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Enhancing Example-Based Learning: Teaching on Video Increases Arousal and Improves Problem-Solving Performance

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Recent findings show that after studying a text, teaching the learned content on video to a fictitious peer student improves learning more than restudying the content. This benefit may be in part due to increased arousal associated with the teaching activity. The present experiment investigated whether teaching on video is also effective for acquiring problem-solving skills from worked examples, and explored the role of cognitive load, worry, and arousal. Participants ($N = 61$ university students) first studied two worked examples on electrical circuits troubleshooting and completed a practice problem. Then they either taught the content of a worked example of the practice problem on video (teaching condition) or studied that worked example (control condition) for the same amount of time. Self-reported cognitive load was measured after each task and self-reported worry after the final task. Effects on arousal were explored via the Empatica wristband measuring electrodermal activity (EDA; i.e., galvanic skin response). Teaching the content of the worked example on video was not associated with more worry, but did result in higher perceived cognitive load, more arousal, and better performance on isomorphic and transfer problems on the posttest. Although this finding has to be interpreted with caution, teaching also seemed to moderate the effect of prior knowledge on transfer that was present in the study condition. This suggests that teaching is particularly effective for students who initially have low prior knowledge.

Educational Impact and Implications Statement
Studying examples of how to solve a problem is a very effective way of learning new problem-solving skills. We examined whether the effectiveness of example study could be enhanced further by teaching the content of an example in front of a camera to a fictitious peer student. Our findings indicate that after an initial study phase, teaching the content of an example on video results in better performance on problems on a posttest than studying the example for the same duration. This benefit does not seem to be a result of the increased excitement/arousal associated with the teaching activity. This study provides further evidence that teaching on video is an effective learning strategy, which could be interesting and relatively easy to implement for educational practice.

Keywords: example-based learning, arousal, teaching, explaining, video

It is well established that novices learn better from studying examples (or example study alternated with solving practice problems) than by solely solving practice problems (for reviews, see Atkinson, Derry, Renkl, & Wortham, 2000; Renkl, 2014; Sweller, Ayres, & Kalyuga, 2011; Sweller, Van Merriënboer, & Paas, 1998; Van Gog & Rummel, 2010). The effectiveness of example study

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has been shown with both video modeling examples in which another person (the model, e.g., a teacher or a peer student) provides a demonstration and explains how to solve the problem (e.g., Kant, Scheiter, & Oschatz, 2017; Schunk & Hanson, 1985) and worked examples in which a written demonstration of the solution procedure is provided (e.g., Cooper & Sweller, 1987; Van Gog, Kester, & Paas, 2011).

Over the past two decades, researchers have been looking for strategies to further improve the effectiveness of example-based learning. According to Van Gog and Rummel (2010), the goal of these strategies is to:

> stimulate more active processing of the examples or emphasize important aspects of the procedure, which helps students not only to learn the problem-solving procedure but also to understand the underlying structure and rationale, which is necessary to be able to solve slightly novel problems. (p. 161)

An example of such a strategy is the completion (cf., fading) strategy in which learners are presented with examples that require some of the solution steps to be studied and other solution steps that are left blank to be completed (e.g., Renkl, Atkinson, Maier, & Staley, 2002; Van Merriënboer, 1990). Another commonly used strategy is instructing learners to generate self-explanations about the underlying principles of the worked-out solution steps (e.g., Atkinson, Renkl, & Merrill, 2003; Chi, Bassok, Lewis, Reimann, & Glaser, 1989).

An issue with these instructional strategies, however, is that they do not seem to *consistently* lead to better learning outcomes as measured by performance on isomorphic and transfer problems than merely studying examples (Renkl, 2014). For example, the benefits of prompting self-explanations are dependent on a variety of context conditions, such as whether learners produce complete and accurate explanations, whether the explanations are supported by training or structure-providing prompt types, and whether the prompts are designed in such a way that they do not take away attention from the learning materials (see, e.g., the recent reviews by Rittle-Johnson & Loehr, 2017; Rittle-Johnson, Loehr, & Durkin, 2017).

Teaching on Video

One promising technique that has shown consistent benefits compared with restudying for learning other types of content, but has not yet been tested with example-based learning, is teaching on video, which entails teaching learned content on video to a fictitious peer student. For instance, Fiorella and Mayer (2013, 2014) provided university students with a text on the Doppler effect. Students studied the text either with the expectation that they would later take a test (i.e., test expectancy) or the expectation that they would later teach the content of the text (i.e., teaching expectancy). Some of those who studied with a teaching expectancy subsequently engaged in a teaching activity in which they explained the learning material to a fictitious peer for 5 min in front of a camera. Results indicated that teaching on video consistently fostered students' performance on an immediate and delayed comprehension test, compared with only expecting to teach or expecting to take a test. Whereas these beneficial effects of teaching in some of the experiments might have emerged from spending additional time on the teaching activity, Fiorella and Mayer (2014, Experiment 2) also found this benefit when students in the other conditions were given the same amount of time to restudy the materials.

Similar results were found by other authors using different learning materials (i.e., a text on syllogistic reasoning; Hoogerheide, Loyens, & Van Gog, 2014). Secondary education students (Experiment 1) and university students (Experiment 2) were randomly allocated to a test expectancy, teaching expectancy, or teaching condition. The test and teaching expectancy conditions were provided with a restudy activity to control for time on task. Students completed an immediate and delayed posttest, consisting of both isomorphic and transfer tasks. Isomorphic tasks were similar to those encountered in the text in the learning phase (syllogistic reasoning items; e.g., is the following conclusion valid or not: "If this is an apple, then it is a fruit. Conclusion: It is not an apple, therefore it is not a fruit"). Transfer tasks were novel tasks to which the same logic rules could be applied (Wason Selection items; e.g., determine which two cards you would need to turn to test the rule "If there is a Y on one side, then there is a 2 on the other side?" with answer options: "X, Y, 2, and 7"). Like Fiorella and Mayer (2013, 2014), Hoogerheide and colleagues (2014) found mixed effects of studying with a teaching expectancy, but teaching on video fostered performance on isomorphic and transfer test tasks on the immediate and delayed posttest compared with restudying. Interestingly, a subsequent study found that benefits of teaching only emerged when teaching on video, not when students explained the learned content to a fictitious peer student in writing (Hoogerheide, Deijkers, Loyens, Heijltjes, & Van Gog, 2016). Note that Hoogerheide and colleagues (2014, 2016) ruled out the possibility that the benefits of teaching on video could simply be attributed to retrieval practice, because students in the restudy condition were provided with a cued-retrieval activity that required them to retrieve information from the text. It was important to control for the effect of retrieval practice, as retrieval practice is inherent to explaining and is a known strategy for enhancing learning outcomes in itself (Roediger, Putnam, & Smith, 2011; Rowland, 2014).

