Educational Technology Expertise Center
Open University of the Netherlands

Research fellow project proposal

This project falls in the following research topic(s):

- Design
  - Competency analysis / domain modeling
  - Learning tasks & learner support
- Delivery
  - Composing instructional messages
- Computer-mediated communication
- Diagnosis
  - Performance-based assessment
  - Quality control & assurance

1 Project chair
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2 Project name
English: Mental workload as a determinant for the dynamic selection of learning tasks in aviation training
Dutch: Mentale werkbelasting als determinant voor de dynamische selectie van leertaken in luchtvaarttraining

3 Place in organization
Design theme of the Otec research program

4 Synopsis of the research problem

**English**
The development of competencies or complex cognitive skills plays a central role in aviation training. MATCH is an already developed methodology for the development of computer-based training in this domain, which is based on van Merriënboer’s four-component instructional design model (4C/ID-model, 1997). The current project aims at a further refinement of MATCH. First, a computer-based design tool will be developed and evaluated (CB-MATCH) in order to support instructional designers in the proper use of the standardized training methodology. One important aspect of this system is that it takes the expected cognitive load of the to-be-presented learning tasks into account from the very start of training design. Second, CB-MATCH will be used by a sample of designers to develop a prototype training in the maintenance domain. The heart of this computer-based training will consist of a set of learning tasks that can be presented to the learners. Three experiments will focus on the question how cognitive load measurements (rating scales) may contribute to the proper selection of learning tasks from this set, in order to improve the efficiency and effectiveness of the training program.

**Dutch**
Bij training in het luchtvaart-domein staan competenties waar complexe cognitieve vaardigheden aan ten grondslag liggen centraal. MATCH is een eerder ontwikkelde standaard-methodologie voor
het ontwerpen van computer-ondersteunde training in dit domein, gebaseerd op van Merriënboer’s 4C/ID-model (1997). Het onderhavige project streeft naar een verdere uitbreiding en verfijning van MATCH. Er wordt een computer-ondersteund systeem ontwikkeld en getest (CB-MATCH) dat ontwerpers ondersteunt in het gebruik van de standaard-trainingsmethodologie. Kenmerkend voor dit systeem is dat vanaf het begin van het ontwerpproces rekening gehouden wordt met de verwachte werkbelasting van de leertaken die aan de lerenden worden aangeboden. Met behulp van CB-MATCH wordt vervolgens een prototype-training ontwikkeld op het gebied van “aircraft maintenance”. Het hart van deze computer-ondersteunde training bestaat uit een verzameling leertaken die aan de cursisten aangeboden kunnen worden. In een drietal experimenten wordt onderzocht of metingen van individuele werkbelasting kunnen bijdragen aan het zodanig selecteren van leertaken uit deze verzameling dat het leerproces geoptimaliseerd wordt.

### Research team

<table>
<thead>
<tr>
<th>Name and titles</th>
<th>Expertise/function</th>
<th>Department</th>
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<tr>
<td>a Project chair</td>
<td>dr. Fred Paas</td>
<td>Otec</td>
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<td>b Project team</td>
<td>AIO (to be recruited)</td>
<td>Otec/NLR</td>
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<td>c Other team members</td>
<td>dr. Jelke van der Pal</td>
<td>NLR</td>
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<td>d Ph.D. supervisor</td>
<td>prof. dr. Jeroen van Merriënboer</td>
<td>Otec</td>
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<td>e Consultants</td>
<td>prof. dr. John Sweller</td>
<td>UNSW</td>
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<td>prof. drs. Peter Jorna</td>
<td>NLR</td>
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### Length of the project

- Begin date: April 1, 1999
- End date: March 31, 2003
- Total length: 4 years

### Intended output

a Publications and conference presentations
- At least three articles in SSCI journals (one for each or the three experiments)
- Yearly reports for NLR - last report is dissertation
- At least three presentations at international conferences (e.g., AECT, EARLI or AERA)

b Instruments and procedures
- CB-MATCH - a computer-based instructional design tool based on the 4C/ID-model and MATCH. CB-MATCH builds on generic software tools for process and task analysis in combination with dedicated Windows help files and worked examples.
- Instructional guidelines for taking mental workload measures into account in training design, especially for the selection of learning tasks.

