Computers in Human Behavior 25 (2009) 360–370

Contents lists available at ScienceDirect

Computers in Human Behavior

journal homepage: www.elsevier.com/locate/comphumbeh

Learning with hypermedia: The influence of representational formats and different levels of learner control on performance and learning behavior

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ARTICLE INFO

Article history:
Available online 31 December 2008

Keywords:
Hypermedia learning
Multimedia design principles
Learner control

ABSTRACT

In this paper, two experiments on the use of hypermedia environments for learning about probability theory are reported. In Experiment 1a it was tested whether multimedia design principles (multimedia principle, modality principle, redundancy principle) are valid in hypermedia environments, despite the fact that hypermedia offers more learner control than multimedia. The results showed only little evidence for this validity, although the hypermedia environment entailed only a rather low level of learner control. In Experiment 1b it was investigated how learner control affects performance and how its possible impact is moderated by learners' prior knowledge. A high level of learner control positively affected the effectiveness of instruction only with regard to intuitive knowledge, but was at the same time accompanied by large increases in learning time, thereby rendering the instruction inefficient. Unexpectedly, effects of learner control were not moderated by students' prior knowledge. The results imply that the idea to use multimedia design principles for hypermedia learning is too simple and that the benefits and drawbacks of learner control depend heavily on learning objectives and time constraints.

1. Introduction

Hypermedia learning environments (HLE) consist of network-like information structures, where fragments of information are stored in nodes that are interconnected and can be accessed by electronic hyperlinks (Conklin, 1987). Hypermedia can be seen as an augmentation of hypertext, in which multimedia elements are included (Rouet & Levonen, 1996). These multimedia elements can be used in flexible ways (Scheiter & Gerjets, 2007): Firstly, learners may be allowed to determine the order in which they access different information units (*sequencing*). Secondly, learners may decide on which contents to receive depending on their prior knowledge, abilities and preferences (*selection*) and thirdly, on how a specific content should be displayed, for instance, by determining whether to represent it in a verbal or in a pictorial format (*representation control*). These features distinguish hypermedia from multimedia, where control over the order and selection of information and its representation is established by the system. Both, hypermedia and multimedia, however, may allow learners to pace the instruction and interact with single dynamic representations (e.g., start, stop and replay them). The high level of learner control is seen as a major advantage of hypermedia for learning in that it increases interest and motivation, allows for instruction that is adapted to learners' preferences and cognitive needs, provides affordances for active and constructive information processing and supports the acquisition of self-regulatory skills (Scheiter & Gerjets, 2007; see also Corbalan, Kester, & van Merriënboer, 2009; Schnotz & Heiß, 2009). Contrary to this claim, comprehensive reviews on hypermedia learning (e.g., Dillon & Gabbard, 1998; Shapiro & Niederhauser, 2004) show that learner control seldom yields these envisioned outcomes.

Two potential reasons for the ambiguity of results regarding the effectiveness of hypermedia for learning will be addressed in the remainder of the paper. The first reason is that in the current literature on hypermedia, concrete design recommendations that prescribe how information in different representational codes and different sensory modalities should be represented, are often missing (Scheiter & Gerjets, 2007). As a solution to this problem it has been recently suggested to use established theories of multimedia learning as a theoretical foundation for hypermedia design. Accordingly, Dillon and Jobst (2005) have proposed that the *Cognitive Theory of Multimedia Learning* (CTML; Mayer, 2005) is the only "dedicated theory of multimedia learning that explicitly aims at guiding our analysis and understanding of learning in hypermedia environments" (p. 570). Because *Cognitive Load Theory* (CLT; Sweller, van Merriënboer, & Paas, 1998) makes similar design recommendations as the CTML, this theory will also be considered in

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doi:10.1016/j.chb.2008.12.015

the remainder as a way to inform hypermedia design (*cf.* Gerjets & Scheiter, 2003). The second possible reason for the lack of evidence in favor of hypermedia learning is that the aforementioned arguments of learner-controlled instruction have been formulated without taking into account potential prerequisites learners need to possess to deal with the additional cognitive demands imposed onto them when having control of the instruction. As a solution, learner prerequisites need to be considered as moderators when analyzing the benefits of different levels of learner control. Both solutions will be discussed in the following two sections.

1.1. Designing content of hypermedia environments

The CTML and CLT both center on the idea that the design of instructional materials should be aligned with the learners' limited cognitive processing resources. They prescribe how different representational codes (i.e., pictorial and verbal information) that may address different sensory modalities (i.e., auditory and visual) should be combined to foster effective learning and keep unnecessary cognitive load as low as possible. CLT distinguishes between three load types. Intrinsic cognitive load (ICL) is "imposed by the basic characteristics of the information rather than by instructional design" (Sweller, 1993, p. 6), that is, their element interactivity. Moreover, ICL depends on learners' levels of prior knowledge. As learners with high prior knowledge possess more complex cognitive knowledge structures than low prior knowledge learners they can chunk multiple information units together and treat them as single elements. It is assumed that ICL cannot be altered by instructional design (for a controversial discussion of this issue see Gerjets, Scheiter, & Catrambone, 2004, 2006; Pollock, Chandler, & Sweller, 2002). Extraneous cognitive load (ECL) results from unnecessary processes of interacting with instructional materials that are not directed towards schema acquisition and automation and that thus hinder learning. Finally, germane cognitive load (GCL) is a consequence of higher-level cognitive processes that go beyond the mere activation and memorization of information and that are directly relevant to schema construction and automation. Hence, the main objective of CLT is to optimize the pattern of different load types by minimizing ECL, which frees up resources that can then be devoted to activities resulting in GCL.

Both, the CTML and CLT, have made several design recommendations that aim at reducing working memory demands or extraneous cognitive load, respectively, by facilitating the mental integration of different representational codes and sensory modalities. Among other things, they suggest using multimedia materials, distributing information across different sensory modalities and avoiding redundant information.

The *multimedia principle*, which has been proposed by the CTML (Mayer, 2005), states that enriching text with pictures or animations helps learners to gain a deeper understanding. In particular, it enables the construction of two qualitatively different internal representations, namely, a verbal and a pictorial mental model. An important design issue pertains to the question of which combinations of texts and pictures are more beneficial than others. The *modality principle* (Mayer & Moreno, 1998; Mousavi, Low, & Sweller, 1995) asserts that it is helpful to distribute information presentation among different sensory modalities. According to this principle, pictorial representations should be accompanied by spoken rather than by written verbal explanations as this allows focusing attention on both representation formats simultaneously rather than splitting it up between reading a text and watching a picture or animation. Finally, the *redundancy principle* (Kalyuga, Chandler, & Sweller, 1999; Mayer, 2005) proposes to avoid duplicating information that has already been presented. For instance, spoken text should not be supplemented with written (on-screen) text of the same content. In the latter case, learners would be forced to process two distinct information sources at the same time without gaining an increased understanding. This principle therefore implies that sometimes less material can result in better learning.

