Education Sciences practice guide that is short, available online, constructed by an
expert panel, and peer-reviewed. Books include [2], which is targeted at university instructors, [3]
is for a general audience and K-12 teachers, and [4] focuses on multimedia learning for both K-16
education and corporate training.

2 Increasing motivation by fostering a Growth Mindset of intelligence

How can students learning online – without the classroom’s structured environment, social
interactions, and academically consequential grades – be motivated to pursue and enjoy learning,
and persist through challenges? Several decades of research have revealed the importance of
people’s beliefs about whether intelligence is “fixed” or “malleable” – whether an individual has a
Fixed Mindset or Growth Mindset of intelligence. This set of beliefs is powerfully correlated with
the effort they put into learning and enduring difficulties [8]. Aside from issues like level of
academic preparation and psychometric scores, students with a Fixed Mindset (who believe
intelligence is fixed) are anxious about making mistakes, demotivated by challenges, and reluctant
to ask questions [9]. Students with a Growth Mindset (who believe intelligence is malleable and
can be improved with effort and strategic learning) interpret very similar mistakes and challenges
as opportunities to learn and to become smarter. They invest more effort into learning, asking for
help, and using effective thinking and learning strategies. In fact, controlled experiments have
found that presenting information and reflective exercises to teach undergraduate and middle
school students that intelligence is malleable can have a directly measurable impact on grades
[10].

In the online context of students learning from Khan Academy’s mathematics exercises, the
minimal experimental manipulation of inserting one sentence messages that emphasized the
malleability of intelligence (e.g. “Remember, the more you practice, the smarter you become.”)
was found to measurably increase how many problems students attempted, and how quickly they

The articles and books cited above [8, 9, 10, 11] provide many concrete examples of how to
encourage beliefs in the malleability of intelligence, including specific resources whose design is
not only motivated by scientific theory, but have also been empirically demonstrated to help
students. Instructors can encourage the belief that intelligence is malleable and the use of a Growth
Mindset by presenting articles and videos that emphasize the malleability of intelligence,
including testimonials about success that emphasize effort and persistence (including their own experience), and emphasizing in lectures how success on particularly challenging topics and assignments relies on effort and effective strategies for learning, rather than ability.

Messages fostering a Growth Mindset can also be embedded in how feedback is presented on problems and assignments. Do messages emphasize the student’s ability or their successful persistence and use of a critical concept? Are grades awarded primarily for achieving the correct answer, or also for the effort displayed or the thought invested in understanding the strategies that underlie successfully solving a problem? Are students given an opportunity to make up for initially low performance by putting in extra effort or figuring out how to better solve a problem?

3 Adding questions before, during, and after videos & exercises

The principles specifically focus on how to appropriately prompt students to answer questions and provide explanations, before, during, and after watching instructional videos or engaging in exercises. It is a common intuition that students learn when they are given comprehensive knowledge: MOOCs deliver high-quality online videos with cogent explanations, and include practice exercises like that in Figure 1, accompanied by clear answers and solutions. However, there is substantial evidence that students can learn far more by trying to answer questions themselves (than by receiving the answers), or by being pushed to construct explanations (rather than provided with them), which will be discussed in the following sections.

4 Context of application: example video and exercise

Each principle for adding question prompts is targeted at the grain size of an online module – a short, self-contained batch of information like a video or exercise.

The principles are abstract in that they can improve learning from a range of online videos and exercises, but to provide concrete and actionable insight they are illustrated through application to specific examples of a video and exercise.

The example video is a three minute Udacity.com video from an introductory statistics course (http://tiny.cc/examplevideo): It explains what the normal distribution is, and how the area under its curve corresponds to the probability of observing certain sampled observations from a population (for an example of how these prompts could be added to a video, see http://tiny.cc/augmentedvideo).

Fig. 1: Example math exercise from Khan Academy: http://tiny.cc/exampleexercise

The example exercise is shown in Figure 1, an algebra word problem from Khan Academy’s collection of mathematics exercises at www.khanacademy.org/exercisedashboard (for an example of how these prompts could be added to an exercise, see http://tiny.cc/augmentedexercise). These
share a common format. Only the problem statement is shown at first (blue & red text in Figure 1). Students can submit an answer for feedback or request a hint at any point. They only move onto the next problem when they are correct, but each hint request reveals the next step in a worked example solution – which ultimately gives the answer as its final step.

Questions or prompts to generate explanations can be added in at least three ways to online modules: pre-module (immediately preceding or at the very beginning of a video/exercise – before content is presented), intra-module (popping up in a video, emphasized as an activity by the instructor, embedded into the steps of an exercise), or post-module (following the student’s engagement with a video/exercise).

### 4.1 Pre-Module: Framing Questions

Even before learners are presented with information in a video or exercise, prompting them to consider framing questions can make them more motivated to learn, as well as help them connect a module’s content to their existing knowledge, and understand how they can apply it to future problems.

In contrast to delivering a traditional sequence of subject-focused videos & exercises (which touch on a succession of topics students may struggle to relate), problem-based learning [12] frames videos & exercises as the knowledge needed to solve particular problems and answer previously articulated questions. For example, a problem-based learning version of an introductory statistics course [13] would precede lessons with a keen emphasis on what problems the lesson would teach students how to solve, rather than a typical focus on the specific facts and concepts in each lesson.

Examples of pre-module framing questions are shown in Table 1.

