Developing a framework for creating heuristic worked example videos to enhance students' modeling competencies

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As a large number of instructional videos can be found online, the question arises to what extent videos can be used in mathematics classroom practice. While many videos address algorithmic domains, this theoretically informed paper focusses on the possibilities of using videos to enhance heuristic skills in the domain of modeling. It introduces a framework for developing heuristic worked example videos based on multimedia learning principles, (heuristic) worked example research and criteria for creating instructional videos. In addition, the framework and directions for future research are discussed.

Keywords: Interactive video, instructional design, cognitive load theory, mathematical modeling, secondary education.

Objective and rationale

Videos are gaining importance in the educational setting. The production of videos has become easier in recent years and many videos are available online (Kay, 2012; Kay & Edwards, 2012). Studies have shown that videos can have a positive effect on learning performance (for an overview, see Kay (2012)). Video formats that contain an instructional method, which is considered particularly beneficial for novices, are so-called worked example videos (Kay & Edwards, 2012). Worked examples present a problem and a step-by-step solution. In mathematics, the efficiency of (text-based) worked examples has been shown in several studies (e.g., Sweller & Cooper, 1985; Renkl et al., 1998). The efficiency is not only observable in algorithmic domains but also in less-structured domains such as proving or modeling using heuristic worked examples (Reiss et al., 2008; Zöttl et al., 2010; Tropper, 2019). First indications of the effectiveness of worked example videos in an algorithmic domain are provided by the study of Kay and Edwards (2012). The question arises, to what extent videos can be used to enhance heuristic skills in mathematics as videos offer new possibilities opposed to the medium "text", such as dynamic visualization. A domain that requires heuristic skills is mathematical modeling because it involves the whole process of mapping a real-world problem to a mathematical model by structuring information, searching for data that is not given, working mathematically and translating the results back to the real world (Niss et al., 2007). The process can be demanding for students because they face many obstacles along the way (Niss et al., 2007). This is why research on teaching through heuristic worked examples to enhance modeling competencies should be continued (Renkl, 2017) and a video provides a new approach. A video can not only explain a step-by-step solution of a modeling problem but it can also establish reality references by presenting scenes from the real world. On the contrary, one main criticism regarding videos is the frequent lack of interactivity and the correspondingly low level of student activation (Brame, 2016). Hence, this paper aims at developing a framework for effective heuristic worked example videos which are interactive and student-activating. To achieve this, principles derived from the cognitive theory of multimedia learning (Mayer, 2020) are considered as well as principles from (heuristic) worked example research. Both are closely related to cognitive load theory (Sweller et al., 1998), which makes this a key component when developing the framework. Moreover, existing frameworks for creating worked example videos (Kay, 2014), educational videos (Brame, 2016) and effective science explanation videos (Kulgemeyer, 2018) are analyzed for the specific demands of developing heuristic worked example videos. The goal is to provide a framework that can be used as an orientation for teachers, educational researchers or anyone who wants to produce interactive videos addressing heuristic domains in mathematics.

Cognitive load theory

When developing a framework for heuristic worked example videos (see Figure 1), criteria for creating educational video/multimedia and (heuristic) worked examples should be taken into account. The effectiveness of both is largely explained by cognitive load theory and design criteria are aiming at minimizing cognitive load. Three different kinds of cognitive load can be distinguished: intrinsic, extraneous and germane cognitive load (Sweller et al., 1998). While intrinsic cognitive load is caused by the intrinsic nature of the material and thus cannot be reduced by the instructor, extraneous cognitive load is imposed by poorly designed material. Germane cognitive load is necessary to construct schemas and is, thereby, an important requirement for storing knowledge in long-term memory (Sweller et al., 1998). Instructors should seek to increase germane cognitive load (e.g., consider suitable cognitive activities), decrease extraneous cognitive load (e.g., avoid confusing instructions, design material carefully) while keeping in mind that each subject imposes an intrinsic cognitive load on learners.

Criteria for developing heuristic worked example videos

In the following, each category for developing heuristic worked example videos (see Figure 1) is described and explained by video/multimedia research and research on (heuristic) worked examples.

Segmentation of the video based on a solution plan

One possibility to enhance germane cognitive load is following the *segmenting principle* by splitting a video into meaningful segments with a break in between two segments (Mayer, 2020, p. 247 ff.). When presenting videos as a continuous unit, learners might have problems processing preceding steps resulting in difficulties connecting them to following steps (Mayer, 2020, p. 252). In a study conducted by Biard et al. (2018), breaks after each main segment of a video and continuing the video by manually pressing the “play-button” led to a reduction of cognitive load. This did not apply when learners could pause a continuous video at self-determined points which might be due to the fact that learners made very little use of the pause-button (Biard et al., 2018). The *segmenting principle* has also been shown as advantageous for (text-based) worked examples (“modular worked examples”) in the domain of probability problems as it resulted in less study time, more correctly solved problems, less cognitive load and a higher feeling of success (Gerjets et al., 2006). If the instructor assigns labels to subgoals and makes the sense of each solution step salient, it can help learners to encode the structure of a problem (Renkl, 2014). This is also included in Kay’s (2014) framework for creating worked example videos as “meaningful steps”. Considering the heuristic worked example literature, it is advised to display a heuristic worked example by following a solution plan (Reiss & Renkl, 2002). Solution plans have been shown as a promising method to scaffold the modeling process of students (Schukajlow et al., 2015; Beckschulte, 2020). Thus, a solution plan provides guidance on how to segment a video into meaningful steps. Furthermore, pauses in between two steps offer the opportunity to prompt for self-explanations (see below).