The aforementioned design recommendations have been confirmed in a number of empirical studies in the context of multimedia learning (for an overview see Mayer, 2005); however, the extent to which they are valid for hypermedia learning has not been proven yet. Although hypermedia environments may include multimedia elements, the differences between multimedia and hypermedia with regard to the amount of learner control suggest that a simple transfer between the two might not be as simple as suggested by Dillon and Jobst (2005). There are at least two important aspects that need to be considered: First, HLEs representations or their combinations need not only to be designed so that they improve learning, but also so that they attract learners. More specifically, due to the fact that in a HLE, learners can decide on whether or not to retrieve a specific representation, it has to provide a sufficient affordance for those learners, whose understanding would benefit from processing the representation. That is, a representation should be designed in a way that a learner is able to perceive that it will fulfill a specific function (e.g., its appropriate processing will close a knowledge gap; *cf.* perceived affordance, Norman, 1999) and that she/he will thus decide to select it for further processing. Accordingly, instructional design decisions for HLEs may not only have to focus on the effectiveness of representations in terms of learning outcomes, but also on their affordances. Second, the aforementioned multimedia design principles have often been tested under time constraints, where limitations in working memory resources should become particularly obvious. Possibly, additional time for processing the instructional materials may be used to compensate for a negative instructional design. For instance, once more time is available so that learners can reread text portions or review animations without the danger of missing important information in the non-attended representation, written text may at least be as effective as spoken text. Accordingly, findings by Tabbers, Martens, and van Merriënboer (2004) suggest that there is no modality effect when learners can control the pacing.

Hence, one research question addressed in this paper is whether multimedia design principles are suitable to inform the design of effective hypermedia environments. As a working hypothesis we followed Dillon and Jobst (2005) by assuming that the design principles could be confirmed in a learner-controlled environment, while we were, however, aware of the possible problems associated with this transfer from multimedia to hypermedia.

1.2. Adaptive information utilization and optimal degree of learner control

Hypermedia learning may not only have proven less effective, because the respective environments' representations were designed inappropriately but also due to the learner prerequisites that they presuppose. Accordingly, an alternative explanation for the disillusioning state of affairs may be that the promises of learner control have been expected to occur for all learners irrespective of their individual prerequisites. In fact, "hypermedia has long been advocated as a way of 'leveling the playing field' and allowing all learners to proceed in a manner that suits their unique learning process" (Dillon & Jobst, 2005, p. 577). Contrary to these expectations, recent reviews demonstrate that the hypothesized advantages of a high level of learner control are valid for learners with high prior knowledge only (Chen, Fan, & Macredie, 2006; Scheiter & Gerjets, 2007; Schnotz & Heiß, 2009). Accordingly, learners with high prior knowledge experience fewer difficulties in navigating hypermedia systems, apply deeper processing strategies, produce better learning outcomes, and need no additional support in handling the environment. Thus, Clark and Mayer (2003) have proposed in their *learner control principle* that hypermedia is only suited for more able students.

A possible explanation for these findings has been offered by Gall and Hannafin (1994), who suggested that prior knowledge (i.e., existing schemas) may guide learner-controlled behavior in that "individuals with extensive prior knowledge are better able to invoke schema-driven selections, wherein knowledge needs are accurately identified a priori and selections made accordingly" (p. 222). Another explanation for the moderating effects of prior knowledge in hypermedia learning can be based on Kintsch's Construction–Integration Model (Kintsch, 1998), which is sometimes being used as a theoretical framework in this context (*cf.* Shapiro & Niederhauser, 2004). According to this model, learners with low prior knowledge require a coherent representation to construct meaning from a text as they are not able to overcome gaps in the text structure on their own (McNamara, Kintsch, Songer, & Kintsch, 1996). Coherence in texts is established by all devices that highlight the micro- and the macro-structure of information (e.g., argument overlap among subsequent sentences, advance organizer, headings etc.). Many of these devices are typically absent in HLEs, which is why hypermedia may only be suited for high prior knowledge learners (Amadieu, Tricot, & Mariné, 2009; Schnotz & Heiß, 2009).

Taken together, it was expected that high prior knowledge learners would benefit from a high level of learner control typical for HLE, whereas for low prior knowledge learners a low level of learner control would be better suited.

1.3. Overview of experiments

Two interleaved experiments were conducted that investigated the validity of multimedia design principles for hypermedia learning (Experiment 1a) as well as the moderating role of prior knowledge on effects of learner control (Experiment 1b). The two experiments consisted of seven conditions overall. Six conditions with a low level of learner control were compared to each other in Experiment 1a, whereas in Experiment 1b the aggregated data from these six conditions were compared to a seventh condition with a high level of learner control. The data collection took place simultaneously for all seven conditions. To investigate the validity of multimedia design principles for hypermedia learning six experimental conditions were designed for Experiment 1a, which were characterized by different combinations of verbal and pictorial information that either followed or did not follow the aforementioned multimedia design principles. The six conditions were implemented with a low level of learner control, where learners could decide on whether to retrieve predetermined representational formats or not (e.g., animations, audio text files), on skipping presented information, and on the pacing of information. While particularly the option to choose between retrieving representations or not makes the learning environment a hypermedia rather than a multimedia environment, the level of learner control is nevertheless lower compared to what could possibly be offered during hypermedia learning. That is, learners had only linear access to the instruction. Moreover, they could not freely decide among all potential representational options; rather, they could decide on only whether they wanted to retrieve a representation if this representation was part of the multimedia assembly typical for the specific condition (e.g., they could decide on retrieving an animation if and only if the condition was designed to offer multimedia materials). This was done to still have experimental conditions with systematic variations in terms of their instructional design to be able to attribute findings to these variations in an unambiguous way. Moreover, it allowed comparing the aggregated data from these six conditions to a condition with a high level of learner control for Experiment 1b that covered the full range of control options (i.e., additional non-linear information access, free representational choices). This comparison was used to test whether only high prior knowledge students would benefit from a high level of learner control.

2. Experiment 1a

2.1. Method

2.1.1. Participants

Participants were 118 pupils, 72 girls and 46 boys from grades 10 and 11 of six German high schools (Gymnasium) with an average age of 16.50 years (*SD* = 0.80). They were paid for participation.