The finding that teaching was not beneficial when done in writing suggests that the benefits of teaching on video may not simply be due to the explaining activity itself (Hoogerheide et al., 2016). Instead, the authors hypothesized that the benefits arise, at least in part, because teaching on video stimulates learners to be aware of their potential audience. The authors found some tentative evidence for this "social presence" hypothesis: the explanations provided in the teaching on video condition comprised a higher proportion of audience-directed utterances (e.g., you, us) than the explanations provided by those in the teaching in writing condition.

Why would being aware of the potential audience lead to better learning? The key factor might be that teaching on video evokes arousal (Hoogerheide et al., 2016). Arousal is a state of being excited or activated, and is characterized by an increased activation of the sympathetic nervous system (i.e., the nervous system responsible for the fight-or-flight response), resulting in an increase in heart rate, blood pressure, and perspiration (Sharot & Phelps, 2004). Compared with low and high arousal levels, a moderate degree of arousal can enhance various cognitive processes that play a role in learning, such as working memory capacity, memory consolidation, alertness, and attentional focus (Arnsten, 2009; Diamond, Campbell, Park, Halonen, & Zoladz, 2007; Roozendaal, 2002; Sauro, Jorgensen, & Pedlow, 2003; Sharot & Phelps, 2004). These findings are in line with the Yerkes-Dodson law, which postulates that the relationship between arousal and task performance follows an inverted-U function (Yerkes & Dodson, 1908). Note that the optimal level of arousal during learning varies from person to person, as learners' arousal depends on task complexity and consequently also on their expertise.

Presenting on video is known to induce arousal. Indeed, it is used for that reason in the Trier Social Stress Test (Kirschbaum, Pirke, & Hellhammer, 1993). Moreover, in social psychology research it is well established that the presence of an actual audience can affect how well people perform a task, and that the effect an audience has on task performance is, at least in part, mediated by arousal (Aiello & Douthitt, 2001; Bond & Titus, 1983). Interestingly, recent research has shown that merely believing that someone is watching you (i.e., a fictitious audience) can also evoke arousal. For example, when participants in an fMRI scanner were told that a peer was monitoring them via a camera embedded in the scanner, their arousal increased (Somerville et al., 2013). Finally, findings from a study by Okita, Bailenson, and Schwartz (2007) showed that believing that spoken information provided by an online avatar was narrated by an actual person enhanced both arousal levels and learning.

In sum, after an initial study phase, teaching on video improves learning outcomes compared with restudy with conceptual learning materials. It is still an open question whether teaching on video would also be an effective instructional strategy for acquiring problem-solving skills from example-based learning. Moreover, these benefits have been suggested to arise because teaching on video stimulates learners to be aware of the potential audience, which might induce arousal. However, this assumption has not yet been tested.

The Present Study

The main purpose of the present study was to investigate the hypothesis that after an initial acquisition phase consisting of studying two worked examples and solving a practice problem, teaching the content of another example on video (teaching condition) would improve learning (as measured by performance on isomorphic and transfer test problems) compared with studying that example (control condition). We also assessed effects on perceived cognitive load (by means of self-reported mental effort investment). It was expected that, in line with findings from prior research (Hoogerheide et al., 2016), teaching a worked example on video to a fictitious peer student would induce cognitive processes that would place higher demands on working memory (i.e., would be more effortful) than studying that example, but would also be more conducive to learning (i.e., these teaching processes would impose *germane* cognitive load; Sweller, 2010), as evidenced by higher test performance attained with equal or less effort investment on the test problems (cf., Paas & Van Merriënboer, 1993; Van Gog & Paas, 2008).

To explore whether teaching on video would indeed increase arousal compared with study, and whether this increase in arousal would be associated with learning outcomes, we measured students' EDA (i.e., galvanic skin response) during learning, via the Empatica wristband. EDA reflects variations in the electrical characteristics of the skin and constitutes an objective indication of a person's physiological arousal (Braithwaite, Watson, Jones, & Rowe, 2013; Critchley, 2002). Importantly, because of the relatively long duration of the learning phase, we focused on tonic EDA, which refers to the general changes in autonomic arousal over longer periods of time, rather than phasic EDA, which relates to short-term changes (peaks) in response to certain stimuli or events. Finally, we also administered a worry questionnaire that asked participants to report on distracting thoughts while teaching or studying the final example, because this distraction is an aspect of stress that could hamper learning (Renkl, 1995, 1996).

Method

Participants and Design

Participants were 63 psychology students (18 male; age: M = 20.63, SD = 2.13) from a Dutch university. Two participants were removed from the sample for failing to comply with the instructions, resulting in a final sample of 61 participants (17 male, age: M = 20.61, SD = 2.16). Participants received course credits for their participation. They were randomly assigned to either the teaching condition (n = 30) or the control condition (n = 31).

Materials

The paper-based materials used in this experiment focused on troubleshooting parallel electrical circuits and were based on prior research (e.g., Hoogerheide, Loyens, Jadi, Vrins, & Van Gog, 2017; Van Gog et al., 2011).