### Further elaboration

a Further elaboration of the problem and aims of the research project, including scientific framework

**Background and previous work**

Aviation training is mainly dealing with highly complex skills, both in the cognitive and the motor domain. For such complex skills, it is generally found to be hard to apply a standard methodology to the design and development of training programs. In addition, on-the-job training is often out of the question due to safety risks. High-fidelity simulator training is a traditional alternative, but also an alternative that is characterized by high costs of training delivery.

From this background, Boot developed MATCH (Method for Aviation Training - Computer-based instruction and Human performance; see NLR memo’s VE-97-006, VE-97-007 and VE-97-008). MATCH is a standard methodology for training development in the aviation domain. It is a dedicated version of van Merriënboer’s four-component instructional design model (4C/ID-model; see, e.g., van Merriënboer, 1997; van Merriënboer & Dijkstra, 1997; van Merriënboer, Jelsma & Paas, 1992), which provides design guidelines that have been formulated for the development of training for highly complex cognitive skills. The 4C/ID-model and MATCH aim at improving the efficiency of training design and development by providing guidelines and
heuristics that guide this development process, as well as the efficiency of training delivery by a more optimal use of various training media (full-flight simulators, part-task trainers, and CBT) within coherent training programs for enhancing various specific skills. In addition, the 4C/ID-model and MATCH are based on recent cognitive-psychological models of skill acquisition and are expected to increase the effectiveness of training programs, and in particular, the ability of learners to transfer acquired skills to new, unforeseen situations.

The current project builds upon this earlier work. It aims at extending previous work into three interrelated directions. First, it aims at a full integration of models of workload into the existing 4C/ID-methodology for training development. Second, it aims at the development of computer-based AID-tools (Automated Instructional Design) that support designers in the proper and efficient use of the methodology. More in particular, this computer-based tool (CB-MATCH) will assist designers in decomposing and analyzing a complex skill to-be-taught in such a way that alternative learning tasks can be developed that vary on the degree of mental workload imposed on the learner. Third, both the use of CB-MATCH and the effectiveness of different training programs developed with CB-MATCH will be systematically evaluated.

Mental Workload and Training Development

The proposed research is concerned with competencies that can best be characterized as high-performance skills (Schneider, 1985). Both the learning and performance of those skills is often constrained by the limited cognitive processing capacity of the human mind. Especially in the early stages of learning, when learners neither have useful cognitive schemata nor automated rules available, performance is often accompanied with excessive mental workload as a result of the high information load and the hierarchical goal structure in which the top-level goal can only be attained by attaining all lower-level subgoals. In addition, every new problem situation poses new demands on the learner and implicitly supposes transfer of knowledge and skills to problems that deviate from the ones trained on. The proposed project is limited to the transfer of knowledge and skills to problems that differ from the ones trained on within the maintenance domain (i.e., troubleshooting faulty components in technical systems).

The cognitive processes schema acquisition and rule automation are considered as prerequisite for transfer (van Merriënboer, Jelsma, & Paas, 1992; van Merriënboer & Paas, 1990; Sweller, 1989; Sweller, van Merriënboer & Paas, 1998). A cognitive schema can be conceptualized as a cognitive structure that enables problem solvers to recognize problems as belonging to a particular category requiring particular operations to reach a solution. Acquired schemata can provide analogies in new problem-solving situations and can be used by mapping processes to reach solutions for unfamiliar aspects of the problem-solving task. The quality of the induced schemata has been found highly predictive of subsequent transfer performance (e.g., Gick & Holyoak, 1983).

Whereas research points out that the acquisition and use of schemata is subject to strategic control (e.g., Anderson, 1987; Proctor & Reeve, 1988), an automated rule is a task-specific procedure that can be used without conscious processing and that can directly control problem-solving behavior. The development of task-specific procedures is a lengthy process, that may be seen as a transition from controlled to automatic processing (Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977). Anderson (1987, 1990) identified knowledge compilation as an important process to make this transition possible. With regard to transfer, automated rules can provide identical elements that may help to solve new problems, and they can free up processing resources that may be devoted to controlled processes. Thus, in solving a transfer problem, familiar aspects can be performed by automated procedures and new aspects can be solved by the use of analogy. The 4C/ID-model and MATCH refer to familiar aspects of problem solving as recurrent constituent skills and to unfamiliar aspects of problem solving as non-recurrent constituent skills. Because schema acquisition and rule automation are mainly a function of the amount and quality of practice, it is obvious that a good design of learning tasks is essential for learning the skill in such a way that it can be transferred to new situations.

design of training may overcome cognitive load constraints. Three basic elements are to:

1. prevent cognitive overload by an appropriate sequencing of learning tasks the learners are confronted with;
2. redirect attention by an appropriate use of problem formats, and
3. decrease mental workload by additional part-task training of selected recurrent constituent skills.