2.1.2. Materials and procedure

The data collection took place in a group setting in the schools' computer rooms, where each pupil worked on a computer on his/her own. Students were randomly assigned to the experimental conditions. The learning environment that the pupils worked with was a modification of an already existing hypermedia learning environment called HYPERCOMB (Scheiter, Gerjets, & Catrambone, 2006). Learners working with the environment had to acquire knowledge on different problem categories from the domain of probability theory. Problems in probability theory deal with situations where the probability of randomly selecting a particular configuration of elements out of a set of elements has to be determined (e.g., taking marbles out of an urn). The learning environment consisted of a personal data questionnaire, a short technical instruction, a pretest to assess prior knowledge concerning probability theory, a domain introduction, an example-based learning phase that was subject to experimental manipulation, and a posttest. The pretest consisted of 12 items: four items assessed knowledge prerequisites necessary for calculating probabilities in general, four items were related to conceptual knowledge, and four items measured procedural knowledge. In the example-based learning phase learners had to acquire knowledge on four different problem categories (permutation with or without replacement, combination with or without replacement). Each category was explained by means of two worked examples. The eight worked examples consisted of a problem statement and a step-by-step solution.

For each of the six instructional conditions, a low level of learner control was established. Firstly, pacing of the worked examples was left to learners. Secondly, in the conditions where dynamic representations (e.g., audio files and animations) were part of the condition, dynamic representation formats were presented only when a student deliberately started the representations to play. For instance, when learners were assigned to the 'plus written text and animation condition' (see below for details), they could choose whether to retrieve the respective animations by clicking a "Play" button. If they decided against it, only the non-dynamic representations available in the respective condition were shown (e.g., arithmetical information and written text). Thirdly, the dynamic representations were interactive in that learners could pause, stop or replay them. With regard to sequencing, the order of the worked-out examples was fixed in the six conditions and only allowed for linear navigation by clicking a "Back" or "Next" button.

During learning, the learners gave ratings of the cognitive load they were experiencing. Once learners had reached the end of the example sequence, they proceeded to the test phase (see below).

2.1.3. Design and dependent variables

As independent variable, we varied the presentation formats of the worked-out examples by manipulating the representational codes and sensory modalities that they addressed (see Fig. 1). *All* six conditions of the learning environment contained arithmetical information for each solution step. The 'arithmetical only' condition provided only this arithmetical information and no further representation. The 'plus written text' condition provided additional written instructional explanations of solution steps. In the 'plus spoken text' condition, the same explanations were presented auditory by a female voice. The 'plus written text and spoken text' condition contained redundant information in that it provided both of the aforementioned types of verbal information. In the 'plus written text and animation' as well as in the 'plus spoken text and animation' condition, either written or spoken text was augmented with animations. There was always one animation that depicted the problem statement by representing relevant objects through marbles, which were then taken out of an urn to illustrate the process of a random selection of elements. Additionally, there was one animation for each solution step as well as for the final solution of each worked-out example. In 'with replacement' problem categories, selected marbles were returned to the urn, whereas in 'without replacement' problem categories they were left outside. The question of whether the order of selection mattered or not, was illustrated by either putting the marbles into a container, so that they would mix with other marbles, or into a box with ordered compartments.

Learning times in the example-based learning phase (in seconds), self-reported cognitive load during learning, and learning outcomes were registered as dependent variables.

To assess the cognitive load experienced during learning, students were asked to give a respective estimate after every second example. Because two examples always illustrated each of the four problem categories, four estimates in total were required (i.e., after problem category one, after problem category two etc.). Whenever a student moved from one problem category to another, a page with five questions appeared, where one item referred to intrinsic cognitive load, three items assessed different aspects of extraneous

(a) Arithmetical information only
(b) plus written text
(c) plus spoken text
(d) plus written text and spoken text
(e) plus written text and animation
(f) plus spoken text and animation

Fig. 1. Experimental conditions with a low level of learner control.

cognitive load, and one item aimed a measuring germane cognitive load (see Table 1). For assessing ICL, students were asked to rate the difficulty of the domain (*cf.* Ayres, 2006). For ECL measurement, two items described specific tasks demands that could potentially hinder learning in this particular environment, namely, the need to distinguish between important and unimportant information and to extract information from different representations. Another ECL item assessed the overall difficulty of handling the environment. For assessing GCL, we expected that asking students how much effort they had exerted to understand an example would most likely reflect activities that go beyond a mere activation of information. With regard to the formulation of this item, it is important to note that in the German language, the term effort is positively associated with concentration (*cf.* Cierniak, Scheiter, & Gerjets, 2009). Each item had to be rated on a 9 point Likert scale. The order of the five items was counterbalanced across the four times of measurement.

For assessing learning outcomes, students were asked to respond to 42 test items that were designed to measure conceptual, procedural, intuitive, and situational knowledge (de Jong & Ferguson-Hessler, 1996). The 12 items for *conceptual knowledge* referred to the comprehension of facts, concepts, and principles that apply within a domain (example item: "You have a deck of cards from which you randomly select three cards, one after another. You want to get a king, queen and ace in this specific order. What happens to the probability if you put each card back into the deck after selecting it?"). *Procedural knowledge* refers to the ability to solve (near and far-transfer) problems in a domain. The eight near-transfer problems had the same structural features as the worked-out examples but different surface features. The four far-transfer problems asked for a combination of two different solution principles (e.g., permutation and combination both without replacement, *cf.* Gerjets et al., 2006) by either applying the addition or multiplication rule of probability theory. The following is a sample item for a near-transfer problem: "Your Latin teacher randomly draws two pupils out of your class of seven pupils to present their homework. Unfortunately, you have copied the homework of your friend this morning. What is the probability that the two of you will be selected?" Thirteen items were used to assess *intuitive knowledge*, that is, students' intuitions about the correctness of statements related to conceptual knowledge. This was done by instructing learners to select one out of two multiple-choice solution alternatives as quickly as possible (i.e., under time pressure). Finally, the five items on *situational knowledge* assessed students' understanding of structural problem features that allows them to represent problem structures in a situation model (*cf.* Nathan, Kintsch, & Young, 1992) by, for instance, asking: "You throw a dice three times and want to throw a 3, 6 and 5 in this specific order. How is this problem characterized? (a) order important, with replacement, (b) order not important with replacement, (c), order important, without replacement, (d) order not important, without replacement?" Participants received 1 point for each correctly solved item. No partial points were given.

