Physics learning and the computer: A review, with a taste of meta-analysis

M. Euler, A. Müller, IPN Kiel, Germany

Abstract. The effects of computers on the learning of physics are reviewed with a focus on specific difficulties of learning physics, such as the abstract nature of many basis concepts. On the one hand, computer-assisted learning of physics (CALP) offers quite promising possibilities to overcome these difficulties; on the other hand, the state of research about these possibilities is unsatisfactory. In a little-known and difficult area it is very useful to have at hand even very approximate and preliminary maps and guidelines. The present contribution therefore presents and applies a theoretical and methodological framework to analyse existing knowledge and guide future investigations about CALP.

Introduction. “Great expectations” (Dickens, 1861) appears as a quite appropriate description of the attitude of the general public as well of parts of the educational research community towards the effects of the computer on learning in general and on science learning in particular. The table below lists some of the hypotheses concerning beneficial effects of computer learning (mainly concerning the physical sciences) together with a few representative references. However, recent reviews (Ayersman, 1996; Komoski, 1996; Watson, 1996) state that there is insufficient knowledge about the educational impact of computers in general. It follows that this is even more true for the impact on science and physics learning in particular. This is certainly a most unsatisfactory situation, as learning physics suffers from some domain-specific learning difficulties, where the computer appears as a very promising help (see Secs. 2 and 4). Thus, CALP is an area which largely remains to be explored. We will therefore first describe a theoretical (Sec.2) and methodological (Sec. 3) framework for its analysis. This framework is then applied to a range of issues as those in the table below. By way of example, only two such applications are discussed in the present synopsis. In the talk, the results from a broad literature survey will be presented.

Hypothesis: educationally beneficial effects of the computer by	**Reference**	**Topic**
self-controlled learning	Milheim, Martin, 1991	general
co-operative learning in small groups	Schnotz et al., 1998	physical sciences
multiperspective learning (preventing inert knowledge)	Jacobson, Spiro, 1995	physical sciences
active, “constructivist” learning (preventing inert knowledge)	Windschitl, Andre, 1998	physiology
developing learning and metacognitive strategies	White et al.,1998	physical sciences

Table 1: Some hypothesis relevant to computer learning in general and CALP in particular

Theoretical Framework. The Mayer Model and Learning Difficulties in Physics. Much of the potential help the computer offers for overcoming learning difficulties in physics can be understood in the framework of the model shown in Fig. 1. It combines two major components: a) Generative Theory of Learning (Wittrock, 1974; Mayer, 1997), where learning is seen as *active* („generative“) selection, organisation and integration of knowledge; b) Dual coding theory of human memory (Paivio, 1986), which posits two distinct channels for the storage and recall of visual and verbal information; and extends them by a third one: c) Domain specific symbolic and graphic representation systems, which are essential for the learning of physics (science, mathematics). They can be understood (shown in Fig. 1) as special subfields of the verbal and visual knowledge basis. However, it is a plausible and interesting hypothesis to assume that they constitute a third coding channel in its own right.

The guiding idea of this model is that computers can help learning by offering *integration aids* for information in two ways: (i) Integration of verbal and visual information (ii) Integration from lower to higher levels (models, knowledge basis) of information processing. This shall be explained for two examples of learning difficulties in physics: a) The abstractness of many fundamental physical concepts (like the reaction force in Newton's 3rd law), can be understood as the difficulty to integrate verbal information (like a statement or an explanation of this law) and visual information (like real word objects acted on by forces or a drawing of the force vectors). An integration aid the computer offers consists in visualising forces by a real-time measurement and a simultaneous screen representation (see Sec. 4). b) The "trilingualism" of physics, i.e. the necessity of a double translation first of common language into the domain specific language of physics and second into the formal language of mathematics can be understood as the difficulty to integrate verbal and visual information into the symbolic and graphical representation systems of physics and mathematics. An integration aid the computer offers consists e.g. in an animation sequence connecting a real world picture of some physical process like a curvilinear motion with the schematic drawing containing velocity, acceleration and force vectors.

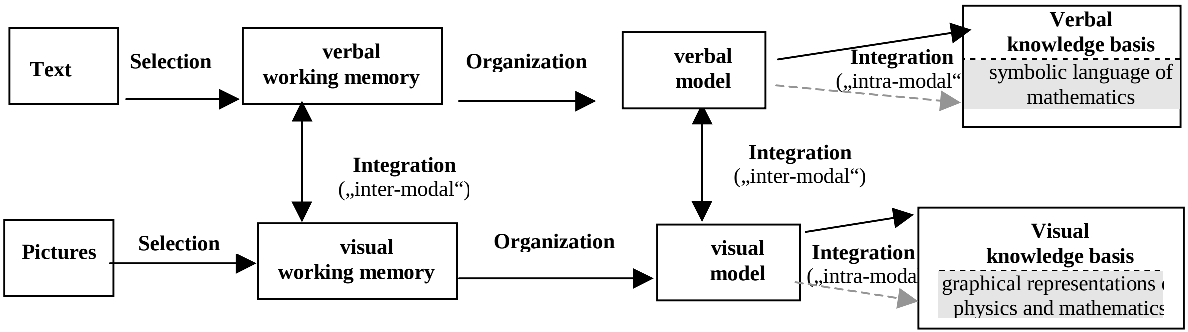

Fig. 1: A theoretical framework for computer-assisted learning of physics: The model of Mayer (1997), extended by domain specific symbolic and graphic representation systems