1. **Prevention of cognitive overload: Sequencing**
   
   In the analysis phase of a complex skill, it is suggested that one starts with a decomposition of the whole skill into its constituent skills. This decomposition allows for the macro-level sequencing of so-called *skill clusters* the learners will subsequently work on (e.g., for a training program for maintenance personnel, subsequent skill clusters may refer to explaining the working of a well-functioning system, predicting the effects of particular errors on the functioning of the system, and diagnosing errors). In addition, further analysis of—especially non-recurrent—constituent skills and the knowledge underlying the performance of those skill allows for the meso-level sequencing of *case types* (i.e., categories of problems and examples) that the learners will have to work on during the training for one particular skill cluster. Both macro-level and meso-level sequencing techniques may prevent cognitive overload during training, because skill clusters and case types within each skill cluster are ordered from simple to complex.

2. **Redirecting attention: Problem formats**

   The analysis of recurrent constituent skills and non-recurrent constituent skills also yields results that allow for the selection of instructional strategies and tactics in the design phase. Those strategies and tactics must provide further control over learners' cognitive load expenditure. In order to achieve this, a training strategy is developed that mainly facilitates rule automation and transfer on the basis of procedural overlap for recurrent constituent skills, and schema acquisition and transfer on the basis of those schemata (e.g., by analogy) for non-recurrent constituent skills. In short, a learning environment is designed that promotes the development of knowledge structures that are optimally tuned to dealing with new situations.

   With regard to schema acquisition and schema-based transfer, the design of whole-task practice forms the kernel of the training strategy. It builds mainly on the analysis results for non-recurrent constituent skills (whereas whole-task practice obviously also includes the performance of recurrent constituent skills), and aims at a general understanding of the subject matter domain and the heuristics and systematic problem approaches that are useful in this domain. This provides both a basis for performing the non-recurrent constituent skills and for monitoring, evaluating and reflecting on solutions generated by automated procedures. Control over cognitive load is mainly provided by redirecting the learners' attention from cognitive processes not relevant for learning (e.g., searching information, weak-method problem solving, integrating different sources of information) to processes that are relevant for learning, and in particular, schema acquisition by induction from concrete cases. Problem-solving support ("scaffolding") by the use of particular problem formats, such as worked-out examples (Paas, 1992; Paas & van Merriënboer, 1994a), completion problems (van Merriënboer, 1990; van Merriënboer & de Croock, 1992), or goal-free problems (Sweller, van Merriënboer, & Paas, 1998) yield an effective way for redirecting attention. In addition, information that may be helpful to performance of the whole task is provided in such a way that it is easily retrievable, accessible, and available during practice.

3. **Decreasing mental workload: Part-task training**

   With regard to rule automation and transfer based on procedural overlap, one might consider the design of additional part-task practice, which is always "extra" to training the recurrent constituent skills in the context of the whole task. It builds on the analysis results of recurrent constituent skills and mainly aims at full automation of constituent skills that are basic to the performance of the whole skill, thereby drastically decreasing mental workload. Central to this idea is the so-called "component fluency hypothesis". Additional practice in recurrent constituent skills will result in more fluent performance of the whole task, both because the extensively trained recurrent skills are performed faster, and because more processing resources become available for the performance of non-recurrent constituent skills (cf., Carlson, Sullivan, & Schneider, 1989). Providing extensive drill-and-practice is the most common instructional tactic to decrease mental workload. In addition, information
that is prerequisite to the performance of recurrent constituent skills is provided “just-in-time,” thereby decreasing cognitive load associated with performing either the isolated recurrent skill (i.e., the part task) or the whole task.

**Tools to support the development process: CB-Match**

One goal of the proposed project is to enrich MATCH with a set of computer-based tools that assist the designer of a training program in the identification of a set of learning tasks that vary on the degree of mental workload imposed on the learner. From the description above, it follows that such tools must help to fulfill three functions:

- Decompose a complex cognitive skills into its constituent skills and identify, in order, skill clusters (i.e., meaningful, interrelated sets of constituent skills) and, for each skill cluster, case types (i.e., categories of problems or examples to-be-presented to the learners) for training. Skill clusters and case types are sequenced in such a way that cognitive overload is prevented.
- Identify problem formats for each case type, where problem formats differ in the amount of problem solving support (scaffolding) provided to the learner and thus in the mental workload imposed on the learner.
- Identify recurrent constituent skills for which additional part-task training is necessary. Part-task training for selected recurrent constituent skills may decrease mental workload during whole-task training.