Due to the different amount of information provided in the six experimental conditions, we expected large differences in learning times across the conditions. Accordingly, measuring only the *instructional effectiveness* in terms of posttest performance for the different conditions without considering the learning times necessary to achieve a particular posttest performance would have been grossly misleading. Thus, *instructional efficiency* scores that integrated posttest performance for the knowledge subtypes and learning times were calculated by adapting an approach of Paas and van Merriënboer (1993; see also van Gog & Paas, 2008). These authors combined the intensity of mental effort being expended by learners with the level of performance attained based on a conversion of raw data into z-scores. Analogously to this approach, we calculated instructional efficiency scores by taking into account the learning time for the worked examples rather than the mental effort as in the original formula as follows: $E = (z_{performance} - z_{learning\ time})/\sqrt{2}$. A negative score for E states that the relative investment of learning time exceeded the performance (i.e., low instructional efficiency), a positive score stands for high performance scores relative to the time taken for learning (i.e., high instructional efficiency). Contrary to the instructional efficiency measure used by Paas and van Merriënboer (1993), the current measure does not intend to make statements about the cognitive load associated with learning, but rather is used to account for potential time-on-task effects during learning.

2.2. Results

Analyzing students' performance in the pretest by an ANOVA revealed no differences across experimental conditions (Table 2; $F < 1$). As expected, the conditions varied strongly in terms of students' learning time, $F(5,112) = 8.59$, $MSE = 11.56$, $p < .001$, $f = 0.62$. Bonferroni-adjusted posthoc tests showed that students in the 'arithmetical only' condition as well as in the condition 'plus written text' had been much faster than students in the condition 'plus written and auditory text' and in the two animation conditions (all $ps < .05$). To account for these differences, we analyzed learning outcomes based on the aforementioned instructional efficiency measure. However, to make sure that this did not conceal possible differences in terms of the instructional conditions' effectiveness, an ANOVA for the raw overall performance score was conducted beforehand. This ANOVA showed that the conditions did not differ in their instructional effectiveness ($F < 1$).

Subsequently, the six experimental conditions were compared with regard to their instructional efficiencies by a MANOVA for conceptual knowledge, procedural knowledge (split up into near and far-transfer), intuitive and situational knowledge. There was a significant overall effect, $F(25,560) = 1.92$; $p = .005$. Furthermore, the ANOVAs for the individual measures revealed significant main effects for all of them: conceptual: $F(5,112) = 5.21$, $MSE = 0.77$, $p < .001$, $f = 0.48$; near-transfer procedural: $F(5,112) = 4.98$, $MSE = 0.89$, $p < .001$, $f = 0.47$; far-transfer procedural: $F(5,112) = 4.44$, $MSE = 0.84$, $p = .001$, $f = 0.50$; intuitive: $F(5,112) = 4.24$, $MSE = 0.76$, $p = .001$, $f = 0.43$; situational: $F(5,112) = 5.62$, $MSE = 0.79$, $p < .001$, $f = 0.50$. Bonferroni-adjusted posthoc comparisons revealed the following picture: The '*arithmetical only*' *condition* was superior to the condition 'plus written text and animation' for conceptual knowledge ($p = .01$), near-transfer procedural knowledge ($p = .009$), intuitive knowledge ($p = .03$), and situational

Table 1
Cognitive load items (translated version).

Intrinsic cognitive load	How easy or difficult do you consider probability theory at this moment? (ICL)
Extraneous cognitive load	How easy or difficult is it for you to work with the learning environment? (ECL1)
	How easy or difficult is it for you to distinguish important and unimportant information in the learning environment? (ECL2)
	How easy or difficult is it for you to collect all the information that you need in the learning environment? (ECL3)
Germane cognitive load	Indicate on the scale the amount of effort you exerted to follow the last example. (GCL)

Note: The original items of the study were presented in German.

Table 2
Means (and *SD*) for prior knowledge, learning times, posttest performance, and instructional efficiencies for Experiment 1a as a function of instructional condition.

	Instructional condition					
	Arithmetical only ($n = 19$)	Plus written text ($n = 20$)	Plus spoken text ($n = 16$)	Plus written and spoken text ($n = 20$)	Plus written text and animation ($n = 25$)	Plus spoken text and animation ($n = 18$)
Prior knowledge (max. 12 points)	6.37 (2.22)	6.30 (2.00)	7.13 (2.19)	6.85 (2.28)	6.67 (1.54)	6.61 (1.54)
Learning time (in seconds)	348.32 (139.25)	415.25 (129.83)	553.38 (157.18)	691.85 (285.20)	720.40 (236.12)	659.78 (208.37)
Posttest performance (max. 42 points)	23.95 (4.81)	23.75 (6.94)	23.75 (8.05)	24.10 (7.60)	23.48 (5.55)	21.94 (6.71)
Efficiencies						
Conceptual knowledge	0.57 (0.59)	0.52 (0.75)	0.01 (0.62)	−0.19 (1.06)	−0.36 (0.99)	−0.48 (1.03)
Near-transfer procedural knowledge	0.62 (0.53)	0.51 (0.80)	0.15 (0.78)	−0.40 (1.15)	−0.40 (0.98)	−0.35 (1.23)
Far-transfer						
procedural knowledge	0.37 (0.73)	0.64 (0.95)	0.11 (0.67)	−0.37 (0.94)	−0.34 (1.07)	−0.32 (0.97)
Intuitive knowledge	0.33 (0.72)	0.59 (0.73)	0.01 (0.79)	−0.12 (1.07)	−0.53 (0.93)	−0.15 (0.99)
Situative knowledge	0.51 (0.60)	0.48 (0.98)	0.38 (0.78)	−0.41 (1.15)	−0.30 (0.79)	−0.53 (0.93)

knowledge ($p = .06$). Moreover, it achieved a higher instructional efficiency compared to the condition 'plus auditory text and animation' with regard to conceptual knowledge ($p = .005$), near-transfer procedural knowledge ($p = .03$), and situational knowledge ($p = .009$). A similar pattern was revealed for the *condition 'plus written text*', which proved to be superior to the condition 'plus written text and animation' for conceptual knowledge ($p = .02$), near-transfer procedural knowledge ($p = .03$), far-transfer procedural knowledge ($p = .008$), intuitive knowledge ($p = .001$), and situational knowledge ($p = .07$). Moreover, the '*plus written text*' condition resulted in more efficient performance compared to the condition 'plus auditory text and animation' for conceptual knowledge ($p = .008$), near-transfer procedural knowledge ($p = .09$), far-transfer procedural knowledge ($p = .02$), and situational knowledge ($p = .01$). Finally, there was a marginally significant difference in favor of the condition 'plus auditory text' when compared to the condition 'plus auditory text and animation' for situational knowledge ($p = .05$). To sum up, there was a reverse multimedia effect as the animation conditions yielded lower efficiencies than conditions not containing animations.