Implementation of self-explanation prompts

When teaching mathematics, self-explanation prompts can help students build up procedural knowledge, conceptual knowledge and procedural transfer (Rittle-Johnson et al., 2017). Writing an explanation after each section of a video is considered as a *generative activity* and enhanced learning from video (especially for low-knowledge learners) (Mayer et al., 2020). This technique has been superior to rewatching the video or generating a drawing (Fiorella et al., 2020). Other options for prompting during videos are having the learners compare the content observed to prior knowledge or other material (Chi & Wylie, 2014). This corresponds to the *self-explanation and comparison principle* in worked example research (Renkl, 2014). In the case of novices or learners being unable to produce self-explanations, instructors should offer scaffolds such as structuring self-explanation responses (Renkl, 2017; Rittle-Johnson et al., 2017). When implemented into heuristic worked examples in modeling, principle-based prompts helped students elaborate the underlying procedures of an example (Tropper, 2019, p. 235).

Category	Indication from video and multimedia research	Indication from (heuristic) worked example research
Segmentation	segmenting principle (Mayer, 2020) meaningful steps (Kay, 2014)	usage of modular examples (Gerjets et al., 2006) following a solution plan (Reiss & Renkl, 2002)
Self-explanation prompts	generative activity principle (Fiorella et al., 2020; Mayer et al., 2020)	self-explanation and comparison principle (Renkl, 2014, 2017) elaboration of underlying procedures (Tropper, 2019)
Larger concept	follow-up learning tasks (Kulgemeyer, 2018) larger homework assignment (Brame, 2016)	example-set principle (Renkl, 2014) fade worked steps (Renkl, 2017)
Heuristic strategies	clear problem label (Kay, 2014) explain key elements (Kay, 2014)	make used heuristics explicit (Reiss & Renkl, 2002)
Layout decisions	weeding (Ibrahim et al., 2012) / seductive details principle (Mayer et al., 2020) / length shorter than 6 minutes (Guo et al., 2014) dynamic drawing principle (Mayer et al., 2020) / video style: preferably showing instructor's hand (Mayer et al., 2020) signaling (Brame, 2016) / highlighting, write down key information (Kay, 2014) / signaling principle (Mayer, 2020) match modality (Brame, 2016) / modality principle (Mayer, 2020) / use visuals (Kay, 2014)	
Conversational language	conversational language (Brame, 2016) / direct addressing (Kulgemeyer, 2018) / personalization principle (Mayer, 2020) engaging voice (Kay, 2014) / voice principle (Mayer, 2020) pace: 185-254 word per minute (Guo et al., 2014)	

Figure 1: Framework for developing heuristic worked example videos

Integration of the video into a larger concept

Rather than presenting standalone videos, videos should be integrated into a larger learning concept. Especially when learning complex skills, presenting only one (video) example might not be sufficient. Brame (2016) suggests to embed videos into a larger homework assignment. Moreover, Kulgemeyer (2018) recommends supplying learners with follow-up learning tasks, so that they have an opportunity to use the explained information for problem-solving. Considering worked example research, there may be limitations when presenting example-problem pairs, as they do not necessarily lead to a greater learning outcome than presenting worked examples only (van Gog et al., 2011). The *interleaving by fading principle* (Renkl, 2014) suggests to rather design a fading procedure with a complete example presented first before gradually fading solution steps. Atkinson et al. (2003) found that this is especially fruitful when combined with self-explanation prompts as it fostered near- and far-transfer performance in the domain of probability calculation. The integration of the video into a larger concept does not only suggest to fade worked steps and to integrate self-explanation prompts on the level of the video, but also implies different usage scenarios: Students could watch a heuristic worked example video at home in order to initiate in-class (group-)work. Moreover, a heuristic worked example video with its integrated prompts and faded worked steps could be used to support group work in class by stimulating discussion and structuring the solution process.

Explication of heuristic strategies

When solving problems, experts in mathematics usually employ heuristic strategies (Collins et al., 1987, p. 12). In order to present an approach to solve a problem, a video should at first clearly label the problem addressed (Kay, 2014). Subsequently, structuring the video on the basis of a solution plan not only offers guidance for the video segmentation as described above, but it can also be used to depict an experts' approach by outlining applied heuristics explicitly along the way (Reiss & Renkl, 2002). This opens up the possibility of explaining key elements in a way that learners understand the problem structure and the essential elements required to solve the problem (Kay, 2014). Transferred to a video aiming at the enhancement of students' modeling competencies, explaining key elements could involve visually displaying how to search for a comparison value. Depending on the example demonstrated, many other modeling-specific heuristic strategies are imaginable. Presenting those in a video compared to explaining them in a text-based heuristic worked example might be promising because a video supports the modality principle as described below.