Pretest. The pretest was a conceptual prior knowledge test (α = .53) consisting of seven open-ended questions on parallel circuit principles and troubleshooting (e.g., "What do you know about the total current in parallel circuits?" and "What is probably going on if you do not measure any current in a parallel branch of the circuit?"). This test served to check whether participants indeed had low (if any) prior knowledge of parallel circuit troubleshooting (because instruction that relies heavily on examples is particularly effective for novices) and to check that there were no prior knowledge differences between conditions.

Formula sheet. A brief introductory text explained the meaning of the abbreviations and components in a circuit drawing and described Ohm's law and the formula's three different iterations: $R = U/I$, $I = U/R$, and $U = I \times R$, with the R referring to the resistance, the I to the current, and the U to the voltage.

Learning tasks. The learning tasks consisted of first two worked examples, then a practice problem, and finally another worked example (i.e., four tasks in total; see Appendices A and B for an example of a worked example and the practice problem, respectively). Each task presented students with a malfunctioning parallel electrical circuit. A circuit drawing indicated how much voltage the power source delivered and how much resistance each resistor provided. The first step in all three worked examples demonstrated how to use this information from the circuit drawing to calculate (using Ohm's law) the current that should be measured in each of the parallel branches and the overall circuit if the circuit would be functioning correctly. The practice problem required the participants to calculate the currents themselves. In the second step, students were confronted with faulty ammeter measurements indicating that the current in one of the parallel branches and the overall circuit was too high compared with what would be expected if the circuit were functioning correctly (this information was given to students in both conditions). The three worked examples then explained that by comparing the calculated measures at Step 1 with those given at Step 2, it could be inferred in which branch a fault occurred and what the fault was (i.e., higher current means lower resistance; Step 3), and how the measures of the actual current from Step 2 could be used to calculate the actual resistance in that branch (Step 4; again using Ohm's law). The practice problem required participants to determine the fault and calculate the actual value of the resistor without any guidance (apart from the information provided on the formula sheet).

The first three tasks (i.e., two examples and practice problem) were isomorphic, which means that they contained the same fault (i.e., lower current in one branch, indicative of higher resistance than indicated in the circuit drawing), but different surface features (e.g., different resistance, different voltage). The fourth task was a worked example of the third task, showing the solution to the practice problem participants had just attempted to solve.

Posttest. The posttest consisted of four troubleshooting problems. The first two were isomorphic to the problems from the learning phase. The internal consistency of the two isomorphic problems on the posttest, which we calculated using the total scores participants attained on each problem, was high ($\alpha = .92$). The third and fourth were transfer problems that contained a different fault. That is, in the third problem, *higher* current was measured in one parallel branch, which is indicative of *lower* resistance in that branch than indicated in the circuit drawing, and in the fourth problem there were two faults in two different branches (in one branch the current was higher, in the other it was lower than indicated in the circuit drawing). The internal consistency of the two transfer problems (which was calculated using the total scores participants received for each problem) was high ($\alpha = .80$).

Perceived cognitive load. After each task in the learning or test phase, participants were asked to rate how much mental effort they had invested in studying that example (worked examples) or solving that problem (practice problems and test problems), on a 9-point rating scale ranging from 1 (*very, very low effort*) to 9 (*very, very high effort*; Paas, 1992). Mental effort is defined as "the aspect of cognitive load that refers to the cognitive capacity that is actually allocated to accommodate the demands imposed by the task. Thus, it can be considered to reflect the actual cognitive load" (Paas, Tuovinen, Tabbers, & Van Gerven, 2003, p. 64).

Worry. A worry questionnaire was administered after the worked example that was used for the experimental manipulation (i.e., teaching or studying) using a translated and slightly adapted version of a German worry scale developed by Renkl (1995, 1996). Students were asked to indicate, on a scale of 1 (*not true*) to 5 (*true*), to which degree the following statements represented how they felt during the fourth task: (a) "I was often distracted by other things," (b) "I thought about irrelevant information," (c) "I thought about my talent for physics," (d) "I often lost my train of thought," (e) "I had troubles focusing," (f) "I was afraid to embarrass myself," and (g) "I thought about what would happen if I did not understand the example." A factor analysis was conducted to check the dimensionality of the worry scale. Results showed that the third item ("I thought about my talent for physics") had a substantially lower factor loading (.48) than the other items, so this item was removed from the worry scale. The remaining six items each showed a factor loading of .60 or more, providing a clear indication of one dimension of unidimensionality. The reliability of the worry scale was acceptable ($\alpha = .76$).

EDA. Participants' EDA was measured during the learning phase as an indicator of learners' physiological arousal (cf., Braithwaite et al., 2013; Critchley, 2002) using the E4 Empatica wristband (www.empatica.com/e4-wristband), which is a smartwatch-like wristband that measures EDA in microSiemens (μS) with a frequency of 4 Hz (i.e., four measurements per second). The Empatica wristband was placed on participants' wrist at least five min before the learning phase to enable students to get accustomed to the wristband prior to the learning phase (Braithwaite et al., 2013).

Procedure

The experiment lasted approximately 50 min. It was run in the university lab in multiple sessions with a maximum of eight participants per session. Participants were seated in individual soundproof cubicles. The doors were left open so that participants could hear the instructions from the experimenter and the experimenter could check compliance, except during the teaching on video activity, when the doors were closed to ensure that participants would not disturb one another. At the start of the experiment, the experimenter gave a general introduction and provided the participants with an envelope containing five separate booklets. The first booklet presented a short demographic data questionnaire (e.g., age and gender) and the conceptual prior knowledge test, for which participants received 6 min. To acquaint participants with the Empatica wristband, they were asked to wear it while working on the first booklet. It was placed on the wrist of the participant's nondominant hand to minimize motion artifacts.