However, there was a redundancy effect as indicated by lower efficiency scores for the condition '*plus written text and spoken text*' compared to the condition 'plus written text' for near-transfer procedural knowledge ($p = .04$), far-transfer procedural knowledge ($p = .01$), and situational knowledge ($p = .03$). Similarly, the redundant condition showed worse performance than the 'arithmetical only condition' for near-transfer procedural knowledge ($p = .02$) and situational knowledge ($p = .01$). There were no other significant differences among the experimental conditions. Most important, there were no cases were the condition 'plus auditory text' outperformed the arithmetical only condition or the condition 'plus written text'. Similarly, there were no differences in favor of the animation condition augmented with auditory rather than written text. Thus, there was no indication for a modality effect.

Because the dynamic representations had been presented only on learners' demand, we determined the retrieval frequency to see whether the way students had used the dynamic representations might explain some of the findings. The retrieval frequency was calculated by dividing the number of dynamic representations retrieved (i.e., audio files or animations for each solution step) by the total number of dynamic representations available. The resulting retrieval rates showed that the dynamic representations had been used only to a very small extent. On average, only 7.81% of the spoken text files had been played in the 'plus auditory text' condition and only slightly more (10.28%) in the 'plus written and auditory text' condition. Of the animations, 14.36% were retrieved in the 'plus auditory text and animation' condition, whereas 67.22% were played in the 'plus written text and animation' condition. We refrained from analyzing whether those students who had used the dynamic representations had learned better than those who had not, because we were not interested in the effects of the representational formats on performance in general. Rather, we wanted to know whether the option to choose representations choices would evoke a use of these representations to an extent that would lead to performance differences among different conditions.

In a final step, the cognitive load data were analyzed by means of repeated-measure ANOVAs with time as the inner subject factor and instructional condition as the between subjects factor (Table 3). There was no main effect of instructional condition on ICL, $F(5,112) = 1.42$, *ns*, nor was there an interaction with time ($F < 1$). However, there was a main effect for time of measurement for ICL, $F(3,336) = 5.44$, $MSE = 0.72$, $p = .001$, $f = 0.23$. Bonferroni-adjusted posthoc comparisons indicated that the highest ICL was experienced after the first problem category had been explained, which was higher than the ICL measured after the second category ($p = .06$), after the third category ($p = .03$), and after all four problem categories ($p = .02$). There were no further significant changes in ICL among the latter 3 points of assessment (all $ps > .10$). For the three ECL items a multivariate repeated measures ANOVA was conducted. The ECL ratings were not affected by instructional condition, nor was there an interaction between condition and time (both $Fs < 1$). The ratings were time-dependent, $F(3,336) = 5.75$, $MSE = 1.37$, $p = .001$, $f = 0.23$: ECL decreased from the first to the second assessment ($p = .002$) and from the third to the fourth ($p = .05$). Moreover, the last assessment yielded lower ECL scores than the first one ($p = .003$), whereas none of the other comparisons were significant (all $ps > .10$). Finally, for GCL there was neither a main effect of instructional condition, $F(1,51) = 1.68$, *ns*, nor an interaction ($F < 1$). GCL, too, varied with the time of assessment, $F(3,336) = 2.94$, $MSE = 2.04$, $p = .03$, $f = 0.16$. Slightly higher GCL was observed for the third compared to the first problem category ($p = .06$); none of the other comparisons were significant ($ps > .10$).

The results of Experiment 1a will be discussed together with those of Experiment 1b in the Section 4.

3. Experiment 1b

To investigate how much learner control should be incorporated in a hypermedia environment, the outcomes of participants learning with a high level of learner control were compared to the six experimental conditions with a low level of learner control from Experiment 1a. Students' prior knowledge was considered as a potential moderator.

3.1. Method

3.1.1. Participants

In addition to the 118 students from Experiment 1a, 78 pupils (42 girls and 36 boys) from grades 10 and 11 with an average age of 16.62 years ($SD = 0.61$) took part in Experiment 1b. They were paid for their participation and took part during the same classroom session as the pupils of Experiment 1a.

3.1.2. Materials and procedure

For the second experiment, the learning environment of Experiment 1a was modified by additionally implementing a condition characterized by a high level of learner control during the example-based learning phase. The remaining materials and the procedure was the same as in Experiment 1a.

3.1.3. Design and dependent variables

The independent variable consisted in the level of learner control, where the collapsed data from the six conditions with a low level of learner control of Experiment 1a were compared to an additional condition with a high level of learner control. In the latter condition, learners started in the example-based learning phase by selecting one out of the eight worked examples shown in a menu bar on the left side of each page (see Fig. 2). Alternatively, participants could navigate the examples in a linear fashion by clicking on a "Next" button (i.e., "Weiter" in German) at the bottom of each page. These options thus allowed for selecting and sequencing information. On top of each page, there were three radio buttons that allowed choosing a representational format for the selected example. That is, learners could determine whether they wanted to retrieve the example in an arithmetical format only by not activating any of the radio buttons, or to enrich it with written text, spoken text, animations or any combination of these formats by selecting the respective radio buttons. Thereby, they were given the opportunity to select among the representational formats that students in the six experimental conditions of Experiment 1a had been assigned to. Once learners had the impression of having studied the examples for a sufficiently long time, they could proceed to the test phase of the learning environment. The same dependent variables as in Experiment 1a were assessed in the condition with a high level of learner control with the exception of cognitive load as it proved to be difficult to link the cognitive load questionnaire to a specific problem category that had been studied by the learners.

3.2. Results

For the analysis the data from the six conditions of Experiment 1a was aggregated and compared to the condition with a high level of learner control. For this analysis new efficiency scores had to be computed as the additional condition changed the overall means and standard deviations and therefore the resulting z-scores had to be adjusted as well. For the comparison of the (aggregated) condition with a low level of learner control and the one with a high level of learner control, students' prior knowledge was used as a continuous factor in the analysis (i.e., ANCOVAs including an interaction term in the design) to determine whether it would moderate the effects of learner control.