Thus, CB-MATCH will include computer-based tools for (1) decomposing and sequencing skill clusters and case types, (2) identifying problem formats for each case type, and (3) selecting recurrent constituent skills for part-task practice. The tools will be relatively simple and mainly have the form of on-line “process worksheets” (implemented in Windows Help), which guide the designer through the development process. For performing actual task analyses, standard software packages will be used (e.g., Protos, Aris, Flow-charter, Inspiration etc.). The tools allow the designer to develop an integrated, hierarchically organized set of learning tasks that clearly differ with regard to the mental workload imposed on the learner. Given actual measurements of mental effort expenditure during the training, new learning tasks can be dynamically selected from this set. It is expected that taking workload into account may greatly improve learning and transfer.

**Simulation-based training of maintenance tasks**

On the basis of the newly developed version of CB-MATCH, a computer-based simulation will be developed for training troubleshooting in the aircraft maintenance domain. Interactive learning environments in the maintenance domain (e.g., MHO, Lesgold, Bonar, Ivill, & Bowen, 1987; SHERLOCK, Lesgold, Lajoie, Bunzo, & Eggan, 1988; PROCESS, Jelsma, van Merriënboer, & Bijlstra, 1990, de Croock & van Merriënboer, in press) can often be conceptualized as an expert module that contains the knowledge about the domain, a learner module in which an understanding of the learners’ knowledge and skills (student model) is deduced from the student-system dialogue, and an instruction module in which on basis of the student model the content and delivery form of learning tasks is determined.

There are many kinds of student modeling methods that can be roughly divided in models that are based on process models of problem solving and those that are not (Littman & Soloway, 1988; Van Lehn, 1988). The existing modeling techniques consider what the learners know and don’t know and if there are any misconceptions. But, the student models do not take account for the amount of mental effort a student has to invest to reach a certain level of performance. As a result of differences in cognitive capacity, expertise, and motivation different students can attain the same performance level with different amounts of invested mental effort. Because the existing student models that are used for the dynamic task generation in interactive learning environments do not consider the cognitive costs at which a certain level of performance is attained, the generation of learning tasks can be based on incomplete student models. So, students may be confronted with learning tasks that are not tailored to their particular needs. The proposed research project investigates whether learning tasks that are intelligently selected on
the basis of a mental-effort centered student model, are better tailored to the particular needs of
the individual learner and hence lead to better learning and transfer performance. Methods for
task selection have been studied by van Merriënboer, Krammer & Maaswinkel (1994), van
Merriënboer & Luursema (1995) and van Merriënboer, Luursema, Kingma, Houweling & de Vries
(1996).

b Importance for the Open University of the Netherlands and the place of the research in the Otec
Research Program
From a theoretical point of view, this project integrates models of workload with a methodology
for training development. More in particular, it studies how mental effort or mental efficiency
measures can improve the optimal selection of learning tasks from a set of available tasks. To
our knowledge, learner models incorporating mental workload measures (gathered by rating
scales) have not been applied before in computer-based training systems.

From a practical perspective, this project further develops a standard methodology for
training design especially suited to the competency-based training of highly complex skills, as
well as a set of development tools (CB-MATCH) that support designers in the application of this
methodology. This methodology will be of interest to both the Open University and NLR. In
addition, it yields information on the usability of mental effort and mental efficiency data in the
selection of learning tasks, which is also directly relevant to the design of competency-based
learning environments.

c Design & Methods
Three experiments have been planned. In the first experiment, a small group of designers (both
from NLR, OUNL and possibly a third location) will develop a blueprint for a prototype training in
the maintenance domain either with or without CB-MATCH. They will work on this small project
for one day. The to-be-developed training will be in a general maintenance domain (e.g., TASK -
an experimental troubleshooting task developed by Rouse). The focus is on the development of
a set of learning tasks that form the kernel of the training. In an in-depth, qualitative study
potential differences between designers working with and without CB-MATCH will be identified.

CB-MATCH is expected to help designers in the systematic development of a hierarchical
network of learning tasks that differ on the amount of workload imposed on the learner.