Next, participants were instructed to take out the second and third booklet. The second booklet presented the formula sheet, which they were instructed to study for 2 min. The third booklet presented the learning tasks. Each task was presented on a separate page, and after each task, the subsequent page presented the mental effort rating scale. Participants received four min and 15 s for each task, and 15 s for filling out the mental effort rating scale. Participants were instructed to briefly push the button on top of the wristband (to create markers in the data for analysis) at the start of the first task and the end of each task in the learning phase. The first two tasks were worked examples; the third was a practice problem. Participants were allowed to use the formula sheet (Booklet 2) and a calculator during practice problem-solving. The fourth task was a worked example of the practice problem. Participants in the control condition were instructed to study the example for 4 min and 15 s and to continue studying until time was up. Participants in the teaching condition were instructed to:

> First study the example for one minute. Then use the example to explain, looking into the webcamera, how to troubleshoot an electrical circuit, as if you were explaining to a peer student who was no knowledge of how to troubleshoot electrical circuits. You have three min and 15 s to do so. Explain it in your own words and continue teaching until time is up, which will be indicated by me knocking on the cubicle door.

After rating how much effort they invested in the fourth task and turning the Empatica wristband off (by pushing the button on the top of the wristband for more than 2 s), participants completed the last part of Booklet 3, the worry questionnaire. Finally, participants were instructed to place Booklets 2 and 3 back into the envelope and to take out the fourth and fifth booklets. The fourth booklet contained a new formula sheet that could be used while working on the posttest tasks in the fifth booklet, and participants were again allowed to use a calculator. Each posttest task was followed by the mental effort rating scale. Participants received 20 min to finish the posttest. Throughout the learning phase, the experimenter repeatedly checked and instructed students to continue working on the tasks until time was up.

Coding and Data Analysis

Test performance was scored using a straightforward coding scheme that was also used in prior research with these materials (e.g., Van Gog et al., 2015; Van Gog et al., 2011). Ten points could be earned for the conceptual prior knowledge test. On the posttest, participants could earn 3 points for each of the two isomorphic tasks (i.e., 6 in total): one point for correctly calculating the values of all ammeters, one for correctly stating which resistor was faulty, and one for correctly calculating the value of the faulty resistor. As for the transfer tasks, participants could earn 8 points in total: three points for the first task containing one fault (scoring, cf., the isomorphic tasks) and five for the second task containing two faults (i.e., an extra point for indicating the second faulty resistor and for calculating the resistance of this faulty resistor). We also scored participants' performance on the practice problem (the third task) during the learning phase (again, 3 points could be earned, scoring, cf., the isomorphic tasks). In scoring the problem-solving practice and posttest tasks, half points were given for partially correct answers. Two raters scored 20% of the tests to calculate an interrater reliability. Cohen's kappa (which corrects for agreement by chance; Cohen, 1960) was very high for both the pretest (κ = 0.94) and the posttest (isomorphic problem-solving: κ = 0.89; transfer problem-solving: κ = 0.95), and therefore one rater scored the remainder of the tests and this rater's scores were used in the analyses. The isomorphic and transfer posttest scores were transformed to percent correct scores for the sake of comparability.

To explore how well students in the teaching condition explained the example, we divided the example into 10 idea units and scored for each video: (a) how many of the 10 idea units were touched upon in the explanation ("completeness"; range 0 to 10), and (b) whether the explanation of each of the mentioned idea units was accurate (no missing elements or mistakes: 1 point), partially accurate (one missing element or mistake; 0.5 points), or inaccurate (multiple missing elements and/or mistakes; 0 points), and computed averages for each student (range 0 to 1). For example, participants could earn 1 point for explaining that the fault was located in the second branch, where the current was smaller (10 mA) than what it should be (20 mA). If only one of the informational elements was missing (e.g., not explaining that the current was smaller than what it should be) or wrong (e.g., explaining that the current was larger than what it should be), 0.5 points were awarded. If multiple elements were missing or explained incorrectly, then no points were awarded. For the sake of comparability, both measures were converted to percentages scores (i.e., we multiplied the completeness score by 10 and the accuracy score by 100 so both could range from 0% to 100%).

The EDA data were processed by selecting all the responses that emerged during the time available for each of the four learning tasks, that is, by selecting all the individual measurements that occurred in between the markers generated at the start and at the end of each learning task. For each person, an average was computed per learning task. Values of 0 were counted as missing data, meaning that these values were not considered when calculating the average EDA of the segment. Only one participant's EDA data showed values of 0 (5% of the data). If fewer than 240 responses (i.e., 60 s) were recorded during one particular task, the EDA for that whole task was coded as a missing value (n = 2, see the Results section). Moreover, following Braithwaite and colleagues (2013), we considered the first two learning tasks (i.e., worked examples) as a baseline for the autonomic changes in the electrical properties of the skin during subsequent tasks. The baseline measure was achieved by summing the average EDA during the first and second learning task and dividing this summed score by 2.

Results

Before addressing our hypotheses, we first checked whether students indeed had low prior knowledge of parallel electrical circuits, which was the case (average pretest score of 1.37 points out of 10). We also compared prior knowledge between the teaching condition (M = 1.24, SD = 1.10) and the control condition (M = 1.50, SD = 1.13), which did not differ significantly, $F(1, 59) = 0.85$, $p = .360$, $\eta_p^2 = .014$. We then checked whether the conditions showed comparable performance on the practice problem during the learning phase (i.e., the third task just prior to the experimental manipulation). An analysis of variance (ANOVA) indeed showed no significant differences between the teaching condition (M = 54.44%, SD = 31.24) and the control condition (M = 47.31%, SD = 36.54), $F(1, 59) = 0.67$, $p = .417$, $\eta_p^2 = .011$.

Does Teaching on Video Enhance Test Performance?

Analysis of the explanations generated by students in the teaching condition showed that, on average, students spoke a total of 401 words (SD = 94.69). The explanations were quite complete and very accurate, as students attained a completion score of 74.67% (SD = 21.93) and an accuracy score of 86.82% (SD = 13.91).