An ANOVA revealed no differences among the two conditions with regard to students' prior knowledge ($F < 1$; see Table 4). The analysis of learning time by means of a two-factorial ANCOVA (learner control *x* prior knowledge) showed that the students in the condition with a high level of learner control had longer learning times than those with a low level of learner control, $F(1,192) = 18.82$, $MSE = 83187.96$, $p < .001$, $f = 0.33$. There was neither a main effect of prior knowledge nor did it interact with learner control (both Fs < 1). As in Experiment 1a, the raw overall performance score was analyzed. The respective ANCOVA showed that learners in the condition with a high level of learner control performed better than those with a low level of learner control, $F(1,192) = 4.31$, $MSE = 25.10$, $p = .04$, $f = 0.12$. Moreover, there was a main effect of students' prior knowledge, $F(1,192) = 122.05$, $MSE = 25.10$, $p < .001$, $f = 0.78$, which, however, did not interact with the level of learner control as had been expected ($F < 1$). Because of the main effect of learner control, it was decided to run a MANCOVA for the raw scores for the different knowledge types to identify the exact locus of this effect. This MANCOVA confirmed the overall effect in favor of a high level of learner control $F(5,188) = 3.23$, $p = .008$. The ANCOVAs for the individual knowledge measures showed a superiority of a high level of learner control only for intuitive knowledge, $F(1,192) = 8.99$, $MSE = 5.70$, $p = .003$, $f = 0.20$. There were no comparable significant effects for conceptual knowledge, $F(1,192) = 2.00$, *ns*, near-transfer procedural knowledge, $F < 1$, far-transfer procedural knowledge, $F(1,192) = 2.41$, *ns*, or situational knowledge, $F(1,192) = 2.64$, *ns*.

Finally, the MANCOVA for the instructional efficiency measures revealed a strong effect in favor of the condition with a low level of learner control, $F(5,188) = 4.70$, $p < .001$, thus showing a reversal of the results pattern when analyzing efficiency rather than effectiveness measures. Moreover, students with a high level of prior knowledge performed better than those with less prior knowledge, $F(5,188) = 10.72$, $p < .001$. Contrary to our initial assumption, there was no interaction between the two factors, $F(5,188) = 1.02$, *ns*. Subsequent ANCOVAs for the individual knowledge measures showed that this superiority of a low level of learner control held for conceptual knowledge, $F(1,192) = 5.87$, $MSE = 0.76$, $p = .02$, $f = 0.16$, near-transfer procedural knowledge, $F(1,192) = 12.22$, $MSE = 0.83$, $p = .001$, $f = 0.23$, far-transfer procedural knowledge, $F(1,192) = 17.85$, $MSE = 0.90$, $p < .001$, $f = 0.30$, and situational knowledge, $F(1,192) = 3.98$, $MSE = 0.87$, $p = .047$, $f = 0.14$, while there was no effect for intuitive knowledge $F(1,192) = 1.19$, *ns*. To conclude, a high level of learner control was partly effective for learning, but proved inefficient at the same time – both findings occurring irrespective of the degree of prior knowledge students possessed.

With regard to the utilization of dynamic representations, on average less than 1% of the audio files had been retrieved by students in the condition with a high level of learner control, whereas 16.63% of the animations were retrieved in combination with spoken text and another 16.42% in combination with written text. Thus, as in Experiment 1a the representations did not provide sufficient affordances for learning in a hypermedia environment.

4. General discussion

A set of two overlapping experiments was reported, which aimed at investigating first whether evidence for the validity of multimedia design principles can also be found in HLEs and second how learner control affects students' performance as a function of their prior knowledge. In Experiment 1a six experimental conditions were implemented that differed in the type of representations offered to students as ways of explaining how to solve probability problems. These conditions were characterized by a low level of learner control. Comparing these conditions to each other revealed only weak evidence for the validity of the multimedia design principles. The option to augment spoken or written explanations by playing animations yielded worse performance than not being given this option, indicating a reversed multime-

Table 3
Means (and *SD*) for the cognitive load data of Experiment 1a as a function of instructional format and time of measurement.

	Instructional condition						
	Arithmetical only (*n* = 19)	Plus written text (*n* = 20)	Plus spoken text (*n* = 16)	Plus written and spoken text (*n* = 20)	Plus written text and animation (*n* = 25)	Plus spoken text and animation (*n* = 18)	
ICL							
Time of measurement 1	3.89 (1.63)	3.40 (1.93)	3.25 (2.02)	3.25 (2.01)	2.96 (1.57)	3.17 (1.72)	3.29 (1.79)
Time of measurement 2	3.84 (1.77)	2.90 (1.74)	3.31 (1.70)	2.65 (1.46)	2.88 (1.33)	2.72 (1.60)	3.03 (1.61)
Time of measurement 3	3.63 (1.57)	2.95 (1.70)	3.13 (1.41)	2.85 (1.98)	2.76 (1.30)	2.50 (1.20)	2.96 (1.55)
Time of measurement 4	3.74 (1.97)	2.90 (1.41)	3.00 (1.59)	2.55 (1.90)	2.72 (1.37)	2.33 (1.08)	2.86 (1.61)
Average	3.78 (1.66)	3.04 (1.53)	3.17 (1.54)	2.80 (1.60)	2.83 (1.22)	2.68 (1.21)	
ECL1							
Time of measurement 1	2.89 (1.56)	2.35 (1.42)	2.38 (1.36)	2.35 (1.50)	1.92 (1.12)	2.61 (1.20)	2.34 (1.37)
Time of measurement 2	2.84 (1.42)	2.25 (1.37)	2.13 (1.26)	1.70 (1.08)	1.92 (1.00)	2.00 (1.28)	2.13 (1.26)
Time of measurement 3	2.79 (1.55)	2.60 (1.85)	2.63 (1.54)	2.00 (1.65)	2.36 (1.70)	2.22 (1.17)	2.42 (1.59)
Time of measurement 4	2.68 (1.77)	2.35 (1.35)	2.25 (1.24)	1.75 (1.21)	1.96 (1.54)	1.83 (0.96)	2.13 (1.39)
Average	2.80 (1.51)	2.39 (1.30)	2.34 (1.20)	1.95 (1.18)	2.04 (1.13)	2.17 (0.87)	
ECL2							
Time of measurement 1	3.21 (1.23)	2.70 (1.30)	2.88 (1.75)	3.00 (1.72)	2.96 (1.51)	3.33 (1.75)	3.01 (1.53)
Time of measurement 2	3.00 (1.33)	2.55 (1.54)	2.69 (1.45)	2.55 (1.70)	2.80 (1.78)	2.72 (1.18)	2.72 (1.51)
Time of measurement 3	3.16 (1.42)	2.80 (1.99)	3.06 (1.39)	2.35 (1.87)	2.80 (1.47)	2.67 (1.19)	2.80 (1.58)
Time of measurement 4	3.21 (1.44)	2.70 (1.78)	2.81 (1.22)	2.30 (1.81)	2.36 (1.60)	2.39 (1.29)	2.61 (1.56)
Average	3.14 (1.26)	2.69 (1.43)	2.86 (1.23)	2.55 (1.62)	2.73 (1.32)	2.78 (1.08)	
ECL3							
Time of measurement 1	2.95 (1.35)	2.85 (1.66)	3.00 (1.86)	2.90 (1.80)	2.68 (1.70)	2.94 (1.59)	2.87 (1.64)
Time of measurement 2	2.89 (1.41)	2.45 (1.28)	3.00 (1.67)	2.60 (1.73)	2.64 (1.70)	2.56 (0.98)	2.68 (1.48)
Time of measurement 3	2.95 (1.54)	2.75 (2.10)	3.19 (1.42)	2.30 (1.78)	2.60 (1.66)	2.78 (1.31)	2.74 (1.66)
Time of measurement 4	3.00 (1.73)	2.45 (1.54)	2.69 (1.20)	2.30 (1.78)	2.36 (1.41)	2.44 (0.98)	2.53 (1.47)
Average	2.95 (1.42)	2.63 (1.36)	2.97 (1.34)	2.53 (1.65)	2.57 (1.41)	2.68 (0.87)	
GCL							
Time of measurement 1	3.89 (2.88)	3.00 (2.53)	3.19 (2.10)	3.45 (2.67)	2.88 (1.94)	2.94 (2.10)	3.21 (2.36)
Time of measurement 2	4.74 (2.79)	2.60 (1.60)	3.63 (2.03)	3.80 (2.69)	3.20 (2.08)	3.17 (2.60)	3.50 (2.37)
Time of measurement 3	4.89 (2.51)	3.50 (2.33)	4.06 (2.08)	3.65 (2.68)	3.44 (2.24)	3.00 (2.11)	3.74 (2.37)
Time of measurement 4	4.58 (2.61)	3.05 (1.85)	3.69 (1.99)	3.10 (2.51)	2.96 (1.99)	2.83 (2.12)	3.34 (2.23)
Average	4.53 (2.50)	3.04 (1.48)	3.64 (1.47)	3.50 (2.23)	3.12 (1.80)	2.99 (2.02)	