Methodology. Effect Sizes. A well-established way of assessing and comparing effects of instructional treatments are effect sizes (Häußler et al, 1998, Ch. 4). Effect sizes are a way of converting the results of various types of statistical analysis into a common measure; for mean value comparison one has: $E = \frac{M_E - M_C}{S_P}$; $S_P = \sqrt{\frac{(N_E - 1)S_E^2 + (N_C - 1)S_C^2}{N_E + N_C - 2}}$ (Eq. 1), where M_E (M_C) and S_E (S_C) and are the mean and standard deviation of an experimental (comparison) group, and S_P is the "pooled" standard deviation (sometimes S_C is used instead of S_P; see e.g. in Bortz, 1989 or Lyons 1998). Using effect sizes, several meta-analyses on the general educational effects of computer-based vs. traditional instruction were carried out in the past (Fletcher-Flinn and Gravatt, 1995; Kulik and Kulik, 1991 and references therein). They contain broad comparisons over different learning domains (from languages over humanities to science and mathematics) and different learner ages (from primary school to university). These studies computed average effect sizes of about $E \approx 0.3$, which is considered between small and moderate. By way of comparison, one of the most intensive teaching methods, viz. one-to-one teaching, has an effect size of about $E \approx 2$ (Bloom, 1984). The present contribution, however, is different from existing meta-analyses in two points. First, due to the focus on the special learning domain of physics, there are by far not enough individual studies, so it does not make sense to take an average. Second, undifferentiated comparisons of overall advantages of computer assisted vs. traditional instruction (“horse race investigations”) are no longer considered as an appropriate research question (Mayer, 1997). Rather, detailed correlations of learning effects with features like learning styles or domain-specific learning goals are needed for further progress. But even if there are few studies and if these have different goals, it is still useful to assess their outcomes quantitatively by effect sizes. This will now be shown for CALP, using an example for each of the learning problems described Sec.2.

Physics Learning and the Computer - Some Results. The first example (Mayer, 1991 and 1997) is about integration of verbal and visual information for understanding simple physical devices (a pump, a brake, and outside physics, the human lung). The main result is that only *parallel* (simultaneous) presentation of animation and explaining text helps learning significantly, while *sequential* presentation (and a stand-alone animation) do not. Taking the number of correct answers to problem solving tasks as measure, considerable effect sizes of parallel vs. sequential presentation were found ($E \geq 1.0$; Mayer 1991, 1997). These findings represent an experimental confirmation of the dual-coding model. Moreover, they offer a possible solution to the puzzle that no superiority of animations over static pictures was found in several studies (see e.g. Lewalter, 1997). In the latter, however, „mute“ animations had been used, whereas the main message of the Mayer (1991, 1997) studies is „*Animations need Narrations*“. The second example is about integration of verbal and visual information concerning mechanical forces into the higher, domain-specific level of the Newtonian concepts of forces. The computer offers students a more direct and active opportunity to link phenomena and concepts: For instance, they had to interpret force measurements of colliding trolleys, taken by an analogue-digital interface and rendered online the screen. The main result is overwhelming evidence for the benefits of such an „*Interactive Engagement*“ (Hake, 1998). Taking the Hake learning gain index $H = (R_{\text{post}} - R_{\text{pre}}) / (1 - R_{\text{pre}})$ (Eq. 2), (where $R_{\text{pre/post}}$ measures the fraction of correct answers in a pre and post test, respectively, and H measures the ratio of the actual learning gain to the initial lack of knowledge), an impressive mean effect size of interactive vs. traditional instruction was found ($E \approx 2$; Hake, 1998). More examples (including those of the table in Sec.1) will be discussed in the talk. The contribution will conclude by summarising fulfilled and unfulfilled expectations about physics learning with the computer and by pointing out possible goals of future research.

References. D.J. Ayersman (1996), J. of Res. on Comp. in Educ., 28, 500-525. /// B.S. Bloom (1984), Educ. Researcher, 13, 4-16. /// J. Bortz (1989). *Statistik für Sozialwisenschaftler*. Berlin: Springer. /// C. Dickens (1861). *Great Expectations*. Modern edition: Oxford: Clarendon Press, 1993. /// C.M. Fletcher-Flinn, B. Gravatt (1995), J. Educ. Comp. Res., 12, 219-242. /// R.R. Hake (1998), Am. J. Phys., 66, 64-74 /// P. Häußler et al (1998). *Naturwissenschaftsdidaktische Forschung. Perspektiven für die Unterrichtspraxis*. Kiel: IPN /// M.J. Jacobson, R.J. Spiro (1995), J. Educ. Comp. Res., 12, 301-333. /// P.K. Komoski (1996). *Computer-managed Learning*. In: International Encyclopaedia of Developmental and Instructional Psychology, Eds. E. De Corte, F. Weinert. Oxford, New York: Elsevier. /// C.C. Kulik, J.A. Kulik (1991), Computers. in Human Behav., 7, 75-94. /// D. Lewalter (1997), Unterrichtswissenschaft, 25, 207-222. /// L.C. Lyons (1998), http://www. mnsinc.com:80/ solomon/MetaAnalysis.html. /// R.E. Mayer, R. B. Anderson (1991), J. Educ. Psy., 83, 484-490 /// R.E. Mayer (1997), Educ. Psychologist, 32, 1-19. /// W.D. Milheim, B.L. Martin (1991), J. Computer-Based Instr., 18, 99-105. /// W. Schnotz et al. (1998), Zeitschrift für Pädagogische Psychologie, 12, 135-145 /// M. Scardamalia et al. (1989). J. Educ. Comp. Res., 5, 51-68. /// D.M. Watson (1996). *Computer Assisted Learning*. In: see Komoski (1996). /// B.Y. White, J.R. Frederiksen (1998), Cognition and Instruction, 16, 3-118. /// M.C. Wittrock (1974), Educ. Psychologist, 11, 87-95.