To test our hypothesis that the teaching condition would show better test performance than the control condition, we first conducted an analysis of covariance (ANCOVA) with students' pretest scores as covariate on students' performance on the isomorphic posttest problems. The teaching condition (M = 71.94%, SD = 23.00) significantly outperformed the control condition (M = 59.41%, SD = 33.59), $F(1, 58) = 4.29$, $p = .043$, $\eta_p^2 = .069$, and students' pretest scores were a significant predictor of their isomorphic problem-solving performance, $F(1, 58) = 6.72$, $p = .012$, $\eta_p^2 = .104$.

Concerning students' performance on the transfer posttest problems, we conducted an ANOVA rather than an ANCOVA because the assumption of homogeneity of regression slopes was violated, as indicated by a significant interaction between condition and pretest performance, $F(1, 58) = 3.92$, $p = .044$, $\eta_p^2 = .102$. Results showed that the teaching condition (M = 72.50%, SD = 19.04) significantly outperformed the control condition (M = 57.46%, SD = 35.95), $F(1, 59) = 6.25$, $p = .047$, $\eta_p^2 = .065$. The significant interaction between condition and prior knowledge could be indicative of an aptitude-treatment interaction effect. To follow-up on this significant interaction, we computed two regression analyses of students' pretest performance on transfer problem-solving performance, one for each condition. As can be seen in Figure 1, results showed a significant association between prior knowledge and performance on the transfer tasks for those in the control condition ($\beta = .560$; $t(29) = 3.641$, $p = .001$) but not for those in the teaching condition ($\beta = .012$; $t(28) = 0.062$, $p = .951$). These findings indicate that teaching the final example was particularly helpful for those who initially had very low prior knowledge, thereby eliminating the relationship between prior knowledge and transfer performance.[1]

Does Teaching on Video Affect Cognitive Load?

We first checked for differences between conditions in the average mental effort investment reported on the first three tasks of the learning phase. On these tasks one would not expect differences in perceived effort investment, as the two examples and the practice problem were the same in both conditions. One participant was not included in this analysis because she forgot to indicate the mental effort investment in the second task during the learning phase. As one would expect, a t test did not show a significant difference between the teaching condition ($M = 4.92$, $SD = 1.85$) and the control condition ($M = 5.26$, $SD = 2.01$) in reported effort investment, $t(58) = 0.68$, $p = .502$, $d = 0.174$.

We then tested our hypothesis that on the fourth task, teaching the example would result in significantly higher perceived effort investment than studying it (one participant failed to fill out this item and was not included in this analysis). As expected, participants in the teaching condition reported significantly higher effort investment ($M = 5.53$, $SD = 1.81$) than participants in the control condition ($M = 3.53$, $SD = 2.21$), $t(58) = 3.83$, $p < .001$, $d = 0.990$.

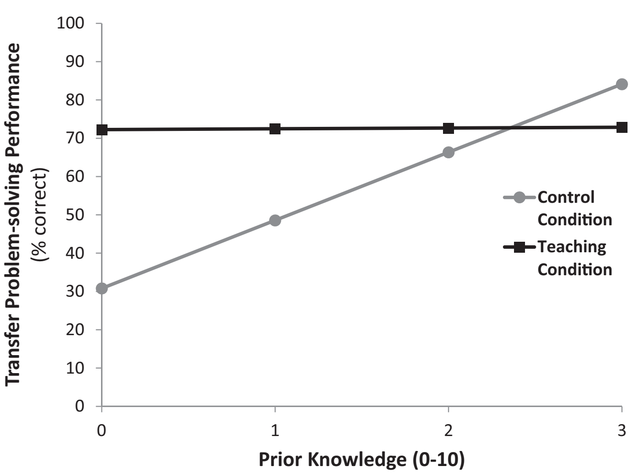

Figure 1. Plot of the significant interaction effect between condition and pretest performance on transfer problem-solving performance. *Note:* The horizontal axis portrays a minimum score of 0.0 and a maximum score of 3.0 because the large majority of participants (i.e., 94%) scored between a 0.0 or 3.0 on the conceptual prior knowledge test.

We also analyzed whether there were differences in the average perceived effort invested in the isomorphic and transfer posttest problems. One participant had a missing value on one of the isomorphic tasks and two participants had a missing value on one of the transfer tasks. These participants were removed from the analyses of perceived effort invested in the isomorphic or transfer posttest problems, respectively. Results showed no significant differences in effort reported by participants in the teaching condition (isomorphic tasks: $M = 4.16$, $SD = 1.82$; transfer tasks: $M = 3.48$, $SD = 1.84$) and the control condition (isomorphic tasks: $M = 4.50$, $SD = 2.11$; transfer tasks: $M = 4.14$, $SD = 2.48$) on the isomorphic problems, $t(58) = 0.67$, $p = .503$, $d = 0.175$, and transfer problems, $t(57) = 1.15$, $p = .253$, $d = 0.300$.[2]

Does Teaching on Video Affect Worry?

With regard to the worry reported after teaching or studying the final worked example of the learning phase, we computed the average score on the six items. An independent samples t test showed no significant difference in terms of worrying thoughts between the teaching condition ($M = 2.07$, $SD = 0.77$) and control condition ($M = 2.18$, $SD = 0.80$), $t(59) = 0.55$, $p = .584$, $d = 0.141$.

Does Teaching on Video Affect Arousal?

Seven participants were excluded from all arousal analyses: five because their Empatica wristband malfunctioned during the learning phase, resulting in insufficient data for analysis, and two because there were insufficient data available to calculate an average EDA during the first task, which meant that no baseline EDA (i.e., average EDA on the first two tasks) could be calculated. Figure 2 provides a visualization of the average EDA levels during all four learning tasks per condition.