**Table 1**: Examples of Framing Questions that could precede videos and exercises.

<table>
<thead>
<tr>
<th>Udacity video on the normal distribution</th>
<th>Khan Academy algebra math exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before a video, a page with a Framing Question can be presented: “Explain what you already know about normal distributions.” “What is a normal distribution useful for?”</td>
<td>If you are only told about the relationships between two people’s ages, what kind of math is useful for figuring out actual ages? The guiding question to keep in mind for this exercise is: “How can you convert word problems into algebra expressions?”</td>
</tr>
<tr>
<td>Instructors can also introduce a fixed time delay (e.g. 10 seconds), a required text response, or a strong emphasis on a Framing Question at the start of a video. Demonstration: <a href="http://tiny.cc/augmentedvideo">http://tiny.cc/augmentedvideo</a></td>
<td>Demonstration: <a href="http://tiny.cc/augmentedexercise">http://tiny.cc/augmentedexercise</a></td>
</tr>
</tbody>
</table>

The motivational benefit is in greater excitement to learn in order to solve a problem, rather than learn to memorize and be tested. The cognitive benefit arises in part by getting learners to activate their existing knowledge, so they connect new information to well-established ideas. Even when prompts do not result in students producing successful explanations, the mere act of considering the prompt can still increase how much is learned once a lesson is presented [4]. [15] showed that students were mostly unsuccessful when asked to solve a problem related to calculating variability, but that having tried to solve this problem changed what they learned from a subsequent lesson. Compared to other students who received alternative instruction without this framing question or problem, these students were better able to apply what they learned in subsequent lessons to new situations.

### 4.2 Intra-Module: Reflection Questions

Typically, instruction is seen as providing learners with answers or giving them explanations. But extensive work in cognitive science, education, and intelligent tutoring has shown that giving
learners the right prompts to self-generate explanations can be more effective than giving students explanations [6] [7]. This provides empirical insight into how and when “teaching is the best way to learn”. Without changing the content of online videos and exercises, MOOCs can improve learning by appropriately embedding questions and prompts for learners to provide explanations.

Videos in MOOCs already have the functionality to pop-up short multiple choice exercises, which could be used to present questions that are more conceptual and that allow open-ended responses. Solutions to exercises can be split up into multiple lines, and have questions and prompts with text boxes to type answers embedded inline. Examples are shown in Table 2.

Table 2: Examples of how Reflection Questions could be embedded in videos and exercises.

<table>
<thead>
<tr>
<th>Udacity video on normal distribution</th>
<th>Khan Academy algebra math exercise</th>
</tr>
</thead>
</table>
| Explain what the video has talked about so far. (@1:35) | The information in the first sentence can be expressed in the following equation:  
\[ v = k + 4 \]  
Do you see why this step makes sense or is justified? |
| What are you thinking about right now? Just say it out loud. (@ 2:15) | Simplifying both sides of this equation, we get:  
\[ k - 4 = 5k - 40 \]  
What step do you think is coming next? |

There is substantial evidence that learners’ understanding is improved by prompts to explain out loud the meaning of what they are learning or say out loud what they are thinking [16]. (So that the sudden appearance of these prompts does not confuse students, the reported studies typically provide advance warning.) Asking learners to explain why particular facts are true or answers are correct has been shown to help them understand key principles and generalizations [18], [19] shows that anticipating next steps in a solution and making predictions about what will be discussed next leads students to a better understanding of how and where to use what they are learning about, and provides implicit feedback as the video continues or the solution is revealed.

4.3 Post–Module Memory Practice Questions

Questions that target information from a past video or exercise are common in MOOCs, but often do not realize their potential for Memory Practice. One reason is that they are often designed to assess learning without attention towards improving it. [20] shows that simply asking students to recall what they read in a science passage (an open ended prompt that is not common in testing, but encourages Memory Practice) greatly improved memory a week later – outperforming students who read the passage three more times, or made elaborate concept maps. Post-module prompts for this paper’s current examples might include “Write down the main points from that video.” or “Explain the method you used to solve these exercises.”

In fact, MOOCs often do include post-module questions designed to help students revisit content – such as review questions or practice exercises. However, these may not successfully produce Memory Practice if they occur so soon after a module that a learner can answer using rote memory. [21] provides an extensive review of how to ensure post-module questions are beneficial, so that Memory Practice helps learners generate the meaningful cues and connections to other concepts that are needed to remember over the long-term.

For example, simply spacing practice exercises improves long-term retention (although benefits are deceptively absent in the short-term), and learning is even further improved by interleaving or mixing problems and concepts that students frequently confuse [22]. For example, a typical practice sequence might be 12 problems of type A, then 12 of type B, and 12 of type C. But it can
be better for deep, lasting learning to use an *interleaved* practice sequence, like [6 A, 4 B, 2 C], [4 A, 6 B, 2 C], and [2 A, 4 B, 6 C].

Often, however, students and instructors may assume that the more challenging learning in the *mixed* condition means that it is a poorer strategy and abandon it – even though it produces larger and lasting benefits *without any increase* in the number of problems [22]. Ironically, the same studies that empirically show the advantages of Memory Practice also find that students expect typical study strategies to help more [20] [21].

### 5 Conclusion

This paper considered how to improve learning in MOOCs by adding question & explanation prompts before, during, and after online videos and exercises. This is not to say that MOOCs *never* incorporate questions into instruction as advised – this is unlikely given the diversity of online instruction. Scientific principles for learning can be used to design novel instruction or to support *benchmarking* – to identify which of the vast set of instructional strategies are supported by cognitive science. Moreover, consulting and working with cognitive scientists (to embed practical experiments and design measures of learning) allows MOOCs to maximize learning by tailoring general learning principles to specific courses and lessons. Collaborations like these between instructors and scientists can provide the best outcomes for students.

### Acknowledgements

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### References