dia effect. While students did not necessarily learned less in the respective conditions, achieving the same performance as in the conditions without animations took much longer, thereby rendering the instruction inefficient. Moreover, there was no evidence in favor of accompanying either only the arithmetical information or animations by spoken rather than written text; thus, there was no modality effect. Only the redundancy principle could be confirmed for hypermedia learning in that arithmetical information that was augmented with spoken and written text yielded less efficient instruction than providing only written explanations. Interestingly, there was no redundancy effect when comparing the redundant condition to the condition where only spoken text was provided, again confirming the observation that spoken text did not aid the understanding of the arithmetical information. To conclude, learners achieved the same understanding in all instructional conditions, but the opportunity to retrieve dynamic representations yielded highly inefficient instruction. In the following sections possible reasons for the lack of differences in the instructional effectiveness as well as for the observed instructional inefficiency of conditions offering dynamic representations will be discussed.

According to the multimedia design principles one might have expected a higher effectiveness for animation conditions (multimedia principle), for spoken rather than written text conditions (modality principle), and for non-redundant presentations (redundancy principle). The finding that neither the multimedia nor the modality principle could be confirmed can be best explained by the fact than none of the representations responsible for the respective effects were selected to a sufficient extent. Hence, the representations seem to have provided only minor affordances for retrieving them with one exception. Students often retrieved animations as an augmentation of written text – a combination that is deemed ineffective according to the modality principle (Mayer, 2005); nevertheless, they did not score any worse than their counterparts, who had the opportunity to study animations accompanied by spoken explanations. However, the latter might simply have scored as low as the prior, because they hardly retrieved these spoken representations. The first conclusion that can be drawn from these findings is that multimedia design rules may simply not be applicable for designing HLEs, because representations following these design rules do not provide sufficient affordances for students to retrieve them. Possibly, students need to be prompted in order to engage in suitable strategies of using external representations (Gerjets, Scheiter, & Schuh, 2008). Moreover, they might need more training with respect to specific abilities that help them to deal with the representational options in HLEs (e.g., representational literacy, Barab, Bowdish, Young, & Owen, 1996; Cognition and Technology Group at Vanderbilt, 1996). Thus, the idea of using multimedia design principles directly to inform hypermedia learning environments is too simple in that good design decisions (e.g., combine animations with spoken explanations) might not attract learners and accordingly will not be selected. This explanation might provide some insights with regard to the missing modality effect, that is, the fact that the data showed no performance improvements when distributing the information across different sensory modalities. An alternative explanation might be that giving learners the opportunity to decide on the pacing of the instructional materials by themselves, may have already sufficiently reduced potential problems associated with splitting attention between the text and the arithmetical information. These results are in line with findings by Baggett and Ehrenfeucht (1983) or Tabbers et al. (2004). Their research demonstrated that when there was sufficient time to read the written materials, for instance, when pacing was determined by the lear-

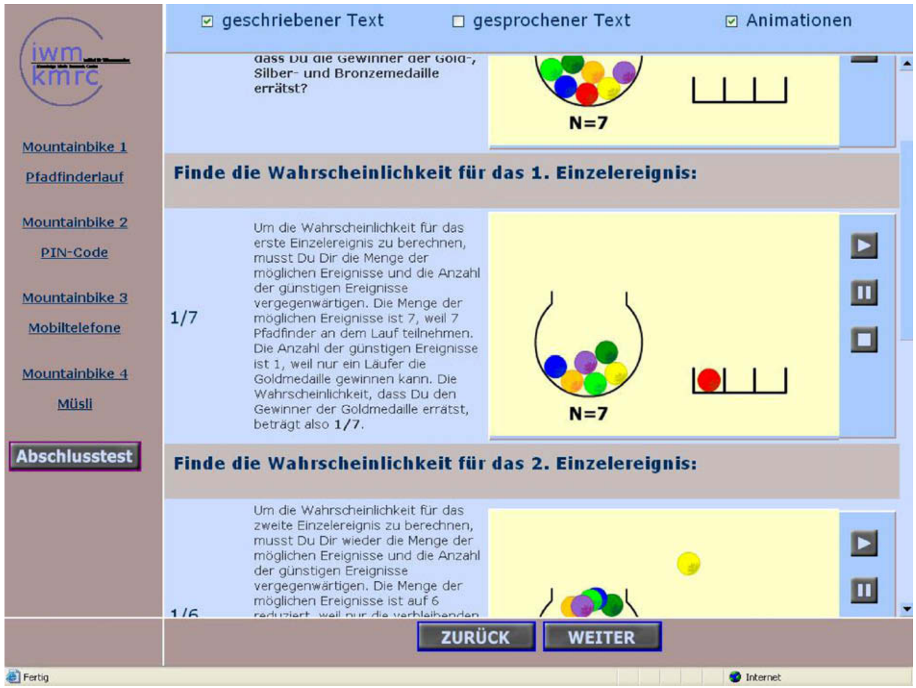

Fig. 2. Version with a high level of learner control. *Note:* The navigation on the left side allows selecting examples in a non-linear way, a linear navigation is enable by next ('weiter') and back ('zurück') buttons at the bottom pf the page; the radio buttons at the top of the page allow selecting written text ('geschriebener Text'), spoken text ('gesprochener Text'), and animations ('Animationen'). The sample screen shows an example with arithmetical information in the left column, written text in the middle column, and an animation in he right column.