We first established whether there were differences between conditions in the baseline EDA, that is, the arousal while studying the two examples at the start of the learning phase. As expected, an ANOVA showed no significant difference between the teaching condition ($M = 0.62$, $SD = 1.06$) and control condition ($M = 0.81$, $SD = 1.42$), $F(1, 52) = 0.30$, $p = .583$, $\eta_p^2 = .006$. We also tested whether there were differences between conditions in the arousal during the third task, the practice problem, while controlling for students' baseline EDA levels (cf., Braithwaite et al., 2013). An ANCOVA showed no significant differences between the teaching condition ($M = 0.64$, $SD = 1.25$) and control condition ($M = 0.70$, $SD = 1.54$), $F(1, 51) = 1.11$, $p = .297$, $d = -0.043$, and

[1] We checked, and with the exception of students' performance on the transfer problems, there were no other significant aptitude-treatment interaction effects, $ps > .050$.

[2] Upon a reviewer's request, we explored whether the effect of condition on test performance was mediated by the perceived effort investment in studying or teaching the final example of the learning phase. There was no such mediation effect, as regression analyses showed that perceived effort investment in studying or teaching the example did not predict students' performance on the isomorphic test problems ($\beta = -.113$; $t(58) = -1.124$, $p = .266$) or the transfer posttest problems ($\beta = -.099$; $t(58) = -0.727$, $p = .470$).

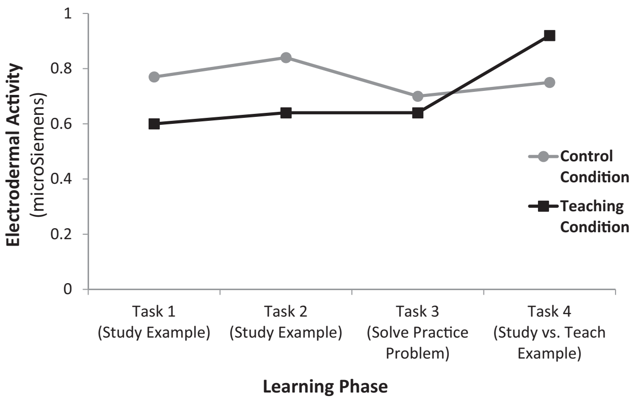

Figure 2. Plot of average electrodermal activity (i.e., objective indicator of arousal) during the four learning tasks per condition.

students' baseline EDA was a significant predictor of arousal during the practice problem, $F(1, 51) = 396.08$, $p < .001$, $\eta_p^2 = .886$. We then compared students' baseline EDA to the arousal during the practice problem (i.e., the third task), to explore the possibility that solving a practice problem would already increase arousal. We did this analysis at a sample level rather than a condition level because both conditions had an identical procedure up to this point and did not differ in their baseline EDA or their arousal during the practice problem. A paired-samples t test showed no significant differences between the baseline EDA ($M = 0.71$, $SD = 1.24$) and the arousal during practice problem solving ($M = 0.67$, $SD = 1.39$), $t(54) = 0.65$, $p = .518$, $d = -0.032$. We also tested whether students' arousal increased from practice problem solving to studying or teaching the final worked example of the learning phase. As expected, paired-samples t tests showed no significant difference between solving the practice problem ($M = 0.70$, $SD = 1.54$) and studying the final example ($M = 0.75$, $SD = 1.67$) for the control condition, $t(26) = .862$, $p = .862$, $d = 0.030$, but for the teaching condition, arousal was significantly higher during teaching ($M = 0.92$, $SD = 1.36$) than while solving the practice problem ($M = 0.64$, $SD = 1.25$), $t(26) = 2.490$, $p = .020$, $d = 0.220$.

Finally, we addressed our main question of whether there were differences in arousal on the final task of the learning phase, that is, between teaching versus studying a worked example. An ANCOVA controlling for students' baseline EDA levels (cf., Braithwaite et al., 2013) indicated that arousal was significantly higher in the teaching condition ($M = 0.92$, $SD = 1.36$) than in the control condition ($M = 0.75$, $SD = 1.67$), $F(1, 51) = 4.32$, $p = .043$, $\eta_p^2 = .078$, and students' baseline EDA was a significant predictor, $F(1, 51) = 213.09$, $p < .001$, $\eta_p^2 = .807$.

Is There a Relationship Between Arousal and Test Performance?

As the teaching condition showed both greater test performance and higher arousal than the control condition, we explored the relationship between arousal and test performance. This analysis was done by computing partial correlations between test performance on the isomorphic or transfer problems and arousal during the final task of the learning phase (i.e., where the experimental manipulation took place), controlling for students' baseline EDA levels. There was no significant association between arousal and isomorphic problem-solving performance, $r = .096$, $p = .495$ or between arousal and transfer problem-solving performance, $r = -.002$, $p = .990$ overall. The same results emerged if we computed the correlations separately for those in the teaching condition (isomorphic problems: $r = .107$, $p = .603$; transfer problems: $r = -.042$, $p = .840$) and those in the control condition (isomorphic problems: $r = .008$, $p = .970$; transfer problems: $r = -.085$, $p = .680$).[3] Note that there were no indications in the data of a quadratic relationship between arousal and test performance (cf., Yerkes-Dodson law; Yerkes & Dodson, 1908). Given the absence of a significant relationship between arousal and test performance, we refrained from testing whether the effect of condition on test performance would be mediated by arousal.

Discussion

With regard to the main question addressed in this experiment, we found, in line with our hypothesis, that after an initial acquisition phase consisting of studying two worked examples and solving a practice problem, teaching the content of another example to a fictitious other student on video resulted in more arousal and improved learning outcomes compared with studying that example. This improvement pertained both to performance on problems that were isomorphic to the learning phase and to transfer problems that contained a novel fault.

In line with our second hypothesis, teaching an example was perceived to be more effortful than studying that example. This finding shows that teaching increased perceived cognitive load, and in combination with the finding that teaching also improved learning outcomes, it seems that this can be qualified as germane cognitive load, that is, working memory load imposed by processes that were conducive to learning (Sweller, 2010). Learning outcomes were analyzed in more detail by looking not only at performance on the test problems, but also at the effort invested in solving those test problems. The finding that there were no significant differences between conditions in perceived effort investment on the test problems further attests to the quality of the acquired problem-solving schemas in the teaching condition. That is, a higher level of test performance attained with equal or less effort investment, is indicative of higher cognitive efficiency (Hoffman & Schraw, 2010; Paas & Van Merriënboer, 1993; Van Gog & Paas, 2008).