Minimizing cognitive load through layout decisions

The underlying principle of the following design recommendations is the reduction of extraneous cognitive load through layout decisions. Since the medium "video" largely differs in the layout possibilities from the medium "text", the criteria are solely based on video/multimedia research. A video containing additional interesting but irrelevant features might increase the precepted learning difficulty and decrease the focus on essential content of the video (Ibrahim et al., 2012). This is called the *seductive details principle* (Mayer et al., 2020) and *weeding* (Ibrahim et al., 2012) describes the process of excluding interesting but irrelevant word or graphics from a video. *Weeding* might also help reducing the length of a video, which has been shown to be an important factor considering student engagement (Guo et al., 2014). Based on the analysis of 6.9 million MOOC videos, Guo et al. (2014) advise that video chunks should not exceed 6 minutes. A video dealing with a complex example probably outranges this recommendation. Nevertheless, it provides orientation when planning the video segmentation as described above, arranging less than six-minute-long segments. Another design feature which should be considered is the display style of the video. Different kinds of videos such as voice-over slide presentations, drawing on a paper and filming from above or drawing on a digital tablet are possible. Mayer et al. (2020) outline that learning outcome increases when an instructor draws graphics on a board rather than adding a voice-over to already drawn graphics (*dynamic drawing principle*), with the instructor's hand visible being an important factor. However, a video containing dynamic drawing without the hand visible still outrated the voice-over to the same already drawn graphics (Fiorella et al., 2019). Altogether, the decision of the video style might be significantly influenced by the content and task presented. When presenting a modeling task through a video including realistic film scenes, the video material may become an essential part to solve the task, if information can only be retrieved from the video (Greefrath & Vos, 2021). In this case, a video including drawings on a digital tablet might be a suitable format. Frames can be used to highlight important information even though the dynamic drawing principle might not unfold its complete potential. Nevertheless, it still offers possibilities for signaling through color codes or arrows. This is seen as an important feature in videos (Brame, 2016; Kay, 2014) explained by the *signaling principle* (Mayer, 2020, p. 166 ff.) because signals provide guidance for learners' attention. Finally, this style allows to address both the audio and visual channel, taking advantage of the *modality principle* (Mayer, 2020, p. 281 ff.), which states that people learn better from pictures and spoken word than from pictures and printed words.

Usage of conversational and engaging language

Other than a text, a video usually relies on visuals and narrated words. This means that the language can have an impact on learning. In videos, a conversational language is preferred over a formal language (Brame, 2016) and using direct addressing is preferred over a passive voice (Kulgemeyer, 2018). The underlying principle is called the *personalization principle* (Mayer, 2020, p. 305 ff.) and its efficiency is explained by learners trying harder to understand the content when the feeling arises that the instructor is talking to them. This is the same reason why speaking in an appealing human voice fosters learning (*voice principle*) (Mayer, 2020, p. 322 ff.) and is considered as an important component of worked example videos (Kay, 2014). It might also be essential to speak relatively quickly (Brame, 2016), with 185-254 words per minute recommended (Guo et al., 2014).

Discussion

The developed framework offers theoretical considerations about how to support student learning from heuristic worked example videos in the domain of modeling by considering the impact of design features on cognitive load.

Even though a comprehensive review of educational video design criteria was conducted and principles of generative learning were taken into account, the criticism that videos frequently lack interactivity cannot be denied completely. The approach of (heuristic) worked examples more or less implies direct instruction. This tension cannot – and should not – be completely resolved in the case of heuristic worked example videos. Providing learners with solution steps is one (if not the) key component of (heuristic) worked examples. It results in a possible limitation of the proposed framework though: Videos based on this framework are probably more suitable for novice learners and may not be a promising approach for advanced learners. The fact that knowledgeable learners might profit more from a minimal instructional approach has been reported as the *expertise reversal effect* in worked example research (for an overview, see Kalyuga (2007)).

Since this theoretical framework has not been tested yet, the next step should be to put it into practice by developing videos based on this approach. Observing students' behavior while working with those videos can allow drawing conclusions about which categories achieve the desired impact. Moreover, the usage of heuristic strategies while working with the videos (especially with the self-explanation prompts and the faded solution steps) should be examined in order to understand to what extent videos can be used to enhance modeling competencies. This may contribute to the proposed further research on worked examples in the domain of modeling (Renkl, 2017) and to the little research done on worked example videos in mathematics (Kay & Edwards, 2012). It is also conceivable to use this framework to produce videos that target other heuristic domains such as problem solving or proving. For this purpose, an adapted solution plan can be used and problem solving or proving strategies can be made explicit analogously to the modeling-specific strategies.

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