In the second experiment, three versions of delivering a maintenance training will be
compared. An existing training program of NLR will be taken as a starting point. The set of
available learning tasks (“problems”) is the same in each version, but the dynamic selection of
problems from this set is either based upon:

1. Performance measures. The selection of each new problem to-be-presented to the learner
   is based upon performance measures. This is the traditional approach used in computer-
   based training: more complex problems are presented only when the learner is performing
   well on simpler problems.

2. Mental effort measures. The selection of each new problem to-be-presented to the learner
   is based upon subjectively experienced mental workload, or, mental effort as measured by
   a rating scale. More complex problems are presented only when the learner is reporting an
   acceptable workload on previous problems.

3. Mental efficiency. Mental efficiency is computed on the basis of both performance
   measures and mental effort measures. Necessary computations are described by Paas
   and van Merriënboer (1993). More complex problems are presented only when the mental
   efficiency on simpler problems is above a pre-set criterion.

It is expected that problem selection based on mental efficiency will yield an optimal learning
trajectory, because both performance and mental workload measures are taken into account.
Learning and transfer results of the three conditions are compared. Sixty subjects from an
Institute for Higher Education in Aviation (“Hogere Luchtvaarschool”) are randomly divided over
the three conditions. Immediately after the instruction and after three weeks a retention and
transfer test have to be performed. The results will be analyzed with a one-way analysis of
variance. To gain insight in (the development of) cognitive schemata, 5 subjects of each group
are randomly chosen to give verbal reports during the instruction and tests. In addition, the subjects will be asked about their attitudes towards the prototype, in particular, towards the learning tasks.

In the third experiment, only the most effective version of the prototype will be used (determined in experiment 2). The aim of this experiment is to find out if positive effects on learning are mainly due to tailoring the learning tasks to the individual data of a learner (i.e., the adaptivity of the learning environment), or simply to a more effective sequence of learning tasks. Forty subjects are randomly divided over two conditions and each subject in one condition is paired to a subject in the other condition. Twenty subjects go through the maintenance course; either their performance measures, reported mental effort, or mental efficiency (depending upon the outcomes of experiment 2) are used for the selection of learning tasks from the set of available tasks. Twenty other subjects serve as “yoked controls”. Their performance, mental effort, or mental efficiency are not taken into account - but they simply receive the same sequence of learning tasks as the subject to which they are paired. It is expected that the adaptivity of the learning environment contributes to learning, so that inferior results are expected for the yoked controls. Retention and transfer tests are identical to the tests used in the second experiment.

d Literature


This project is jointly funded by the Open University of the Netherlands and the National Aerospace Program.
Laboratory NLR. Literature study, data analysis and writing of reports will take place at the Open University. Necessary software development and data collection will take place at NLR, ensuring that data are gathered in a realistic environment and from learners that belong to the target group for aviation training. The University has the obligation to conduct the study and each of the three experiments according to scientific standards and to report the results as described in the contract accompanying this project description. NLR will support the university in the development of both CB-MATCH and course materials and assist in finding subjects for the experiments.

**Time plan**

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<thead>
<tr>
<th>Month</th>
<th>Activity</th>
<th>Deliverable</th>
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<tbody>
<tr>
<td>1-4</td>
<td>literature study</td>
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<tr>
<td>5-10</td>
<td>development of CB-MATCH and user testing</td>
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<tr>
<td>11-12</td>
<td>write documentation for CB-MATCH</td>
<td>12: Documentation CB-Match</td>
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<tr>
<td>13-15</td>
<td>preparing experiment 1</td>
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<td>16-17</td>
<td>conducting experiment 1</td>
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<tr>
<td>18-22</td>
<td>data analysis and report</td>
<td>22: NLR report/article 1</td>
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<td>23-25</td>
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<td>26-27</td>
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<td>28-32</td>
<td>data analysis and report</td>
<td>32: NLR report/article 2</td>
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<td>33-35</td>
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<td>36-37</td>
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<td>38-42</td>
<td>data analysis and report</td>
<td>42: NLR report/article 3</td>
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<tr>
<td>43-48</td>
<td>writing dissertation</td>
<td>48: Dissertation</td>
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**10 External partners**
National Aerospace Laboratory NLR, Amsterdam

**11 Motivation for external partners**
Expertise in simulator- and simulation-based aviation training

**12 External financial support for the project**
See accompanying contract