An unexpected finding was that prior knowledge moderated the effect of condition on transfer. Follow-up analyses showed that this interaction signified that there was a strong association between prior knowledge and transfer performance for those who studied the final example, but not for those who engaged in teaching on video. Although the finding that teaching seemed to moderate the effect of prior knowledge on transfer should be interpreted with caution because of the relatively low reliability of the conceptual prior knowledge test and the fact that we had not

[3] Note that correlations computed using the difference score between baseline arousal and arousal during the final task of the learning phase yielded the same results (no significant relationship between test performance and arousal).

predicted this interaction effect, these results do warrant further discussion as they suggest an aptitude-treatment interaction effect (Cronbach & Snow, 1977). That is, these findings seem to suggest that teaching on video was particularly effective for enhancing understanding and improving transfer performance of those who initially had very low prior knowledge. Whether the benefits of teaching on video truly depend on how much knowledge learners have prior to teaching needs to be examined in future research, for instance by varying how much and what learners know prior to the teaching activity.

Another unexpected finding was that teaching the final example was not associated with more worrying thoughts than studying the example. A potential explanation might lie in the participant sample and the nature of the setting: university students might not be particularly prone to worry over a teaching activity, especially in the context of an experiment in which their performance does not affect their grade.

Overall, our findings indicate that in addition to being an effective strategy for learning conceptual materials (Fiorella & Mayer, 2013, 2014; Hoogerheide et al., 2014, 2016), teaching on video can also be an effective strategy for acquiring problem-solving skills from worked examples. It is important to note that whereas earlier studies used a relatively weak control condition (i.e., restudying the text), the present study compared teaching to a stronger control condition (i.e., studying an example that showed the worked-out solution procedure to a practice problem the learner had just completed). Moreover, our findings add further evidence to the notion that the benefits of teaching on video cannot simply be attributed to retrieval practice, because students explained the content of a worked example *while having access* to that worked example.

So what would explain the beneficial effects of teaching on learning? We explored the possibility that this benefit might, in part, arise from the arousal associated with teaching (Hoogerheide et al., 2016), by measuring learners' EDA (i.e., galvanic skin response). Teaching the final example was associated with significantly higher arousal than studying, which makes sense, because presenting in front of a camera is an often-used strategy for inducing arousal (Kirschbaum et al., 1993). This finding also adds further evidence to the notion that situations higher in social presence induce more arousal than situations lower in social presence. Prior research has shown for instance that arousal was increased when students were led to believe that a peer was watching them via a camera versus was not watching them (Somerville et al., 2013), when students were led to believe that another person in the same room could see them versus could not see them (Myllyneva & Hietanen, 2015), and when students were led to believe that an online avatar was controlled by a real person versus not a real person (Okita et al., 2007). Surprisingly, however, an exploration of the relationship between arousal and test performance showed no significant association between arousal and students' performance on the isomorphic or transfer problems on the posttest when controlling for baseline arousal.

One possible explanation for the lack of a significant relationship between arousal and test performance is that the benefits of teaching on video are not a result of increased arousal as such, but can instead be attributed to the cognitive processes elicited by considering one's potential audience and considering how one's explanations may affect the audience's learning (i.e., productive agency; Schwartz & Okita, 2004). For instance, engaging in teaching on video could entice learners to focus on monitoring whether the recipients would be able to understand their explanations (Ploetzner, Dillenbourg, Preier, & Traum, 1999) and on providing complete and accurate explanations (Roscoe & Chi, 2007, 2008). In line with this cognitive processes hypothesis, an exploration of the teaching videos showed that students covered most of the idea units in the example and produced very accurate explanations, which is perhaps unsurprising, because students had access to the example during the teaching activity. Cognitive processes such as generating complete and accurate explanations can be expected to help learners to deeply elaborate on the learning material, to expose and repair knowledge gaps, and thereby to organize the acquired information into coherent and rich cognitive schemas (Coleman, Brown, & Rivkin, 1997; Fiorella & Mayer, 2016; King, 1994; Ploetzner et al., 1999; Roscoe & Chi, 2007, 2008; Webb, 1989).

Future research should further examine the mechanism(s) responsible for the benefits of teaching on video. A related suggestion for future research would be to compare the effects of learning by teaching a fictitious audience to learning by generating explanations for oneself. We know that the effectiveness of self-explaining depends on a variety of contextual factors (Rittle-Johnson & Loehr, 2017; Rittle-Johnson et al., 2017), and although this may also apply to teaching on video, the evidence available thus far suggests it is an effective instructional strategy for a variety of learning materials and student populations. A possible reason why teaching on video might be more conducive to learning than self-explaining is that teaching stimulates learners to be aware of their potential audience (i.e., social presence; Hoogerheide et al., 2016). Investigating whether these two instructional strategies produce different effects and if so, why, might help to shed light on the conditions under which generating explanations is an effective instructional strategy.

A limitation of the present experiment is that the technology used to measure EDA is relatively new. Although initial findings indicate that the E4 Empatica wristband provides a reliable measurement of EDA (McCarthy, Pradhan, Redpath, & Adler, 2016; Ollander, Godin, Campagne, & Charbonnier, 2016), it is important to remain cautious when interpreting the arousal findings. For instance, it is rather surprising that practice problem solving did not increase arousal compared with example study, which raises the question of how sensitive this measure is and how robust the measurement is to motion (i.e., the practice problem was solved with pen and paper). Another—though speculative—explanation for why arousal did not increase from example study to practice problem solving might be that students' knowledge about troubleshooting parallel electrical circuits increased as a result of studying the two worked examples. Because there is an inverse association between expertise and arousal, solving a practice problem after having studied two examples might not have increased arousal significantly (Aiello & Douthitt, 2001; Bond & Titus, 1983). Nevertheless, further research is needed to validate measures of EDA within authentic learning situations. A second limitation is that we only conducted an immediate posttest, so future research should investigate whether the benefits of teaching for problem-solving performance would hold on a delayed test. Based on prior research with conceptual materials, however, it can be expected that the benefits of teaching remain (Hoogerheide et al., 2014,

2016) or become even more pronounced after a 1-week delay (Fiorella & Mayer, 2013, 2014). Similarly, the benefits of increased arousal for memory have been shown to be greater after a delay (Sharot & Phelps, 2004).