Table 4
Means (and *SD*) for prior knowledge, learning times, posttest performance (including subtests) and instructional efficiencies for Experiment 1b as a function of learner control.

	Level of learner control	
	Low ($n = 118$)	High ($n = 76$)
Prior knowledge (max. 12 points)	6.66 (1.94)	6.87 (2.04)
Learning time (in seconds)	586.52 (234.79)	769.13 (352.13)
Posttest performance (max. 42 points)	23.51 (6.51)	25.03 (6.30)
Conceptual knowledge (max. 12 points)	6.97 (2.17)	7.35 (2.12)
Near-transfer procedural knowledge (max. 8 points)	3.51 (1.81)	3.42 (1.79)
Far-transfer procedural knowledge (max. 4 points)	0.61 (1.77)	0.45 (0.68)
Intuitive knowledge (max. 13 points)	8.66 (2.67)	9.71 (2.46)
Situational knowledge (max. 5 points)	2.98 (1.47)	3.31 (1.37)
Efficiencies		
Conceptual knowledge	0.12 (0.86)	−0.19 (1.09)
Near-transfer procedural knowledge	0.18 (0.92)	−0.28 (1.09)
Far-transfer procedural knowledge	0.23 (0.91)	−0.35 (1.04)
Intuitive knowledge	0.06 (0.86)	−0.09 (1.15)
Situational knowledge	0.11 (0.89)	−0.17 (1.05)

ner, written text yielded either equal or even superior performance compared to spoken text.

According to the results for the instructional efficiency measures, offering students the opportunity to retrieve dynamic representations yielded inefficient instruction. The question of what causes this inefficiency cannot be completely answered by referring to students' actual use of the presentations, which were hardly retrieved. That is, while part of their time loss may go back to an actual retrieval of representations, part of it seems to be due to learner control itself. For instance, Niederhauser, Reynolds, Salmen, and Skolmoski (2000) have argued based on Cognitive Load Theory that students' "decisions about which content to access, the sequence for reading it, and the rate of reading" (p. 238) impose additional cognitive load onto the user. Thus, even if a learner decides against retrieving spoken text or an animation, she/he may have had to invest cognitive resources and time for reaching this decision, which are no longer available for learning. In line with this reasoning, we found evidence in a computational cognitive model of hypermedia learning that the mere availability of additional information within the hypermedia environment and the corresponding necessity to decide about whether to retrieve this information or not substantially impeded performance in later problem solving due to cognitive resources devoted to executive control instead of learning (Gerjets, Scheiter, & Schorr, 2003). This effect showed up in the computational model as well in the empirical data used to test the model irrespective of whether the additional information had been retrieved or not.

To conclude, the differential efficiency of the six instructional conditions may be a result of the learners' selection decisions for or – more often – against retrieving dynamic representations and a result of the cognitive resources necessary to pursue these decisions. This may explain why the 'arithmetical only' condition and the condition augmented with written text, which both did not allow for any selection decisions, yielded high instructional efficiencies, whereas the redundant condition as well as the two animation conditions allowed selecting dynamic representations and resulted in considerably lower efficiencies.

Experiment 1b was conducted to investigate how much learner control a hypermedia environment should allow for in general to ensure optimal and efficient learning. A high level of learner control yielded effective posttest performance, which could be mainly traced back to students' better intuitive knowledge. Contrary to the learner control principle advocated by Clark and Mayer (2003), however, this effect occurred for all learners irrespective of their prior knowledge level. It thus seems that for specific learning objectives a high level of learner control is advisable at least when there are no time constraints for learning. One reason why learner control positively affected learning for all students may have been that the HLE used in the study was a well-structured one that contained only a limited number of links and levels of information depth. Both, the structure of the hypermedia environment as well as the number of links and information depth have been shown to have an impact on learning outcomes (Amadieu et al., this issue; Shapiro, 1993; Zhu, 1999). These features have been shown to be particularly helpful for learners with a low level of prior knowledge (*cf.* Shapiro & Niederhauser, 2004), which is possibly why even learners with a low level of prior knowledge were able to benefit from the various learner control options provided to them. That is, due to the fact that the HLE was not too complex in terms of its structure, they still had sufficient cognitive capacity available to familiarize themselves with the learner control options.

However, this process required more time to be devoted to the HLE, thereby rendering the instruction inefficient. Thus, the positive effect of a high level of learner control reversed for the instructional efficiency measures, that is, knowledge improvements were achieved at the cost of much longer learning times. This finding suggests that it might have been a problem that the learner control options provided by the hypermedia environment where quite unfamiliar to learners. Increasing the exposition time to such a learning environment or even training learners to use the learner control options provided by the environment might improve the efficiency of learner-controlled hypermedia environments substantially. Another option might be not to make all representations and control options available to learners from the very beginning, but to use a fading-in method for these representations and options, thereby adjusting to learners' increasing familiarity with the environment. For instance, the cognitive load data from Experiment 1a indicate that learners' ICL and ECL decreased substantially during the learning phase (possibly due to an increased familiarity with the content domain and the learning environment), whereas GCL increased indicating that more cognitive resources became available for additional elaboration. In a similar way, we might want to use very simple and system control learning environments for initial instruction and include more representations and control options as soon as learners are able to cope with the corresponding cognitive demands.

It remains an open question whether learners who are more advanced – not only with regard to their domain-specific prior knowledge but also with regard to their familiarity with the learning environment and their representational options – might benefit from higher levels of learner control in terms of efficiency as proposed by Clark and Mayer (2003). In sum, our results indicate that designing effective hypermedia learning environments based on multimedia design theories is not as simple as it seems, but that there are nevertheless promising avenues to apply the basic assumptions of theories of multimedia learning to improve hypermedia learning.

Acknowledgement

The research reported in this article was funded by the "Deutsche Forschungsgemeinschaft" (DFG GE 992/3-1). We thank the members of the Dutch-German LEMMA (Learning Environments, MultiMedia and Affordances) cooperation project (principle investigators: Peter Gerjets, Ton de Jong, Jeroen van Merriënboer and Alexander Renkl) for fruitful discussions and for jointly constructing the tasks of the learning environment and the test materials.

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