Our findings also have potential for educational practice. Problem-solving skills are fundamental to many academic disciplines, particularly within science, technology, engineering, and mathematics fields (Jonassen, 2000). Our findings show that example-based learning, which is an effective instructional method for acquiring problem-solving skills, can be made even more effective by adding a teaching activity. Given the ubiquity of video cameras nowadays (e.g., in mobile phones, tablets, and laptops), teaching on video to a fictitious (or real) other is an easy-to-use strategy for fostering meaningful learning.

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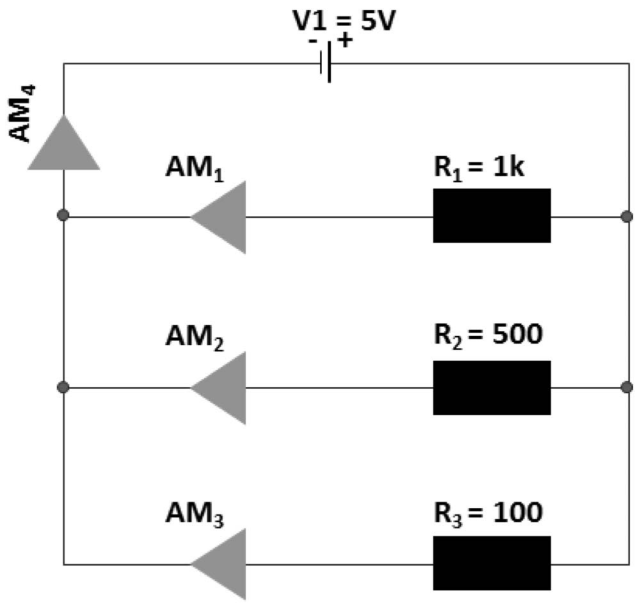
Appendix A

Worked Example Used in the Learning Phase

Study this example thoroughly.



1. **Determine how this circuit *should* function using Ohm's law, that is, determine what the current is that you should measure at AM1 to AM4. AM1 to AM3 indicate the current in the parallel branches, AM4 the total current.**

In parallel circuits, the total current (I_t) equals the sum of the currents in the parallel branches (I_1, I_2, etc.).

The total current should be: $I_t = I_1 + I_2 + I_3$

$$or: I_t = \frac{U}{R_1} + \frac{U}{R_2}\frac{U}{R_3} = \frac{5\text{ V}}{1\text{ k}\Omega} + \frac{5\text{ V}}{500\ \Omega} + \frac{5\text{ V}}{100\ \Omega} = 5\text{ mA}$$
$$+ 10\text{ mA} + 50\text{ mA} = 65\text{ mA}$$

This means you should measure:

AM1 = 5 mA AM2 = 10 mA AM3 = 50 mA AM4 = 65 mA

2. **Suppose the ammeters indicate the following measurements:**

AM1 = 5 mA AM2 = 8 mA AM3 = 50 mA AM4 = 63 mA

In this case, the calculation of what you should measure does not correspond to the actual measures, so something is wrong in this circuit.

What is the fault and in which component is it located?

If the current in a branch is lower than it should be, the resistance in that branch is higher (equal U divided by higher R results in lower I).

The current in the second branch is smaller than it should be: $I_2 = 8$ mA instead of 10 mA. Thus, R_2 has a higher resistance than the indicated 500 Ω. The actual resistance of R_2 can be calculated using the measured current:

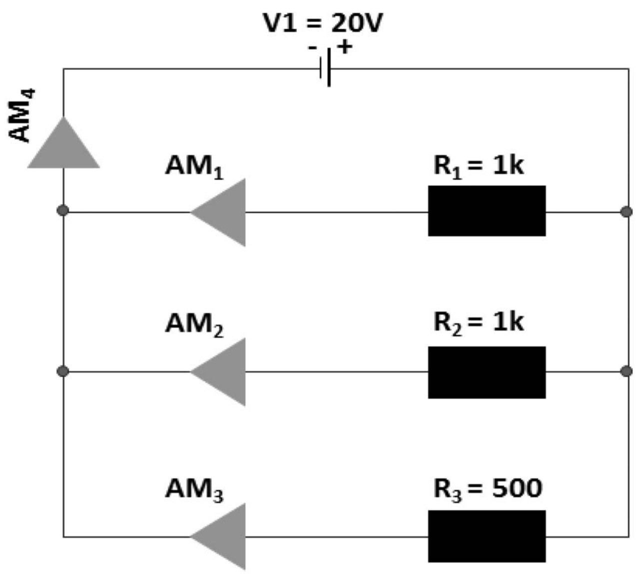
$$R_2 = \frac{U}{I_2} = \frac{5\text{ V}}{8\text{ mA}} = 0,625\text{ k}\Omega = 625\ \Omega$$

(*Appendices continue*)

Appendix B

Practice Problem Used in the Learning Phase

Try to solve this problem to the best of your abilities.



1. **Determine how this circuit *should* function using Ohm's law, that is, determine what the current is that you should measure at AM1 to AM4. AM1 to AM3 indicate the current in the parallel branches, AM4 the total current.**
2. **Suppose the ammeters indicate the following measurements:**

AM1 = 20 mA AM2 = 10 mA AM3 = 40 mA AM4 = 70 mA

What is the fault and in which component is it located?

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